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FIELD-ORIENTED INVESTIGATION OF CONVENTIONAL AND EXPERIMENTAL SHOTCRETE FOR TUNNELS

AUGUST, 1975

FINAL REPORT

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16. Abstract

The placement of shotcrete by the dry-mix process and the engineering properties of shotcrete, typically used for underground support, were investigated in detail. Processes and quality control aspects of shotcrete, previously taken for granted, were described, evaluated, and, where possible, quantified. Coarse-aggregate mixes of conventional shotcrete, steel fiber shotcrete, and regulated-set cement shotcrete were tested successfully underground using typical crews and equipment. Documentation included water-cement ratio, high-speed photographs of the airstream, x-rays of fibrous shotcrete, and special rebound tests that determined the change in rebound with thickness. The most important parameter affecting the measured value of average rebound was the total thickness shot. The process of rebound was described in detail qualitatively and in terms of newly-defined parameters. The economics of rebound was discussed.

Compressive, flexural, and pull-out tests were conducted through an age of six months. Moment-thrust tests were also conducted. Samples were rectangular prisms sawed from panels by a special method. Samples with a strength of 20 psi (0.14 MPa) were tested soon after shooting. This method of obtaining samples is recommended. A very cold shooting environment made the normal accelerator dosage ineffective. A homemade nozzle having an extra-long hose tip was found to be superior to conventional nozzles.

Shotcrete must be evaluated from a different perspective than used in concrete technology. Several new or improved rational concepts that can be used for evaluation of the engineering behavior of shotcrete with fast-set accelerators were presented.

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PREFACE

This research was supported by the Federal Railroad Administration, Department of Transportation through contract No. DOT FR 30022. The sponsor's technical representative was Mr. William N. Lucke during the planning and execution of the study and Mr. Russell K. McFarland while the study was being completed. The research is part of a much larger project being conducted by the University of Illinois at Urbana-Champaign for the sponsor under the overall direction of Dr. S. L. Paul who also contributed directly to every aspect of this research.

The study was planned and conducted by the senior author who was assisted by numerous consultants, staff, and administrative personnel without whom the project could not have been possible.

The field program was planned and carried out with the very capable assistance of Ronald A. Jones, University of Illinois, and Mr. Jan A. Blanck, A. A. Mathews, Inc. Mr. Blanck supervised all the field work and made many valuable suggestions and comments regarding the evaluation of the results. His encouragement and assistance were invaluable to the authors in developing a perspective for shotcrete practice and for needed shotcrete research. Mr. Warren Alvarez, who was in charge of field work for Granite Construction Company and nozzleman for all shooting, was the driving force that made the field work successful; he contributed greatly to field aspects of the program. Mr. Owen Richards conducted the pull-out tests.

The field program was made possible by the special interest shown by Mr. Frank L. Lynch, Washington Metropolitan Area Transit Authority (WMATA) whose decision to take an active interest in the program made the contractual arrangements possible. Mr. J. S. Bhore, Granite Construction Company, made special efforts to make the construction site and crews available.

Dr. John D. Bledsoe, A. A. Mathews, Inc., coordinated the contractual arrangements for all parties with the assistance of L. B. True and C. H. Arnold. Mr. John J. Kamerer, University of Illinois represented the University during all contract negotiations.

Dr. R. B. Peck was senior Co-Principal Investigator for the project. Dr. E. J. Cording paved the way for the field work through his research project at the site for WMATA. The field work was successful because of the coordination and cooperation of Dr. Cording and his team of experienced field engineers. Professor C. E. Kesler made many valuable suggestions regarding the field and testing aspects of the study.

Mr. Steven J. Hahn and Mr. Corwin E. Oldweiler made many important contributions in the planning, execution and preliminary analyses of the field studies. Mr. James W. Mahar enriched the study through his parallel efforts on other shotcrete research for this contract and his direct contributions both in the field and during subsequent phases of the study.

The enthusiastic work of numerous graduate students made the field work successful; their untiring efforts are greatly appreciated. Many have since graduated but they include Mark E. Alt, Dr. Gary S. Brierley, Bernard Bruss, Dr. Edgar Febres-Cordero, Dr. Harold C. Ganow, Dr. William H. Hansmire, David K. Keefer, Hobart H. MacPherson, Gary M. Mathes, Randall E. Ranken, Robert A. Robinson, Dr. Robert M. Semple, and Dr. Peter J. Tarkoy. Graduate students who contributed to the testing and analysis include some of those listed above and William W. Wuellner, Raymond J. Castelli, Frederico Montemayor, and I. Shimada. Mr. L. J. Jaudon, A. A. Mathews, Inc. assisted Mr. Blanck during the field study.

The project would not have been possible without the capable services of the Civil Engineering Shop and the Shop Director, Mr. Owen H. Ray. Shop personnel were invaluable in outfitting and mobilizing the field crew and in subsequent testing. In particular, Mr. Glen H. Lafenhagen, conducted both the high-speed photographic and x-ray studies and was an invaluable member of the field testing team. The versatile electronics gear for the portable testing machine was assembled by Mr. James N. Sterner.

The entire manuscript was typed capably and patiently by Mrs. Laura Hickman. Figures were drafted by Mr. Ronald L. Winburn. The manuscript was proofread and edited by K. M. Parker and D. L. Barrier.

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LIST OF SYMBOLS

A	Area
A_o	Area overhead
A_w	Area on wall
A_{o+w}	Total of overhead and wall area
b	Average width of beam specimen at failure section
d	Average depth of beam specimen at failure section
D	Internal diameter of pull-out ring, also maximum diameter of pull-out frustrum
E	Modulus of elasticity
e	Eccentricity
f'_c	28 day compressive strength of concrete obtained from testing 6 x 12 in. (15 x 30 cm) cylinders in a standard way
FRP	Fiber retention percentage
G	Point of compaction curve at glossy criterion
H	Height of pull-out frustrum
i	Sequential number of tarps in multiple-tarp rebound test
l	Span length in beam test
L	Long nozzle
M	Maximum moment
MDR	Material delivery rate; the following suffixes define an MDR for a specific constituent:

a	- air	fa	- fine aggregate
aw	- water in aggregate	g	- gravel
c	- cement	nw	- nozzle water
ca	- coarse aggregate	s	- sand
dm	- dry mix	w	- total water
f	- fibers		

NS	Designation of round steel fibers made by National Standard Steel Co.
OD	Outside diameter
OSF	Overshoot factor
P	Maximum applied load
R	Regulated-set cement
RAVE	Average rebound
$RAVE_{10}$	Average rebound measured in a 10-cm thick standard rebound test
RR	Rebound rate (see MDR for suffixes for each constituent)
RR_i	Rebound rate during stage i
RRR	Rebound rate ratio (see MDR for suffixes for each constituent)
RRR_{10}	Rebound rate during standard 10-cm thick rebound test
RRR_t	Rebound rate ratio at any given thickness t
RSUM	Total weight rebounded during some specific time of shooting or thickness (see MDR for suffixes for each constituent)
$RSUM_i$	Total weight of rebound collected during stage i
$RSUM_t$	Total weight of rebound collected to some given thickness, t
$RSUM_{10}$	Total weight of rebound collected during a standard 10-cm thick rebound test
S	Standard short nozzle
SSUM	Total weight shot during some specific time of shooting or thickness (see MDR for suffixes for each constituent)
$SSUM_i$	Total weight shot during stage i of a multiple rebound test
$SSUM_t$	Total weight shot to some given thickness, t
$SSUM_{10}$	Total weight shot during a standard 10 cm thick rebound test
t	Any thickness
t_c	Critical thickness

t_i	Thickness at end of stage i
T	Any time
T_c	Time of shooting to end of Phase 1 rebound at critical thickness
US	Designation of steel fibers with rectangular section made by U. S. Steel Co.
V	Any volume
V_{10}	Volume of material on rebound panel at end of 10-cm thick standard rebound test
W	Outside diameter of anchor washer of pull-out anchor that defines minimum diameter of pull-out frustrum
w/c	Water-cement ratio
WSC	Wettest stable consistency
YAVE	Average yield (see MDR for suffixes for individual constituents)
YR	Yield rate (see MDR for suffixes for individual constituents)
YR_i	Yield rate during stage i of a multiple rebound test
YRR	Yield rate ratio
YSUM	Total weight retained on wall during some specific time of shooting or thickness (see MDR for suffixes for individual constituents)
$YSUM_t$	Total weight retained on wall to some given thickness t
$YSUM_{10}$	Total weight of material retained on the wall during a 10-cm-thick standard rebound test
α_u	Upper airstream scatter angle
α_ℓ	Lower airstream scatter angle
α_c	Central angle of airstream
γ	Unspecified unit weight in place
γ_d	Dry unit weight
σ	Unspecified stress

σ_c	Unspecified compressive strength. Age at testing denoted by subscripts
	σ_{c2h} = compressive strength at 1 hour
	σ_{c1} = compressive strength at 1 day
	σ_{c28} = compressive strength at 28 days
	σ_{c180} = compressive strength at 6 months
σ_f	Unspecified flexural strength (see σ_c for nomenclature for age at testing)
σ_p	Unspecified pull-out strength (see σ_c for nomenclature for age at testing)
%	Percent
$\sim$	Approximately

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF STUDY

The results of a comprehensive investigation of the behavior of coarse-aggregate shotcrete are contained herein. The investigation included field and laboratory testing of conventional and experimental shotcrete. New test methods and field documentation procedures were developed to permit a detailed study of the mechanisms of the shotcrete process, and of the development of strength and other engineering properties of shotcrete with time. The results of the field test program were complicated because it was necessary to shoot in a near-freezing environment. Interpretation of these field test results required the development of new conceptual models or theories as well as the clarification or improvement of prevailing concepts about the engineering behavior of shotcrete. The new test procedures and the new concepts of engineering behavior form a substantial portion of the results of the study and they have become at least as important as the test results themselves since they substantially improve our understanding of the behavior of shotcrete.

1.2 IMPORTANCE OF APPLIED RESEARCH IN SHOTCRETE

Shotcrete has been defined as mortar or concrete conveyed through a hose and pneumatically projected at high velocity onto a surface (ACI 1966). In the past 10 years, shotcrete, especially coarse-aggregate shotcrete using the dry-mix process, has become a popular, practical, and important underground structural support. It is being used with success in progressively poorer and more challenging tunnel ground conditions. Significant and major applications of shotcrete are not confined just to tunnel support, but include: shafts for civil engineering and mining projects, support for coal and ore mines, stabilization of above-ground slopes, support for braced excavations, rehabilitation of tunnels, and support for large underground caverns such as subway stations and underground power houses. Many other applications exist for the fine-aggregate shotcrete of the gunite industry.

The technology of coarse aggregate shotcrete has changed only slightly since the acceptance of large aggregate in the last decade. An increasing scale of operations, a tighter economy, and a sharply increased competitive situation contribute to the increased use of shotcrete in progressively more challenging applications that tax the state of the art of the shotcrete industry for civil engineering projects.

The nature of the materials used, the equipment and the techniques of the application are readily amenable to significant improvement as a result of applied research programs. Because of an increased sense of awareness of the limitations of shotcrete and its needs for improvement, a considerable amount of work is being done both by federally-sponsored projects and by private industry. Primarily this development work concerns large aggregate shotcrete produced by the dry-mix and wet-mix processes.

1.3 SELECTED PROBLEMS FACED BY THE SHOTCRETE INDUSTRY

Several of the recent articles and reports on shotcrete have identified many of the key problems in shotcreting. Many of these problems were brought to a focus by the five-day-long conference under the auspices of the Engineering Foundation and sponsored by the American Society of Civil Engineers and the American Concrete Institute at South Berwick, Maine, in July of 1973 (ASCE 1974). Some of these problems relate to important quality-control aspects of mix design such as the compatibility between cement and accelerators and the optimum amount of accelerator to be used. Both of these aspects are reflected in the development of high-early strength and the reduction in 28-day strength with the use of accelerators. The very important and elusive factor of rebound is responsible for extremely high cost penalties. Other problems relate to the selection of shooting and backup equipment, the design of nozzles, and the operation of the equipment. One of the most important aspects in the shotcrete process is the training, experience, and constant interest and attention of the nozzleman necessary to produce a uniform quality product. This is especially true in the dry-mix process.

Important questions in the design of shotcrete linings include: when to use shotcrete, when should shotcrete be avoided, how thick should the lining be, how soon after excavation should shotcrete be placed, and how long the shotcrete will last and continue to provide support. There is growing and well-founded concern that shotcrete should seldom be used as the sole type of support and that, in almost every case, at least rock bolts should supplement the shotcrete. Clear evidence exists of the need for shotcrete with increased flexural or tensile strength and considerable post-crack resistance such as that which can be provided by shotcrete with steel fibers or shotcrete reinforced with mesh (Cording, 1974; Jones and Mahar, 1974). However, simple and proven rational design techniques for shotcrete applications are still needed.

Finally, there are safety considerations in the use of shotcrete, especially those with respect to the hazard of rebounding particles and the caustic nature of the materials.

1.4 RECENT RESEARCH ON SHOTCRETE FOR UNDERGROUND SUPPORT

A good summary of the state of the art of shotcreting and of the results of research in the mid-1960's is contained in a very valuable publication, "Shotcreting," (ACI, 1966). Another important summary of the technical aspects of the state of the art was presented by Lorman (1968). A significant paper which described the first case history of coarse-aggregate shotcrete for underground support in North America was presented by Mason (1970), in which the results of a considerable amount of research on the material properties and the behavior of shotcrete were given. A comprehensive state of the art of the design of shotcrete linings for tunnel support was presented by Deere, et al., (1969).

A significant laboratory research project was recently conducted by the Illinois Institute of Technology Research Institute on the physical properties and strength of shotcrete having different compositions and methods of placement. They presented the results of studies on strength and other physical properties for both wet- and dry-mix processes as well as regulated-set shotcrete. The details of this research are presented by Bortz, et al., (1973). while the results are summarized by Singh and Bortz (1974) and Anderson and Poad (1974). Other references on experimental shotcretes are given in Appendix A.

Since the Berwick Conference two important reports have been issued by the Corps of Engineers. The details of the use of shotcrete at New Melones Dam are reported by the Corps of Engineers (1974); earlier summaries of this project were given by Case (1974) and Reading (1974). The other report, Tynes and McCleese (1974), presents the results of a test program on wet and dry processes for both fine and coarse aggregate.

Many of the papers given at the Berwick Conference, although not necessarily 'funded" research, represent the result of effort of each of the authors and of the engineers and crew working with them to improve a product which they believe is a superior product. Although these are not studies by research-oriented agencies or institutions, their results are particularly valuable because they represent practical solutions to practical problems. In addition, several firms and agencies have conducted small-scale or laboratory tests on several experimental shotcretes. The next logical step was to conduct a research project on conventional and experimental shotcrete under actual field conditions, the major goal of this study.

1.5 SCOPE OF WORK

This study is the first of a series directed toward solving the important technical questions facing the shotcrete industry. It deals primarily with practical construction aspects of the equipment and materials used in shotcrete, the effects of variables on the end product in the tunnel wall, and on some of the geotechnical implications of these variables on shotcrete support.

The work consisted of field research on conventional and experimental shotcrete supplemented by laboratory tests and analyses. Conventional shotcrete is the typical coarse-aggregate dry-mix shotcrete used in the United States for support of civil-works tunnels. It is composed of 1/2 in. or 3/4 in. (12.7 or 19.5 mm) maximum size aggregate with approximately 6 to 8 bags per cu yd (340 to 450 kg per cu m) of Type I cement and fast-set accelerators. The two experimental shotcretes treated in this study are regulated-set shotcrete and steel fiber shotcrete, both of which have been considered promising for several years (Parker, et al., 1971). Regulated-set shotcrete, made with regulated-set cement, can achieve a compressive strength of about 1000 psi (6.9 MPa) or more in about one hour without additives. Steel fiber shotcrete contains thousands of 1 in. (25 mm) long needle-like steel fibers which provide higher flexural strength, improved ductility, and considerable post-crack resistance. Additional information on these experimental shotcretes is presented in Appendix A.

The purposes of the study were to conduct full-scale field research on shotcrete at an active civil engineering tunnel construction site and to demonstrate the practicality of the experimental shotcretes for routine construction by using the normal crews and equipment available to the contractor at the time the field tests were conducted. One major goal was to develop as much information as possible on the experimental shotcretes to provide a potential user a factual basis for his evaluation of their advantages and disadvantages. Naturally, a control of conventional shotcrete was required and the scope of work also included research on conventional shotcrete.

The original scope of work was divided into two classes: (1) the field investigation of variables affecting shotcrete application and, (2) the evaluation of the physical properties of the various types of shotcrete placed. These objectives are summarized in Table 1.1.

The field portion of this study was conducted in an underground station being constructed for the subway in Washington, D.C. Extensive observations and collection of field data were made during these field tests. Up through 7 days, strength tests were made on samples cut from test panels in a specially-equipped mobile testing facility located at the field site. A large number of panels and samples were then transported back to the Civil Engineering Department of the University of Illinois in Urbana-Champaign for more comprehensive laboratory testing of the samples shot in the field. The fulfillment of these objectives led to a critical assessment of selected aspects of shotcrete and to the formulation of conceptual models or theories regarding the engineering behavior of shotcrete.

The comments, studies, and conclusions are primarily derived for coarse aggregate shotcrete with fast-set accelerators. Although the results relate specifically to the dry-mix process, the concepts and some of the data will be valuable to users of all types and applications of shotcrete. Preliminary results from this study were given by Parker (1974).

1.6 ORGANIZATION AND METHOD OF PRESENTATION

There were several distinct phases to this investigation. First, there were preliminary studies that preceded the field work. Then the

TABLE 1.1

OBJECTIVES OF RESEARCH

I. FIELD INVESTIGATION OF VARIABLES AFFECTING SHOTCRETE APPLICATION

1. Gain experience and practical construction data in shooting new types of shotcrete including regulated-set shotcrete and shotcrete with different types and quantities of steel fiber.

2. Conduct research on selected problems with conventional shotcrete such as effects of water temperature, air pressure, nozzle design, and mix design.

3. Evaluate the causes and magnitude of rebound for different mix and shooting conditions. Document changes in rebound behavior with build-up of shotcrete on wall. (Overhead shooting was not within the scope.)

4. Conduct a photographic study of the airstream of various nozzle configurations and of various types of shotcrete by means of a high speed stop-action camera.

II. EVALUATION OF PHYSICAL PROPERTIES

1. Determine strengths and the related stress-strain relations

   a) compressive
   b) flexural
   c) pull-out
   d) moment-thrust interaction

2. Evaluate fresh shotcrete specimens for cement content, grain size, and water content of the shotcrete in the wall and of the rebound.

3. Study retention, distribution, and orientation of fiber.

4. Evaluate other physical properties such as shrinkage characteristics and unit weights.

shooting, observations, and tests were conducted in the field. Laboratory investigations were then undertaken to supplement the information that was obtained in the field. Evaluation of the results included studies concerning the field operations, physical properties, strengths, and geotechnical implications of the results. Correlations with previous laboratory research and data collected on actual field projects were attempted. All of these items are somewhat interrelated in the sense that the preliminary studies bear on the results of the laboratory and field tests and in the evaluation of the final results. Also physical properties should correlate with aspects such as rebound and strength. Throughout the report, the reader is referred to other sections of the report which are also pertinent to the subject.

The entire test program is described in Chapter 2. The results of the field work, except for rebound studies, are presented and discussed in Chapter 3. A critical assessment of rebound of shotcrete is made in Chapter 4 and the results of a high-speed photographic study of the airstream are presented in Chapter 5. An evaluation of water and cement content of fresh shotcrete is given in Chapter 6 and Chapter 7 contains the results of an evaluation of fiber content, orientation and distribution. Chapter 8 is a description of the strength testing program. Compressive strength, flexural strength, load-deformation relations, moment-thrust interaction tests, and pull-out strength are presented in Chapters 9, 10, 11, 12 and 13 respectively. A summary of the results and conclusions of the study are contained in Chapter 14.

As with any large testing program, a large mass of data was collected. In order to make the report more readable and more useful, many of the detailed tables and plots of data have been assembled in the Appendices. In the text the test methods are described in general terms, the data are summarized, and various correlations are discussed in detail along with the limitations of the data. The reader is referred to the Appendices for the detailed tabulations and plots of results. In some cases selected tables and figures contained in an appendix are reproduced in the body of the report to aid the discussion.

CHAPTER 2

DESCRIPTION OF TESTING PROGRAM

2.1 GENERAL OBJECTIVES OF FIELD PROGRAM

The data to be collected in the field tests were intended to provide information needed to improve conventional shotcrete materials, equipment or techniques. They were also to demonstrate the practicality of the experimental shotcretes for routine construction using the normal crews and equipment available to the contractor at the time the field tests were conducted. The field program was conducted so that conditions for successive tests were intended to be the same as those in shooting the control or standard mix with the exception of the one variable to be investigated. As will be seen, this was not always possible with the existing equipment and field conditions because of the interdependence of variables. However, there were a sufficient amount of data collected on the equipment, the materials, and the shooting conditions to provide a means for explaining differences in observed or measured results that were not anticipated or could not otherwise be explained.

2.2 PLANNING OF FIELD WORK AND PRELIMINARY TESTING

2.2.1 GENERAL

Preceding the field work, considerable planning and preliminary testing were necessary. This preparation included evaluation of some of the most important practical problems in shotcrete, and development of new test procedures and test equipment. The scope of the field work was formulated in detail while a search for a suitable test site and contractor was conducted. Once a test site and contractor were chosen, laboratory tests were made on samples of the materials to be used, testing equipment was checked and calibrated, test procedures were verified and an extensive training program was conducted to prepare the University testing team. Finally, extensive legal and contractual negotiations were necessary.

2.2.2 SELECTION OF TEST SITE

Several test sites were considered. Ultimately, the Dupont Circle Station project, Contract 1A0044 (A4b), of the Washington Metropolitan Area Transit Authority (WMATA) was selected as the most appropriate test site. On this project, shotcrete was being used extensively as part of the temporary and final support system. Another field research project on the behavior of the rock and the support system of the Dupont Circle Station was already being conducted by the Civil Engineering Department of the University of Illinois at Urbana-Champaign. Thus, full-time University personnel were at the job site and had established a good working relationship with the Contractor, Granite Construction Company, the Resident Engineer, A. A. Mathews, Inc., and WMATA. This extant instrumentation research project was being funded by WMATA.

Preliminary contacts were made with A. A. Mathews, Inc., early in 1973. Following the selection of the A4b project as the most suitable testing site, a verbal expression of interest was obtained from Granite Construction Company in the Spring of 1973. It was hoped that field testing could be completed by the end of the summer to take advantage of the favorable summer weather.

2.2.3 CONTRACTUAL ARRANGEMENTS

The field program required the cooperation of the Federal Government, a rapid transit authority, a state university, a private consulting firm, and a private contractor. Legal arrangements were complex and contracts were required with all parties. Negotiations and arrangements to accomplish this goal were difficult and time consuming.

Contractual negotiations took about six months to complete. None of the parties had any previous experience in setting up a contract of this type and a large number of legal obstacles had to be surmounted for the first time. One of the accomplishments of the program was the successful negotiation of contracts among the parties to conduct field research on an on-going construction job.

A formal contract was prepared and signed between the University and A. A. Mathews, Inc., who then acted in the capacity of a Resident Engineer for this research project during negotiations with the contractor and during preparations for the field work. The firm also provided field supervision and inspection personnel during the shooting program.

Legal negotiations between the University and the Contractor were difficult because of potential interference to regular station construction. Several types of agreements were investigated. In the meantime, permission to use the construction site was requested from WMATA, the owner, who elected to take an active interest in the study and offered to administrate the test program by issuing a change order to the regular station construction contract already in effect between WMATA and the Contractor. This arrangement was acceptable to both the University and the Contractor. The provisions of the existing contract for station construction became the basis of the supplemental agreement for the test program. The Contractor, the University, and the Resident Engineer discussed and agreed upon the details of the test program. Legally, the University dealt directly with WMATA who in turn passed the specific provisions for the test program to the Contractor by a change order. Eventually, the final agreement between WMATA and the University was a 1/2 page Letter of Understanding with a "not to exceed figure", and an attached statement of work and unit price schedule.

The agreement was finally signed on November 9, 1973 and shooting began November 10, 1973. The cooperation of all the parties permitted sufficient preparations to be made in anticipation of the signing of the legal documents so that field testing could begin immediately. Unfortunately, the time required to finalize the contract extended the work into winter months; a fact which had significant influence on the test results.

The agreement called for research work to be conducted only on a "non-interference basis" to the station construction work. This basically limited research work to weekends and required complete mobilization and demobilization of test equipment to be accomplished during the weekend periods. A second requirement was that experimental materials could not become part of the permanent lining of the station. This requirement minimized the shooting against genuine rock walls; only temporary walls or faces that eventually would be removed by blasting could be used.

2.3 CONSTRUCTION ENVIRONMENT

2.3.1 DESCRIPTION OF SITE

All field work was conducted in Dupont Circle Station shown in Fig. 2.1. The station was excavated in a mica schist and was driven in multiple drifts using drill and blast methods. The arch was supported by steel ribs and shotcrete whereas the vertical side walls were supported by rock bolts and shotcrete.

At the time the shotcrete research program began, excavation of the Station was in its latter stages. The top heading was completed and about one-half of the bench was finished to invert level. The remainder of the bench was being blasted out at the time the shotcrete field work began in November. Cushion benches, 17 ft wide (5.2 m) and 20 ft high (6.1 m) contained the only temporary rock surfaces which could be shotcreted with experimental materials. Figure 2.2 is a photograph of the blasted face of a cushion. Since these faces were advanced during the week, there was not enough time for curing so that cores could be obtained in order to compare the strength of shotcrete sprayed on rock surfaces with that shot on wood panels.

For the first two of the four days of shooting, a construction shaft was the only practical access for all equipment and material, all of which had to be lowered into the shaft by means of a crane. More than 100 man hours were required for mobilization and slightly less than that for demobilization. All of the mobilization had to be done during the off hours or lightly scheduled times of the construction of the station to avoid interference with the normal work crews. By January, when the last two days of shooting were performed,

FIG. 2.1 TEST SITE, DUPONT CIRCLE STATION

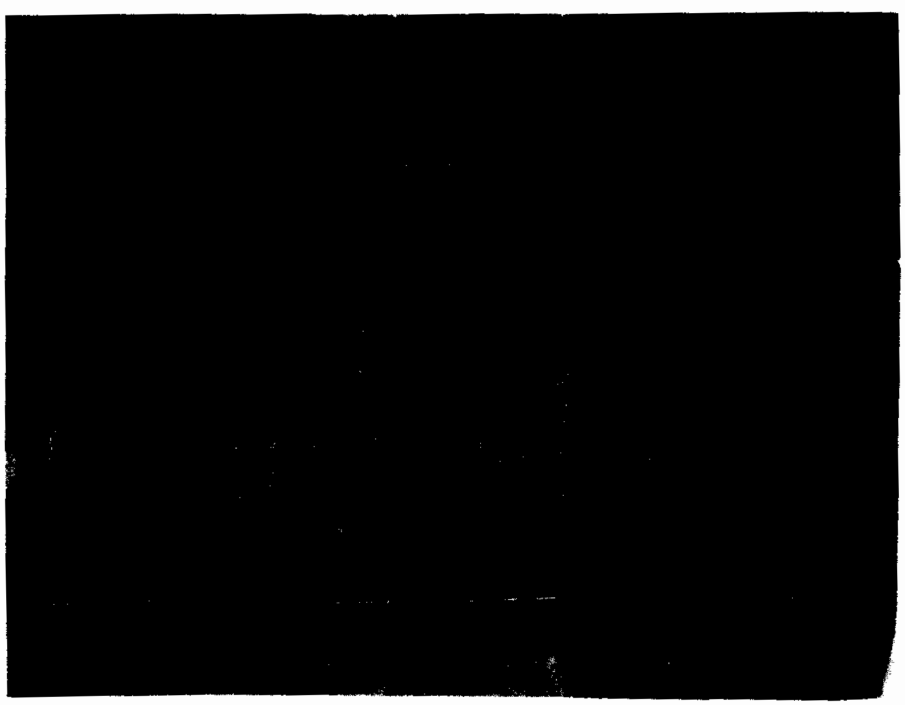


FIG. 2.2 TEMPORARY ROCK FACE OF SIDE WALL CUSHION

access to the station was also available through the Rock Creek Tunnel because the center drift of the bench had reached an existing tunnel which had a portal approximately one mile north of the station. Much of the material was brought to the test area by rubber-tired construction vehicles. This greatly reduced mobilization time.

In the specific shooting area, normal tunnel lighting was supplemented by four 1000-watt mercury-vapor lamps placed on tripods specially prepared by the Contractor.

2.3.2 TEMPERATURE CONDITIONS

The air temperature at the ground surface was cold (roughly 40 to 50°F; 5 to 10°C) on the first two days of shooting and below freezing (approximately 20°F; -7°C) for the last two days of shooting. During the coldest days, the tunnel temperature ranged from 30° to 60°F (-1 to 15°C) and space heaters were used to warm the areas where shooting and testing took place. Nevertheless, the environmental conditions for high quality shotcrete were not ideal. Therefore, consideration was given to postponing or cancelling shooting on the days when temperatures were too cold. However, because of the enormous amount of mobilization already completed at the time these decisions had to be made together with the possibility that there were no other times within the remaining contract period which would be suitable, it was decided to carry out the work and at least document the capabilities of shotcrete placed during cold weather.

2.4 EQUIPMENT AND MATERIALS

2.4.1 GENERAL

Since one of the major goals was to demonstrate the use of the experimental shotcrete with equipment and materials normally associated with civil-works tunnels, all of the experimental shotcrete mixes were batched, mixed, transported, and gunned with the same contractor's equipment normally used for placing shotcrete in the station. Special procedures or equipment were seldom used. A list of the equipment used and some of their details are assembled in Appendix B.

The cement and aggregates used in shotcreting the station at the end of the Friday "graveyard" shift were also used in the test program, except where regulated-set cement was substituted for portland cement and accelerator. Data describing these materials are also contained in Appendix B. All shotcrete, including both fiber and regulated-set mixes, contained both coarse, 1/2 in., (1.3 cm) maximum, and fine aggregate.

2.4.2 EQUIPMENT

STORAGE, BATCH, AND CONVEYING EQUIPMENT

Type I cement, coarse aggregate, and fine aggregate were stored in the Contractor's bulk-storage bins located at street level. The top of the aggregate bin was open and aggregate was exposed to weather. Though the aggregate bins had provisions for heating, the temperature of the aggregates were generally close to the outside temperature depending on the rate of usage of material. The aggregate was usually brought from the source on Friday night and was sometimes frozen on arrival. Approximately one day was required for the heaters to warm the entire bin to acceptable temperatures, but none of the aggregates were frozen at the time of their use. The nozzle-water temperature before heating was typically between 45 and 55°F (7 and 13°C); most of the water was heated to provide an earlier set.

Batching was performed in the station construction area. Materials were delivered through chutes to the weigh hopper which had been calibrated a few weeks before the field test program began. Mixing was accomplished in a 2 cu yd (1.5 cu m) pug-mill mixer having two counter-rotating paddle-blades as shown in Fig. 2.3. The mixer discharged the dry mix into the scoop of a front-end loader that transported the dry mix to the shooting area.

SHOTCRETE RIG

Two shotcrete machines, an accelerator dispenser, a 1-1/2 to 2 cu yd (1.15 to 1.5 m^3) holding hopper and their accessories were mounted on the skid rig shown in Fig. 2.4. A continuous auger moved material from the holding hopper past the powder-type accelerator dispenser and into one of the two shotcrete machines. The entire rig was air-operated; the speed of the auger, accelerator dispenser, and machine could be controlled independently. The accelerator dispenser operated from the same air supply as the feed auger so that the accelerator dispensing stopped when the feed screw stopped. However, the feed screw could be throttled independently of the accelerator dispenser, a fact that affected the test results for the intermittent shooting and slow-feed-type operations sometimes necessary for these tests.

FIG. 2.3 PADDLE WHEEL OF PUG MILL MIXER

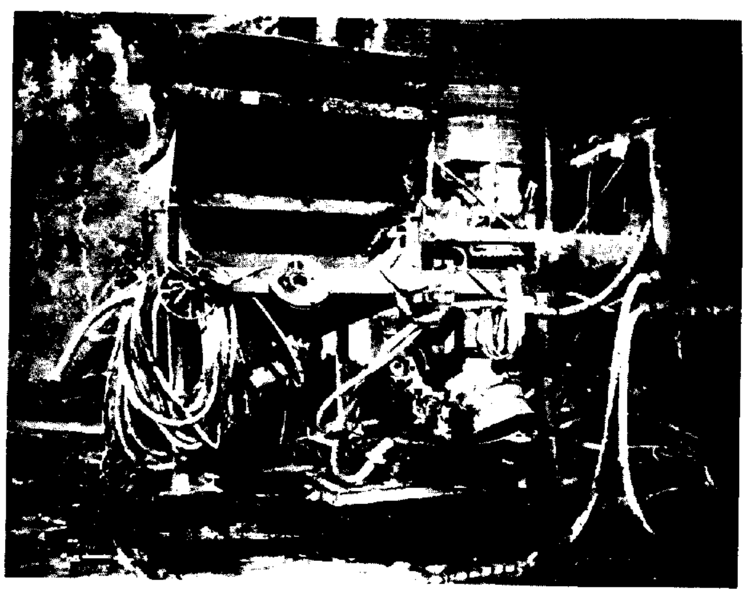


FIG. 2.4 SHOTCRETE RIG

SHOTCRETE MACHINE

The shotcrete machine was a Meynadier dry-mix machine, Model GM 57. Its moderately slow-rotating barrel turned about 15 revolutions per minute. The dry mix in each of the 9 cylinders of the barrel was blown into the material hose during each revolution. A screen placed over the hopper kept balls of fiber from entering the gun.

HOSES AND NOZZLES

Material hoses were 2-in. (50-mm) diameter and ranged from 50 to 150 ft (15 to 45 m) long. Three different nozzles were used; they were a short nozzle tip with a single water ring, a long nozzle tip with a single water ring, and a short nozzle tip with a double water ring. These nozzles and component parts are illustrated in Fig. 2.5. The conventional short nozzle had a single water-ring in the nozzle body and a short 15 in. (0.38 m) hose tip as illustrated in Fig. 2.5a. The single water ring had six, 1/16 in. (1.6 mm) diameter holes oriented normal to the surface and equally spaced about the ring. Figure 2.5c is a cross section of this nozzle.

About 10 mixes were shot with a homemade "long nozzle" that consisted of the same conventional nozzle body with a single water ring except that a 13.5 ft (4.1 m) long, 2-in. (50-mm) diameter hose served as a tip as shown in Fig. 2.5b.

The third nozzle type was a new design (Valencia, 1974) containing two water rings in the same nozzle body as shown in Fig. 2.5d. Unfortunately, the high water pressure recommended by the developer of the double water ring

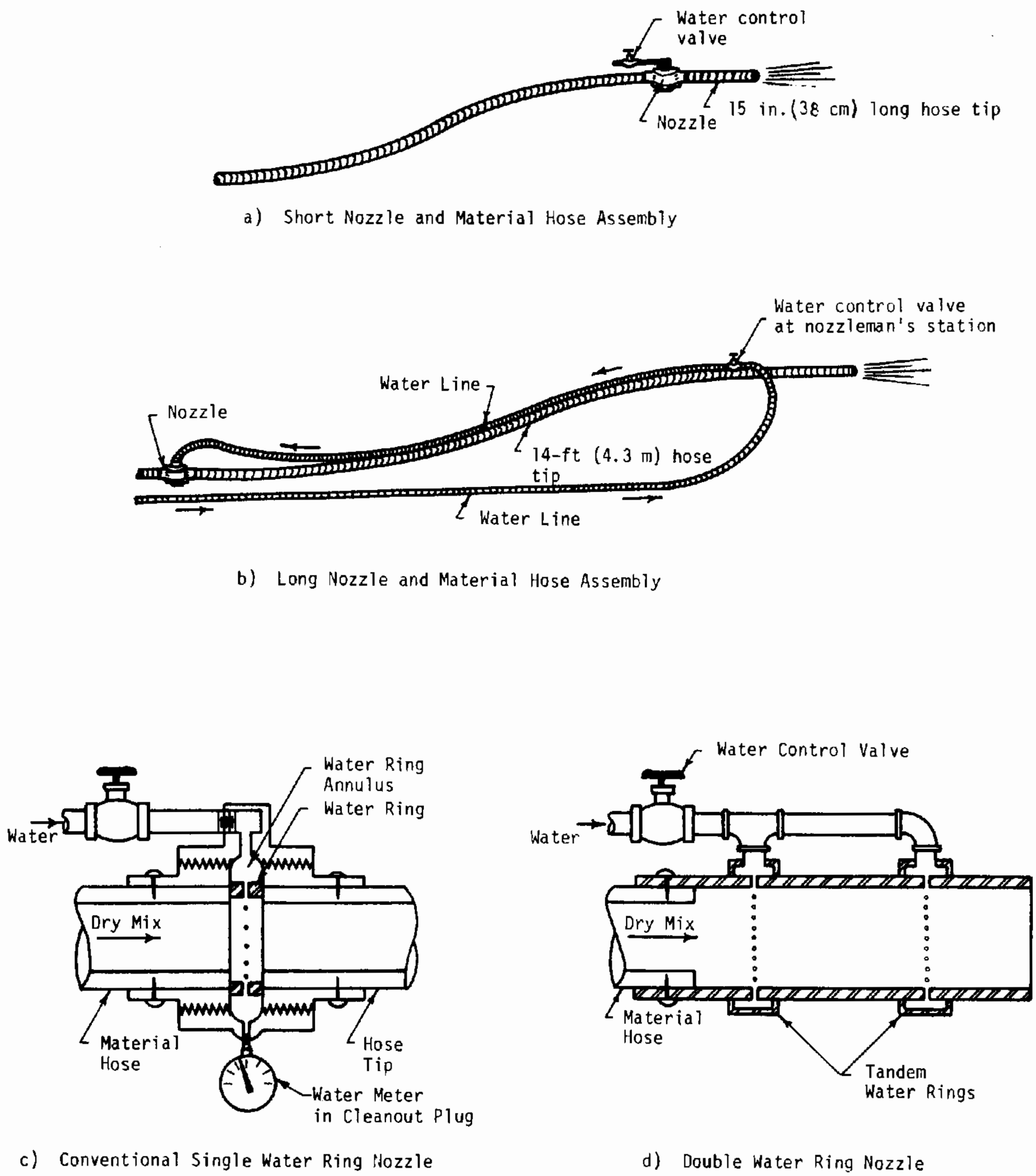


FIGURE 2.5 ARRANGEMENT FOR SHORT AND LONG NOZZLES AND DETAILS OF THE BODIES FOR CONVENTIONAL AND DOUBLE WATER RING NOZZLES

nozzle could not be achieved and the results of the one mix shot with this nozzle cannot be considered a representative test of the nozzle.

MISCELLANEOUS EQUIPMENT

The hot water for regulated-set mixes, and other mixes on cold days, was provided by two 80-gallon (300 ℓ) capacity fast-recovery-type electric water heaters similar to those used for hot water heating in homes. They were wired to provide the fastest rate of heating possible, consistent with safety standards. For the first two days of shooting, these heaters were brought into the tunnel and connected to the shotcrete water line each time. For the third and fourth days, however, the heaters were both placed into a small trailer and were hooked up prior to pulling it into the tunnel. Figure 2.6 is a photograph of this equipment. The hot water was mixed with cold water by

FIG. 2.6 HOT WATER HEATERS

a temperature regulator and mixing valve. The temperature, volume, and pressure of the mix water were monitored during the shooting of each batch at one-minute intervals. The two heaters provided a total capacity of 160 gallons (605 ℓ) at 170°F (77°C) plus the recovery of the heaters. While the heaters were heating the water, a small pump circulated water between them. A sketch of the water heater hookup and of the temperature regulator and monitoring box is shown in Fig. 2.7.

2.4.3 MATERIALS

CEMENTS AND ACCELERATORS

The Type I cement was not from the same source for all four days of shooting because of a general shortage of cement at that time. Hence, the contractor used whatever kind of cement that was available and still consistent with accelerator compatibility. Specific data on the cements used are contained in Appendix B. For the first two days of shooting, Type I cement "A" was used. However, since the first two days of shooting took place two weeks apart, the cements used were from different batches. This does not present a serious problem for strength considerations because the comparative strength tests were made mostly on shotcrete samples gunned on the third and fourth days of shooting. Since the third and fourth days were on the same weekend, all of the Type I cement "B" in these mixes was from the same truck.

Type I cement was batched from bulk storage. Powder accelerator was dispensed at the nominal rate of 3 percent by weight of cement, but because of problems the actual percentage ranged from 3 percent to 8.4 percent.

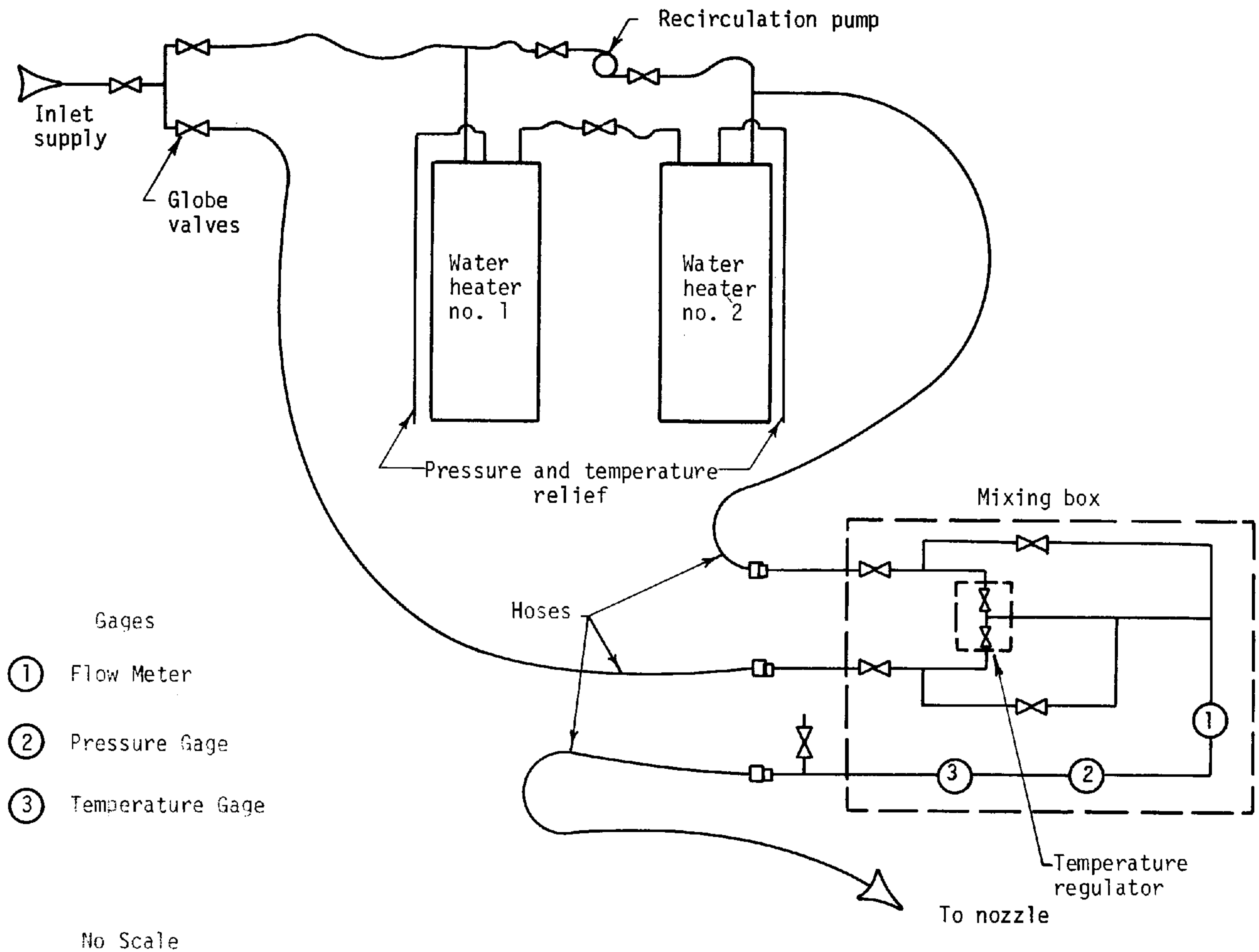


FIG. 2.7 SCHEMATIC OF WATER HEATING AND MEASURING SYSTEM

Two separate shipments of regulated-set cement (Cement "R") Burn No. 4 were shipped to the site. The initial shipment was used during the first two days of shooting and the second shipment during the third and fourth days. The manufacturer has confirmed that both shipments should be nearly identical. Regulated-set cement was provided in 94 lb (43 kg) bags.

Average chemical and physical properties and results of compatibility tests of Type I and of regulated-set cements are given in Appendix B. Gillmore Needles tests on Cement B and Accelerator A resulted in an initial set of 3 minutes and a final set of 10-1/2 minutes when 4 percent accelerator was used and tests were conducted at room temperature. However, when tested at 40°F (4.5°C) these set times increased to 4-1/2 minutes and 33 minutes, respectively. Good compatibility is considered to require an initial set time of 3 minutes and a final set time of 12 minutes (Blanck, 1974). These results and their effect on other tests are discussed elsewhere.

AGGREGATES

Fine and coarse aggregates were processed aggregates from pits in Silver Hills, Maryland. The fine aggregate basically fell between the No. 4 and No. 100 sieves (4.76 and 0.150 mm). The maximum nominal size of the coarse aggregate was 1/2 in. (13 mm). Grain size data are contained in Appendix B.

FIBERS

Most of the fiber mixes shot for this project contained rectangular-shaped fibers 0.010 x 0.022 x 1 in. (0.25 x 0.56 x 25 mm) made by U.S. Steel Company, and designated as US fibers. Some mixes contained round fibers 0.016

in. (0.41 mm) in diameter by 1-in. (2.5 cm) long made by National Standard Steel Company, and designated as NS fibers.

2.5 MIX DESIGNS

Most mixes were prepared in equivalent one-cubic-yard (0.76 cu m) batches. The standard mix design for research purposes was selected as that being used on the station construction, a 7-1/2-bag (705 lb, 320 kg) mix as shown in Table 2.1. The actual batch proportions for each of the mixes shot for strength testing are given in Appendix C both in terms of weight and in terms of percentages of the total dry weight. Other mixes generally conformed to the standard mix design. The approximate or nominal cement content for each mix is given in its Mix Designation code described in Section 2.6.

TABLE 2.1

STANDARD MIX DESIGNS

	Standard conventional and regulated-set shotcrete batch weights lb (kg)	Standard steel fiber shotcrete batch weights lb (kg)
Cement	705 (320)	705 (320)
Fine aggregate	1550 (704)[1]	1485 (675)[1]
Coarse aggregate	1550 (704)[2]	1440 (655)[2]
Fibers		130 (60)
Total	3805 (1730)	3760 (1710)

Note: [1]Includes 5.5-8.5% moisture
[2]Includes 1.5-2% moisture

The standard mix design for steel fiber mixes was similar to that of the conventional shotcrete mixes except that fibers were added and the aggregate quantities were adjusted slightly as shown in Table 2.1. Generally, the total batch weight was maintained to within 100 lb (45.4 kg) by reducing the amount of both fine and coarse aggregate. When changes were made to the standard mix designs to evaluate the effects of mix proportions on shotcrete properties, an attempt was made to maintain the 3800 lb (1727 kg) batch weight to within about a 100 lb (45.4 kg).

2.6 SHOOTING PROGRAM

The focus of the program was the field work which consisted of four separate days of shooting listed in Table 2.2. For ease of reference they will be referred to as shooting Day I, II, III and IV.

TABLE 2.2

DATES OF SHOOTING

Day I	November 10, 1973
Day II	November 24, 1973
Day III	January 12, 1974
Day IV	January 13, 1974

Each shooting day consisted of an eight-hour shift. Specific goals were established for each day. Day I was devoted to evaluation of rebound under different conditions as well as to the initial trials to give the shotcrete crew experience with regulated-set and steel fiber shotcrete. Day II consisted of additional shooting of rebound tests, special shooting of rock boulders to evaluate shrinkage, the effect of clay gouge and slickensides on shotcrete-rock bond, and some initial strength testing on regulated-set cement and conventional cement shotcrete.

Days III and IV consisted primarily of the comparative strength test program. On Day III, the primary comparison was between conventional and regulated-set cement shotcrete. Day III also included some initial testing of the steel fiber shotcrete in preparation for Day IV. On Day IV a new long nozzle and hot nozzle-water were used. The primary comparison was between conventional and various types of steel fiber shotcrete.

A control mix of conventional shotcrete was shot at the beginning of each day. Each successive mix was to differ from this control mix by one parameter, usually in the batch design or in a shooting condition. The nozzleman was instructed to shoot good quality shotcrete, i.e., the water-cement ratio, nozzle distance, etc., were controlled by the nozzleman. The variables that were changed intentionally during the test program are listed in Table 2.3; there were other minor conditions that changed between tests that could not be controlled during shooting.

The most significant variations in the mixes were the cement content, cement type, mix water temperature, type of nozzle, fiber content and type of fiber. A code has been developed to assist the reader in immediately recognizing the significant features of each mix. Each time a batch or a portion of a batch was shot for a different purpose it was arbitrarily called a different "mix" and was given a sequential number for identification. Thus, the first mix batched on Day I was number 1 and mixes were numbered consecutively

TABLE 2.3

CONDITIONS CONTROLLED AND CHANGED INTENTIONALLY DURING FIELD TESTS

Mix conditions varied	Shooting conditions varied
1. Cement content	1. Type of nozzle
2. Cement type	2. Mix water temperature
3. Ratio of coarse to fine aggregate	3. Air pressure at gun
4. Fiber content	4. Nature of surface shot
5. Fiber type	

through Mix 45 at the end of Day IV. Numbers from 1 through 45 were used with the exception of Mixes 32, 36, 37, 41 and 44 which were never shot since the planned schedule could not always be followed. In order to aid the reader, a code is added to the mix number to show the primary conditions of the mix in an abbreviated form. The code shown in Table 2.4 will be called the "Mix Designation".

Tables 2.5a through 2.5d summarize the pertinent data for each of the four days of shooting. Each table lists the objectives for the day, all the mixes shot that day, and the conditions under which the mixes were shot. The various comparisons possible for evaluation of this program together with comments about the applicability of the comparison are given in Table 2.6. The large number of variables that affected the results prohibits unrestricted comparison between mixes.

TABLE 2.4

EXPLANATION OF MIX DESIGNATION NOMENCLATURE

*34-7½I-60S-1US-25CA

- 25CA — % coarse aggregate when not 50%
- US — Type of Fibers: US = U.S. Steel Co.; NS = National Standard Co.
- 1 — Nominal percentage of fiber by volume
- S — Nozzle type: S = standard short nozzle; L = long nozzle; D = double water ring nozzle
- 60 — Nominal temperature of mix water in degrees fahrenheit
- I — Cement type: I = Type I; Cement A for Days I and II, Cement B for Days III and IV; R = Regulated-set cement
- 7½ — Nominal cement content in bags per cubic yard
- *34 — Mix number (an asterisk indicates a mix which was subjected to substantially more testing than other mixes)

TABLE 2.5a

SUMMARY OF SHOTCRETE FIELD TESTING: SHOOTING DAY I

Day Shift, Saturday, November 10, 1973

OBJECTIVES:

Extensive tests on rebound of shotcrete under various conditions.
Preliminary shooting of reg-set and steel fiber shotcretes.
Give crews experience with experimental shotcretes.

MIXES SHOT:

All are 7½-bag[1] standard-mix conventional shotcrete unless otherwise shown

Mix Designation[2]	Description and Purpose	
1-7½I-45S	"Butter up" and adjust equipment.	
2-7½I-45S	Measured rebound for 40 psi (280 KPa) air pressure.	(Series to evaluate effect of air pressure on rebound)[3]
3-7½I-45S	Measured rebound for 30 psi (210 KPa) air pressure.	
4-7½I-45S	Measured rebound for 55 psi (380 KPa) air pressure.	
5-7½I-45S-1US	Preliminary shooting of USS steel fiber shotcrete, measured rebound (compare to Mix 2).	
6-7½I-45S-1½NS	Preliminary shooting of NSS steel fiber shotcrete, measured rebound (compare to Mixes 2 and 5)	
7-7½R-110S	Preliminary shooting of 7½-bag regulated set shotcrete, measured rebound (compare to Mix 2)	

SHOOTING CONDITIONS:

Standard short nozzle; hose: 50 ft (15.2 m), 2 in. (51 mm) diameter
Water temperature: Natural = 45 F (7.2 C), Water not heated except for reg-set mix no. 7 which was heated to 110 F (43.3 C)
Air pressure: 40 psi (280 KPa) except where noted

MIX CONDITIONS:

Cement: Type I Cement "A"; Cement "R" for Mix 7
Sand: 5½ percent moisture
Gravel: 1½ percent moisture
Aggregate temperature = 40 to 45 F (4.4 to 7.2 C)

ENVIRONMENTAL CONDITIONS:

Air temperature in Tunnel 40 F (4.4 C)
Air temperature outside tunnel 33 to 43 F (.6 to 6.1 C)

NOTES:

1 Standard mix contained 7½ bags of cement at 94 lbs per bag (43 kg) (Table 2.1)
2 See Table 2.4 for key to mix designation code.
3 Intended comparisons are in parentheses. Other uncontrollable conditions sometimes made intended comparisons invalid. See Table 2.6.

TABLE 2.5b

SUMMARY OF SHOTCRETE FIELD TESTING: SHOOTING DAY II

Day Shift, Saturday, November 24, 1973

OBJECTIVES:

Additional rebound tests of shotcrete against natural rock surfaces and against specially prepared panels. Shotcreting of boulders for detailed observations of shooting effects on gouge on joint surfaces and for shrinkage measurements. Preliminary strength tests on conventional and regulated-set shotcretes.

MIXES SHOT:

All mixes are 7½-bag[1] standard-mix conventional shotcrete unless otherwise shown

Mix Designation[2]	Description and Purposes	
8-7½I-60S	"Butter up" and adjust equipment.	
9-7½I-60S	Rebound measured from blasted vertical rock wall.	
10-7½I-60S	Preliminary shooting of panels for strength tests; shotcrete laminated, so discontinued test early.	
11-7½I-60S	Rebound measured from sloping rock surface; 45 psi (310 KPa).	
12-7½I-60S	Rebound measured from sloping rock surface; 35 psi (240 KPa).	
13-7½I-60S	Strength and shrinkage test panels shot at 45 psi (310 KPa). (strength not tested)	
14-7½I-60S	Strength and shrinkage test panels shot at 45 psi (310 KPa). (strength representative of Mix 13)	
15-7½I-60S	Shot boulders for shrinkage measurements.	
16-7½I-60S	Mix shot for high-speed photographic studies.	
	(Following mixes are 9-bag regulated-set shotcrete.)	
17-9R-60S	Rebound measurement for mix using 60 F (15.6 C) mix water.	Series to determine optimum temperature for Reg-Set.[3]
18-9R-80S	Rebound measurement for mix using 80 F (26.7 C) mix water.	
19-9R-100S	Rebound measurement for mix using 100 F (37.8 C) mix water.	
20-9R-120S	Rebound measurement for mix using 120 F (48.9 C) mix water.	
21-9R-100S	Strength and shrinkage test panels shot at 45 psi (310 KPa).	

SHOOTING CONDITIONS:

Standard short nozzle; hose: 100 ft (30.5 m), 2 in. (51 mm) diameter
Water temperature: Natural 58 F (14.4 C). All mix water heated to 60 F (15.6 C) except regulated-set mixes 18-21 which varied from 60 to 120 F (15.6 to 43.3 C)
Air pressure: 45 psi (310 KPa) except where noted

MIX CONDITIONS:

Cement: Type I Cement "A"; Cement "R" for Mixes 17-21
Sand: 5½ percent moisture
Gravel: 1½ percent moisture

ENVIRONMENTAL CONDITIONS:

Air temperature in tunnel 60 F (15.6 C)
Air temperature outside tunnel 50 to 58 F (10 to 14.4 C)
Relative humidity in tunnel = 80 percent

NOTES

1 Standard mix contained 7½ bags of cement at 94 lbs per bag (43 kg) (Table 2.1)
2 See Table 2.4 for key to mix designation code.
3 Intended comparisons are in parentheses. Other uncontrollable conditions sometimes made intended comparisons invalid. See Table 2.6.

TABLE 2.5c

SUMMARY OF SHOTCRETE FIELD TESTING: SHOOTING DAY III

Day Shift, Saturday, January 12, 1974

OBJECTIVES:

Shoot comparative panels for testing of strength and other physical properties of several different mixes of conventional and regulated-set shotcretes. Make preliminary tests on steel fiber shotcrete.

MIXES SHOT:

All mixes are 7½-bag[1] standard-mix conventional shotcrete unless otherwise shown. Rebound measurements and stop-action photos taken for most mixes.

Mix Designation[2]	Description and Purpose	
22-7½I-60S	"Butter up" and adjust equipment.	
*23-7½I-60S	Conventional shotcrete. CONTROL for this day of shooting.	
24-7½I-60D	Same as Mix 23 but with new nozzle with 2 water rings in same body.	
25	(NOT SHOT UNTIL DAY IV)	
26	(NOT SHOT UNTIL DAY IV)	
27-7½R-100R. . . .	Practice shooting reg-set. Same as Mix 23 but reg-set cement plus 100 F (37.8 C) mix water.	
*28-7½R-100S. . . .	Regulated-set shotcrete strength panels; same as Mix 27. (compare with Mix 23)	(Compare cement content)[3]
29-6½R-100S. . . .	Regulated-set shotcrete strength panels; same as Mix 27 but with only 6½ bags[1] cement.	
30-8½R-100S. . . .	Regulated-set shotcrete strength panels; same as Mix 27 but with 8½ bags cement (compare with Mix 28)	
31-7½R-60S	Regulated-set shotcrete strength panels; same as Mix 27 but with 60 F (15.6 C) mix water. (Compare with Mix 28 for effect of mix water temp.)	
32	(NEVER SHOT)	
33-7½I-60S-1US. . .	Same as Mix 23 but with 1 percent USS steel fiber (compare with Mix 23)	
34-7½I-60S-1US-25CA .	Same as Mix 33 but reduced percentage of coarse aggregate to 25 percent (compare with Mix 33)	

SHOOTING CONDITIONS:

Standard short nozzle (except Mix 24); Hose: 150 ft (46 m), 2 in. (51 mm) diameter
Air pressure at manifold generally 60 psi (415 KPa)
Water temperature: Natural 48 F (9 C). Mix water heated to 60 F (15.6 C) except reg-set mixes no. 27-30 which used 100 F (37.8 C) mix water

MIX CONDITIONS:

Cement: Type I, Cement B; Cement R for Mixes 27 through 31, temperature 47 F (8 C)
Sand: 8½ percent moisture; Gravel 2 percent, aggregate temperature 55 F (13 C)

ENVIRONMENTAL CONDITIONS:

Air temperature in tunnel 39 to 43 F (3.9 to 6.1 C)
Relative humidity in tunnel 86 percent
Air temperature outside tunnel 35 to 39 F (1.7 to 3.9 C)

NOTES:

1 Standard mix contained 7½ bags of cement at 94 lbs per bag (43 kg) (Table 2.1)
2 See Table 2.4 for key to mix designation code.
3 Intended comparisons are in parentheses. Other uncontrollable conditions sometimes made intended comparisons invalid. See Table 2.6.
* Mixes selected in advance to have special and more comprehensive studies conducted on strength and other physical properties.

TABLE 2.5d

SUMMARY OF SHOTCRETE FIELD TESTING: SHOOTING DAY IV

Day Shift, Sunday, January 13, 1974

OBJECTIVES:

Shoot comparative panels for testing of strength and other physical properties of several different mixes of conventional, steel fiber, and regulated-set steel fiber shotcretes.

MIXES SHOT:

All mixes are 7½-bag[1] standard-mix conventional shotcrete unless otherwise shown. Rebound measurements and stop-action photographs taken for most mixes. All mixes shot with special long nozzle.

Mix Designation[2]	Description and Purpose	
35-7½I-60L	"Butter up" and adjust equipment.	
25-7½I-60L	Same as Mix 23 (including water temperature) except used long nozzle (compare with Mix 23).	
*26-7½I-100L	CONTROL for Day IV; same as Mix 23 but with long nozzle and hot water. (compare to Mixes 23 and 25)	
33A-7½I-100L-1US	Same as Mix 26 but with USS steel fiber added; also same as Mix 33, Day III but with long nozzle and hot water (compare to 26 and 33)	(Series to evaluate optimum cement content)[3]
36	(NEVER SHOT)	
37	(NEVER SHOT)	
38-8½I-100L-1US	Fiber mix with increased cement.	
*39-7½I-100L-1US	Same as 33A, CONTROL for steel fiber mixes (compare to Mix 26).	
40-7I-100L-½US.	Steel fiber mix with only half as much steel fiber and only 7 bags cement. (compare to Mix 39 for effect of amount of fiber)	
41	(NEVER SHOT)	
42-10½R-100L-1US	Steel fiber, regulated-set shotcrete; 10½-bag mix. (compare to 26, 33A, 39 and 45)	
43-0-100L	No cement in mix for stop-action photos of cement-free aggregate in airstream.	
44	(NEVER SHOT)	
*45-7½I-100L-1NS	Same as Mixes 33A and 39 but with NSS steel fibers (compare to 39)	

SHOOTING CONDITIONS:

Long nozzle; Hose: 150 ft (46 m), 2 in. (51 mm) diameter
Air pressure at manifold generally 65 to 68 psi (450 to 470 KPa)
Water temperature: Natural 48 F (8.9 C). All mix water heated to 100 F (37.8 C) except Mix 25 which was at 60 F (15.6 C).

MIX CONDITIONS:

Cement: Type I, Cement B; Cement R for Mix 42
Sand: 8½ percent moisture; gravel 2 percent moisture
Aggregate temperature 55 F (12.8 C); Cement temperature 47 F (8.3 C)

ENVIRONMENTAL CONDITIONS:

Air temperature in tunnel 30 F (-1.1 C)
Relative humidity in tunnel 85 percent (estimated)
Air temperature outside tunnel 23 to 32 F (-5 to 0 C)

NOTES:

1 Standard mix contained 7½ bags of cement at 94 lbs per bag (43 kg)(Table 2.1)
2 See Table 2.4 for key to mix designation code.
3 Intended comparisons are in parentheses. Other uncontrollable conditions sometimes made intended comparisons invalid. See Table 2.6.
* Mixes selected in advance to have special and more comprehensive studies conducted on strength and other physical properties.

TABLE 2.6

COMPARISONS OF STRENGTH AND REBOUND TEST RESULTS

Comparisons	Comparative mixes	Evaluation of influence on strength: Expected results	Evaluation of influence on strength: Remarks	Evaluation of influence on rebound**: Expected results	Evaluation of influence on rebound**: Remarks
1. Effect of nozzle					
a) Long vs short	23-7½ I-60S* 25-7½ I-60L	Higher strengths with long nozzle because of fewer laminations and better mixing; may show more in flexural strength and in long-term strength.	Expectations confirmed but effects masked by other conditions except in flexural strength (see Sec. 9.7.12 and Chapter 10).	Less rebound because of better mixing.	Overshadowed by thickness effect.
b) Single vs double water ring	23-7½ I-60S* 24-7½ I-60D	Same as above.	Comparison invalidated because conditions did not meet specifications by developer.	Same as above.	Comparison invalidated because conditions did not meet specifications by developer.
2. Effect of nozzle-water temperature					
a) Conventional mixes	25-7½ I-60L* 26-7½ I-100L	Higher early strength (<1 day) with hottest water; possibly lower long-term strength.	No clear trend (see Sec. 9.7.9).	Less rebound with hotter water; should be able to place thicker layers with hotter water.	Overshadowed by thickness effect
b) Regulated-set mixes	17-9R-60S 18-9R-80S 19-9R-100S 20-9R-120S	Strength not measured on these mixes.	-----	Same as for conventional mixes except reg-set shotcrete expected to be more responsive to hotter water.	Expectations confirmed (see Sec. 4.5.3).
	28-7½ R-100S* 31-7½ R-60S	Higher early strength (<1 day) with hottest water.	Opposite results obtained; hot water was too hot (see Sec. 9.7.9).	Rebound not measured.	-----

* Control mix.
** The most significant variable in the measured average rebound was the thickness of shotcrete on the wall at the time of shooting. All other parameters were subordinate to thickness as described in Chapter 4.

TABLE 2.6 (continued)

Comparisons	Comparative mixes	Evaluation of influence on strength: Expected results	Evaluation of influence on strength: Remarks	Evaluation of influence on rebound**: Expected results	Evaluation of influence on rebound**: Remarks
3. Effect of regulated-set cement					
a) Non-fibrous mixes	23-7½ I-60S* 28-7½ R-100S 20-9 R-120S	Higher early and final strength with reg-set cement.	Expectations confirmed (see Sec. 9.7.7).	Hot water acceleration not expected to be as effective as additive, so rebound expected to be slightly higher for reg-set.	Results inconclusive. Reg-set Mix 28(27) had higher rebound but reg-set Mix 20 had lowest rebound of all(see Sec. 4.5.3)
b) Steel fiber mixes	39-7½ I-100L-1US* 42-10½R-100L-1US*	Same as above.	Higher early strength confirmed but mix was too active; mix 42 had lower final strength.	Same as above; mix 39 not measured.	Overshadowed by thickness effect.
4. Effect of cement content					
a) Conventional mix	None				
b) Regulated-set cement	29-6½ R-100S 28-7½ R-100S* 30-8½ R-100S 21-9R-100S	Early strength may continue to increase with cement content. Long-term strength may increase with cement to optimum, then decrease.	Both early and long-term strength had an optimum cement content (see Sec. 9.7.8).	Rebound not measured.	-----
c) Steel fiber mixes	40-7-I-100L-½US* 39-7½ I-100L-1US 38-8½ I-100L-1US	Same as b); also, expect greater flexural strength with greater cement content.	Results inconclusive.	Lower rebound with higher cement content.	Cement content not particularly important.
5. Effect of percentage accelerator	23-7½ I-60S* (3.4% accelerator) 33-7½ I-60S-1US (4.9% accelerator) 34-7½ I-60S-1US-25CA (8.4% accelerator)	Higher early strength, lower long-term strength with increased accelerator dosage. Drastic reduction with high dosages.	Expectations confirmed except that highest accelerator dosage did not give fastest rate of gain of early strength (see Sec. 9.7.6).	Lower rebound with higher accelerator dosage.	Results overshadowed by thickness effect, except that very high dosage of accelerator had higher rebound. Believe optimum dosage exists (see Sec. 4.5.3).

* Control mix.

** The most significant variable in the measured average rebound was the thickness of shotcrete on the wall at the time of shooting. All other parameters were subordinate to thickness as described in Chapter 4.

TABLE 2.6 (continued)

Comparisons	Comparative mixes	Evaluation of influence on strength: Expected results	Evaluation of influence on strength: Remarks	Evaluation of influence on rebound**: Expected results	Evaluation of influence on rebound**: Remarks
6. Effect of fiber content	39-7½ I-100L-1US* 40-7 I-100L-½US	Higher flexural strength with higher fiber content.	Flexural strengths not increased; fiber contents too low (see Chapter 10).	Less total rebound with more fiber.	Results inconclusive; other factors just as important.
	23-7½ I-60S* 33-7½ I-60S-1US	Higher flexural strength with fiber.	Same as above; also accelerator dosage too high in Mix 33.	Less total rebound with fiber.	Same as above. Accelerator dosage too high in Mix 33.
7. Comparison of type of fiber	39-7½ I-100L-1US* 33A-7½I-100L-1US 45-7½ I-100L-1NS	Similar results for the fibers considered.	Results confirmed (see Sec. 9.7.14).	Similar results for the fibers studied.	Overshadowed by thickness effect
8. Effect of gravel content on fiber mixes	33-7½ I-60S-1US* 34-7½ I-60S-1US-25CA	Higher expected fiber content with 25% coarse aggregate should produce higher flexural strength.	Comparison invalidated by plugging of gun and by erratic and high accelerator dosages (see Sec. 9.7.15).	Much lower rebound with lower gravel content.	Overshadowed by thickness effect and high accelerator dosages.
9. Variability among similar (but not exact) mix and shooting conditions					
a) Conventional mixes	14-7½ I-60S 23-7½ I-60S* 24-7½ I-60D 25-7½ I-60L 26-7½ I-100L*	Similar rate of gain of strength and similar long-term strength.	Expectations confirmed except for mixes 14 and 24; mix 14 had better curing; mix 24 had poor shooting conditions(see Sec.9.7.16).	Rebound expected to vary significantly with shooting conditions. Mix design not expected to be as important.	Overshadowed by thickness effect
b) Regulated-set mix	None were similar.	--------	--------	--------	-------
c) Steel fiber mixes	33A-7½ I-100L-1US 39-7½ I-100L-1US* 45-7½ I-100L-1NS	Same as for conventional mixes.	Shooting conditions varied enough to affect results.	Same as for conventional mixes.	Overshadowed by thickness effect and varying shooting conditions.

* Control mix.

** The most significant variable in the measured average rebound was the thickness of shotcrete on the wall at the time of shooting. All other parameters were subordinate to thickness as described in Chapter 4.

2.7 DESCRIPTION OF TEST PROGRAM

2.7.1 FIELD CONTROL

The shotcrete equipment was rated to shoot approximately 6 cu yd/hr (4.6 m^3/hr) but for many reasons material was shot either faster or slower than the rated capacity. To account for this irregularity and to document shooting conditions a timekeeper accurately logged the sequence of events of the entire field operation, many to about the nearest second. Each time air, water, or material reached the shotcrete nozzle or was stopped, the time was recorded to the nearest second. The precise time the nozzleman pulled off a panel or moved back onto a panel for another operation, such as rebound, strength panels, photographic tests, or for a plug, was also recorded to the nearest second. Logging field operations to the nearest second may not seem necessary; however, about 3 to 10 lb/sec (1.4 to 4.5 kg/sec) are delivered by the shotcrete equipment customarily found in civil works tunnels. Thus, 5 to 10 seconds is significant; about 60 to 80 lb (27 to 36 kg) of material were shot during this time.

MATERIAL DELIVERY RATE

The net shooting time was taken as the gross shooting time less the cumulative time for plug-ups and other stoppages. The Material Delivery Rate (MDR) is the total batch weight plus the weight of water added at the nozzle divided by the net shooting time. This is an average total material delivery rate since it was assumed that the rate of delivery of the material was the same throughout the total time of shooting. The rate of delivery may be represented as an average value over the span of ten minutes or so. Often, a cubic yard (0.76 cu m) was batched and used partly for rebound, partly for photographic studies, and partly for making strength panels. In this case, the actual amount of time that the nozzle was directed at the rebound panel or used for any other phase of testing was easily calculated from the time-keeper's records. The total amount of material shot against the rebound wall during the time that rebound was measured equals the average material delivery rate MDR in lb/sec (kg/sec) times the net shooting time.

Other field measurements were taken to document conditions of shooting. All the water injected at the nozzle passed through a special instrument box that measured the temperature, pressure and volume of water used. These measurements were made at one minute intervals so that any adjustments of the water made by the nozzleman could be detected quickly. A needle-type pressure meter was used to determine the air pressure profile in the material delivery hose from the gun to the nozzle. Temperatures of the dry mix and of the in-place shotcrete were also taken. Modifications were made to the nozzles to measure the water pressure in the water ring itself. Results of this documentation program are contained primarily in Chapter 3.

2.7.2 REBOUND

The most extensive field observations were those made on the nature and magnitude of rebound of shotcrete when shooting against vertical walls. No overhead shooting was conducted during this study. Rebound was evaluated in a number of different ways. The nozzlemen who were watching or shooting made observations of relative rebound on the basis of their experience.

Rebound was also measured as often as possible by collecting and weighing the rebounded material on a series of tarpaulins placed beneath the test surfaces.

It has been known for a long time that significantly greater rebound occurs during early stages of shooting against a hard surface (Studebaker, 1939). Special measurements of rebound were made to determine this effect quantitatively by a series of multiple tarps. By placing additional layers of tarps at selected times of shooting, while the thickness of shotcrete was building up, the rebound was collected and measured at several stages including during the build-up of the first 1/2 in. (12 mm). The new tarps were placed within 15 seconds so the shooting could, for all practical purposes, be considered continuous. In one case, three layers of tarps were placed to evaluate the rebound rates at three different thicknesses on the wall. In other cases, two layers of tarps were placed; one for the first 1/2 in. (12 mm) and then another to collect all subsequent rebound. On several mixes, rebound was collected only on one set of tarps.

The large tarp area was composed of several 4 x 4 ft (1.2 x 1.2 m) square tarps arranged in a quilt-like pattern so that the amounts and the distribution of rebound from side to side and front to back could be evaluated by weighing each of the tarps individually. The small tarps also permitted the use of a relatively accurate spring scale hung from a portable tripod.

Throughout the shooting program rebound was measured whenever possible and practical. Rebound was measured against several rock walls, against specially prepared 4 x 8 ft (1.2 x 2.4 m) plywood panels covered with about 4 in. (10 cm) of hardened shotcrete, and against bare plywood panels. Some rebound panels had water running down their face to simulate difficult groundwater conditions.

The effect of water temperature on rebound was determined by changing the nozzle water temperature in successive rebound tests from 60°F (15.5°C) to 120°F (48.8°C) in 20°F (11.1°C) increments. An evaluation of the effect of air pressure, cement contents, type of nozzles, and percentages of steel fiber on rebound was also attempted. However, no parameter was as important as the thickness of shotcrete on the wall. Results of the rebound tests are contained in Chapter 4.

2.7.3 EFFECT OF JOINT SURFACES

During Day II, several boulders representing typical rock surfaces were selected from the muck pile. Some boulders had clean surfaces while others were coated with an appreciable layer of clay gouge. These boulders were washed carefully and then inspected to observe the effect of washing on the gouge layer. Shotcrete was placed on them under various conditions to observe the effect washing and shooting had on the gouge layer itself and to measure the shrinkage of shotcrete on actual rock surfaces. Whittemore points and vibrating wire strain gages were embedded into the shotcrete to measure shrinkage and thermally-induced strains. The shotcrete temperature was also measured. The results of washing the boulders are contained in Chapter 3.

2.7.4 PHOTOGRAPHIC STUDY OF AIRSTREAM

A careful observation of the shotcrete airstream on several projects led to the conclusion that a shotcrete airstream is quite nonuniform. In many cases water added at the nozzle in the dry-mix process never really mixed with the dry solids, but tended to form a conical shroud around the airstream or a layer on the top or bottom of the airstream. Often, the water did not become mixed until it reached the wall. Furthermore, there were questions about the velocity of the particles and whether or not the velocity had a significant effect on the nature of the shotcrete. Therefore, a photographic study of the airstream was conducted with a special high-speed camera that takes pictures at a rate of 7500 frames per second. Particles were followed in successive frames from the nozzle, to the wall, and back off as rebound. The speed, distribution of particles, and mechanisms of rebound and build-up of shotcrete were observed. These results are contained in Chapter 5.

2.7.5 FRESH SHOTCRETE SAMPLES

In order to document some of the results of strength and other physical property tests, a large number of samples of fresh shotcrete were taken immediately after shooting. These samples were taken from rebound walls, from rebound material on the tarpaulins and from the strength test panels. Samples were collected in bottles containing alcohol which retarded the setting of the cement. Following their return to the University, the specimens were subjected to tests to determine the water content, the cement content, (i.e., the water-cement ratio), grain size distribution, and the amount and condition of fiber in the samples. The results of these tests are contained in Chapter 6.

2.7.6 FIBER STUDIES

The content of fiber in the steel fiber shotcrete was evaluated by several means; indirectly by counting fibers on cut surfaces and directly in the fresh shotcrete samples and by pulverizing samples of hardened shotcrete. The distribution and orientation of the fibers were also evaluated by x-ray photographs of samples of hardened shotcrete. These data are presented and evaluated in Chapter 7.

2.7.7 COMPARATIVE STRENGTH PROGRAM

Several different types of strength were determined. Plywood panels 2 x 2 ft (1.2 x 1.2 m) in size were shot and cut up so that compressive and flexural strength tests could be conducted. A few compression tests were conducted when the shotcrete was less than 1 hour old; testing continued through six months. Flexural tests were conducted from 4 hours to 6 months. Pullout tests were conducted on almost every mix. Panels were brought to the University for additional testing through 6 months including the determination of a moment-thrust interaction envelope. Modes of failure and stress-strain relations were evaluated. The results of these studies are contained in Chapters 8 through 13.

2.8 POST-FIELD TESTING AND EVALUATION

A post-shooting conference was held immediately after each day's shooting was completed. The practical results of the days work were reviewed and plans were revised for the next day.

Strength testing began immediately after each mix was shot and continued through 6 months. All tests up to 28-day tests were conducted in the field. The evaluation of other physical properties followed a similar schedule. Numerous samples were transported back to the University for further testing.

CHAPTER 3

FIELD OBSERVATIONS

3.1 INTRODUCTION

A large number of observations and measurements were made by the University's, the Contractor's and the Resident Engineer's field crews in order to document or to improve the shooting operation. Field observations during the four days of shooting made on the operation of the equipment, on the shooting operation and on the behavior of the materials are assembled in this chapter. Observations on rebound are contained in Chapter 4.

3.2 BEHAVIOR OF CEMENTS AND ACCELERATORS

3.2.1 SETTING TIME OF TYPE I CEMENT AND ACCELERATOR

The compatibility between the cement and the accelerator is often tested by evaluating the initial and final set times for different percentages of accelerator by means of the Gillmore Needles Test. The ASTM test procedure (C-266) is usually modified by reducing mixing times to a few seconds to account for the fast setting times. Generally, the compatibility between cement and accelerator may be considered acceptable if the initial set is less than 3 minutes and the final set is less than 12 minutes (Blanck, 1974).

Results of Gillmore Needles Tests conducted for routine job control of the shotcrete lining for Dupont Circle Station are summarized in Table 3.1. These tests were done at room temperature on samples of cement and accelerator obtained prior to starting the field testing program.

TABLE 3.1

GILLMORE NEEDLES TEST RESULTS ON TYPE I CEMENT
DONE FOR ROUTINE CONSTRUCTION CONTROL

Accelerator, percent	Initial set	Final set
A. CEMENT AND ACCELERATOR OF THE SAME TYPE USED ON DAYS I AND II (Cement A)		
2	2 min 21 sec	5 min 7 sec
3	25 sec	2 min 6 sec
4	1 min 9 sec	2 min 25 sec
B. CEMENT AND ACCELERATOR OF THE SAME TYPE USED ON DAYS III AND IV (Cement B)		
2	2 min 12 sec	18 min 35 sec
3	1 min 27 sec	11 min 12 sec
4	1 min 20 sec	10 min 37 sec

Note: Tests made at room temperature

Samples of the cement and accelerator actually used on Days III and IV were obtained and subjected to additional Gillmore Needles tests. The tests were performed by a qualified engineer on samples of about 50 grams of cement mixed with water at a water-cement ratio of 0.40. The tests were conducted at various temperatures in order to determine the effect on temperature initial set and early strength. These test results are summarized in Table 3.2 and shown graphically in Fig. 3.1.

It can be seen from Tables 3.1 and 3.2 that, at room temperature, the cements and accelerator appear to be compatible. In the tests conducted on samples taken from the cement used on Days III and IV (Table 3.2, I) the cement and accelerator meet the compatibility criteria at a dosage

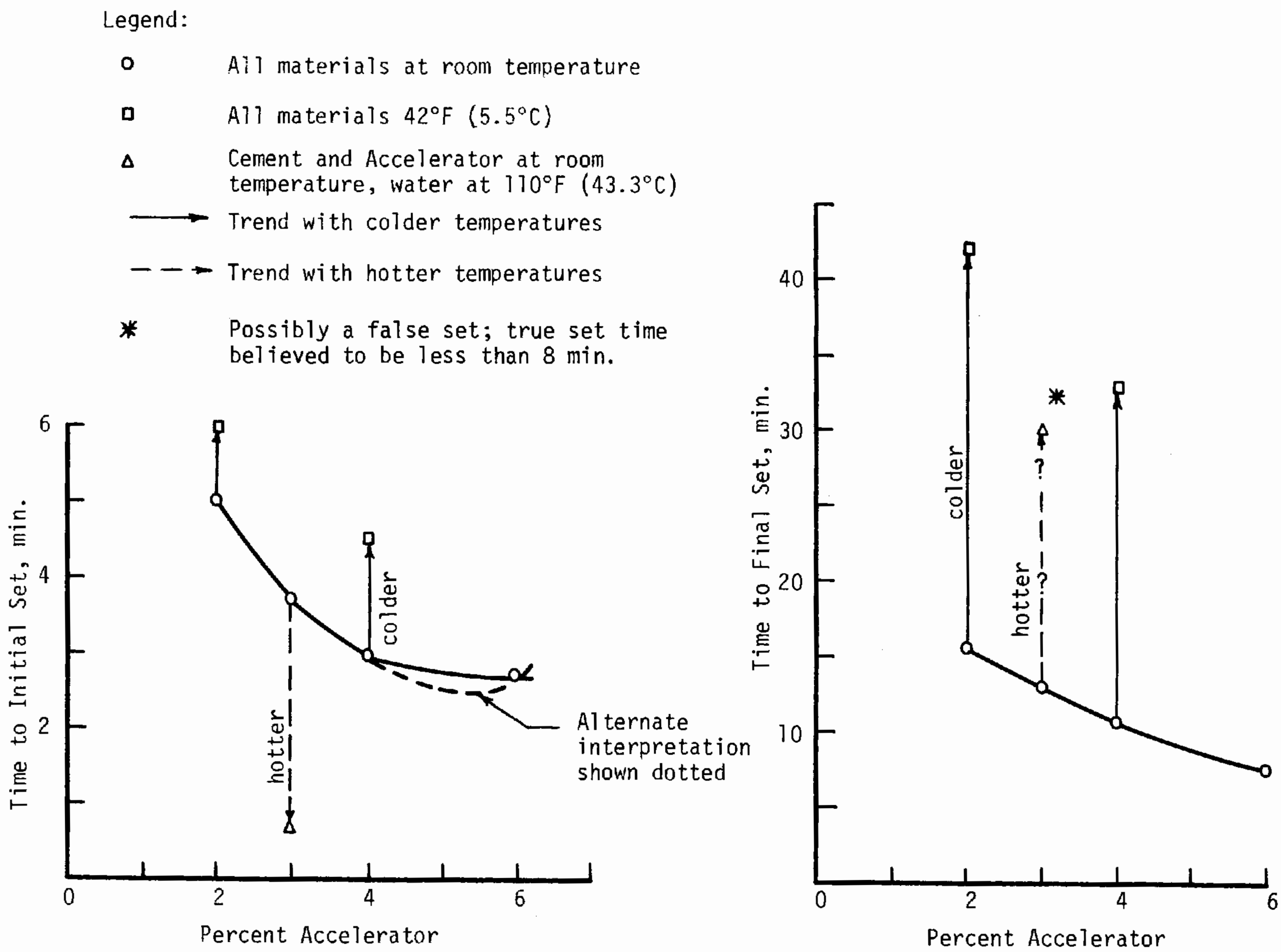
TABLE 3.2

GILLMORE NEEDLE TEST RESULTS ON SAMPLES OF MATERIALS USED ON DAYS III AND IV

Accelerator[1] percent	Initial set min-sec	Final set min-sec	Temperature °F (°C)	
			Cement	Water
I. TYPE I CEMENT AND ACCELERATOR AT ROOM TEMPERATURE				
2	5-00	15-30	68 (20)	64 (17.7)
3	3-40	13-00	68 (20)	64 (17.7)
4	3-00	10-30	68 (20)	66 (18.8)
6	2-40	7-30	68 (20)	66 (18.8)
II. TYPE I CEMENT AND ACCELERATOR AT ROOM TEMPERATURE, WATER HEATED				
3	0-35	30-00[2]±	68 (20)	110 (43.3)
III. TYPE I CEMENT, ACCELERATOR AND WATER REFRIGERATED				
2	6-00	42-00	42 (5.5)	42 (5.5)
4	4-30	33-00	42 (5.5)	42 (5.5)
IV. REGULATED-SET CEMENT WITHOUT ACCELERATOR AT VARIOUS TEMPERATURES				
0	1-30	7-00	70 (21.1)	65 (18.3)
0	0-30	3-50	70 (21.1)	100 (37.7)
0	34-00	160-00	42 (5.5)	42 (5.5)

[1] Cement sample 50 grams; water-cement ratio 0.40.

[2] Sample set rapidly to approximately 80 percent of final set. A false set restricted further development of early strength. Possibly a shorter mixing time would have prevented this problem.



a) Initial Set

b) Final Set

FIG. 3.1 EFFECT OF TEMPERATURE ON GILLMORE NEEDLES TEST RESULTS ON TYPE I CEMENT somewhere between 3 and 4 percent. However, the temperature was extremely low at the time of shooting and the data in Table 3.2 show that at these low temperatures, the cement and the accelerator, in terms of initial and final set times, are no longer compatible.

The data for initial set from Table 3.2 are plotted in Fig. 3.1a. For the cases shown the low temperature appears to increase the time of initial set by about 1 to 1-1/2 minutes. On the other hand, the hotter water decreased the initial set for 3 percent accelerator from 3 minutes 40 seconds to 35 seconds, a drop of about 3 minutes.

Comparable data on final set are plotted in Fig. 3.1b. The lower temperature increased final set times by about 20 to 30 minutes. In the test where hot water was used, a false set was obtained and final set was not reached. These results are not considered representative of the true relationship between setting times and temperatures for samples not disturbed by overmixing. Test procedures affect the results significantly and it is extremely difficult to mix and place a fast-setting cement patty in a manner that will not alter either the initial or final set time. It is believed that a shorter mixing time would have resulted in a final set substantially faster than that at room temperature, possibly on the order of 5 to 8 minutes.

3.2.2 EFFECT OF TEMPERATURE ON COMPATIBILITY OF TYPE I CEMENT AND ACCELERATOR

From the compatibility test results given in the previous section, an important trend between temperature and setting time can be established, even though the number of tests are small and results are sensitive to other parameters such as the dosage of accelerator and test procedures. As expected, lower temperatures increase both initial and final set times. However, the temperature appears to be more important to the final set time (which increased by a factor of 2 or 3) than the initial set time (which increased only 30 percent).

It is recommended that Gillmore Needles Tests be conducted in a temperature environment and using materials at temperatures that approximate the anticipated field conditions. In cases where flexibility in shotcrete plans would permit changes in accelerator dosage to economize or where the temperature of either the water or materials may change seasonally, a family of curves of Gillmore Needles test results on materials and water at different temperatures should be determined. The compatibility test has no value if it does not represent actual field behavior. When environmental and material temperatures drop in the winter, additional accelerator may be required to place the shotcrete and to achieve a rapid gain in early strength. However, the reduction in long-term strength that accompanies such increases in accelerator dosage must be considered.

3.2.3 SETTING TIMES OF REGULATED-SET CEMENT

There were two reasons for evaluating the setting times of the regulated-set cement; the cement must set quickly to be most beneficial in construction, yet it must not hydrate significantly in the presence of the moisture so as to cause plugs or undergo a false set before it is placed.

GILLMORE NEEDLES TESTS ON REGULATED-SET CEMENT

When regulated-set cement was first considered for use in shotcrete, Gillmore Needles tests were conducted to determine whether or not its strength gain was rapid enough for shotcrete work. Since no accelerator is used with this cement, setting times are controlled by the temperature of the mix water. Gillmore Needles Tests conducted long before field testing on Burns 3 and 4 of regulated-set cement are plotted in Fig. 3.2. The initial set appears to decrease steadily with an increase in mix water temperature and the two cements appear to behave about the same.

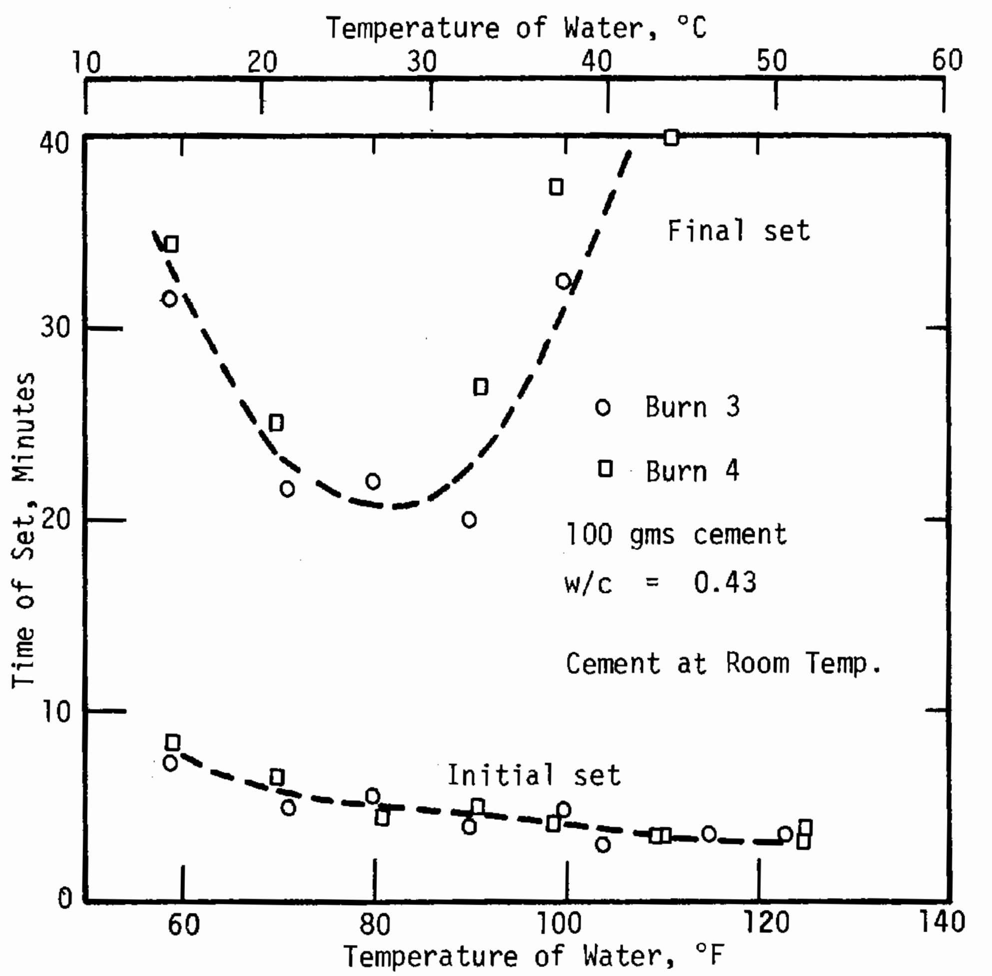


Fig. 3.2 TYPICAL EFFECT OF WATER TEMPERATURE ON GILLMORE NEEDLES TEST RESULTS OF REGULATED-SET CEMENT

The apparent time to final set appears to be a minimum at about 75 to 85°F (23.8 to 29.4°C). The reason for the increase in final set times with higher temperatures is believed to be related to test procedures. Above these temperatures, the cement undergoes a flash-set before the patty is made and the needle test performed. The test method breaks down in this case giving misleading results. The time indicated by the initial-set needles may be more representative of a final set than an initial set at these higher temperatures and the times given by the final-set needle may be a function of disturbance of the cement patty after flash set occurs. In a crude manner, this flash-set may be an indication of similar problems to be encountered during placement of the shotcrete in the field. The test results explain why some highly active mixes probably set on the way to or just after hitting the test panel. All subsequent shooting serves to disturb rather than to compact the in-place shotcrete.

Before the field tests were conducted, these test results indicated that water having temperatures in excess of 80 to 100°F (26.7 to 37.8°C) would be required. The higher temperatures were not believed to be detrimental to shotcrete operations, however. On the basis of field observations during Day II, 80°F (26.7°C) and 100°F (37.8°C) mix water was found to produce the same results (Mixes 17 through 20). Arbitrarily, 100°F (37.8°C) was selected as the nozzle-water temperature for the rest of the mixes. It appears that the lower mix-water temperature may have been more desirable. A detailed discussion of the effects of mix-water temperature on compressive strength is given in Chapter 9.

A series of carefully controlled Gillmore Needles Tests was conducted on samples of regulated-set cement used on Days III and IV. These results, tabulated in Table 3.2, are plotted in Fig. 3.3; they indicate a consistent reduction in set times with higher water temperatures.

PREHYDRATION TESTS

One of the important questions to be answered before the shooting began was whether or not regulated-set cement could be batched, transported,

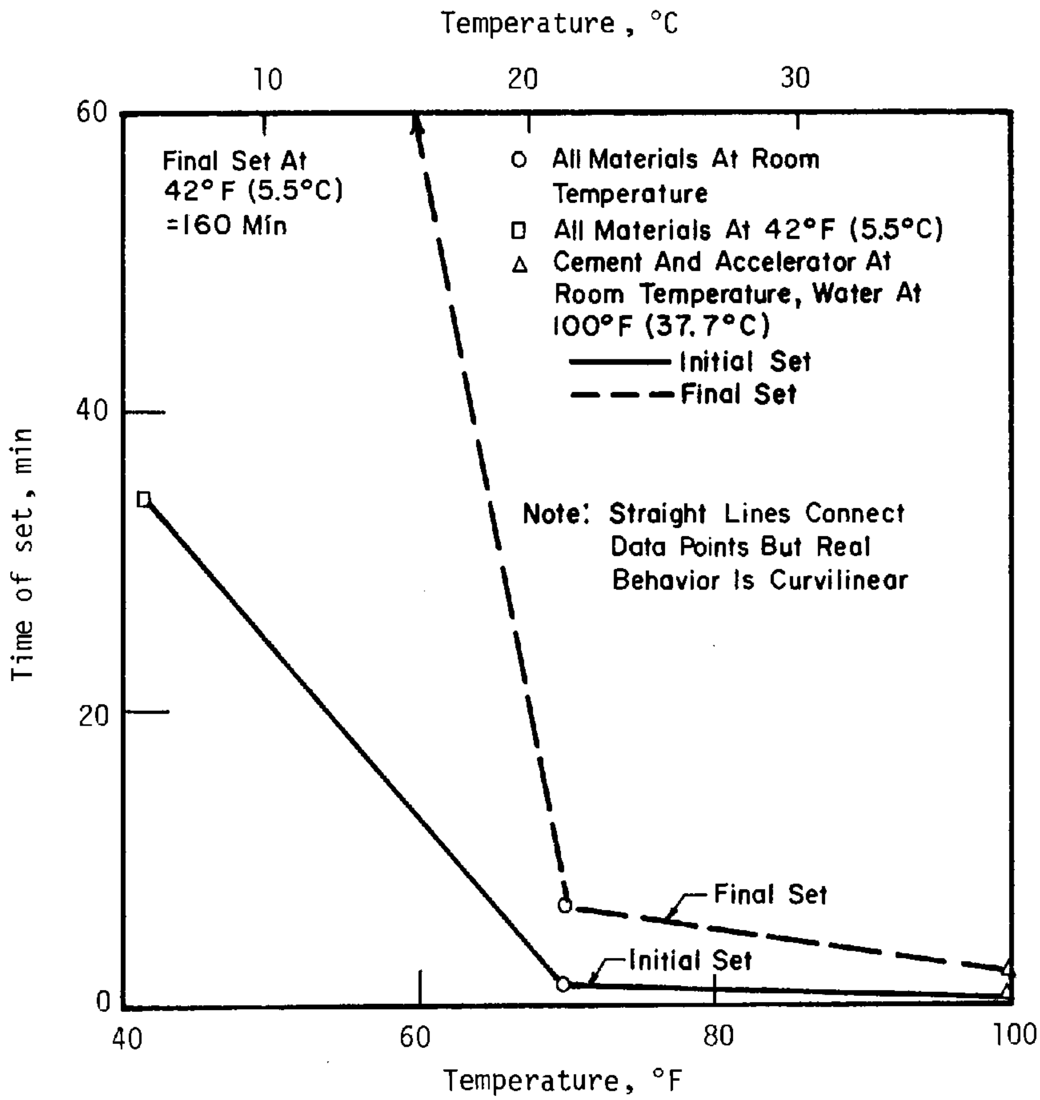


FIG. 3.3 EFFECT OF TEMPERATURE ON GILLMORE NEEDLES TEST RESULTS ON REGULATED-SET CEMENT USED ON DAYS III AND IV

and temporarily stored in a hopper for a few minutes before shooting without undergoing prehydration to an undesirable degree. A series of simple preliminary tests were conducted in the laboratory to evaluate this problem. Several small samples of regulated-set cement dry-mix were prepared and then placed in a container to measure temperature changes during hydration. The mixes included ranges of expected water contents of the aggregates and cement contents. Water in aggregates ranged from about 4 percent to 8 percent. The results indicated a general increase in temperature to a maximum of about 10 to 15°F (5 to 8°C) within the first half hour. As expected, richer mixes and higher water contents resulted in higher temperature gradients. On the basis of these tests, it was concluded that weight batching of regulated-set cement shotcrete would be possible if done quickly, although cement contents higher than about 20 percent by weight and aggregate water contents more than about 6 percent should be avoided.

3.3 BATCHING AND MIXING

The contractor had a bulk storage facility consisting of bins for cement, fine aggregate, and coarse aggregate. Usually, the cement, sand, and gravel were weighed separately. Batch sizes ranged from 1/2 to 1-1/2 cu yds (0.4 to 1.1 cu m); most batches were 1 cu yd (0.8 cu m). The order of batching was aggregates, fiber (when used), then cement. The standard mix design was given in Table 2.1. Batch proportions for Days III and IV are given in Appendix C.

Once all ingredients were batched, they were mixed for about 1 minute, the dry mix was then dumped into a front-end loader and transported to the hopper of the shotcrete machine. Transportation took only a minute or two since the shotcrete rig was usually located within 700 ft (210 m) of the batch plant.

3.3.1 CEMENT

Because the aggregate was wet, the weigh hopper also became wet Thus, cement and fine aggregate collected on its sides during batching. The batch plant operator and the inspector watched for this condition and cement and fine aggregate deposits were manually scraped down into the mixer. The blades of the mixer also tended to collect material so that the paddle blades and the shaft became coated and had to be cleaned with air spades about once a day. The build-up of cement in the weigh hopper and mixer tends to reduce the amount of cement in the dry mix below that desired. This is the reason for wasting the first batch shot at the beginning of each day to "butter-up" the equipment. Cement-rich material has a tendency to stick to clean surfaces of equipment it comes in contact with. Once the equipment becomes coated, the rate of build-up decreases so that subsequent mixes have the desired cement content. However, there were always losses in the next batch each time the weigh hopper and paddle wheels were cleaned. Build-up on the equipment and loss of cement was much greater on Days III and IV than on the first two days of shooting because the moisture content of the aggregate was much higher.

Regulated-set cement was batched from bags rather than from bulk. It reacts with water much faster than Type I cement and can hydrate significantly even in the presence of small amounts of moisture in the aggregates. For this reason, equipment that is capable of mixing just prior to shooting such as the continuous auger-type mixers are strongly recommended for preparing regulated-set shotcrete. However, batch type mixing was satisfactory under the cold conditions occurring during the field tests. Only one mix (Mix 42) hydrated to any significant degree before shooting. There were many reasons for this premature hydration, including a very high cement content. On hot days, the results may not have been satisfactory.

3.3.2 STEEL FIBER

Boxes of steel fibers weighing about 40 to 50 lb (18 to 23 kg) were hoisted onto the platform of the batch plant. The steel fibers were introduced into the mixer at the same time the aggregates were being blended. Cement was added last. Separation of the fibers before they entered the mixer was accomplished by means of a simple vibrating screen. This screen consisted of a sheet-steel table about 3 x 10 ft (0.9 x 3 m) in size with a screen having a 1-in. (2.5 cm) square grid at one end. A small, air-operated vibrator was attached to the screen end-of the table. Fibers were dumped onto the table, then dispersed and raked toward the screen. The vibrating table appeared to disperse the fibers quite well, however, it was relatively slow and at times it was necessary to dump the fiber directly from the boxes into the mixer in order to speed up the batching process. This method of batching the fibers worked satisfactorily; however, other methods developed from fibrous concrete work could also be used (Sather, 1974).

Balling of the fibers was a problem but never reached serious proportions. Because of their greater flexibility, the U.S. Steel fibers were more prone to balling than National Standard Steel fibers. Samples of both types of fiber taken from the dry mix were bent; however, the U.S. Steel fibers were more severely contorted. Most of the bending probably took place in the mixer or to a lesser extent in the auger of the shotcrete rig and not in the gun since samples taken from fresh shotcrete do not show a significant difference in bending as compared with samples of dry-mix taken before it entered the machine. Other augers have not affected fibers and the evidence points to the robust mixing of the fibers in the two counter-rotating paddle wheels as the most likely cause of the bending. It appears that as a paddle came in contact with individual fibers or mats of fibers, the fibers were bent or kinked. Some U.S. Steel fibers were bent almost "U-shaped"; Figs. 3.4 through 3.11 show fibers before batching, after mixing, and after gunning, from fresh and hardened samples of shotcrete. The greater distortion in U.S. Steel fibers was one major reason for the greater amount of balling as compared with the National Standard Steel (NS) fibers. NS fibers were not immune to bending, however. Thus, the pugmill mixer does appear to cause an undesirable bending of steel fibers, which increases the tendency for interlocking and balling, reduces the effective length of the fiber, and inhibits compaction of the shotcrete. On other projects, neither type of fiber has exhibited appreciable bending when batched properly (Mahar, Parker and Wuellner, 1975).

3.3.3 MOISTURE IN AGGREGATES

The very wet aggregates were difficult to mix and to shoot. The wetness also aggravated the mixing of fibers and probably increased balling. Mix 34 was batched with 25 percent instead of 50 percent coarse aggregate. The excessive water in the fine aggregate made mixing and shooting very difficult. It was decided not to shoot a batch consisting of 100 percent fine aggregate because of anticipated shooting difficulties.

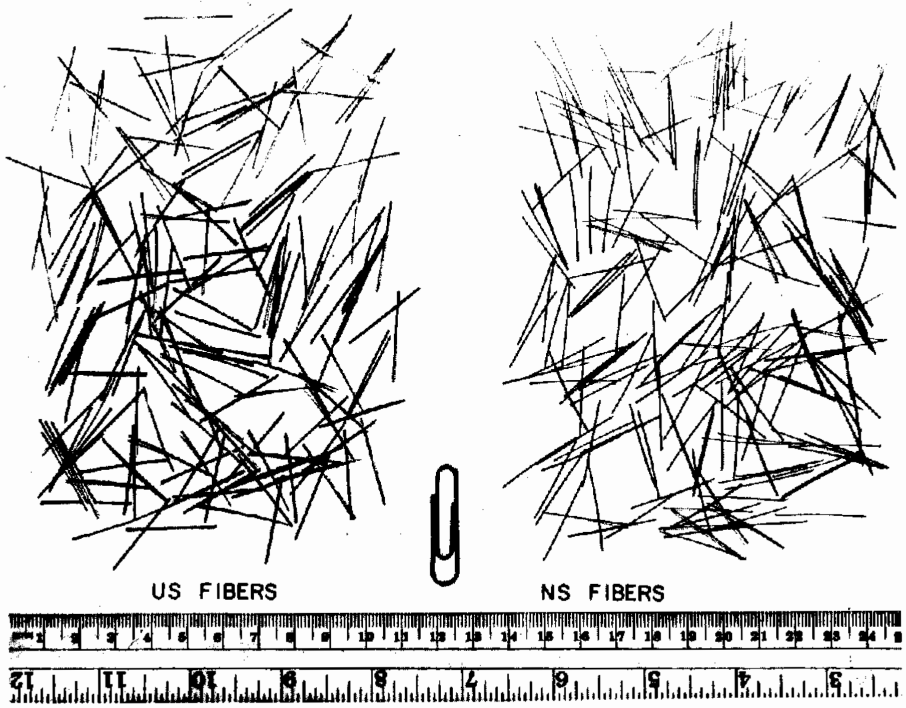


FIG. 3.4 TYPICAL CONDITION OF FIBERS BEFORE BATCHING

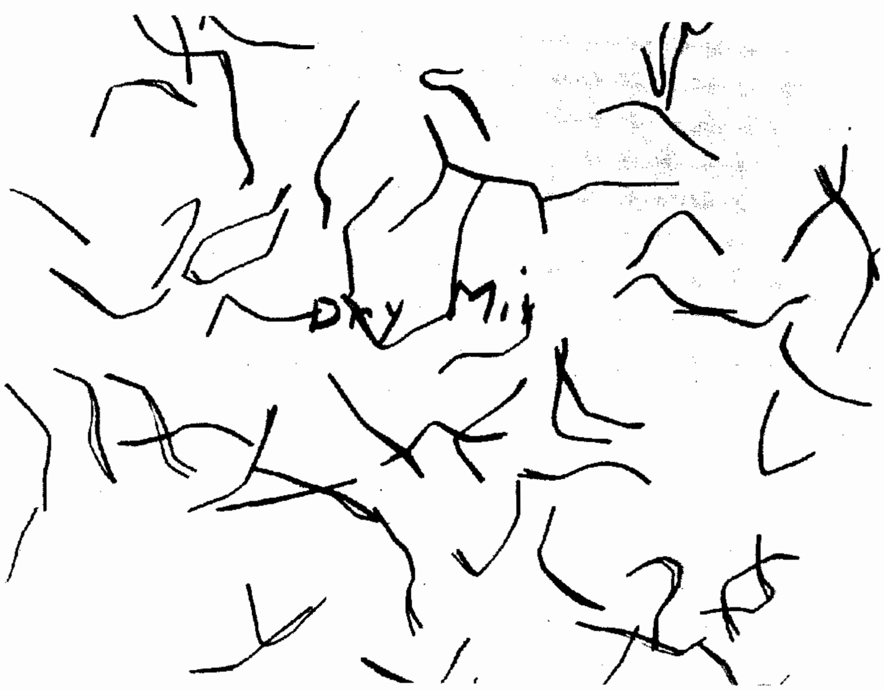


FIG. 3.5 TYPICAL US FIBERS FROM FRESH SAMPLE OF DRY MIX

FIG. 3.6 TYPICAL US FIBERS FROM FRESH SAMPLE OF IN-PLACE SHOTCRETE

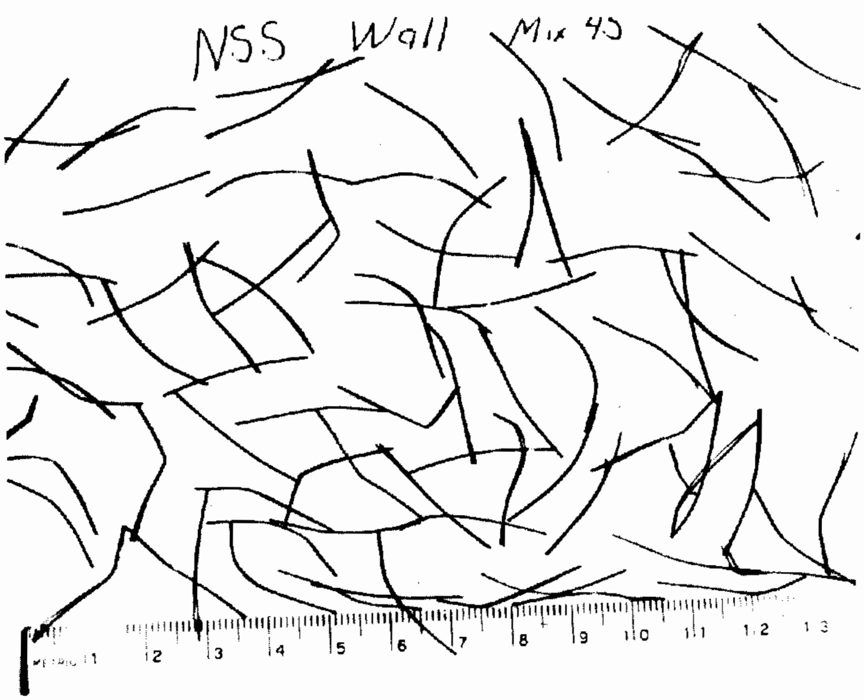


FIG. 3.7 TYPICAL NS FIBERS FROM FRESH SAMPLE OF IN-PLACE SHOTCRETE

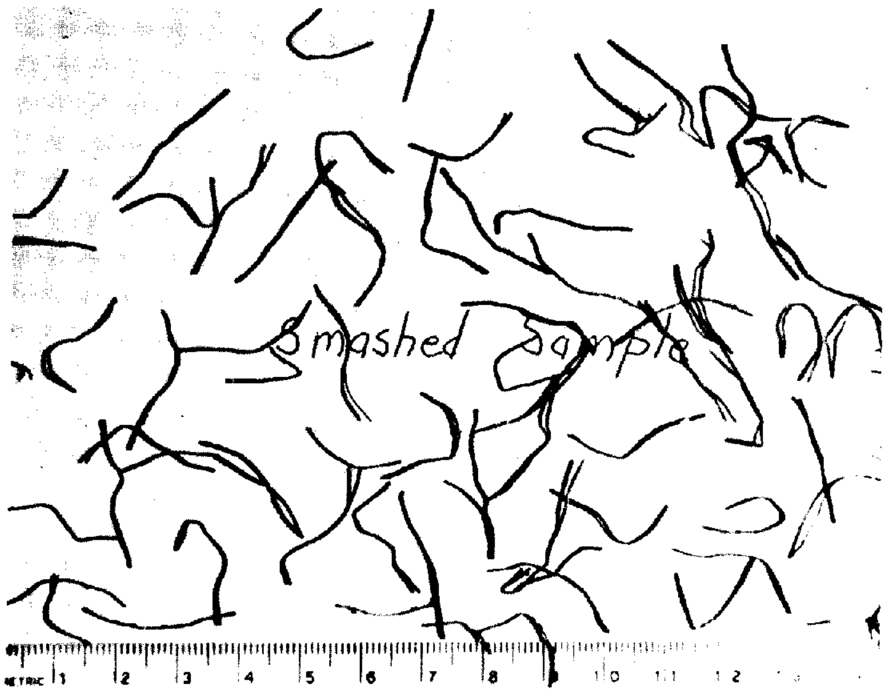


FIG. 3.8 TYPICAL US FIBERS FROM PULVERIZED SAMPLES OF HARDENED SHOTCRETE

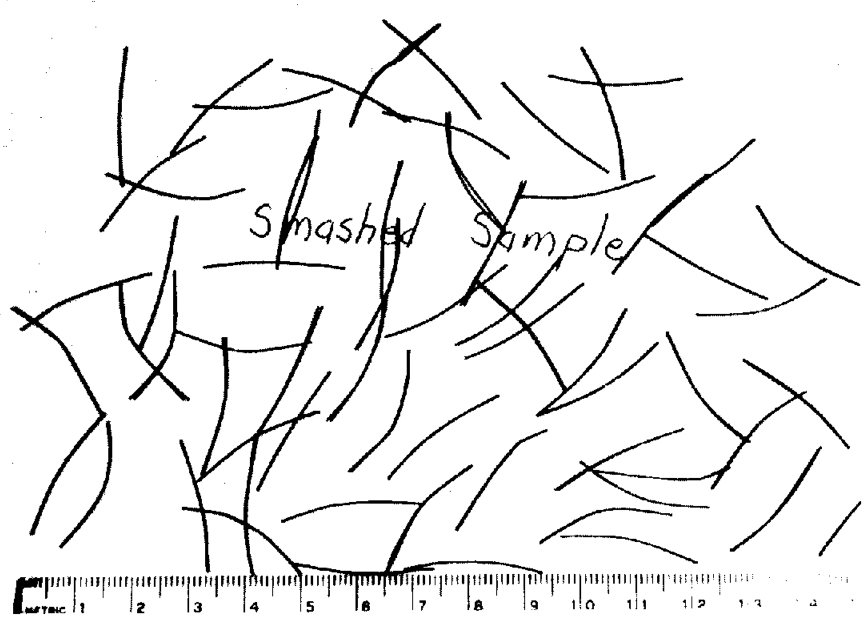


FIG. 3.9 TYPICAL NS FIBERS FROM PULVERIZED SAMPLES OF HARDENED SHOTCRETE

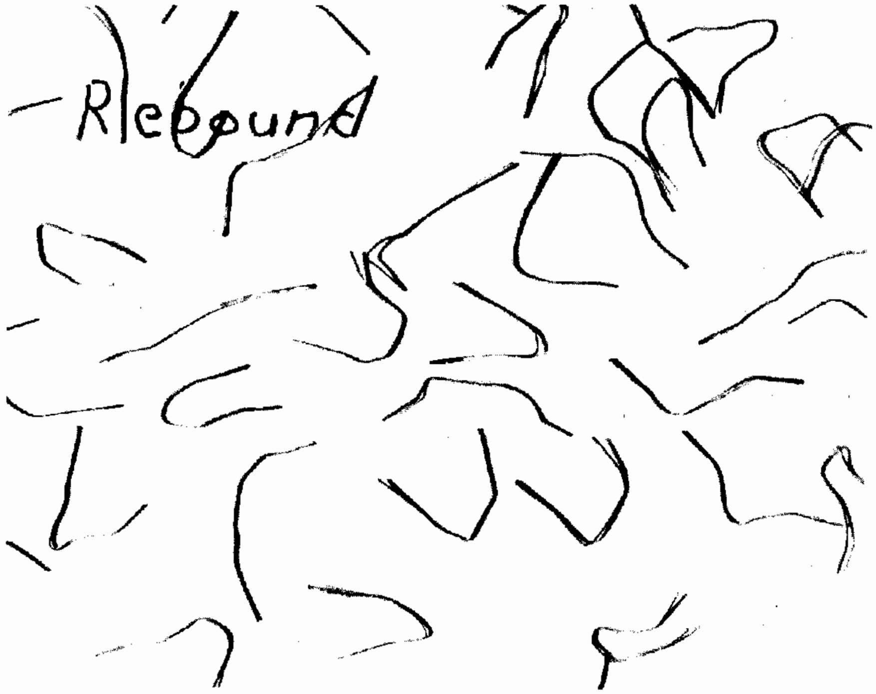


FIG. 3.10 TYPICAL US FIBERS FROM FRESH SAMPLES OF REBOUND

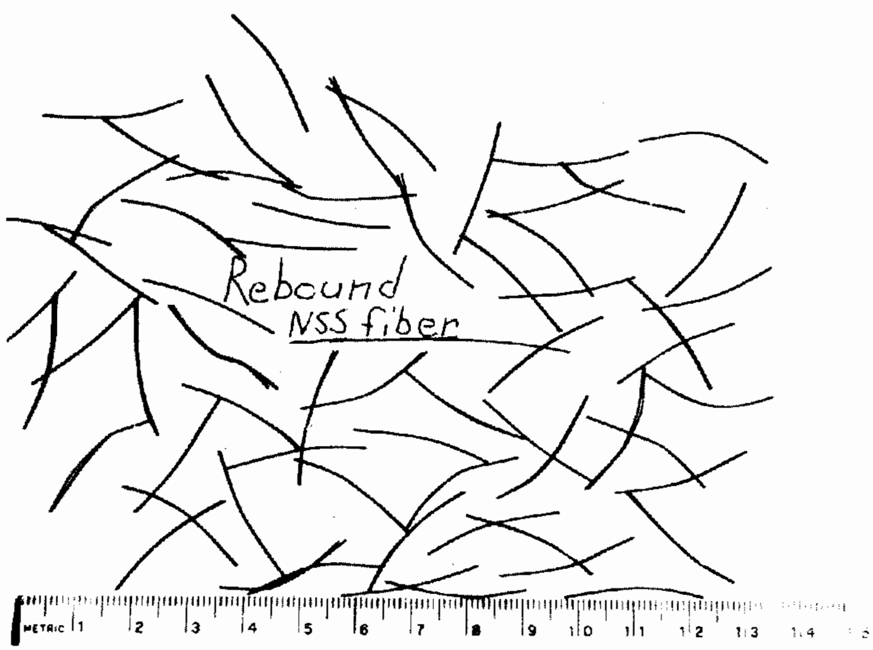


FIG. 3.11 TYPICAL NS FIBERS FROM FRESH SAMPLES OF REBOUND

3.4 OBSERVATION OF EQUIPMENT PERFORMANCE

3.4.1 EXPERIMENTAL MATERIALS

Conventional equipment was able to handle the experimental materials including fibers without appreciable difficulty. The presence of steel fibers did not appear to cause any additional abrasion or wear of the equipment. However, the period of testing was short and the amount of experimental material was small, so the long-term effects were not seen. Plugging of the material hose was a problem throughout the program primarily because of the high water content of the aggregate. However, the presence or the amount of fiber did not appear to increase the number of plugs. Fibers were a nuisance to personnel cleaning the equipment.

3.4.2 MATERIAL DELIVERY RATE

The material delivery rate (MDR) was one of the most important and useful parameters measured in the field. The batch weight divided by the net shooting time (total shooting time minus interruptions in shooting) is the MDR. A more detailed definition and discussion is given in Chapters 2 and 4. In order to measure MDR it was necessary to shoot the entire batch or weigh or otherwise estimate the amount of material left in the holding hopper.

Once the MDR was determined, the shooting rate of each constituent in the mix was calculated using the relative percentages of the materials as batched. Once the rates of delivery of cement and accelerator were determined, the accelerator dosage in percentage of cement by weight was calculated.

Each mix had a different MDR just because of minor differences in shooting conditions such as air pressures, levels of material in hoppers, friction, etc. However, the accelerator feed auger screw provided a rather constant amount of accelerator to the dry-mix as it passed beneath the dispenser. The accelerator feed rate was set to provide about 3 percent accelerator by weight of cement for normal operations. However, the difference in operation of the equipment caused changes in the rate of material feed to the shotcrete machine hopper and in some cases was severe enough to produce significant deviations from the amount of accelerator desired.

The rates of delivery of each total batch and of each constituent within the batch were calculated. Summaries of these calculations are presented in Appendix C. The rates of delivery occurred over a definite range of values. Typical MDR values of all materials going toward the wall was about 350 to 450 lb/min (160 to 200 kg/min). This corresponds to roughly 7 lb (3 kg) every second. A few mixes, notably Mix 34, had an extremely low MDR. In addition to containing very wet aggregates, the mix had so many fiber balls that they had to be thrown off of the screen protecting the machine and as a result the effective MDR was only 181 lb/min (82 kg/min). The typical and extreme ranges of delivery rates are summarized in Table 3.3. Because MDR was so important to the rebound study, additional details of the MDR concept are presented in Chapter 4.

3.5 NOZZLE-WATER MEASUREMENTS

During all shooting operations the water temperature, pressure, and volume readings were recorded. During the latter stages of the field work, the water meter readings were obtained at about one-minute intervals and each

TABLE 3.3

AVERAGE AND EXTREME RANGES OF MATERIAL DELIVERY RATES ON DAYS III AND IV

	Typical range lb/min (kg/min)	Extreme range lb/min (kg/min)
All ingredients (MDR)	350-450 (160-200)	181-600 (82-272)
Cement (MDR_c)	65-80 (30-36)	33-119 (15-54)
Aggregate (MDR_a)	280-360 (128-163)	130-515 (59-234)
Water in aggregate (MDR_{aw})	12-16 (6-7)	7-25 (3-12)
Water added at nozzle (MDR_{nw})	7-9 (3-4)	4-21 (2-10)
Total water (MDR_w)	19-25 (9-11)	13-33 (6-15)
Fibers (MDR_f)	11-12 (5-6)	6-13 (3-6)

Note: Accelerator dosage typically 3 percent by weight of cement (range 3-8%) for all but regulated-set mixes.

time the water was turned on or off while material was moving through the nozzle. These data, together with the timekeeper's log were reduced to obtain an approximate value of the actual nozzle water used. The data were studied to determine significant changes in water rates during shooting of each mix and between mixes. Often the rates were slightly different when shooting panels for measuring rebound than when shooting panels to obtain samples for strength tests.

To estimate the amount of water in the material stream, the water in the aggregates at the time of batching must be added to the water injected at the nozzle. The rates of shooting water in the aggregates and water injected at the nozzle are designated MDR_{aw} and MDR_{nw}, respectively; the total amount of water in the material stream is designated MDR_{w}. Each of these water rates was studied to determine if they had any effect on strength or rebound. In addition, the percentage of total water added at the nozzle (MDR_{nw}/MDR_{w}) was also evaluated. Calculated water-cement ratios were obtained by dividing MDR_{w} by MDR_{c}. These calculated water-cement ratios were compared to measured values obtained from fresh samples. The calculated values of water-cement ratios were higher than the water-cement ratios of the in-place materials, as explained in Chapter 7.

Plots of volume of water injected at the nozzle versus the total time of shooting were made for each batch. Four typical plots are given in Fig. 3.12. Figures 3.12a and 3.12c are plots for Mixes 23 and 33 in which many changes in the volume of water were made by the nozzleman. On the other hand, almost no water adjustments were made while shooting Mixes 30 and 39 (Figs. 3.12b and 3.12d). Regulated-set mixes typically required more nozzle-water than the other mixes.

3.6 PERFORMANCE OF NOZZLES

3.6.1 LONG NOZZLE

The long nozzle had the same nozzle body as that used in the short nozzle except a 13.5 ft (4.1 m) rather than a 15 in. (38 cm) long section of material hose served as a nozzle tip. The water hose and valve were located

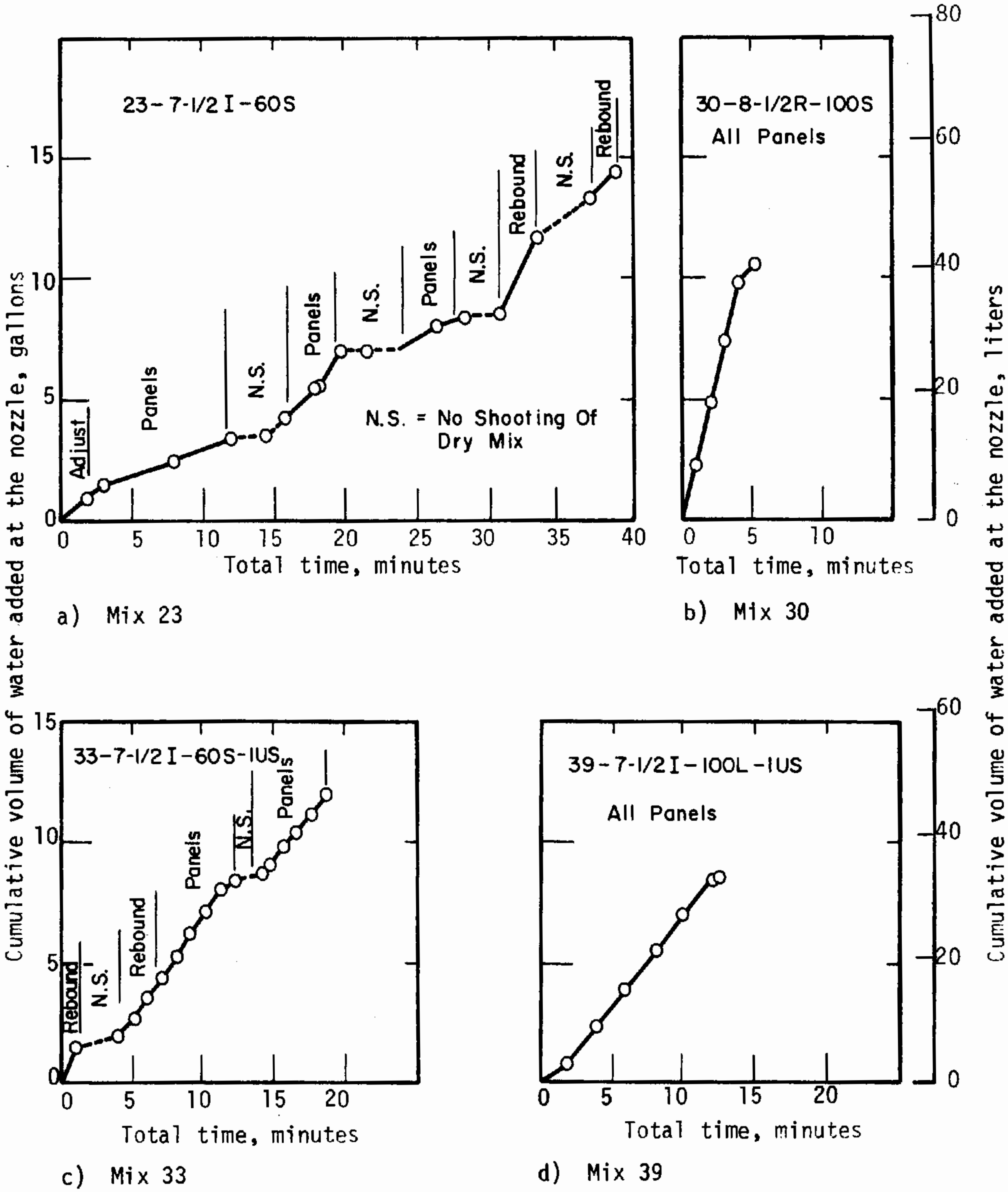


FIG. 3.12 TYPICAL MEASUREMENTS OF WATER FLOW THROUGH NOZZLE, DAYS III AND IV

near the end of the tip so that the nozzleman could adjust the nozzle-water. A water hose extension was used to connect the control valve with the nozzle body. These aspects of the nozzle are described in Section 2.4.2.

Visual observations of nozzle performance were made by experienced nozzlemen who indicated that the long nozzle was superior to the short nozzle. In particular, the long nozzle appeared to mix the water much better and produce less dust, thus the nozzleman had better visibility. These characteristics were also seen in the high-speed movies of the material stream as described in Chapter 5. Because other features masked the effect of the long nozzle, improvements in rebound or in strength are only partly indicated by this study. The nozzleman was also able to hold the nozzle tip closer to the wall when the long nozzle was used.

The long nozzle is, however, more prone to plugging because the water is added farther back in the material hose and particles tend to accumulate before they leave the nozzle. It may also be more difficult to hold and these important safety aspects must be considered when evaluating the use of a long nozzle.

3.6.2 DOUBLE WATER RING NOZZLE

This nozzle consisted of one nozzle body containing two water rings located about 6 in. (15 cm) apart. This nozzle is shown in Fig. 2.5. The developer recommends that best results are obtained when high water pressures are used. Unfortunately, a source of water under high pressure was not available at the test site and thus the studies on its performance cannot be considered representative. Only one mix (Mix 24) was shot with this nozzle;

shooting of more mixes would be necessary to give the nozzleman experience with the nozzle. The strength and rebound test results were probably not as good as one might expect if high water pressures had been used.

3.7 AIR AND WATER PRESSURES IN THE MATERIAL HOSE AND NOZZLE

Although the air pressure at the shotcrete machine and water pressure in the supply line are the most commonly reported operating pressures, the air and water pressures in the nozzle are also important. It has been implied in the literature that the water pressure must be greater than the air pressure at the machine.

In reality, the air pressure at the nozzle is only a very small fraction of the air pressure at the machine and the water pressure behind the water ring is some fraction of the pressure in the supply line because the control valve is only slightly open and restricts flow, thus causing a high pressure loss between the line and the water ring. Some simple field measurements were made to determine the magnitude of these pressures.

Measurements of air pressure in the material hose were made using a small, hand-held, hypodermic needle-type pressure gage. The instrument used is available commercially from manufacturers of compressed air equipment (Appendix B). The thin, hollow needle is pushed into the material hose until the gage registers the pressure in the hose at that point.

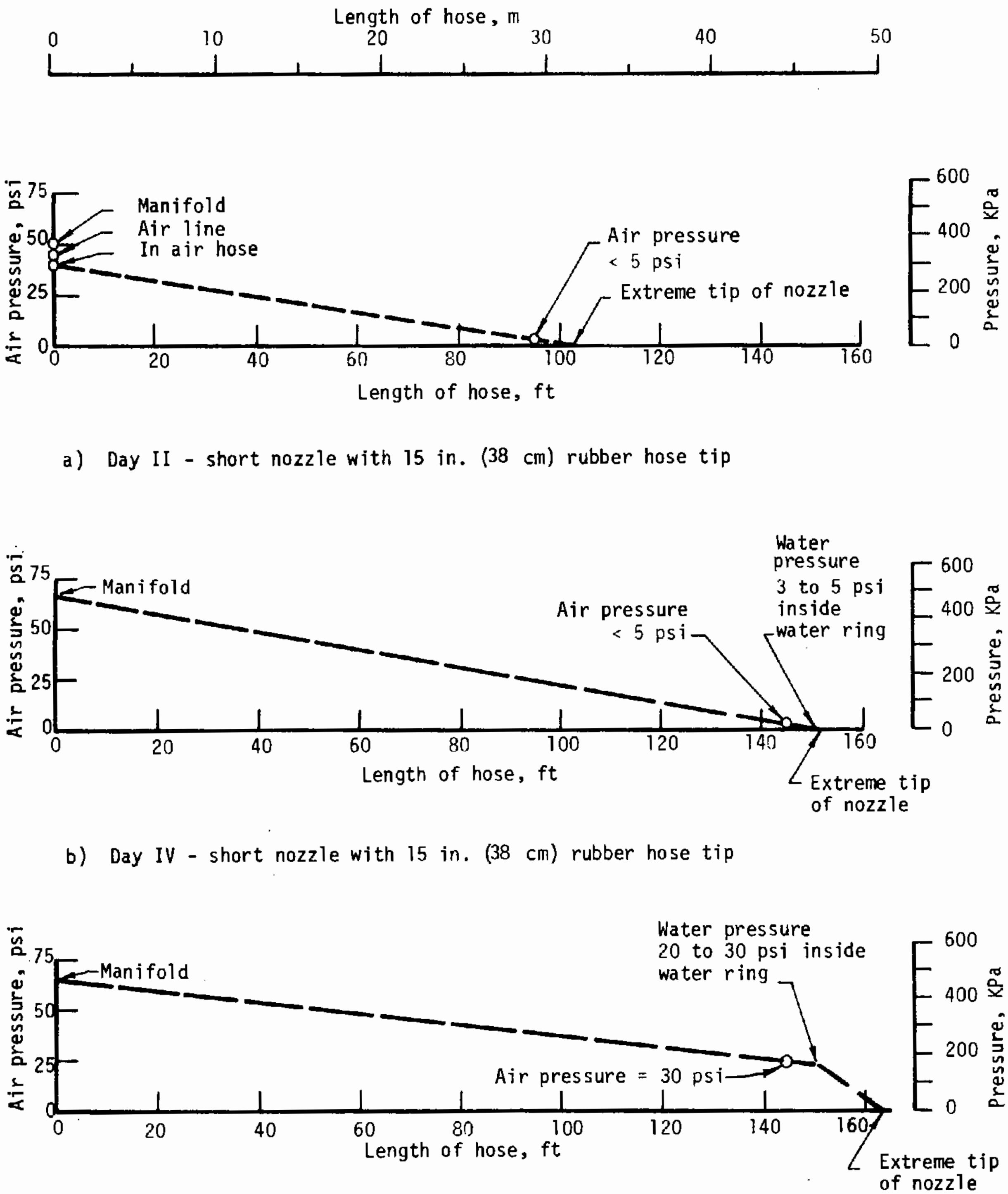
A conventional nozzle body was modified by placing a pressure gage in the cleanout plug so that the water pressure behind the water ring could be measured. A diagram of this modified nozzle is given in Fig. 2.5c. Since the pressure gage inhibited the nozzleman's performance during shooting, this special nozzle body was used for shooting only one mix with a short nozzle. No nozzling problems were encountered when this special nozzle body was used with the long nozzle tip. Part of the reason for running these tests was to compare the water pressures in the nozzle when it was located 13.5 ft (4.1 m) and 15 in. (38 cm) from the orifice.

The results of the air and water pressure measurements are given in Table 3.4 and illustrated graphically in Fig. 3.13. It can be seen that the air pressure dropped from 65 psi (448 KPa) at the machine to less than 5 psi (35 KPa) approximately 5 to 7 ft (1.5 to 2.1 m) behind the orifice of the short nozzle; the gage would not register below this value. A measurement was made about mid-length along the hose to determine the distribution of air pressure between the machine and the nozzle (Fig. 3.13). Other tests at

TABLE 3.4

AIR AND WATER PRESSURE MEASUREMENTS

Location	Short nozzle (15 in. (38 cm) rubber tip) psi (KPa)	Long nozzle (13.5 ft (4.1 m) rubber tip) psi (KPa)
Air pressure at machine	65 to 68 (448 to 469)	65 to 68 (448 to 469)
Air pressure in material hose 5 ft to 7 ft (1.5 to 2.1 m) behind nozzle	< 5 (<35)	20 to 30 (137 to 207)
Static pressure in hose about 100 ft (30.5 m) behind nozzle	65 (448)	65 (448)
Water pressure behind water ring	3 to 5 (21 to 34)	20 to 30 (137 to 207)



a) Day II - short nozzle with 15 in. (38 cm) rubber hose tip

b) Day IV - short nozzle with 15 in. (38 cm) rubber hose tip

c) Day IV - long nozzle with 13.5 ft (4.1 m) rubber hose tip

FIG. 3.13 MEASURED AIR AND WATER PRESSURES the University of Illinois have shown this distribution to be approximately correct. Further, they show that the air pressure in the material hose is very low when dry mix is not being gunned. Once the material flow is started, air pressure builds up abruptly to the operating levels.

The gage air pressure where the material leaves from the nozzle tip must be almost zero. The water pressure behind the water ring of the short nozzle was about 3 to 5 psi (21 to 34 KPa) and was probably slightly higher than the air pressure.

Similar relationships were observed with the long nozzle except that, as expected, the air and water pressures were higher than those in the short nozzle. The air pressure in the material hose about 5 ft (1.5 m) behind the nozzle body was about 30 psi (207 KPa). The water pressure behind the water ring was about 20 psi (137 KPa) when the nozzleman was shooting slightly dry and about 30 psi (207 KPa) when he was shooting slightly wet. Considering possible differences in calibration of the instruments, in the head losses resulting from flow through the holes in the water ring, and in the significant drop in air pressure from behind the nozzle to the nozzle tip, the data indicate that the water pressure was slightly higher than the air pressure in the nozzle.

3.8 OBSERVED TEMPERATURES

3.8.1 INTRODUCTION

The temperature of the environment, of the raw materials, of the nozzle-water, and of the in-place shotcrete are needed to interpret the test results. They were recorded as part of the field documentation program.

This program was also carried out to determine, in a rough fashion, some of the temperature conditions associated with shooting underground. No attempt was made to make more than spot checks. This was accomplished by thrusting a conventional, mercury-type, rod thermometer into the material about 1 to 2 in. (2.5 to 5 cm). Since the thickness of materials and the time elapsing after batching or shooting are significant to the build-up and decay of temperatures, these conditions were logged for nearly all of the temperature measurements. The environmental and raw material temperatures have been given in Tables 2.5a through d and are summarized in the following section. Shooting conditions, particularly on Days III and IV, were cold by most shotcreting standards.

3.8.2 TEMPERATURES OF DRY MIX

Cement begins to hydrate as soon as it comes in contact with any water including any moisture present in the aggregate. For most shotcrete operations, this is not a problem since the Type I cement reacts relatively slowly, the moisture contents in many aggregate sources are low, and the dry mix is usually gunned shortly after mixing. However, on this project the moisture content of the sand was as high as 8-1/2 percent. In these cases, the moisture content of the aggregate and cement together was about 4 to 5 percent and the water-cement ratio was about 0.15 to 0.2 after the materials were mixed. At such high moisture contents there was enough water to hydrate much of the cement prior to shooting.

Therefore, the temperatures of the prepared materials of several mixes were measured to evaluate the degree of hydration that took place before the material was shot. These data were obtained only for the dry mix without accelerator since the accelerator was not added until immediately before the material entered the machine.

Results of the temperature measurements are presented in Table 3.5. The air temperatures typically ranged between 30 to 60°F (-1 to 15.6°C) and material temperatures were about 45 to 55°F (7 to 13°C). The length of time between batching and the end of shooting ranged from 10 to 43 minutes. Most mixes were completely gunned within 15 to 25 minutes after mixing. Temperatures of dry mix generally increased some 5 to 20°F (3 to 11°C) before the materials were shot.

A few mixes, notably some regulated-set cement mixes began to hydrate more than desired but none were rejected. Mix 42 was marginally acceptable because of premature hydration. The materials of Mix 42, a steel fiber, regulated-set mix, reached a temperature of 98°F (36.7°C), an increase of some 41°F (8.3°C) while in the hopper. It was a particularly rich mix containing 10-1/2 bags (585 kg/m^3) of cement at a water-cement ratio of about 0.1 while it was stored in the hopper. When it was shot, the air pressure at the manifold was increased from 65 to 76 psi (450 to 520 KPa) on the nozzleman's request in order to prevent plugs in the material hose. The airstream of this mix was noticeably steamy, which interfered with the nozzleman's visibility. Substantial strength loss is attributed to the richness of the mix and to its premature hydration.

3.8.3 IN-PLACE SHOTCRETE

Two types of measurements were made of the temperature of in-place

TABLE 3.5

MEASURED TEMPERATURES OF DRY MIX

Mix designation	Temperature of dry mix, °F (°C)	Time since batched min	Maximum time between batching and completion of shooting, min	Remarks
DAY I				
Average of conventional mixes	49 (9)		~30	7-1/2 bag Type I cement Aggregate 44°F (6.7°C)
7-7½R-110S	58 (14.4) 58 (14.4) 58 (14.4) 60 (15.5) 60 (15.5)	5 12 15 25 30	~30	7-1/2 bag reg-set Aggregate 44°F (6.7°C)
DAY II				
20-9R-120S	72 (22.2)	5		
DAY III				
22-7½I-60S	61 (16.1)	17	22	Aggregates 54°F (12.2°C)
34-7½I-60S-1US-25CA	75 (23.9)		43	Sand was very wet and constituted 75% of aggregate. Aggregate 50°F (10°C)
DAY IV				
26-7½I-100L	63 (17.2)	17	27	Aggregate 55°F (12.8°C) Cement 47°F (8.3°C)
42-10½R-100L-1US	98 (36.7)	15-18	18	

shotcrete. On a few selected mixes, a thermometer was inserted in the shotcrete at random locations. On other mixes, electrical thermo-probes were embedded in shotcrete sprayed on panels and boulders. These data are representative of temperatures in relatively thin shotcrete linings. The effect of curing temperature on strength is discussed in Chapter 9.

THERMOMETER MEASUREMENTS

The temperature of shotcrete on the panels was measured with a thermometer in five cases. All but one were regulated-set cement mixes. These results are summarized in Table 3.6.

TABLE 3.6

TEMPERATURE OF IN-PLACE SHOTCRETE

Mix number	Shotcrete temperature, °F (°C)	Elapsed time after shooting, min	Air temperature, °F (°C)
IN-PLACE SHOTCRETE			
13-7 1/2I-60S	71 (21.7)	30	60 (15.6)
	72 (22.2)	60	
18-9R-80S	70 (21.1)	5	60 (15.6)
20-9R-120S	75 (23.9)	5	60 (15.6)
	78 (25.6)	8	
21-9R-100S	82 (27.8)	26	60 (15.6)
	92 (33.3)	42	
	94 (34.4)	43	
	95.5 (35.3)	46	
	110 (43.3)	61	
30-8 1/2R-100S	65 (18.3)	3	40 (4.5)

The regulated-set Mix 21 had a very high cement content (9-bag, 22 percent by weight). It also gained strength very fast and had roughly 1000 psi (6.9 MPa) in an hour. Temperature measurements were made at closer intervals than for the other mixes. It achieved a temperature of 110°F (43.3°C) in 1 hour. Figure 3.14 is a plot of the measured temperatures against time.

THERMO PROBES

In a few panels shotcrete temperatures were measured with an electrical thermal probe located at mid-thickness of the 3 in. (7.6 cm) thick

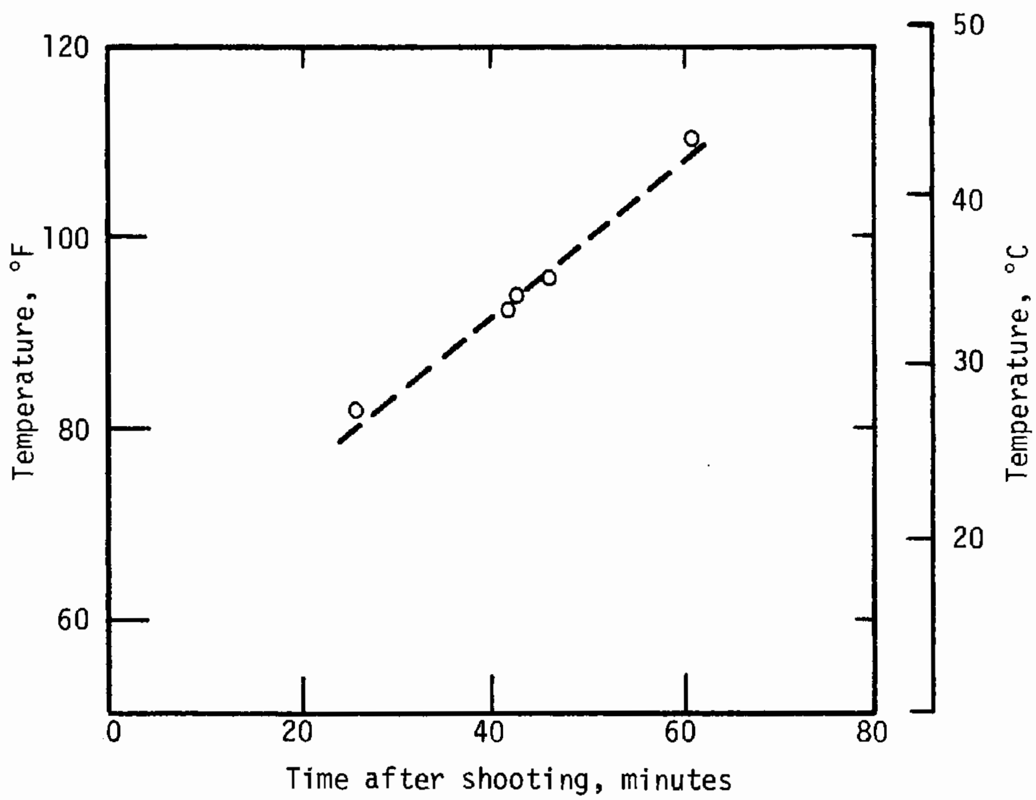


FIG. 3.14 TEMPERATURE OF SURFACE OF SHOTCRETE OF MIX 21

layers. Some of these panels were also instrumented with vibrating wire strain gages and/or Whittemore points to evaluate shrinkage strains in the shotcrete. Temperature measurements made using thermo-probes were at closer intervals than those made with thermometers and are more representative of temperatures in the interior of the panels. Selected temperature results have been plotted in Figs. 3.15 and 3.16.

The shrinkage results are presented by Jones (1976). However, it was shown that there was a significant reduction in measured shrinkage when the shotcrete was bonded to rock surfaces compared to the free shrinkage condition measured in plywood test panels. Thus, shrinkage measurements on plywood test panels are probably not representative of in situ conditions. Furthermore, data from embedded vibrating wire strain gages were significantly different from those given by Whittemore points placed on the exterior surface.

3.9 ADDITIONAL OBSERVATIONS DURING SHOOTING

3.9.1 WASHING WITH AN AIR-WATER JET FROM THE SHOTCRETE NOZZLE

Air-water jets are commonly used to clean rock surfaces prior to shotcreting. This washing usually improves the shotcrete-rock bond and prepares the surface to receive the layer of shotcrete. Studies were conducted to determine the effectiveness of washing with an air-water jet on removal of clay gouge from the surfaces of joints and shears.

The washing studies were conducted on three boulders 1 to 2 ft (30 to 60 cm) in size. Each boulder had at least one slickensided surface coated with clay gouge. The thickness of clay gouge was different on each

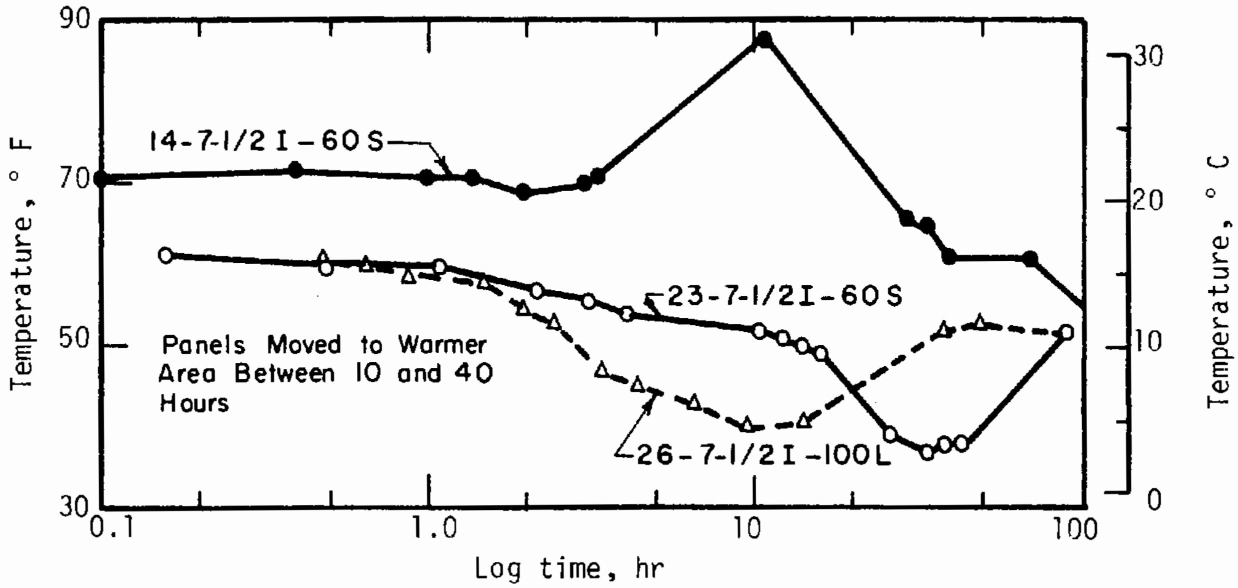


FIG. 3.15 TEMPERATURE MEASUREMENTS IN THE INTERIOR OF CONVENTIONAL SHOTCRETE, DAYS II, III AND IV

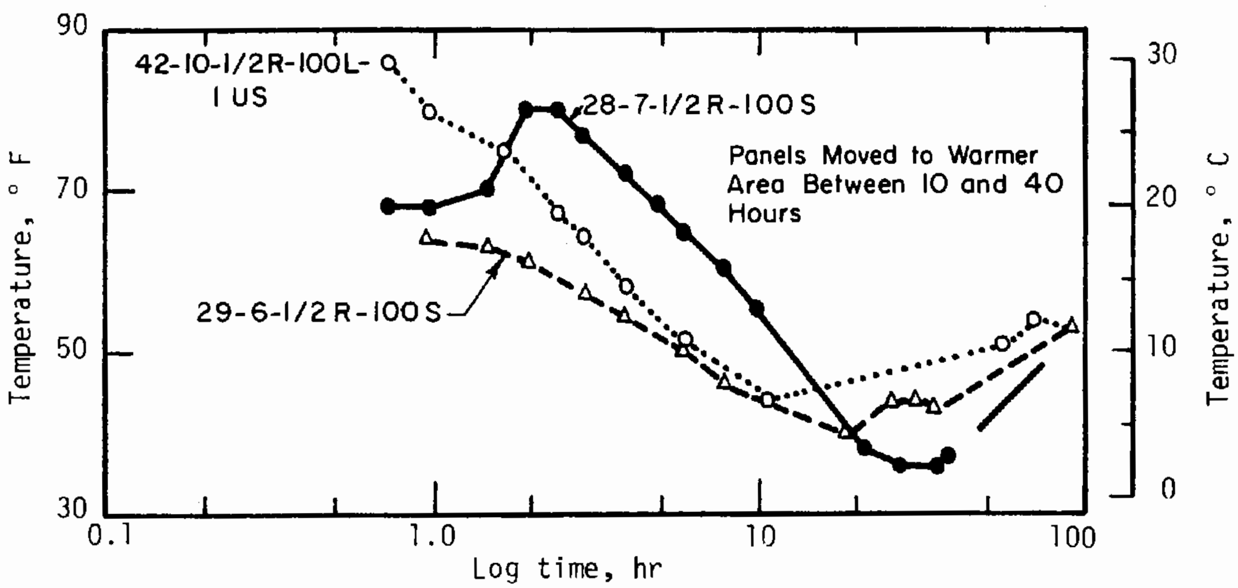


FIG. 3.16 TEMPERATURE MEASUREMENTS IN THE INTERIOR OF REGULATED-SET SHOTCRETE, DAYS III AND IV

boulder; the thicknesses were 1/8, 1/4 and 1/2 in. (3.4, 6.7, and 12.7 mm). The air-water jet was applied through the shotcrete nozzle at a right angle to the surface. The nozzle was held 3 to 6 ft (0.9 to 1.8 m) from the boulders. Each surface was washed between 30 to 60 sec. The washing procedures used in these studies were more intense than those normally used in the heading in a tunnel.

The air-water jet removed all of the gouge except in a small area of the boulder which, originally contained 1/2 in. (12.7 cm) of gouge. The gouge remaining on this surface was approximately 1/16 in. (1.6 mm) thick and was located in a slight depression. This depression constituted a 2 in. (5 cm) square area of the total area of the surface (1 ft^2 (0.09 sq m).

The washing exposed the slickensided and polished rock surfaces beneath the gouge. These surfaces were not affected by the washing action of the air-water jet. The slickensided surfaces would reduce shotcrete-rock bond relative to a rough joint but would provide a stronger bond than that developed if gouge were present between the rock and the shotcrete. Thus, extra care in washing joint surfaces containing clay gouge will improve shotcrete-rock bond.

3.9.2 SHOOTING OF REGULATED-SET SHOTCRETE ON SURFACES COVERED BY FLOWING WATER

On occasion shotcrete must be able to adhere to and build-up on rock surfaces covered by flowing water. Such ground conditions are frequently encountered in tunnel work. A simple test was conducted on Day III to evaluate the capability of regulated-set shotcrete in stopping water inflows. The test consisted of connecting a 1-in. (2.5 cm) water hose to the top of a bare plywood panel and allowing the water to flow down the center of the panel.

Conventional Mix 23 and regulated-set Mixes 28 and 31 were gunned onto this panel. The conventional mix and the regulated-set mixes (nozzle water of 100°F (37.8°C) in Mix 28 and 60°F (15.6°C) in Mix 31) adhered to the plywood panel satisfactorily. It should be noted that the conventional shotcrete was underaccelerated because of the cold temperatures. The ability of regulated-set shotcrete to stop high water flows can be improved by adding accelerators such as soda ash to the mix. Control of severe water flows with shotcrete should be studied further.

3.10 MISCELLANEOUS STRENGTH TESTS AND OBSERVATIONS

Several miscellaneous strength tests were made on the in-place shotcrete. Concrete penetrometer tests were attempted but found to be of little value. The Schmidt Hammer was also tried on shotcrete only a few hours old but the shotcrete had not gained enough strength to obtain a reading. The Schmidt Hammer would be of more value at greater ages but time was not available to perform additional tests.

Mixes 14 and 21 were shot onto panels mounted on large frames rather than onto individual panels. Each frame contained a mosaic of separate, but closely spaced, 2 x 2 ft (61 x 61 cm) plywood panels. After shooting, each panel was removed by cutting through the shotcrete along its borders. The shotcrete was given sufficient time to gain enough strength so that disturbance was minimized during removal of the panels from the frame. However, the regulated-set mix (21) gained strength so fast that it was nearly impossible to cut through it, even with axes.

Shotcrete which fell off some of the panels shortly after shooting showed a large contrast in strength from the back to the front of the panel; shotcrete in contact with the panel was moist and soft. The strength difference was most pronounced in the regulated-set shotcrete. Pull-out tests on the back of the panels of Mix 21 gave no reading at all even though the front of the panel could hardly be indented with an ax. The higher strength at the surface of the shotcrete may give a misleading impression of its support capability especially if the primary mode of load-carrying capacity is through bond strength. An investigation of the rate of development of strength through the layer and including bond strength at ages of one day or less would be a worthwhile undertaking.

3.11 SAFETY ASPECTS OF SHOOTING

3.11.1 STEEL FIBER SHOTCRETE

The safety aspects associated with shooting steel fiber shotcrete are a major concern yet there were no problems or accidents during these tests. In shooting the fiber mixes, the nozzleman wore a face mask and all personnel in the shooting area were required to wear goggles. When the first fiber mix was shot (Mix 5), the nozzle was first held far from the wall and then was brought closer to the wall, during this time the nature of fiber rebound was carefully observed. It was found that the rebound of the fibers posed no more of a safety problem than rebound of coarse aggregate.

The fibers lose considerable energy when they rebound; most fibers fall close to the wall. The relatively flexible US fibers appeared to bounce off the wall with less energy than the stiffer NS steel fibers. The high speed movies of the material stream show that both types of fibers usually tend to float away from the surface rather than to ricochet hard like coarse aggregate. Many fibers were carried up and away by the remnants of the airstream and simply dropped close to the wall. There were occasional fibers that rebounded a significant distance from the wall. Thus, all personnel in the shooting area must wear goggles to protect their eyes. Full face protection reduces chances for injury to those close-up to the wall, such as the nozzleman and his hose handler.

Since fibers generally rebound at lower velocities than coarse aggregate, clothing suitable for protection from rebounding aggregate was also adequate for protection from steel fiber. However, steel fibers tend to penetrate small folds, flaps, and seams in cloth. Protective clothing for steel fiber shotcrete should contain as few places as possible where fibers can collect. Otherwise, personnel could get injured by the fibers when they remove their clothing. Apron-type, protective clothing can also be used.

The immediate shooting area is not the only place where injury can occur from the fiber. Throughout the batching, transporting, gunning, and shooting operations, the fibers present a potential hazard and extra precautions should be taken. During batching, fiber handlers should wear gloves and should use rakes or other devices to disperse the fibers. Cloth and rubber gloves provide only partial protection. Even the use of leather gloves does not prevent injury, since the fibers are able to get into the stitching of the gloves, especially in the fingers. The crew must be cautioned and trained not to wipe their face or brow with gloved hands because fibers sticking to gloves could injure their eyes or face.

Fiber balls should be removed before shooting in order to reduce chances for hose plugs and to prevent large projectiles from being discharged at the nozzle. A coarse wire screen was placed over the machine to keep fiber balls from entering the pot. Although there was no noticeable increase in the numbers of plugs with steel fiber shotcrete, it must be realized that there is a greater potential for plugs when steel fiber is used and even more so if fiber balls are not removed.

The possibility exists of personnel being sprayed by fiber shotcrete if an accidental hose break occurs. All equipment should be in excellent condition and all couplings should be assembled tightly and protected by safety cables. All hoses and couplings should be made with extra care with nothing protruding into the hose line that might catch fibers and cause a plug.

Once the fibers are shot, a hazard still exists. Fibers partially embedded in the surface make the surface very abrasive. Any contact with the shotcrete will produce ripping of clothing and/or cutting. A thin coat of gunite without fibers could reduce this problem but adds to the cost and will not be permanent. The rebound material also contains abundant fibers and care must be taken during cleaning of the invert.

Cutting and handling of strength specimens of steel fiber shotcrete also required special precautions. Sometimes the saw blade pulled fibers out of the shotcrete, especially if it was young, and propelled them in the direction of rotation. Fortunately, the blade turned in the direction so that the fibers were propelled away from the operator and a board was placed to protect personnel working behind the saw. The saw operator wore gloves, a protective apron, a full face mask as well as ear protection for noise. Gloves were also worn and are recommended when handling shotcrete test specimens. The cut specimens usually have just enough fiber sticking out of the surface to make them a nuisance to handle.

Fibers which fall on the floor usually lie flat so they are not much of a safety hazard to personnel or equipment. In the invert, they were most dangerous when they clumped together or were standing on end in hardened rebound. Rubber-tired vehicles are usually not affected by the fibers. Fibers do tend to adhere to grease and oil so equipment repair and maintenance must also be done with care.

Most personnel contacts with fiber are likely to be a nuisance-type hazard rather than a serious injury, although there are reports of serious injury (Ryan, 1975). The fibers usually do not fully penetrate clothing but if they become stuck they can be worked through the clothing to the skin. The fibers are thin and therefore very sharp. They penetrate flesh with very little difficulty. Yet, getting stuck in the finger with them is more analogous to getting stuck with a fish hook except that fibers have no barb. Generally, the fibers only penetrate the skin a little bit but the wounds are painful and are sources of infection, particularly if the fibers are coated with accelerator or cement. The fibers can penetrate the eyes or any part of the body just as easily if unprotected. Thus, the hazard of the shooting fibrous shotcrete is mostly that of a painful nuisance or a superficial cut, but it also poses a potential for a much more serious injury and as such, extra safety precautions are necessary.

3.11.2 LONG NOZZLE

The long nozzle has a greater potential for material hose plugs than a short nozzle. These plugs are safety hazards themselves since they can cause a large whipping action at the nozzle, rupture of the material hose or failure of the couplings. In addition, injury can be caused by materials which are driven out of the hose at very high velocities during blow-out of the plug. The long nozzle is more prone to plugs when shooting is intermittent. When a plug occurs there is also a great possibility that the water may not be turned off in time and that water may run back into the hose. If this water is not cleared from the line it may knock the nozzleman off his feet when shotcreting is resumed or may cause another plug.

3.11.3 REGULATED-SET CEMENT

Cement and accelerators are known for being caustic and capable of causing serious chemical burns. The handling and use of caustic accelerators appears to be one of the more common causes of burns. Regulated-set cement requires no such accelerators and thus avoids direct personnel exposure to the accelerators themselves. However, regulated-set cement, like portland cement is caustic itself and the degree of reduced hazard should be investigated.

3.12 CONCLUSIONS FROM FIELD OBSERVATIONS

1. Combinations of cement and accelerators that are compatible at room temperature may not be compatible at other temperatures; low temperatures increase set times significantly. Compatibility tests should be conducted for the range of temperatures anticipated throughout the project.

2. Both regulated-set and steel fiber shotcrete were successfully mixed and gunned using typical construction crews and equipment. The use of a continuous auger-type mixer is believed essential for routine regulated-set shotcreting. Steel fibers were bent severely during mixing in the paddle-wheel mixer to the degree that it affected the test results; fibers should be inspected after mixing and gunning.

3. Determination of the material delivery rate (MDR) of all constituents was essential to proper interpretation of the tests. Significant variations in the accelerator dosage and other parameters that strongly affected strength were discovered only because of the documentation. Accurate records of the actual accelerator dosage for each shift should be maintained on all projects.

4. The long nozzle was superior to the short nozzle primarily because of better mixing. In both nozzles, air pressure at the nozzle and water pressure in the water ring were measured to be a fraction of line pressures. Specification of water line pressure on the basis of air pressure at the gun could be misleading.

5. Care in washing rock surfaces will improve rock-shotcrete bond, especially when thin layers of clay gouge are present. The strength of the exterior of recently-placed shotcrete may not be representative of the interior strength and bond strength. The interior strength was negligible in one case where the strength on the surface was substantial.

6. Rebound of fibers posed no more of a safety problem than rebound of coarse aggregate. However, goggles or face masks should be mandatory for everyone in the shooting area. Before and after shooting, though the possibility of serious injury from the fibers is greater, fibers should pose no more than a nuisance with proper precautions.

CHAPTER 4

REBOUND STUDIES

4.1 INTRODUCTION

4.1.1 IMPORTANCE OF STUDIES ON REBOUND

Rebound is one of the major problems facing the shotcrete industry. Excessive rebound is undesirable both from an economic and quality control standpoint. Someone must pay for the extra materials that rebound and for the cost of removal. There are intangible cost and safety factors associated with rebound too. The crews operate at a reduced efficiency because of the rebound hazard and because of reduced visibility from airborne dust. In terms of quality, rebound and dust from rebound, prevent the nozzleman from clearly seeing how well he is doing. Further, entrapped rebound is one of the major potential causes of poor quality shotcrete.

Some rebound is an inevitable consequence of the shooting operation. It has been observed that the nozzleman should get relatively close (about 3 ft; 1 m) to the wall to minimize rebound, yet the rebound tends to make the nozzleman keep his distance. The many various factors leading to excessive rebound were identified and appreciated by those familiar with shotcrete long ago. However, the relative significance of many of these factors is not well understood. The magnitude of rebound is difficult to determine in the field either by eye or by measurement. Consequently "eyeball estimates" cannot always be relied upon to base conclusions about the various factors of rebound.

4.1.2 SCOPE OF FIELD REBOUND STUDIES

This chapter deals with the results and conclusions of the measurements of rebound made during the field portion of this project. The results are discussed and conclusions are made on the basis of these results. Whenever necessary, data from other chapters are used to amplify the conclusions.

During the planning of this rebound study, it was found that new ways of thinking about the shotcrete operation, in general, and about the detailed behavior of the individual components of the mix, as they hit the wall and rebound, were necessary. The need for more information about the processes causing rebound led to the multiple-tarp rebound test and to the development of supplementary means of studying rebound such as the use of the stop-action camera and of the analyses of fresh shotcrete and rebound samples.

The evaluation of the results from all these studies generated new concepts and improved our knowledge of many of the previous concepts about rebound. The processes of shooting and of rebound were studied in detail. The evaluation verified the fact that the mechanisms leading to rebound change drastically after a thin initial layer of shotcrete is established on the wall. The rate of rebound decreases as the shotcrete on the wall increases in thickness. Further, the evaluation showed that the different constituents in the airstream rebound at different rates which vary with the mix and shooting conditions.

The concepts of rebound rates varying with time and of the different constituents rebounding at different rates are intuitive and thus can be explained without extensive field measurements and documentation. In the first sections of this chapter, the processes will be discussed in detail with the aid of several figures and simplified examples based on hypothetical data prepared to illustrate a point in a clear and concise manner. Following these conceptual sections, the actual results from the field program will be presented. The scope of these field rebound tests are introduced below. Their significance in light of the concepts will then be discussed.

All rebound tests were shot against vertical or near vertical walls. It was intended that rebound measurements from several different mixes shot against comparable rebound surfaces would be compared. Since bare rock walls were not plentiful in the station at the time of shooting and since significant variations in the roughness and texture of the walls were expected to affect the results, most rebound tests were shot against specially prepared rebound panels. For the purposes of this work, all these panels were uniform surfaces similar in geometry and in hardness. Thus, these rebound studies were not intended to give absolute values of rebound. It was sufficient that the rebound measurements fell within the normal limits of rebound for similar shooting and mix conditions. The important question was whether one mix resulted in more rebound than another.

A special feature of the rebound study involved the measurement of rebound for different thicknesses of in-place shotcrete. Finally, the duration of collection of rebound was relatively short (3 to 5 minutes) for each mix since other portions of the batch were used for other studies such as strength. However, a sufficient amount of shotcrete was shot against a 4 ft by 6 ft area (1.2 x 1.8 m) so the thickness shot ranged from 1.0 to 5.5 in. (2.5 to 14 cm).

It was recognized that the ideal rebound test might consist of the collectior of rebound over a much longer duration of shooting and over a much larger sur face area. This was quite impractical for a multi-faceted research program such as this. The rebound study program was carefully planned and executed with the assistance of experienced field personnel so that meaningful data were obtained. These "mini-rebound tests" were the results of this comprehensive effort.

4.1.3 COMPLEMENTARY STUDIES ELSEWHERE IN THIS REPORT

The research summarized in this chapter is only one part of the overall effort on this project to determine the physical mechanisms leading to rebound. Other aspects of this project which deal with rebound are discussed in the following sections.

Chapter 2: Description of field studies and rebound test procedures.

Chapter 5: Photographic evaluation of airstream. Describes rebound mechanism in detail and discusses principal factors affecting rebound.

Chapter 6: Evaluation of fresh shotcrete samples. Presents data on percentage of components in rebound. Evaluation of rebound rate of each component of mix individually.

Chapter 7: Evaluation of steel fiber content and distribution. Discussion of fiber rebound and retention rates.

4.2 VARIATION OF REBOUND RATES WITH TIME AND THICKNESS

4.2.1 GENERAL DISCUSSION

A critical observation of the rebound from a shotcrete operation will indicate that there appears to be much more rebound when shooting against a bare hard surface than after a thin shotcrete layer has been established. The very high rebound rates during the first phase (Phase 1) occur primarily because the aggregate bounces off the bare hard walls with little or no energy dissipation. Some fines begin to stick to the wall, however, and a layer of fines or paste is gradually built up. The paste acts as a cushion to absorb some of the impact energy of particles and as a restraining layer tending to hold particles in it. As the layer of paste gets thicker, its effect on restraining the particles increases and particles lose an increasing amount of energy penetrating the cushion. Consequently the energy after impact is lower and the thicker cushion provides more resistance against breakout. The smaller particles are first affected by this cushion of paste and they begin to stay on the wall. As the thickness increases, larger particles are affected similarly. Eventually sufficient thickness is built up so that the hardness of the original wall has no effect on the rebound or on the properties of the material being deposited. The rebound rate during this latter stage (Phase 2) is determined by the consistency of the material on the wall and is believed to be constant.

It is very important to clearly distinguish between the rate of rebound at any given instant in time and the average rebound after shooting for a certain length of time. This distinction is very important to the development of the concepts to be established in the next few sections.

MATERIAL DELIVERY RATE

Since the rebound test was conducted using only part of a batch, it was necessary to determine accurately the weight of material shot during the time rebound was collected. The method consisted of determining the rate that material was delivered to the wall and multiplying that rate times the exact amount of time material was shot at the wall during rebound collection on any given tarp.

The total amount of dry mix batched for each mix was measured by the calibrated weigh hopper during batching. All shooting times were recorded precisely so that the time required to shoot the entire weight batched was known. Any stoppages of material flow were subtracted from the gross time of shooting to obtain a net shooting time. A very important parameter can be calculated from this data. It is called the MATERIAL DELIVERY RATE (MDR) (see Section 2.7). Assume for now that this delivery rate is constant and defined as follows.

$$\text{MDR} = \frac{\text{Total Weight of Material Shot}}{\text{Net Time to Shoot Batch}}$$

The units are weight per unit of time. MDR is defined as the total of all constituents as shown in Table 4.1. A typical shotcrete gun for tunnel construction may deliver 18,000 lbs (8180 kg) of material per hour which will be defined as the "Material Delivery Rate" (MDR) for this example. The example in Table 4.1 also lists typical values and the same constant MDR expressed to different units of time. The numbers differ only since each is expressed to a different unit of time. The term cu yd/hr

TABLE 4.1

DEFINITION OF MATERIAL DELIVERY RATE

I. MATERIAL DELIVERY RATE = MDR = $\frac{\text{Weight of all material shot}}{\text{Net time to shoot all material}}$

II. Units: Weight per unit time

a) One minute is a practical unit of time

b) Other units illustrated by following example

EQUIVALENT UNITS FOR MDR

Weight lbs (kg)	Time to shoot weight	MDR
5 (2.3)	1 second	5 lb/sec (2.3 kg/sec)
300 (135)	1 minute	300 lb/min (135 kg/min)
18,000 (8180)	1 hour	18,000 lb/hr (8180 kg/hr)

III. Typical values:

a) Range 60 to 600 lb/min (27 to 270 kg/min)

b) Range for this project 180 to 600 lb/min (82 to 272 kg/min)

IV. Remarks:

a) MDR can vary considerably during shooting of one batch if machine operates erratically

b) For this project, average MDR is assumed to be constant for each batch (cu m/hr) is the volumetric equivalent of MDR which is defined here in terms of weight.

It should be noted in Table 4.1 that MDR represents the total of all constituents in the airstream but the concept can be extended to each of the individual constituents being shot (cement, fine and coarse aggregate, water, and fiber) by using special notation as shown in Table 4.2. The significance of these breakdowns will become important later when the rebound rate of each of the constituents will be discussed.

REBOUND RATE

The weight of material bouncing off the wall during a very short period of time is the Rebound Rate (RR) which typically ranges from about 1 to 5 lb/sec (0.5 to 2.3 kg/sec). Table 4.3 summarizes the definition, units, and typical values for Rebound Rate (RR). The Rebound Rate (RR) reduces considerably as the initial layer becomes established and gets thicker even though MDR is constant. This is characteristic of shotcrete operations; much more rebound occurs during the first few seconds of shooting against a bare rock surface. This effect is partly masked by the fact that the nozzleman is usually moving the nozzle back and forth between the bare rock and fresh shotcrete surfaces.

YIELD RATE

Similarly, the Yield Rate (YR) is defined as the weight of material retained in the wall during a very short period of time. It is the Material Delivery Rate less the Rebound Rate. Yield Rate (YR) is also defined in Table 4.3.

TABLE 4.2

BREAKDOWN OF MDR INTO MDR OF CONSTITUENTS

$$\text{MDR Airstream (MDR)} = \begin{cases} \text{MDRair (MDRa)} \quad \text{(Negligible in terms of weight)} \\ \text{MDR nozzle water (MDRnw)} \\ \begin{array}{l}\text{MDRdry mix (MDRdm)} \\ \quad \text{which equals}\end{array} \begin{cases} \text{MDRcement} \quad \text{(MDRc)} \\ \left.\begin{array}{l}\text{MDRfine aggregate} \quad \text{(MDRfa)} \\ \text{MDRcoarse aggregate (MDRca)}\end{array}\right\}\text{MDRag} \\ \text{MDRwater in aggregate} \quad \text{(MDRaw)} \end{cases} \end{cases}$$

$$\text{MDR} = \text{MDRnw} + \text{MDRdm}$$

$$\text{MDR} = \text{MDRnw} + (\text{MDRc} + \text{MDRfa} + \text{MDRca} + \text{MDRaw})$$

$$\text{MDR water in airstream (MDRw)} = \text{MDRaw} + \text{MDRnw}$$

Note: Most parameters defined in this chapter can be broken down into subparameters for each of the mix constituents as shown here for MDR. (See Table 4.5 for example for SSUM)

Fine and coarse aggregate each contain both sand and gravel-sized particles. The weights as batched from the corresponding fine or coarse aggregate bin are then converted to equivalent weights of sand and gravel according to the definition of gravel as that retained on the No. 4 sieve (4.76 mm). Hence, MDRfa and MDRca are only approximately equal in magnitude to MDRsand (MDRs) and MDRgravel (MDRg) respectively.

TABLE 4.3

DEFINITION OF REBOUND RATE AND YIELD RATE

I. Rebound Rate = RR = Weight of all materials rebounding off surface per unit of time

A. Units: Weight per unit time

One second is a practical unit of time for measurements but could be converted to per minute figures

B. Typical Values:

a) Initially: high percentage of MDR; 4 to 7 lb/sec (1.8 to 3.2 kg/sec)

b) After critical thickness established: 5 to 25 percent of MDR; 0.2 to 2.5 lb/sec (0.1 to 1.1 kg/sec)

C. Remarks: Though defined as the weight rebounding per instant of time (dw/dt) it is not practical nor necessary to discuss in terms of differential calculus terms here. (See Section 4.8 and Appendix F)

II. YIELD RATE (YR) = weight of material retained in the wall per unit of time

$$YR = MDR - RR$$

Note: Each value of RR and YR must be documented by the thickness of shotcrete on the wall.

REBOUND RATE RATIO (RRR)

As defined in this report, the Rebound Rate Ratio (RRR) is the weight of material which rebounds during a very short period of time expressed as a ratio of the weight of material shot at the wall during the same short interval of time (see Table 4.4). For convenience, this parameter will be abbreviated RRR. The Rebound Rate Ratio (RRR) is the amount of material that has rebounded to the ground per unit of time divided by the amount of material being shot per same unit of time. Thus, it is the ratio of two weight rates; the rate of material rebounding per unit of time (RR) divided by the rate of material being shot to the wall per same unit of time (MDR). As will be seen later, this parameter changes at every interval of time, especially at the beginning of shooting. RRR is always expressed as a ratio to avoid confusion with the customary usage of the term "percentage rebound."

YIELD RATE RATIO (YRR)

Similarly, the Yield Rate Ratio (YRR) is defined as the weight rate retained in the wall expressed as a ratio of MDR. The parameter YRR is equal to (1 - RRR) as shown in Table 4.4.

CUMULATIVE WEIGHT CONCEPTS

It is necessary to use batch weights and finite weights of rebound when calculating the preceding weight-rate-parameters. The parameters SSUM, Total Weight Shot; YSUM, Total Weight Retained in Wall; and

TABLE 4.4

DEFINITION OF REBOUND RATE RATIO

I. Rebound Rate Ratio = RRR = $\frac{RR}{MDR}$

$$= \frac{\text{Weight of all material rebounding per second}}{\text{Weight of material shot per second}}$$

A. Units: Dimensionless

B. Typical Values:

a) Initially 1.0

b) After critical thickness established 0.05 to 0.20

C. Remarks:

a) Expressed only as a ratio; never expressed as a percentage to avoid confusion with average rebound percentage customarily reported by industry.

II. YIELD RATE RATIO (YRR) = $\frac{YR}{MDR}$

$$= \frac{\text{Weight of material retained on the wall per second}}{\text{Weight of material shot per second}}$$

$$YRR = 1 - RRR$$

Note: Each value of RRR and YRR must be documented by the thickness of shotcrete on the wall.

RSUM, Total Weight Rebounded are defined in Table 4.5. These represent the accumulation or the integral of MDR, YR, and RR respectively over some length of time, usually the time required to shoot a batch or the time required for rebound tests.

4.2.2 BASIC MACRO-RELATIONSHIPS BETWEEN MDR AND REBOUND

The following concepts were developed primarily for coarse aggregate dry-mix shotcrete. The concepts apply to fine aggregate shotcrete to some degree and to wet-mix shotcrete to a lesser degree because the initial cushion is established immediately as materials arrive at the wall in a plastic, coherent mix.

If shooting takes place at a constant rate (constant MDR), the total amount of weight shot at the wall increases uniformly with time as shown in the example in Fig. 4.1a. The slope of the line is the numerical value of the Material Delivery Rate, MDR. Figure 4.1b illustrates the same relationship of constant MDR in a different way; the area under the MDR line up to any given time in Fig. 4.1b is the numerical value of the y axis at that time in Fig. 4.1a as shown by the construction lines.

Figure 4.2 illustrates a reasonable hypothetical example of how rebound decreases with time as the shotcrete on the wall gets thicker. Two relationships are shown on Fig. 4.2; the solid horizontal line is MDR while the dashed line is the rate of rebound, RR. The length of any vertical line from the x axis to the solid line is the numerical value of MDR in pounds per second (kg per second). The length of any vertical line between the x axis and the dashed curve is the numerical value of RR in pounds per

TABLE 4.5

DEFINITION OF CUMULATIVE WEIGHT PARAMETERS

I. SSUM = Total weight material shot during any specific interval of time

$$SSUM = MDR \cdot (\text{time shot}) = \int_0^t MDR\, dt$$

$$SSUM = YSUM + RSUM$$

$$SSUM = \begin{cases} \text{SSUMair (SSUMa)} \quad \text{(Negligible in terms of weight)} \\ \text{SSUMnozzle water (SSUMnw)} \\ \text{SSUMdry mix (SSUMdm)} = \begin{cases} \text{SSUMcement (SSUMc)} \\ \text{SSUMfine aggregate (SSUMfa)} \\ \text{SSUMcoarse aggregate (SSUMca)} \\ \text{SSUMwater in aggregate (SSUMaw)} \\ \text{SSUMfibers (SSUMf)} \end{cases} \end{cases}$$

$$SSUM = SSUMnw + SSUMdm$$

$$SSUM = SSUMnw + (SSUMc + SSUMfa + SSUMca + SSUMaw + SSUMf)$$

Note: For practical purposes, nozzle water is not a significant component for average rebound considerations. Therefore SSUM $\approx$ SSUMdm.

II. RSUM = total weight of material rebounded during any specific interval of time.

$$RSUM = RR \cdot (\text{time shot})$$

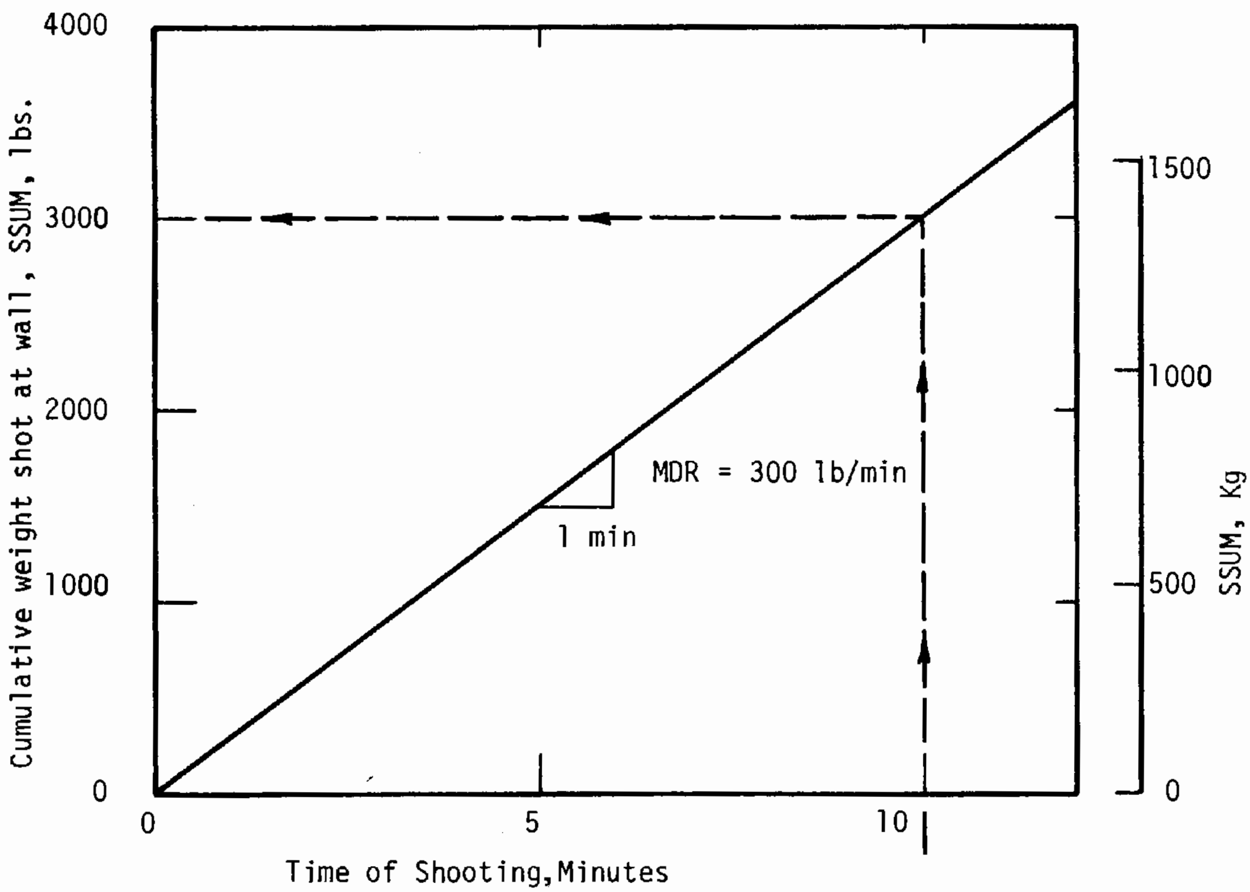
$$RSUM = SSUM - RSUM$$

III. YSUM = Total weight of material retained on wall during any specific interval of time

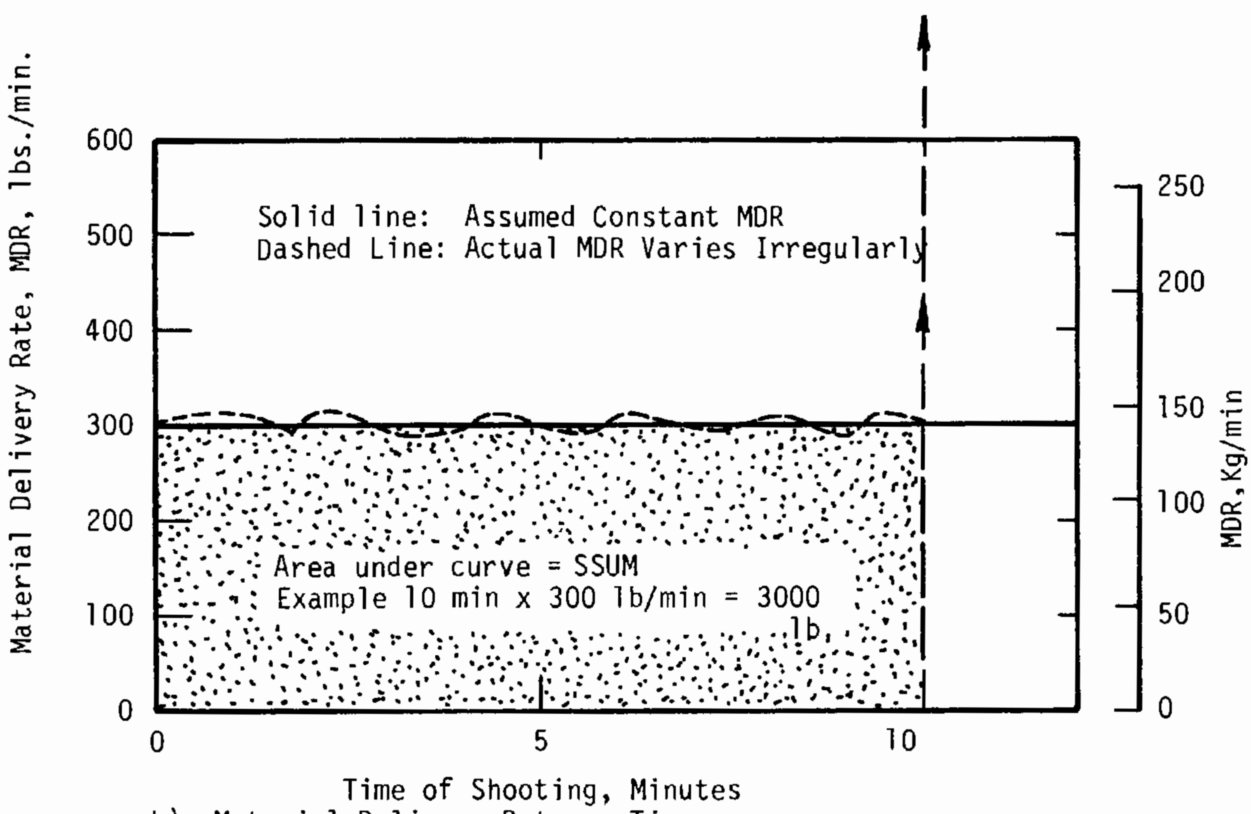
$$YSUM = YR \cdot (\text{time shot})$$

$$YSUM = SSUM - RSUM$$

Note: These cumulative weight parameters refer to the total cumulative weight during some specified activity such as for a given tarp or for the whole rebound test.

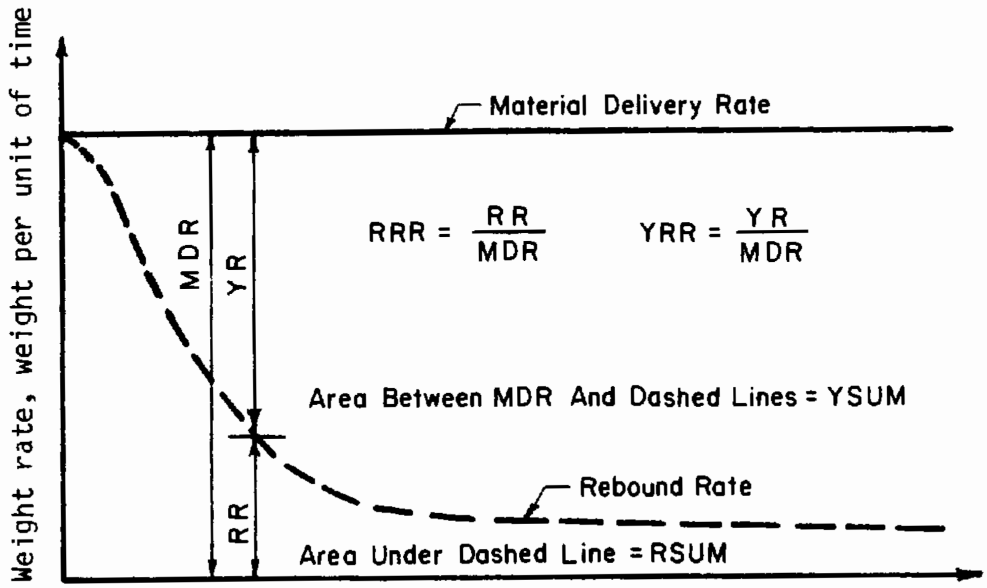


a) Cumulative Weight Diagram



b) Material Delivery Rate vs Time

FIG. 4.1 CONCEPT OF MATERIAL DELIVERY RATE, MDR



Time

FIG. 4.2 VARIATION OF REBOUND RATE WITH TIME

second (kg per second). The length of any vertical line from the dashed line up to the solid MDR curve is the numerical value of the rate of yield YR or the number of pounds per second (kg per second) which stick to the wall. Thus, YR is equal to (MDR - RR).

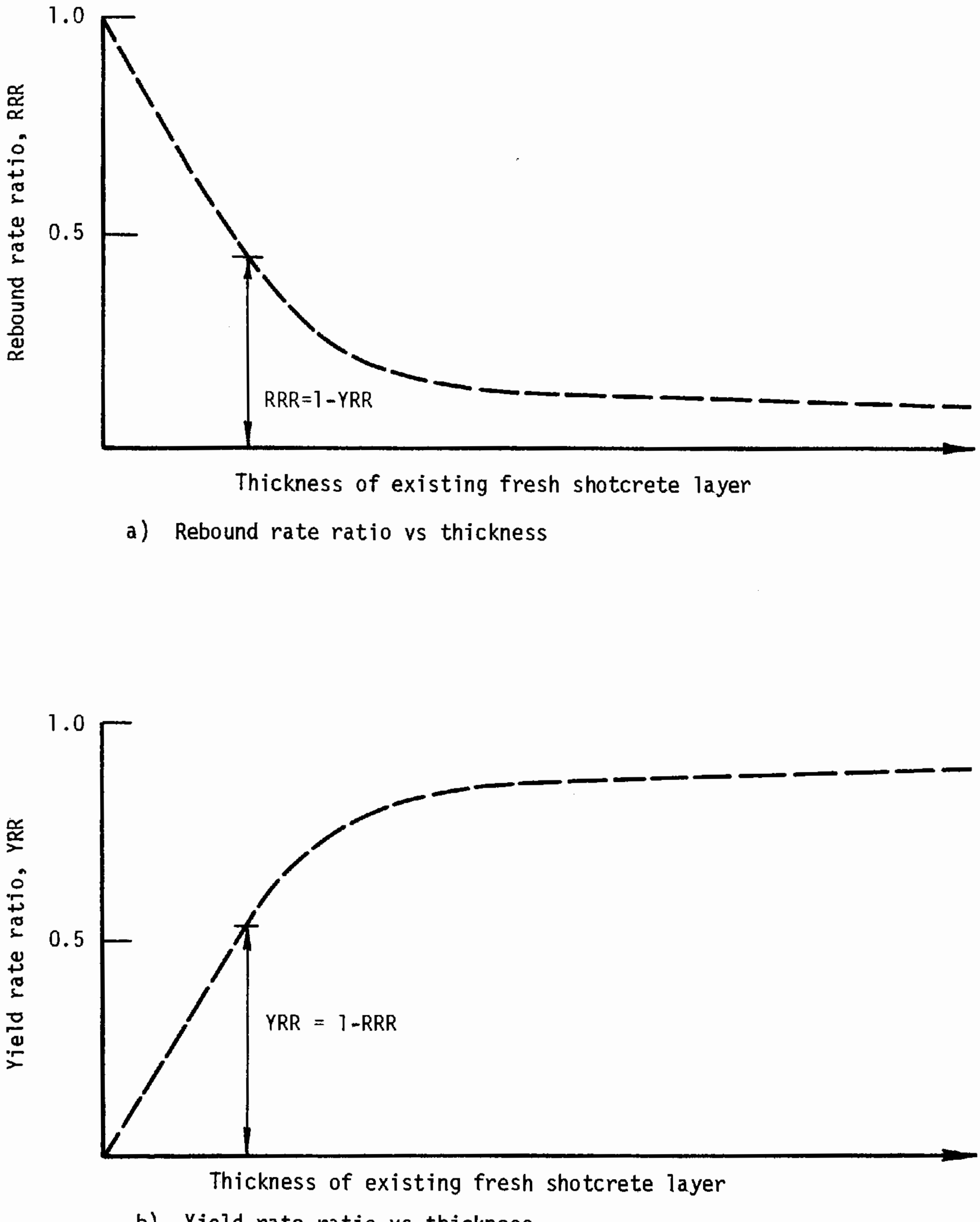
The area under the RR-versus-time of shooting curve (the integral of the curve) in Fig. 4.2 is the total weight of material that has rebounded, RSUM.

It is convenient to think about rebound and yield not only in terms of weight per unit of time but also as a ratio of the amount of material shot against the wall. The ratio of the length of the line RR to the length of MDR is termed the rebound rate ratio, RRR, while YR to MDR is the yield rate ratio, YRR. RRR is the ratio of the amount of material falling to the ground to the amount of material shot at the wall at any given precise instant or any convenient short period of time. RRR must not be confused with percentage of rebound commonly reported in the literature. To avoid confusion, RRR is expressed as a ratio, never as a percentage.

So long as MDR is constant, the RRR-versus-time curve is similar in all respects to the RR-versus-time curve; the area under the RRR curve is directly related to RSUM by the term MDR. Intuitively, if one layer of a small area is continuously built up without moving the nozzle, at the beginning, almost 100 percent of the material bounces off with very little sticking. This is shown in Fig. 4.2 at zero time of shooting where RR is as large as MDR. The rebound rate ratio RRR is 1.0 at this instant. As the layer increases in thickness, the rebound rate decreases and, thus, RRR decreases.

It is more appropriate, however, to plot rebound and yield data with respect to thickness rather than to time since the phenomenon is governed by the thickness on the wall. Thickness of the layer of shotcrete on a given area is related to time of shooting by a non-linear function (see Section 4.8 and Appendix F). The overall characteristics of plots with respect to thickness are similar to plots with respect to time; both plots are characterized by the high rebound losses at the beginning of shooting though the curves differ in the details of their shapes. Therefore, many conclusions drawn from one set of curves are applicable to the other. For the discussions based upon the thickness curves, it is sufficient to recognize that the area under the RR-or-RRR-versus-thickness curve is closely, but non-linearly related, to its corresponding RAVE curve.

Figure 4.3a expresses, in terms of RRR, how much of the material being shot at the wall is falling to the ground at any given thickness. Figure 4.3b illustrates the same relationship in terms of material being retained on the wall. The yield rate ratio, YRR, is plotted against thickness; the curve is the plot of (1-RRR). Figure 4.3b expresses how much of the material being shot at the wall is being retained in the wall to become a useful product.



a) Rebound rate ratio vs thickness

b) Yield rate ratio vs thickness

FIG. 4.3 REBOUND RATE RATIO AND YIELD RATE RATIO RELATIONSHIPS

Figure 4.4 is a plot of the total weight rebounded, RSUM, after shooting against a certain area, versus time. The total weight shot, SSUM, is shown also as a dashed line. The slope of the tangents (light lines) to the RSUM curve is the rebound rate RR which has the units weight per second. The length of a vertical line up to the solid line is the numerical value of the total weight of material that has rebounded, RSUM, while the length of a vertical line to the dashed line is the numerical value of the total weight shot.

The ratio of these two quantities, expressed as a percentage, is what the industry customarily calls "percentage rebound" and is the value commonly reported in the literature. It shall be called Average Rebound, RAVE, in this report. RAVE is defined in Table 4.6.

Note, however, that the ratio of these lines decreases considerably with time or thickness. At the very beginning of shooting the total amount rebounded is a high percentage of the amount shot while after a cushion has been built-up, the ratio decreases slowly. Figure 4.5 is a plot of the ratio of the lengths of the two lines in Fig. 4.4. This plot of Average Rebound (RAVE) shows how the values for rebound commonly reported in the literature are dependent upon the total length of time of collection (or more properly, with the thickness of the cushion or layer of fresh shotcrete).

4.2.3 PHYSICAL SIGNIFICANCE OF RRR AND RAVE

When rebound is measured in terms of average rebound, RAVE, the magnitude of RAVE is always affected by the higher losses during Phase 1.

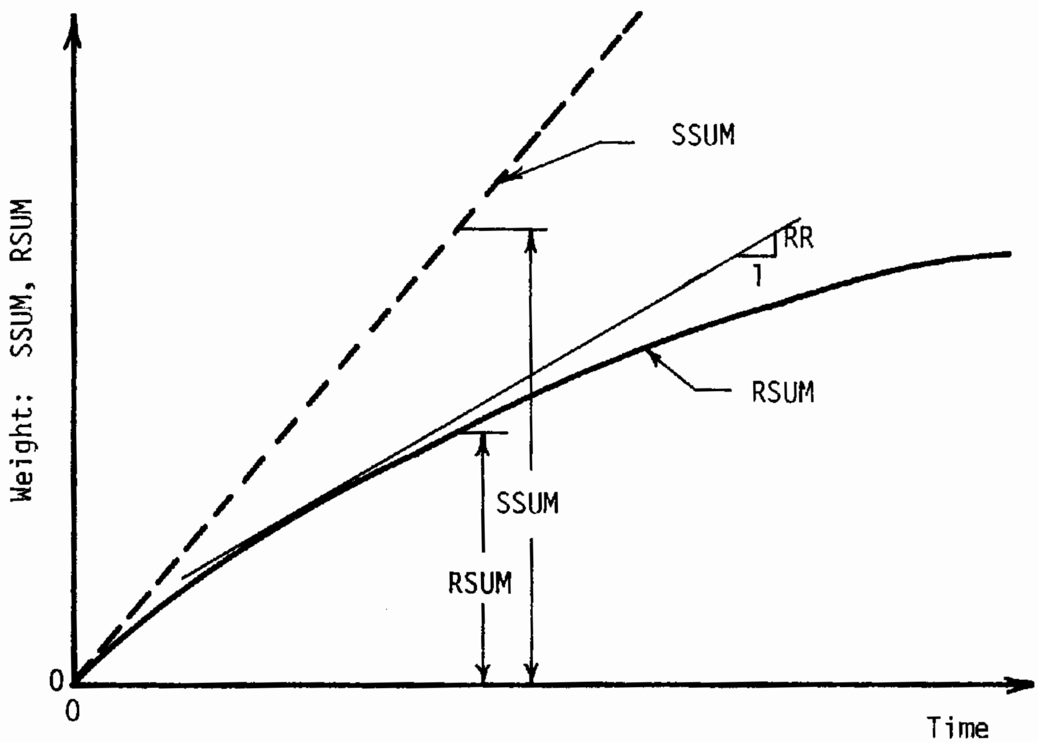


FIG. 4.4 TOTAL WEIGHT VERSUS TIME RELATIONSHIPS FOR SHOOTING AT A UNIT AREA

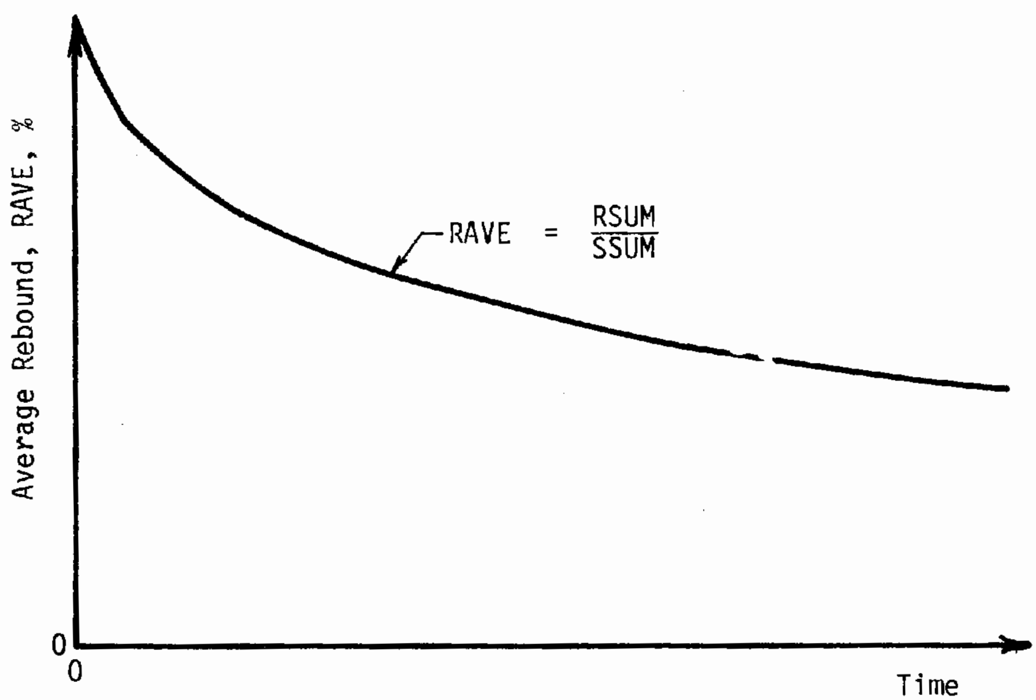


FIG. 4.5 AVERAGE REBOUND (RAVE) VERSUS TIME

TABLE 4.6

DEFINITION OF AVERAGE REBOUND, (RAVE), AND AVERAGE YIELD, (YAVE)

I. RAVE = AVERAGE REBOUND

A. $$\text{RAVE} = \frac{\text{Total weight of material collected to full thickness}}{\text{Total weight of material shot during period of collection}} \cdot 100$$

$$= \frac{\text{RSUM}}{\text{SSUM}} \cdot 100 = \text{RAVE in percent}$$

B. RAVE is the value closest to what Industry calls "Percentage Rebound"

II. YAVE = AVERAGE YIELD

A. $$\text{YAVE} = \frac{\text{Total weight of material stuck on wall}}{\text{Total weight of material shot during period}} \cdot 100$$

$$= \frac{\text{YSUM}}{\text{SSUM}} \cdot 100 = \text{YAVE in percent}$$

Note: RAVE and YAVE must be documented by the total thickness shot.

The magnitude of RAVE is decreasing at a time when the rate of rebound is constant. Long after the rate of rebound during Phase 2 has been constant at a relatively low value, RAVE, because of the fact that it is an average value, is still decreasing with thickness. This gradual reduction in RAVE with thickness is only a manifestation of the mathematics, based on its definition as an average, and the fact that there is a significant difference in the rebound rates between Phase 1 and 2.

In spite of the fact that RAVE does not reflect the precise physical behavior, RAVE does accurately reflect the total amount of rebound lost when shooting to any thickness, which is what the Contractor really cares about. RAVE is the only practical parameter on which economic assessments of rebound should be based.

When rebound is measured properly in terms of rebound rate ratio, RRR, the true rebound behavior is measured and the rate of rebound at all times is accurately reflected. To make such measurements, rebound must be measured at frequent intervals during the shooting (multiple-tarps) so that the calculated values closely approximate a true rate.

In conclusion, the best parameter to use when comparing different mix or shooting conditions is RRR. However, the economic comparison between any two mixes must be made based on RAVE or some other parameter based upon RAVE such as one introduced in Section 4.7.1.

4.2.4 EFFECT OF INITIAL CRITICAL THICKNESS

TIME REQUIRED TO BUILD UP THICKNESS

The cumulative losses due to the high rebound rates at the beginning stages of shooting against a bare surface are related not only to thickness of the shotcrete on the wall, but also to the length of time needed to establish the initial critical thickness. Obviously if the mix and shooting conditions are such that the initial critical layer (probably mostly cement paste and some fines) is built-up very slowly, the cumulative losses will be very high. Figure 4.6 illustrates this effect conceptually. The reduction in rebound rate with thickness does not even begin until some initial layer is established. The thickness of this initial critical layer depends upon the effective size of the incoming particles. When a mixture of different

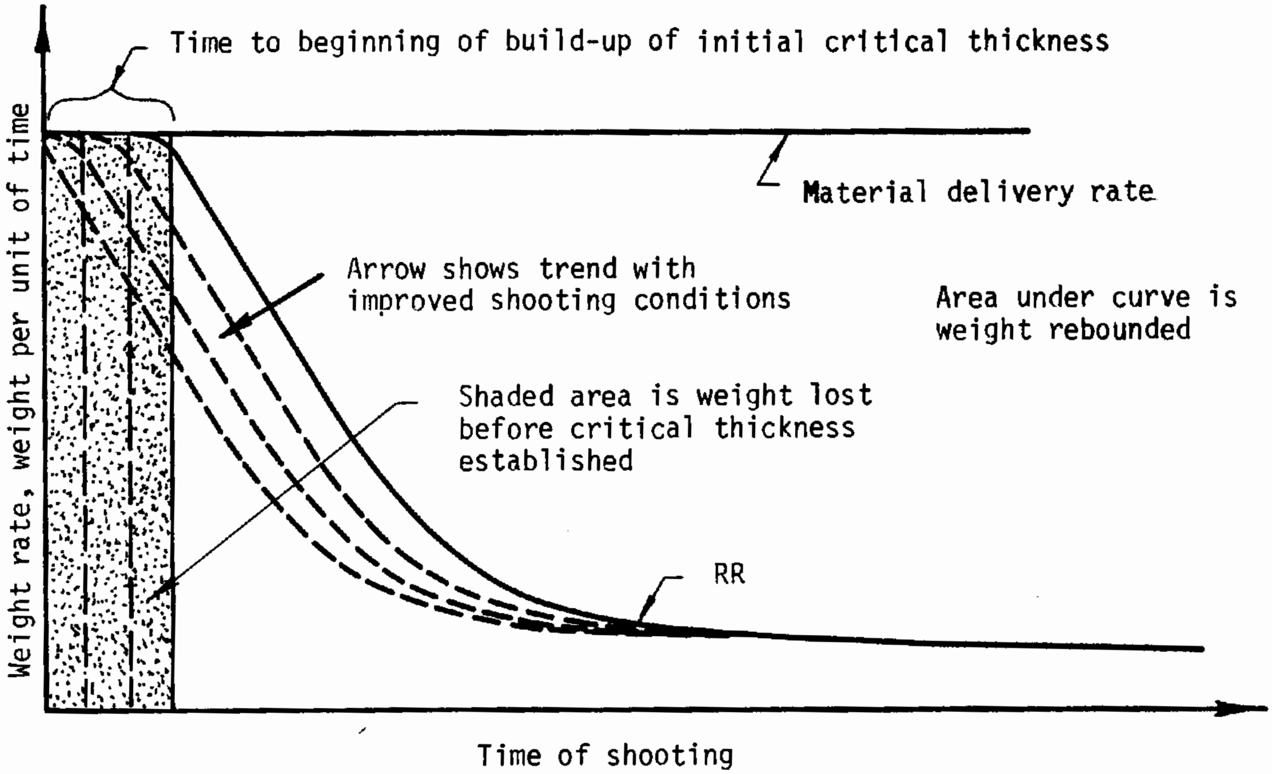


FIG. 4.6 SHIFT OF RR CURVE FOR VARIOUS TIMES TO ESTABLISH INITIAL LAYER

gradations are incoming, the thickness effect is the result of the combined effect of all gradations as discussed in subsequent paragraphs.

The area under the curve in Fig. 4.6 is the total weight rebounded. The area shown shaded is the weight of the losses that occur before the critical thickness is established.

Improvements in mix design or shooting conditions, which establish the critical thickness faster, result in substantial reduction in these losses. Dashed lines show the alternate RR curve and corresponding shaded losses before the critical thickness is established. The area below the curved portion (the thickness effect) is the same, but with shorter times to establish the critical thickness, the size and area of the rectangle diminishes. Whenever the length of time to establish the critical thickness increases, the RAVE curve is shifted upward as Average Rebound increases.

It is very difficult to separate the rebound losses associated with the establishment of the critical thickness from the rebound associated with the thickness effect. In fact, the thickness effect given by experimental data includes a substantial component of rebound losses while establishing the critical thickness.

INFLUENCE OF EFFECTIVE PARTICLE SIZE ON CRITICAL THICKNESS

The mechanisms of rebound are very complex and only partly understood. A discussion of the entrapment of rebound is presented in Chapter 5 on the basis of the high speed photographic study. The thickness of material on the wall must be sufficient to reduce the impact and subsequent energy available for rebound so that the forces tending to keep the particle on the wall overcome the tendency for the particle to bounce back. Intuitively, if the particles are 1 in. (2.54 cm) in diameter, a thickness of paste 0.1 in. (2 mm) thick will not affect the rebound tendency of the particle. Yet the same thin layer of paste would affect the behavior of fine sand particles.

The thickness effect is shown conceptually in Fig. 4.7 in which RRR curves are estimated for the different constituents in the mix. A rough estimate of the values of the Rebound Rate Ratio, RRR, after the initial layer is established,are estimated in Section 6.5.3 and these are used to estimate the level of the horizontal part of the RRR curves. The integral or combined

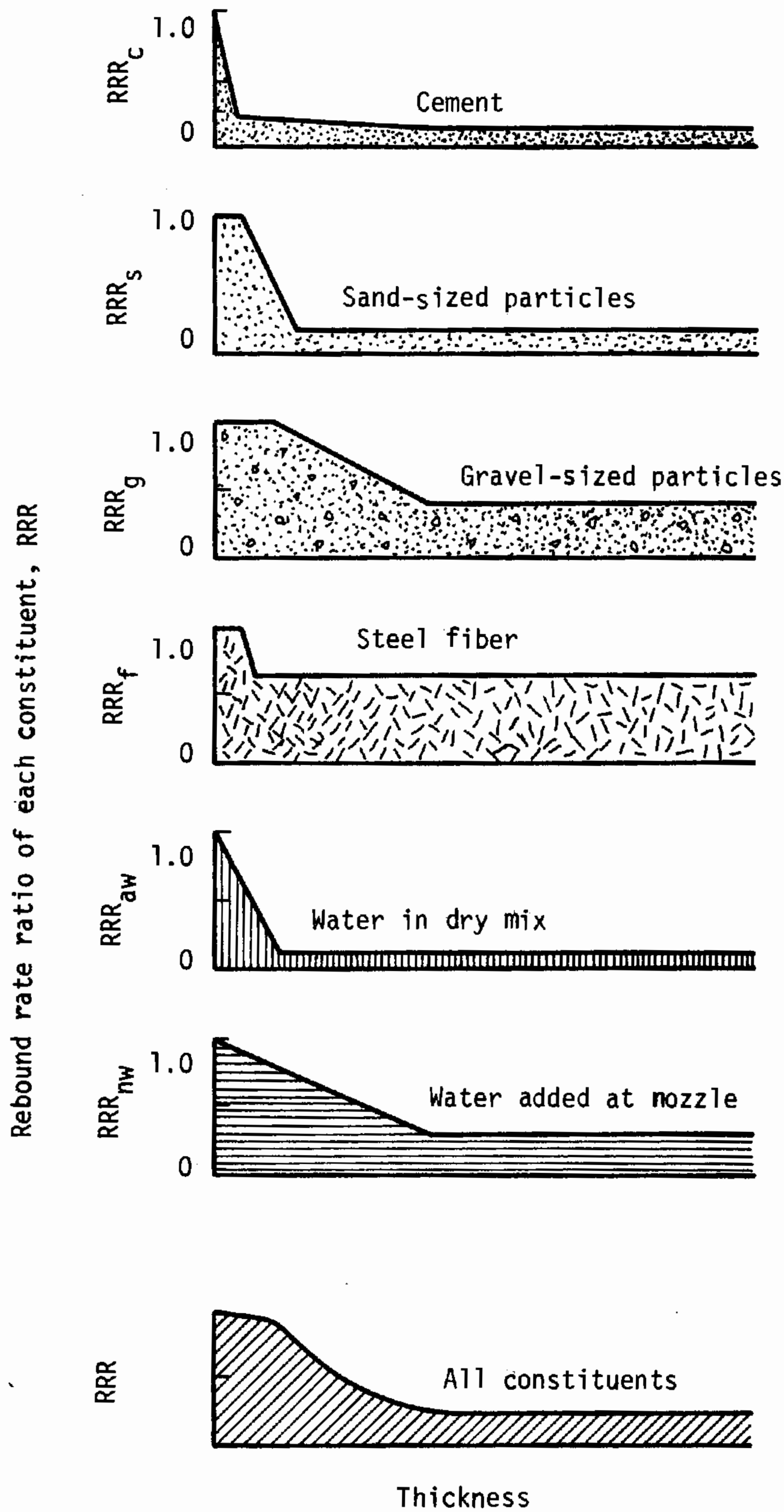


FIG. 4.7 CONCEPTUAL RELATIONSHIPS OF REBOUND RATE RATIO VERSUS TIME OF SHOOTING FOR INDIVIDUAL MIX CONSTITUENTS

effect of all these RRR curves after accounting for the actual percentages of each constituent in the mix is the overall RRR curve of the dry mix.

The philosophy behind Fig. 4.7 is explained below. Cement, some nozzle water, and some of the water in the dry mix are believed to begin sticking to the wall about as soon as shooting against a bare wall begins. Most of the cement losses stop immediately upon establishment of a very thin layer of cement paste on the wall. The dog-leg in the RRR_c curve reflects the fact that the cement still coating the rebounding coarse sand and gravel particles is being lost. Once the RRR curves for these coarser constituents become constant, the cement curve becomes horizontal at about 10 percent of the cement content in the dry mix. Sand-sized particles do not begin sticking until the initial cement layer is established. Rebound of sand-sized particles eventually becomes constant at about 14 percent (RRR=.14). At some time after the sand-sized particles begin sticking on the wall the coarse sand particles and the gravel-sized particles begin to embed themselves into the established layer of sand-cement. Once the largest-sized gravel fraction is being embedded in the wall, all constituents are rebounding at their more or less constant rate. About 40 percent of the gravel is rebounding. Steel fibers, because of their very small effective size, are believed to become embedded almost as soon as the cement layer is established. However, about 60 percent of the fibers are rebounding. All this conceptual reasoning is modified in practice by external factors such as nozzle angle, angle of impact, interference of particles including collisions between particles on their way to the wall and with particles traveling away from the wall after rebounding. Yet it is a rational model of the process of rebound.

TABLE 4.7

ESTIMATED REBOUND RATE RATIO FOR INDIVIDUAL CONSTITUENTS IN MIX AFTER CRITICAL LAYER ESTABLISHED

Constituents	RRR
Cement (RRR_c)	0.11
Sand (RRR_s)	0.14
Gravel (RRR_g)	0.40
Fiber (RRR_f)	0.62
Water (RRR_w)	0.22
Estimated overall (RRR)	0.25

RATES OF REBOUND FOR EACH CONSTITUENT IN AIRSTREAM

A Rebound Rate Ratio for each constituent in the mix was estimated in Section 6.5.3 by means of a hypothetical example using realistic rebound rates and realistic proportions in the dry mix, in-place shotcrete, and in the rebound material. These strictly approximate but reasonable estimates of RRR after the initial layer has been established are summarized in Table 4.7 from Table 6.10; fiber retention is taken from Chapter 7.

EFFECT OF CONSISTENCY OF LAYER AND OTHER VARIABLES

Naturally the rate of rebound is not just a function of the thickness; the consistency of the layer and the energy of the incoming particle are also important. It appears that a soft, thick layer of fresh shotcrete; low impact energy of the incoming particles; and low coefficient of restitution of the bare wall all should be conducive to entrapping particles and thus lower rebound.

On the other hand, a hard, thin layer of fresh shotcrete; high impact energy of the incoming particles; and high coefficient of restitution of the bare wall should be conducive to high rebound rates. In fact, what we see as rebound is the summation of all the effects discussed here and earlier, together with other effects such as the angles of impact, particle interference, etc.

SUMMARY

It is clear that the mechanisms leading to rebound are complex and varied. It is likely that the mechanisms of rebound during the establishment of the initial critical layers are different from those mechanisms controlling subsequent rebound.

The dominant parameter governing rebound rate ratio (RRR) is the characteristic of the surface receiving the shotcrete whether it be bare rock or fresh shotcrete. However, the combined effect of these two conditions is to make the rebound percentages normally reported by industry almost totally dependent on the thickness shot. Rebound of fine aggregate shotcrete, gunite, is expected to be less affected by this thickness effect but it still will be significant. The constituents of a proper wet mix operation arrive at the wall in a state in which they can stick immediately, so that the thickness effect in rebound is believed to be least with wet-mix shotcrete.

The concepts described in these sections will be used in later sections to show why it is more economical to shoot one thick layer rather than several layers. An evaluation of the economy associated with improving nozzle and mix designs is also presented. Also, concepts for a standard rebound test which accounts for the thickness effect will be presented. The variables which must be reported to document rebound studies are also presented in the sections following the presentation of field results.

4.3 METHODS OF FIELD TESTING AND PRESENTATION OF RESULTS

4.3.1 BACKGROUND

Control of all of the mix and shooting conditions was not always possible during the field testing. In anticipation of this problem, a large number of pertinent parameters were monitored continuously during the shooting so that the actual conditions were always known. This monitoring program was analagous to the flight recorder on commercial airliners. When something goes wrong, the flight recorder provides enough data so that conditions in the aircraft are known and can be re-created. During the field tests, enough data on temperatures, pressures, weights, speeds, etc., were recorded often enough that they could be correlated with precise times of beginning and ending of field events so that actual conditions were accurately documented.

As a result of this documentation, field results that appeared contradictory or contrary to previous observations could be explained. Usually some parameter other than the one changed intentionally also changed and caused the apparent anomaly. For instance, it is impossible for a nozzleman, even a highly experienced nozzleman such as the one on this project, to control the water-cement ratio exactly and consistently, especially with different shooting conditions. On mixes 2, 3 and 4 only the air pressure was changed; the air pressure was 45, 30 and 55 psi (310, 210 and 380 KPa) respectively. It was anticipated that lower air pressure would result in lower rebound.

However, the nozzleman reported that the 30 psi (210 KPa) shooting was a little too dry. This low water content was confirmed by the measured water content and thus would have been noticed even if the nozzleman had not made the observation but the on-the-spot visual observation was the most important and most timely. The increased rebound from the lower water content overshadowed the lower air pressure with the result that the rebound for the mix shot at the lower air pressure appeared to have the highest rebound. This one example illustrates the importance of the nozzleman and especially the importance of the water content to rebound. Moreover, it illustrates the need to know all the shooting conditions (not just the ones that are supposed to be controlled) before making conclusions about shotcrete.

Each of the following sections concern a specific rebound problem studied. For each problem, the basic rebound data will be presented and the results described with respect to the concepts already discussed. Basic rebound data are contained in Appendix C. This data will be regrouped, discussed, and evaluated in the next sections.

4.3.2 DESCRIPTION OF REBOUND TEST EQUIPMENT

The rebound test generally consisted of shooting against a specially prepared 4 x 8 ft (1.2 x 2.5 m) plywood panel for a period of about 3 to 5 minutes. The tests were planned specifically to obtain data on the relationship between rebound and thickness. A finite surface area is necessary for this thickness study. In this case it was an area 4 x 8 ft (1.2 x 2.5 m).

Large plywood panels were previously prepared by covering them with about 6 in. (15 cm) of shotcrete that had hardened. This layer provided a smooth hard surface (similar in hardness to rock) which was similar for all rebound tests. The special panels eliminated any variable that could have resulted from the differences in roughness of blasted rock surfaces. A few tests were shot against blasted rock surfaces for comparison. A sketch of the panel configuration is shown in Fig. 4.8. The upper and lower foot (30 cm) of the panel were designated non-shooting areas so that the area shot during the rebound test was 6 ft (1.8 m) high by 4 ft (1.2 m) wide.

Rebound was collected on from 1 to 3 individual tarpaulins placed successively on top of each other as shown in Fig. 4.8. A scheme for making one large tarpaulin out of several smaller ones was devised. Several 4 x 4 ft (1.2 x 1.2 m) tarps were made out of heavy waterproof canvas. Grommets along the perimeter of each tarp permitted any number of small tarps to be assembled with toggle bolts into a mosaic of the various dimensions possible with the 4-ft (1.2 m) module. Most often, the outside dimensions of the tarps were 16 x 16 ft (4.9 x 4.9 m); several of these were assembled prior to shooting. Sometimes large plywood panels were placed as wing walls to the panel being shot to ensure no rebound would fall outside the tarps. The mosaic of smaller tarps permitted an evaluation of the geometrical distribution of rebound (distance from the wall, etc.). Their small size also made weighing of rebound faster, easier, and more accurate. The tarps were merely hung individually on a spring scale. The scale was hung either from a convenient hook on the wall or from a portable tripod.

Special attention was given to the base of the rebound panel where most of the rebound material fell. A long board was usually laid along the base of the panel so that it would keep the tarp from blowing up from the

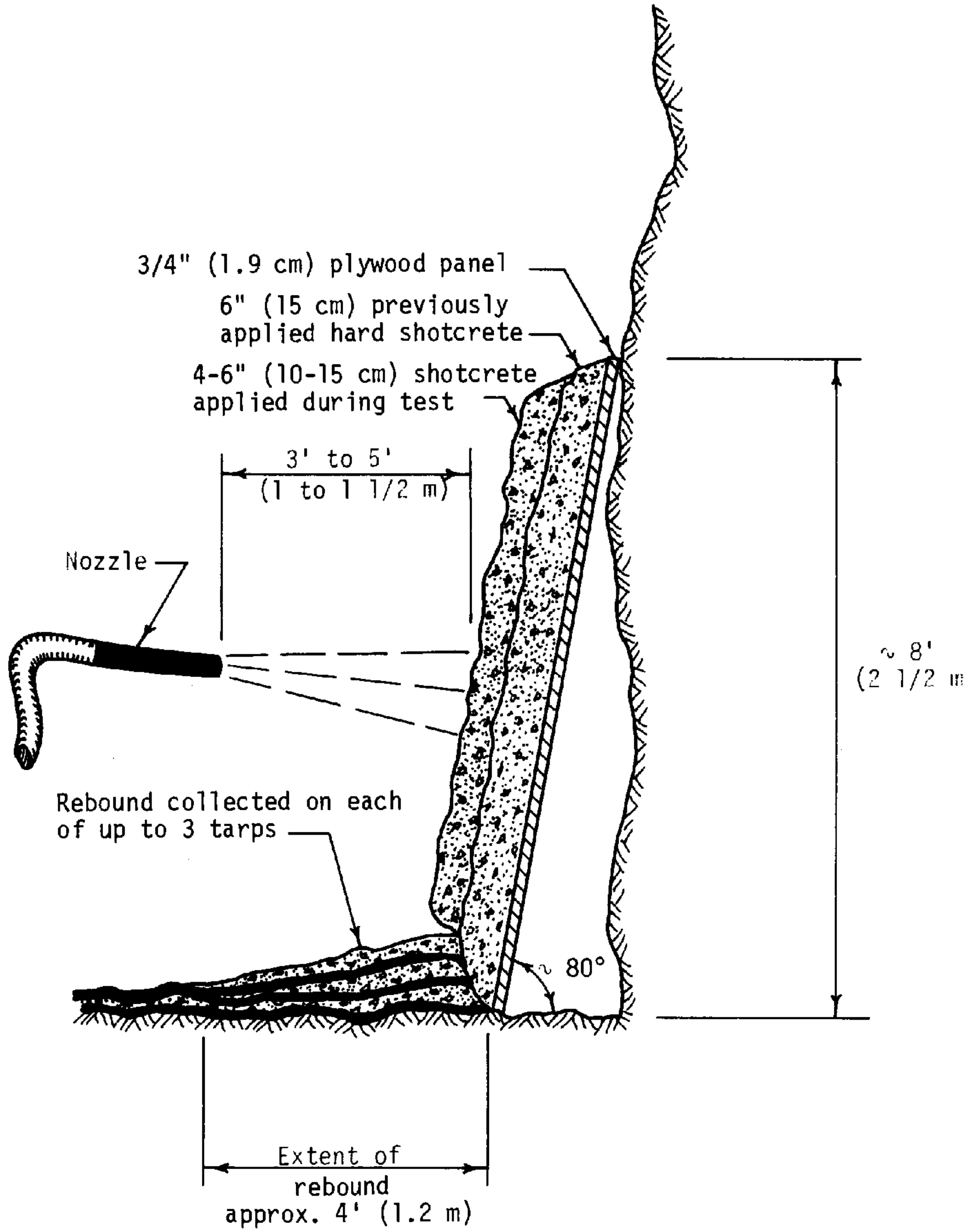


FIG. 4.8 PHYSICAL LAYOUT FOR MULTIPLE-TARP REBOUND TESTS

air currents generated by the air stream. The board also prevented rebound from being lost under the tarp at the base of the panel.

4.3.3 DESCRIPTION OF SHOOTING OF REBOUND TEST

SINGLE-TARP TEST

Before shooting began, a clean tarpaulin was assembled and placed on the ground in front of the rebound panel. Care was taken that the tarp was large enough to recover essentially all the rebound. Generally the strength panels, the photo study, and the rebound test for that mix were all shot from the same batch of dry mix. The test area was set up so that each of these shooting areas were in very close proximity. For example, the nozzleman could move from a strength panel area to the rebound test area in less than about 5 seconds. At the beginning of shooting of every batch, the nozzleman shot at a practice panel until the proper water content was achieved. He then usually shot the rebound panel for about 3 to 5 minutes, after which he shot at another panel for the photographic study. Then all the strength panels were shot. Precise times of each stage of shooting were recorded. In some cases the entire mix was shot at the rebound panel.

Immediately following the completion of shooting the rebound test, samples of the rebound material were collected in bottles and then the rebound on each of the small, square tarps was weighed.

MULTIPLE-TARP TEST

Initial preparations for the multiple-tarp test were the same as those for the single-tarp test except that one or two other mosaics of tarps were assembled and readied so that each could be placed as fast as possible. The nozzleman moved the nozzle quickly over the entire rebound panel until, in his judgement, the panel was coated with a uniform layer just thick enough to get the shotcrete to stick to the surface. All the material that rebounded during this time (usually less than 30 seconds) was collected on the bottom tarp. The nozzle was then pointed away from the rebound panel for a short time while a second tarp was placed on the ground on top of the rebound collected for the first stage of shooting.

In this manner, the rebound for any stage of shooting was collected separately from that resulting from other stages. As soon as the additional tarp was in place (usually in about 15 seconds), shooting at the rebound panel was resumed. Material was built up on the wall uniformly until the rebound test was either complete or until another tarp was placed in the same manner. Thus, at the end of each stage the thickness of shotcrete was approximately uniform all over the rebound panel.

Rebound material after the first stage of shooting did not travel very far from the panel so the additional tarps often did not have to be as large as the bottom tarp. In order to be more efficient, the photographic area was immediately adjacent to the rebound area and the nozzleman shot for the photo study during the time the second tarp was being placed.

4.3.4 REDUCTION OF DATA AND ANALYTICAL PROCEDURES FOR EVALUATION OF REBOUND

All rebound data was evaluated in the field immediately after shooting the mix. In some cases it was believed a minor amount of rebound material may not have been collected and these losses were estimated immediately.

The data was reevaluated subsequently in detail. The method of calculation is summarized in Table 4.8. The weight of material shot at the rebound panel during the time of any stage of the test (SSUM) was calculated by multiplying the total material delivery rate (including water added at the nozzle) times the net time of shooting at the rebound panel. Thus any shooting while placing tarps, or other times when the nozzle was not pointed at the rebound panel, is not considered. The weight of rebound (RSUM) was the total net weight measured in the field. Rebound Rate (RR) was taken to be RSUM divided by the net shooting time. Rebound Rate Ratio (RRR), Average Rebound (RAVE), and thickness were calculated as shown in Table 4.8.

The results of this data reduction program are contained in Appendix C. The raw weights, times, and rates for all rebound tests are contained in Tables C.4 and C.5; Table C.2 is a summary of the more important mix and shooting conditions for Days III and IV.

4.4 EXPERIMENTAL EVALUATION OF THICKNESS EFFECT

The reduction in RRR and RAVE with increasing thickness was documented in 6 tests. No other factor exerted as great an influence on the rebound results than thickness of the fresh shotcrete layer on the wall.

4.4.1 TESTS WITH BOTH RRR AND RAVE DATA

Rebound for Mix No. 2, a conventional mix, was collected on three separate tarps. The bottom tarp was used to collect rebound during the first 0.3 in. (0.76 cm) of thickness, rebound during the build up of shotcrete from 0.3 to 2.5 in. (0.76 to 6.3 cm) was collected on the second tarp, and the rebound for the remaining shooting out to a total of 4.2 in. (10.5 cm) was collected on

TABLE 4.8

CALCULATIONS FOR REBOUND TESTS

I. CALCULATION OF MATERIAL SHOT AT WALL AND REBOUND COLLECTED DURING ANY STAGE OF THE REBOUND TEST

$SSUM_i$ = (MDR) x (Net time of shooting at wall during stage i)

$RSUM_i$ = Total net weight measured during interval i

where i = sequential number of tarps or stage of shooting

II. CALCULATION OF RR AND YR

$$RR_i = \frac{RSUM_i}{\text{Net time of shooting at wall during stage } i}$$

$$YR_i = \frac{SSUM_i - RSUM_i}{\text{Net time of shooting at wall during stage } i}$$

III. CALCULATION OF RRR and RAVE

Tarp	Rebound rate ratio, RRR	Average rebound, RAVE
1	$\frac{RSUM_1}{SSUM_1}$	$\frac{RSUM_1}{SSUM_1} \times 100$
2	$\frac{RSUM_2}{SSUM_2}$	$\frac{RSUM_1 + RSUM_2}{SSUM_1 + SSUM_2} \times 100 = \frac{RSUM_{1+2}}{SSUM_{1+2}} \times 100$
3	$\frac{RSUM_3}{SSUM_3}$	$\frac{RSUM_1 + RSUM_2 + RSUM_3}{SSUM_1 + SSUM_2 + SSUM_3} \times 100 = \frac{RSUM_{1+2+3}}{SSUM_{1+2+3}} \times 100$

IV. CALCULATION OF THICKNESS SHOT

$YSUM_i = SSUM_i - RSUM_i$

$$\text{Est. in-place volume} = \frac{YSUM_i}{\gamma}$$

where γ = est. unit weight of shotcrete in-place taken as 145 pcf (2300 kg/m^3)

$$\text{Estimated thickness at end of stage } i = t_i = \frac{\text{Est. in-place volume}}{\text{Area covered}}$$

where area (a) = 24 sq ft (2.2 sq m) in these tests the third tarp. The data are summarized in Table 4.9 and presented graphically in Fig. 4.9. The ordinate of the bar graphs in Fig. 4.9 represents the rebound rate ratio (RRR) calculated for each tarp.

It can be seen that the losses during the establishment of the cushion, 0.3 in. (0.76 cm) thick, were extremely high (RRR ≈ 0.6). Once the initial critical thickness was established, the rebound rate ratio decreased and stabilized at about 0.12 for the remainder of shooting. The fact that RRR for Tarp 2 was approximately equal to RRR for Tarp 3 indicates that the thickness of shooting for Tarp 1 was greater than the initial critical thickness for the gradation of the materials shot. The nozzleman had been instructed to shoot only to the initial critical thickness and it appears that he was correct in his estimate.

TABLE 4.9

RESULTS OF THREE-TARP REBOUND TEST ON MIX 2

Tarp	Thickness at completion of collection on tarp in.	(cm)	Weight of rebound on tarp lb	(kg)	Rebound rate ratio, RRR	Average rebound, RAVE, %
1	0.3	(0.8)	121	(54.1)	.56	56 %
2	2.5	(6.2)	72	(32.5)	.10	21.3 %
3	4.2	(10.7)	82	(37.0)	.13	18.3 %

During the build-up of this initial critical thickness, the amount of rebound collected was 44 percent of the total material eventually collected during the shooting of the entire thickness. However, this initial critical thickness corresponded to only 7 percent of the total thickness shot.

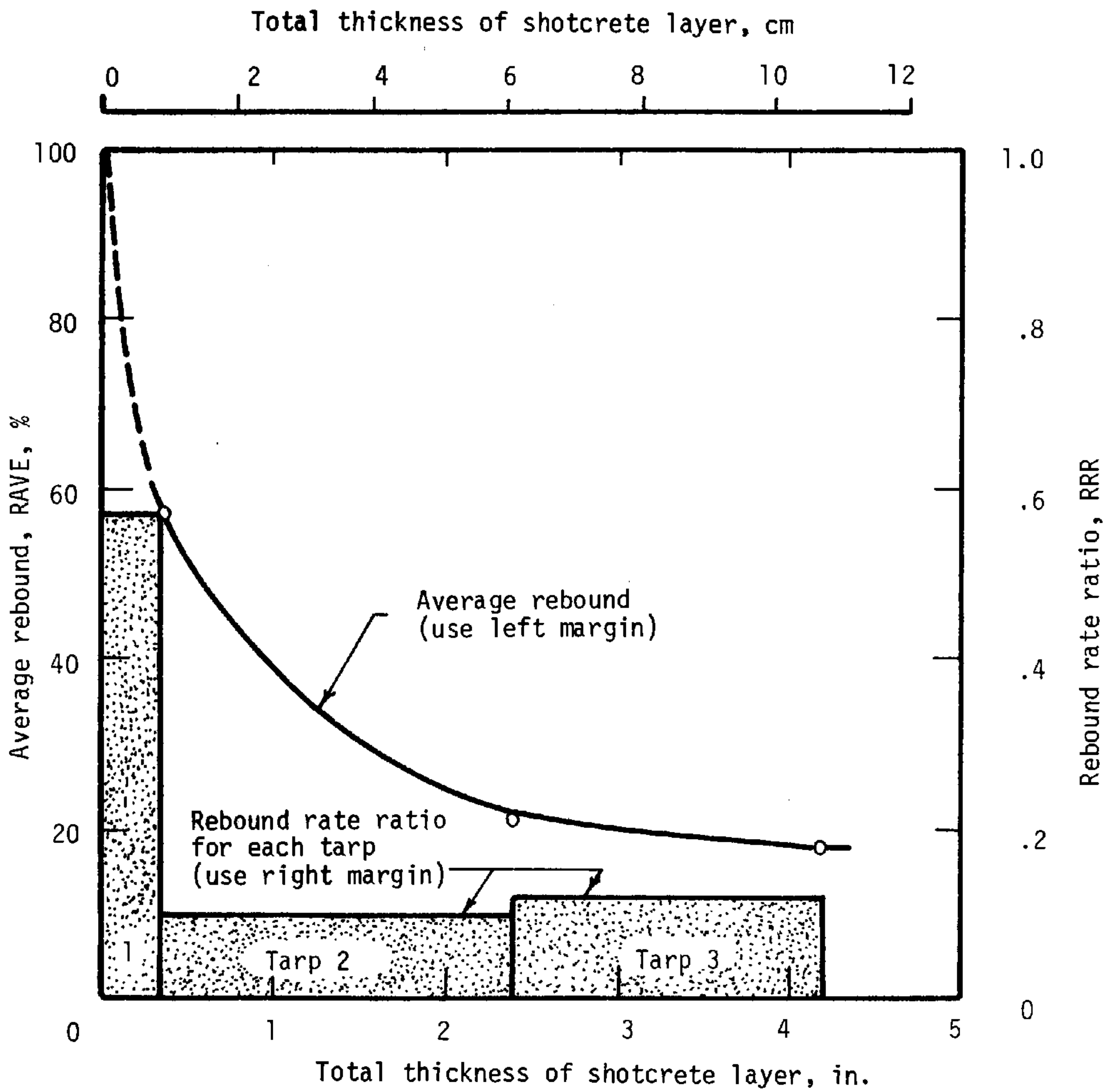


FIG. 4.9 EVIDENCE FOR THICKNESS EFFECT IN THREE-TARP REBOUND TEST FOR MIX 2

The continuous reduction of average rebound, RAVE (solid line) with increments of thickness does not reflect the fact that RRR was constant during Phase 2, because of the very high losses at the beginning of shooting and because of the way RAVE is calculated.

The data in Fig. 4.9 represents one continuous test. If the rebound test had been stopped arbitrarily when the layer was 1 in. (2.5 cm) thick, an average rebound of 39 percent would have been reported. However, if the test would have been stopped when the layer was 2, 3, or 4 in. (5, 7.6, or 10 cm) thick, the average rebound values reported would have been 25, 20, and 19 percent, respectively. This rebound test is experimental proof that the average rebound as reported by industry may depend as much or more on the thickness shot as it depends on the mix and shooting conditions. The same shooting will result in different values if the test is stopped at different final thicknesses.

Similar results were obtained in other multiple tarp tests. The following convention is used in subsequent figures; rebound rate ratio, RRR, will be plotted against average thickness while average rebound, RAVE, is plotted against total thickness. Figure 4.10 is a summary of the measured rebound rate ratio for each tarp in each of the multiple-tarp tests. Straight lines connect the points for each test for identification only; the lines do not represent a locus of points. In each case, RRR for the first tarp was greater than 0.53; it ranged from 0.5 to 0.9. The rebound rate ratios for all subsequent tarps were less than 0.15; the range was from 0.05 to 0.15. The effect of thickness in all tests is clearly seen in this figure.

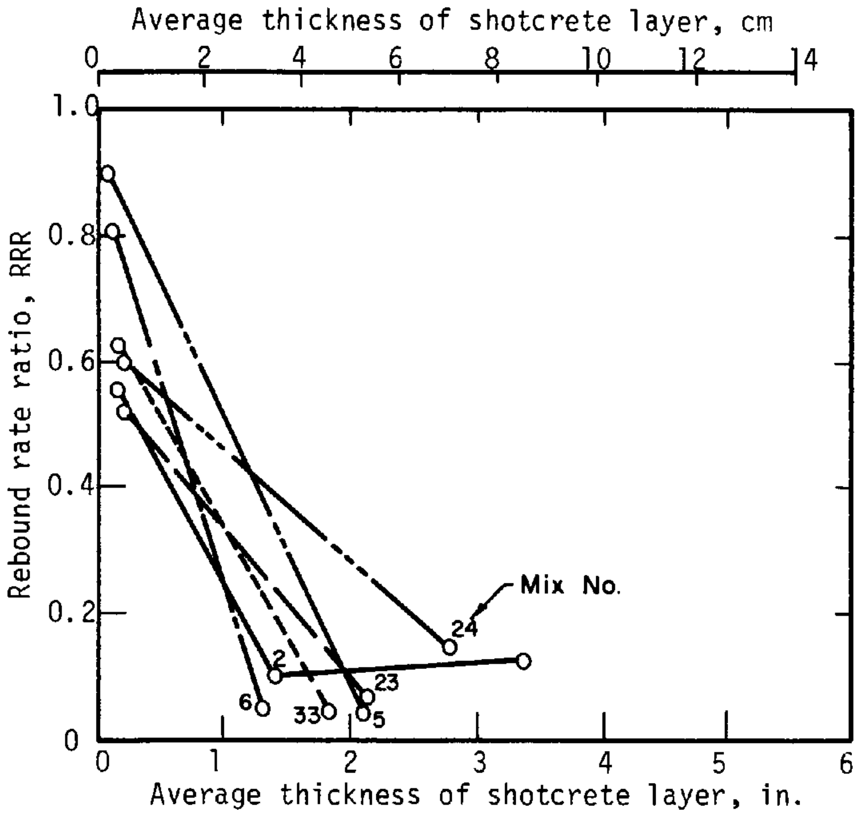


FIG. 4.10 SUMMARY OF REBOUND RATE RATIO TEST DATA

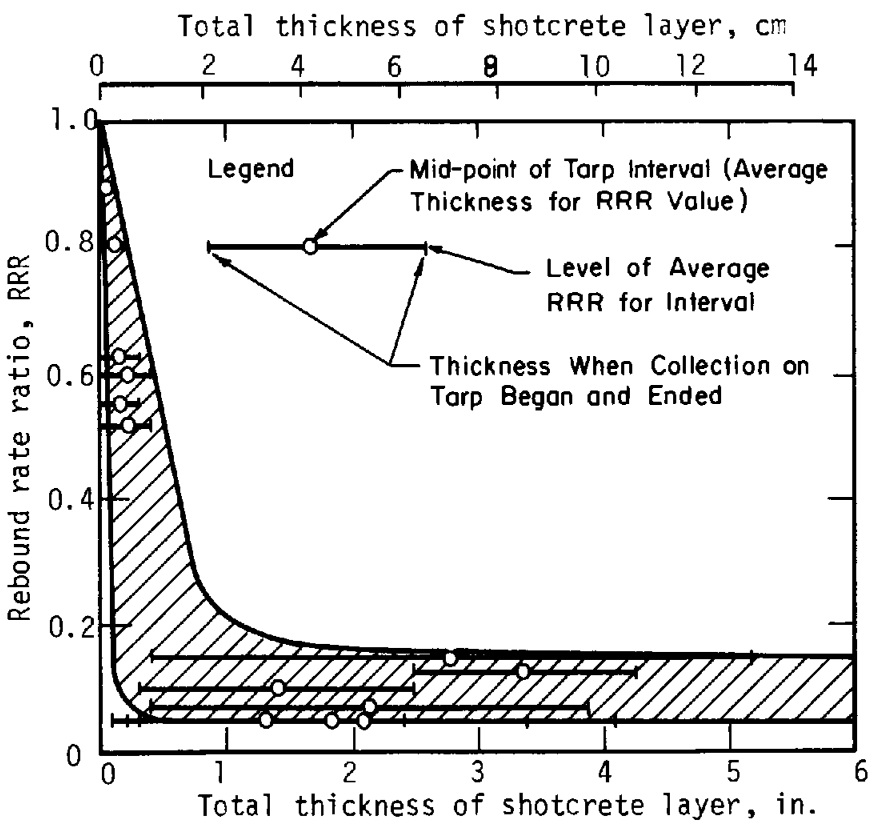


FIG. 4.11 ENVELOPE OF TEST DATA FOR REBOUND RATE RATIO

Figure 4.11 is the same as Fig. 4.10 except that the lines connecting individual tests have been omitted and an envelope encompassing all the points has been drawn to illustrate the anticipated behavior of RRR versus thickness. Data points in the 1/2 in. (1 to 2 cm) range are not needed to define the shape of the band since the points that lie around 1.5 to 2.0 in. (3.8 to 5 cm), such as those of Mixes 2, 6, and 33, really represent the average RRR for a range of thickness varying from about 1/4 to 4 in. (.06 to 10 cm). Thus, the points represent a range that is reflected in the shape of the band.

4.4.2 EXPERIMENTAL EVALUATION OF RAVE

The sharp contrast in the RRR during the establishment of the initial critical thickness and all subsequent stages was also reflected in the experimental average rebound curves. Figure 4.12 is a plot of average rebound (RAVE) versus total thickness for all tests including single-tarp tests. All tests for which thickness is less than 1 in. (2.5 cm) resulted in an average rebound (RAVE) greater than 45 percent; tests with thicknesses between 2 and 4 in. (5 and 10 cm) thick generally resulted in a RAVE value between 15 to 35 percent. A good correlation between RAVE and thickness is shown by the approximate curve drawn through the test data. Data points generally stray no more than 5 percentage points from the curve. An envelope or band enclosing the RAVE data points is shown in Fig. 4.13.

It should be noted that the data shown in Figs. 4.12 and 4.13 were obtained for rebound tests on 27 different mixes shot under very different conditions. They include cement contents ranging from 7-1/2 to 10-1/2 bags per cu yd (420 to 585 kg/m^3), water-cement ratios ranging from .26 to .41,

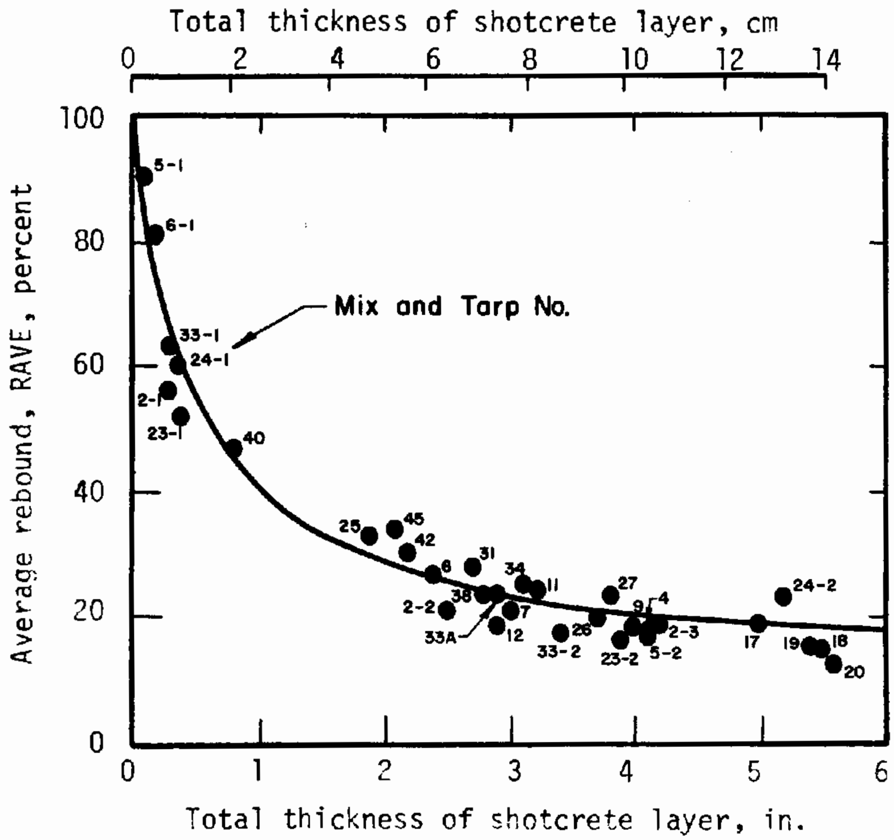


FIG. 4.12 RELATIONSHIP BETWEEN AVERAGE REBOUND AND THICKNESS

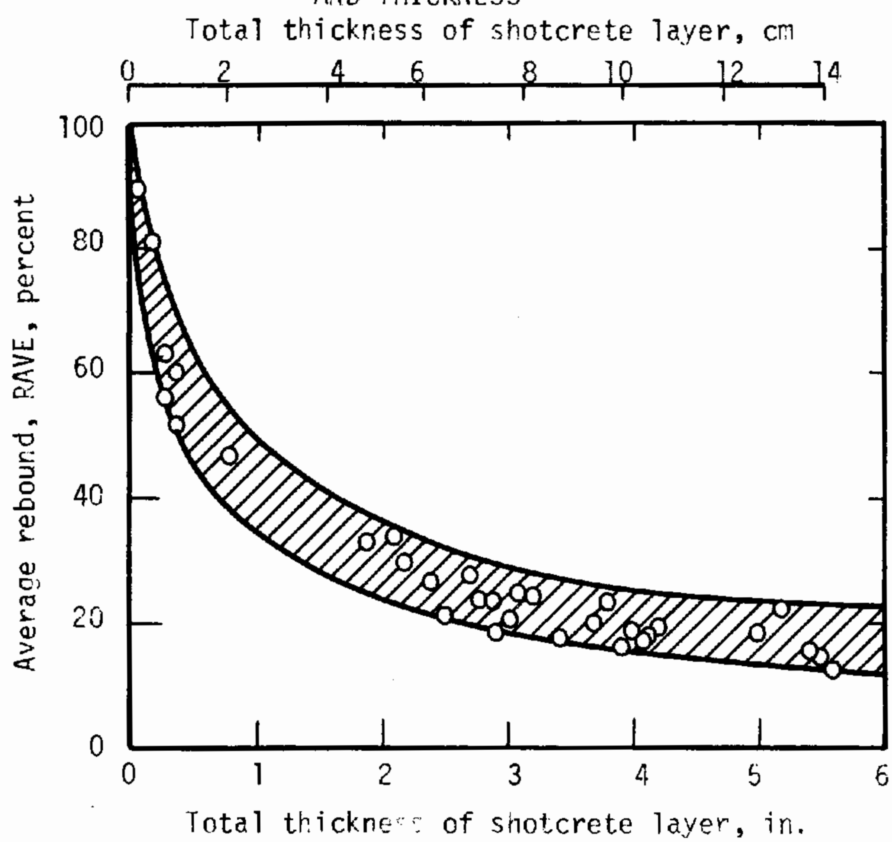


FIG. 4.13 ENVELOPE OF TEST DATA: AVERAGE REBOUND VERSUS TOTAL LAYER THICKNESS

nozzle-water temperatures ranging from 45 to 120°F (7 to 48°C), variations in coarse aggregate, different nozzles, fibrous and non-fibrous mixes. Yet the final thickness of the in-place shotcrete overshadows the significance of any other variables.

4.4.3 THICKNESS OF INITIAL CRITICAL LAYER

When multiple tarp-tests were conducted, the nozzleman was instructed to shoot the first stage until the initial critical thickness had been established uniformly over the rebound test panel. The data thus selected, permit an evaluation of the range of thicknesses the nozzleman shot as representative of the initial critical thickness. These data indicate a range from 0.1 to 0.4 in. (2.5 to 10.2 mm). The results of the high-speed photographic study given in Chapter 5 tend to confirm that the critical thickness for these conditions was on the low end of this range.

4.5 EXPERIMENTAL EVIDENCE FOR THE EFFECT OF SELECTED PARAMETERS ON REBOUND

4.5.1 CRITERIA FOR COMPARISONS

It was not practical to make all rebound tests multiple-tarp tests. Therefore, most of the experimental data collected was in terms of average rebound, RAVE, instead of the more desirable rebound rate ratio, RRR. It was originally intended that the total amount of material shot for each of the rebound tests for any given day would be approximately constant. Field conditions made this impossible. Consequently, each test was shot to a different final thickness which precludes valid comparisons between many tests. However, some comparisons do appear appropriate, especially where the differences in thickness were minor.

The rebound results in Appendix C have been regrouped in Table 4.10 to permit easier comparisons between mixes. Because of the importance of thickness, the first criterion before a comparison can be made is that the final thicknesses for each of the mixes to be compared must be similar. This criterion is satisfied within the groups given in Table 4.10. Other important criteria of similarities include accelerator dosage, air pressure, nozzle-water temperature and fiber content. Fortunately, there are cases where just one of these parameters varied so that comparisons are possible as discussed in the following sections. It should be noted that these results are for a particular set of conditions that did not vary widely. The magnitudes of rebound and perhaps even the trends between different parameters could change significantly for other conditions.

4.5.2 EFFECT OF TEMPERATURES AND WATER CONTENT

These parameters were not studied specifically in these tests. However, their effects can be assessed qualitatively from the rebound observations and from other results, since the compressive strength results were also affected by environmental temperatures.

EFFECT OF TEMPERATURES

The low air and material temperatures reduced the rate of reaction of the cement and accelerator drastically. Evidence from the compressive strength results (Chapter 9) indicates that, at the near-freezing temperatures, the nominal 3 percent dosage of accelerator was essentially ineffective. A dosage of about 5 percent accelerator appeared to be close to the necessary

TABLE 4.10

SUMMARY OF REBOUND RESULTS FOR SELECTED COMPARISONS OF MIXES

	Final thickness, in.	(cm)	Accelerator dosage[1] %	Air pressure psi	(MPa)	Nature of surface shot[2]	Water-cement ratio, w/c	Average rebound, RAVE, %	Rebound rate ratio, (Phase 2), RRR
1. EFFECT OF AIR PRESSURE									
a) 4-7 1/2I-45S	4.1	(10.2)	~3	55	(.38)	CP	--	17.8	
2-7 1/2I-45S	4.2	(10.7)	~3	40	(.28)	CP	--	18.3	.12
3-7 1/2I-45S	4.0	(10.2)	~3	30	(.21)	CP	--	25.1	
b) 11-7 1/2I-60S	3.2	(8.3)	~3	45	(.31)	SR	--	24.9	
12-7 1/2I-60S	2.9	(7.4)	~3	35	(.24)	SR	--	18.4	
2. COMPARISON OF TYPE OF SURFACE SHOT									
9-7 1/2I-60S	4.0	(10.2)	~3	45	(.31)	VR	.35	18.7	
2-7 1/2I-45S	4.2	(10.7)	~3	40	(.28)	CP	--	18.3	.12
3. EFFECT OF CEMENT CONTENT									
33A-7 1/2I-100L-1US	2.9	(7.4)	3.0	60	(.41)	CP	.31	24.9	
38-8 1/2I-100L-1US	2.8	(7.1)	3.2	65	(.45)	CP	.26	23.8	
4. EFFECT OF ACCELERATOR DOSAGE									
33-7 1/2I-60S-1US	3.4	(8.6)	4.9	60	(.41)	CP	.32	17.8	.054
34-7 1/2I-60S-1US-25CA	3.1	(7.9)	8.4	60	(.41)	CP	.38	25.5	
5. EFFECT OF STEEL FIBER									
a) 2-7 1/2I-45S	4.2	(10.7)	~3	40	(.28)	CP	--	18.3	.12
5-7 1/2I-45S-1US	4.1	(10.4)	~3	40	(.28)	CP	--	17.7	.05
b) 23-7 1/2I-60S	3.9	(9.9)	3.6	60	(.41)	CP	.37	15.9	.072
33-7 1/2I-60S-1US	3.4	(8.6)	4.9	60	(.41)	CP	.32	17.8	.054
6. COMPARISON BETWEEN REGULATED-SET AND TYPE I CEMENT									
23-7 1/2I-60S	3.9	(9.9)	3.6	60	(.41)	CP	.37	15.9	.072
26-7 1/2I-100L	3.7	(9.4)	3.1	65	(.45)	CP	.40	20.1	
27-7 1/2R-100S	3.8	(9.6)	0	60	(.41)	CP	.28	23.7	
7. EFFECT OF WATER TEMPERATURE									
17-9R-60S	5.0	(12.7)	0	45	(.31)	BP	--	19.4	
18-9R-80S	5.5	(14.0)	0	45	(.31)	BP	--	14.6	
19-9R-100S	5.4	(13.7)	0	45	(.31)	BP	--	15.3	
20-9R-120S	5.6	(14.2)	0	45	(.31)	BP	--	12.2	

Note: [1]) Accelerator dosage is given where measured for Mixes 23-45, nominal 3 percent for Mixes 1-23 where not measured shown as "~3".
[2]) Following key refers to nature of surface shot:
CP = Plywood panel covered with 4-6 in. (10-15 cm) of hardened shotcrete
SR = Sloping rock joint surface
VR = Irregular blasted vertical rock face (Fig. 2.2)
BP = Bare plywood panel

accelerator dosage for early-strength gain. It is believed that the tendency for a quicker set and, thus, the reduction of rebound were affected in a manner analagous to that observed in the strength results.

There are no specific comparisons that can be made to illustrate the overall effect of temperatures experimentally. One set of tests was conducted on four mixes of regulated-set shotcrete specifically to determine the effects of the temperature of nozzle-water on rebound. These results are presented in detail in Section 4.5.3; increasing water temperature, tended to reduce rebound.

A review of all the rebound results indicates, however, that the temperature of the environment and materials could not have been a very important parameter. Tests conducted on Mixes 2, 9, 23, and 26 when the air temperature in the tunnel was 40, 60, 41, and 30°F (4.4, 15.5, 5, and -1.1°C), respectively, resulted in a measured rebound that ranged only from 16 to 20 percent. Though the mix and shooting conditions represented by these four tests vary somewhat they are considered sufficiently similar to permit such an approximate comparison and their thicknesses were close enough (3.9 to 4.2 in.; 9.9 to 10.6 cm) to minimize bias from the thickness effect.

Accordingly, it is concluded that the low temperatures should have caused slightly higher rebound values; the effect of temperature was not as great as other parameters.

EFFECT OF WATER CONTENTS

This parameter was not studied specifically in the tests either. It is well known that a wetter consistency generally results in lower rebound

(Studebaker, 1939). The consistency of shotcrete on the wall was more or less uniform since the nozzleman shot to his best criterion which implied similar consistency.

The nozzleman was instructed to shoot the test and rebound panels at whatever water rate he deemed necessary to produce a uniform high quality shotcrete. He was, however, particularly careful in controlling the water to the desired degree. In addition, the nozzle water used was monitored every minute and the nozzleman was notified of any particularly high or low water rates. Nevertheless, he still had a free hand in the water contents and he, in turn, made comments whenever he felt a particular mix was either too dry or too wet. In general, his comments correlated well with changes in the observed water rates.

There were variations in water-cement ratio but such variations do not necessarily reflect variations in consistency. Plots of rebound (RAVE) versus the in-place water content or water-cement ratio do not show any promising trends because of the masking of the RAVE data by the thickness effect, variations in accelerator dosage, and the fact that the nozzleman shot to the same consistency in most of the tests. If more RRR data had been obtained, trends may have been observed.

It is believed that water content (water-cement ratio) is a dependent variable, not an independent variable. The mix and shooting conditions determine a fairly narrow range of water content between too dry and the wettest stable consistency and the nozzleman must shoot within this range. He can however, by adjusting the nozzle, vary the water content within this range and he can affect rebound significantly by such adjustments. However, changing nozzle-water temperatures, type of nozzle, type of cement, accelerator dosage, etc., is believed to affect the numerical value of the resultant water content significantly, even though the nozzleman consistently shoots to the same criterion of consistency. Those parameters that make the consistency on the wall stiffer (for instance, high accelerator dosages, high cement contents, and high temperatures) make a mix more active and the mix must be shot with more water to obtain the same consistency on the wall.

The phenomenon of water content as a dependent variable was observed in one test (Mix 17) and, by accident, the strong effect of water content on rebound was observed in another test (Mix 3). The water-cement ratio for Mix 17, shot with a 60°F (15.5°C) nozzle-water temperature was 0.292, yet it was shot to the same consistency and criterion as Mixes 18, 19, and 20 which were shot with a nozzle-water temperature of 80°F (26.7)C), 100°F (37.8°C), and 120°F (48.9°C) that had water-cement ratios ranging from .41 to .42. The water-cement ratios were calculated from batch weights and metered nozzle-water rather than from fresh samples. In this case, the higher water contents are believed to be dependent on the shooting conditions and they are not cause for invalidation of the comparison of rebound with nozzle-water temperatures. The experienced nozzlemen observing the shooting did not notice any particular difference between the tests. The second example, Mix 3, is a case where shooting too dry by accident is believed to have increased rebound significantly. Each of these cases are described in Section 4.5.3.

4.5.3 COMPARISON OF REBOUND RESULTS OF SELECTED MIXES

EFFECT OF AIR PRESSURE

There are two comparisons that can be made between mixes that had different air pressures. The first comparison is made on group 1a of Table 4.10. Here the only condition that changed between Mixes 4, 2, and 3, was the air pressure which was 55, 40, and 30 psi (.38, .27, and .21 MPa) respectively. All were shot to about the same thickness. The nozzlemen who shot and observed the shooting reported that Mix 3, the one with the lowest pressure, was shot too dry while the shooting for Mixes 2 and 4 was at a proper water content. Water content data was inadequate to permit detailed comparisons, but they generally confirmed this observation. The measured RAVE was 17.8, 18.3, and 25.1 percent for Mixes 4, 2, and 3 respectively, in decreasing order of air pressure. The difference between 17.8 and 18.3 for the mixes shot at 55 psi (.38 MPa) and 40 psi (.27 MPa) respectively, is too small to be considered significant. The RAVE of 25.1 percent for the mix with the lowest air pressure is believed to be caused by the fact that the mix was shot too dry. It is concluded that shooting too dry can increase rebound significantly. In this case, it overshadowed other parameters.

The second comparison of mixes with different air pressures is summarized in Section 1b of Table 4.10. The conditions of Mixes 11 and 12 compare favorably in every respect except that the air pressures were 45 and 35 psi (.31 and .24 MPa) respectively. Both were shot against a rock joint surface sloping about 50° from the horizontal. These tests using natural rock surfaces as shooting surfaces could not be controlled as easily as the shotcreted panels used on other mixes. Nevertheless, the mix with the lowest air pressure had the lowest RAVE at 18.4 percent while the mix with the high air pressure had the highest RAVE at 24.9 percent. Since the differences are not due to the thickness effect and other conditions were similar, it is concluded that, for these conditions, a lower air pressure reduced RAVE.

TYPE OF SURFACE SHOT

Section 2 of Table 4.10 contains a summary of results from similar mixes shot against different surfaces; one mix (9) shot against a vertical blasted rock surface (see Fig. 2.2) and the other mix (2) shot against a hard shotcrete-covered panel. Both mixes had about the same RAVE (18.5 and 18.3 percent respectively). It appears that the hard, shotcreted panels at least were not unrealistic models of real rock surfaces for measurements in terms of RAVE. More tests, especially those that determine RRR for Phase 1 rebound losses, would be necessary to make any definitive conclusions other than the fact that the types of panels worked well.

EFFECT OF CEMENT CONTENT

Section 3 of Table 4.10 is a summary of conditions for Mix 33A that was a 7-1/2 bag (418.4 kg/m^3) mix and Mix 38 that was a 8-1/2 bag (474 kg/m^3) mix. Both mixes contained the same amount of fiber and both mixes were comparable in all other respects including thickness. Since RAVE was nearly identical for the mixes (24.9 and 23.8 percent respectively), it appears that other conditions dominated the RAVE of these mixes besides moderate changes in cement content.

EFFECT OF ACCELERATOR DOSAGE

Conditions for a set of fibrous mixes that can be compared to evaluate the effect of accelerator dosage on rebound are summarized in Section 4 of Table 4.10. Mixes 33 and 34 are similar in most respects except the accelerator dosage which was 4.9 and 8.4 percent respectively. Mix 34 with the highest accelerator dosage also had a significantly higher RAVE (25.5 percent) than the RAVE for Mix 33 (17.8 percent) with the low accelerator dosage.

It is believed that an increase in accelerator dosage should reduce rebound up to an optimum dosage above which rebound should increase because the high accelerator dosage makes the mix too active and the material on the wall too stiff and less receptive for embedment of incoming material. It is known that, for the temperature conditions prevailing when these tests were conducted, the nominal accelerator dosage of 3 percent was essentially ineffective (see Chapters 3 and 9). For strength results it was found that the 4.9 percent accelerator dosage was probably close to the optimum for the conditions (Chapter 9). It is believed that the 4.9 percent dosage was close to the optimum for its effect on rebound also; certainly the 8.4 percent accelerator dosage was far above the optimum. Accordingly, the test results confirm the hypothesis that above an optimum dosage, increased accelerator will result in increased rebound.

EFFECT OF STEEL FIBER

There are two possible combinations of mixes that compare the effect of steel fiber on rebound (Sections 5a and 5b, Table 4.10). The first is a comparison of Mix 2, a non-fibrous mix and Mix 5, a mix with 1 percent fiber by volume. The non-fibrous mix had a slightly higher RAVE (18.3 percent versus 17.7 percent). The results of the multiple-tarp tests carried out with these mixes indicated that RRR after the initial critical thickness was established (Phase 2) was also higher for the non-fibrous mix (0.105 and 0.053 respectively). However, the differences in the rebound values are small and it is concluded from these data that other factors appeared to be more important than the presence of fiber.

The second set of mixes that can be compared are summarized in Section 5b of Table 4.10. Conditions for these two mixes, a non-fibrous Mix 23 and the fibrous Mix 33, were not as similar as those for previous comparisons. The measured RAVES were 15.9 and 17.8 percent for the non-fibrous and fibrous mix respectively; RRR values for Phase 2 losses were 0.07 and 0.05 respectively. The small differences in the rebound values of these mixes indicate again that factors other than the presence of fiber determined the rebound characteristics of the mixes. However, the final thickness for Mix 23 was 0.5 in. (1 cm) thicker than the one in Mix 33. Furthermore, Mix 23 had 3.6 percent accelerator while Mix 33 had 4.9 percent accelerator. Conclusions about accelerator dosage were given in the previous paragraph in which the 4.9 percent accelerator was estimated to be close to the optimum possible for the temperature conditions which should give Mix 33 an advantage. However, the effects of the differences in thickness tend to offset the effects of the differences in accelerator contents. The extent that these factors affected the rebound results cannot be reliably assessed. The conclusion remains that other factors were more important than the presence of the fibers for the conditions of these tests. It should also be noted that the fibers were bent and contorted before shooting and that a very low percentage of fibers remained on the wall. The effect of these problems with the fibers also cannot be reliably assessed. At the present time, it can be concluded that if mix or shooting conditions can be improved because of the use of fibers, there is a chance that rebound can be reduced but the mere presence of fibers in a mix does not affect rebound appreciably (Mahar, Parker, and Wuellner, 1975).

COMPARISON BETWEEN REGULATED-SET AND TYPE I CEMENT

Section 6 of Table 4.10 is a summary of a set of mixes that can be used to assess the differences in rebound between regulated-set cement and Type I cement. The rebound values measured for two mixes with Type I cement (Mixes 23 and 26) might be compared to the one obtained with the regulated-set Mix 27. Mix 23 was accelerated with about 3.6 percent accelerator, the regulated-set cement was only accelerated by means of heated water added at the nozzle. Rebound measured by RAVE was 15.9 and 23.7 percent for Type I (Mix 23) and regulated-set cements respectively. Mix 26 was shot with the long nozzle (Mixes 23 and 27 were shot with the short nozzle) and was accelerated both by 3.1 percent accelerator and hot water; its RAVE was 20.1 percent.

The comparison of either Type I cement Mixes 23 or 26 with the regulated-set mix indicates that the use of regulated-set cement may result in slightly higher rebound than Type I cement with accelerators. However, Mix 27 was a particularly active mix that did not achieve the anticipated early strength. Thus, it can be assumed that the effect of the shooting conditions might not have been optimum for rebound considerations either. Because of these factors, this comparison must be considered inconclusive.

However, it must be pointed out that regulated-set cement shot under proper conditions need not have excessive rebound. It will be shown in the next section that a rich mix of regulated-set cement shot with very hot water achieved the lowest average rebound value (RAVE) measured in this entire series of tests (12.2 percent).

EFFECTS OF NOZZLE-WATER TEMPERATURE ON AVERAGE REBOUND

For one set of regulated-set mixes, the mix design and all shooting conditions were constant, except for the nozzle-water temperature, for one set of regulated-set mixes which varied as shown in Section 6 of Table 4.10 and as summarized in Table 4.11. The final thicknesses of the four tests were not only similar (5.25 in., ±0.25 in.; 13.3 cm, ±.63 cm) but the thickness was great enough to be on the more or less horizontal portion of the RAVE curve where small changes in thickness were not significant. The total thickness is also shown in Table 4.11.

TABLE 4.11

EFFECT OF NOZZLE-WATER TEMPERATURE ON REBOUND

Mix no.	Temperature °F	(°C)	Thickness in.	(cm)	RAVE %
17	60	(15.5)	5.0	(12.7)	19.4
18	80	(26.6)	5.5	(14.0)	14.6
19	100	(37.8)	5.4	(13.7)	15.3
20	120	(48.0)	5.6	(14.2)	12.2

The RAVE values shown in Table 4.11, are plotted in Fig. 4.14 as a function of water temperature. There is a tendency of the average rebound percentage to be reduced when water temperature is increased. Increasing the temperature of the water added at the nozzle from 60 to 120°F (15.5 to 48°C) reduced average rebound from 19.4 to 12.2 percent. Higher water temperatures increase the rate of hydration that begins once water comes in contact with the cement, thereby producing a more cohesive material in the shotcrete stream.

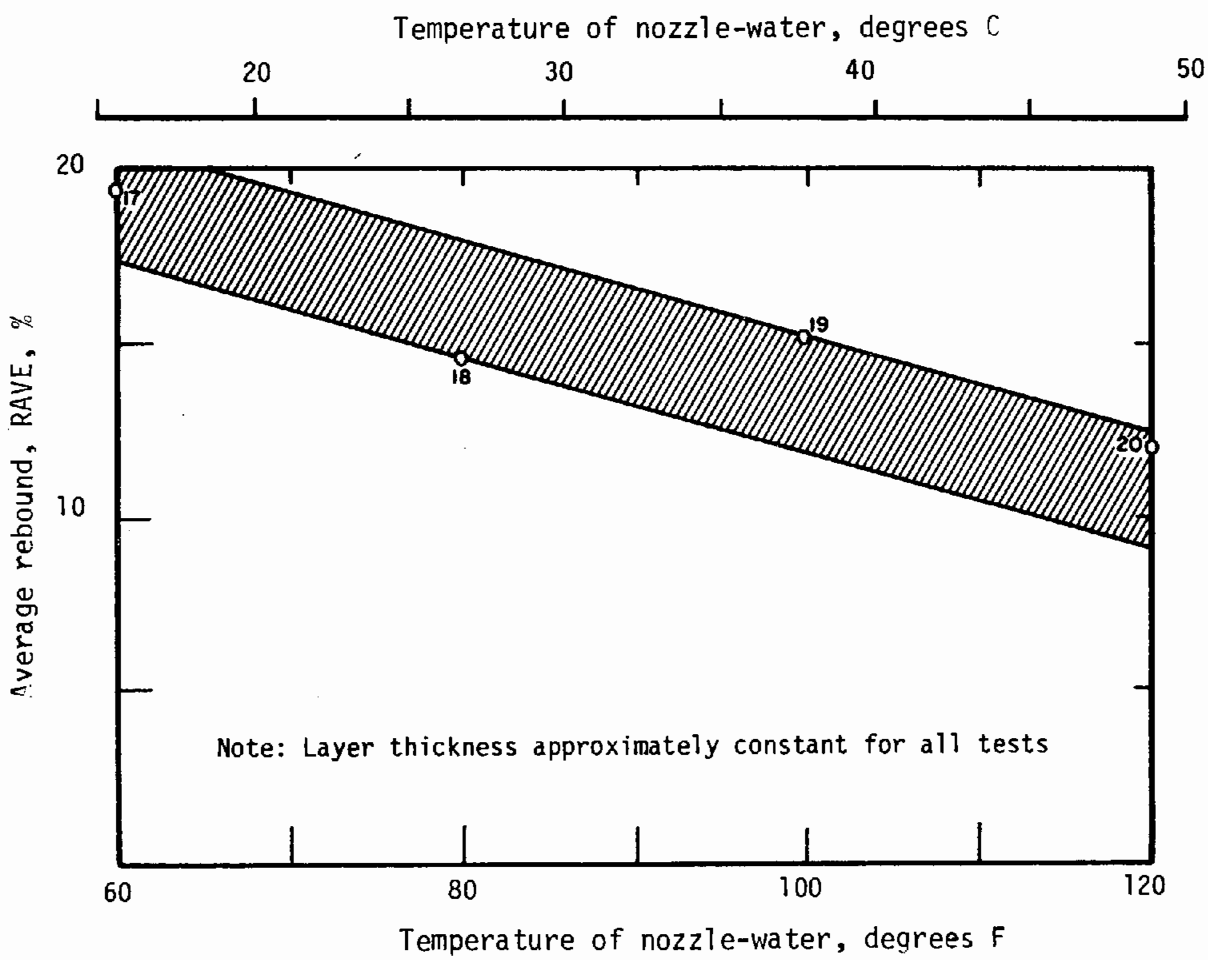


FIG. 4.14 RELATIONSHIP OF AVERAGE REBOUND TO NOZZLE-WATER TEMPERATURE FOR CONSTANT LAYER THICKNESS

Up to some optimum value, increased water temperature should reduce rebound. It is reasonable to assume that if the water temperature is too high, the above mentioned hydration process will be over-accelerated or become too active (see Section 9.7.10), thereby producing shotcrete that stiffens so fast that the material on the wall is not receptive to embedment of incoming material and rebound will increase.

EFFECT OF THE TYPE OF NOZZLE USED ON THE AVERAGE PERCENTAGE OF REBOUND, RAVE

Two rebound tests carried out with conventional Mixes No. 23 and 25 were designed to assess the effects of a change in nozzle type (from a short nozzle to a long nozzle) on the average percentage of rebound. Unfortunately, the in-place thickness of the layers shot during the rebound tests were quite different and, therefore, overshadow any possible differences in the measured RAVE values produced by the change in the nozzle type.

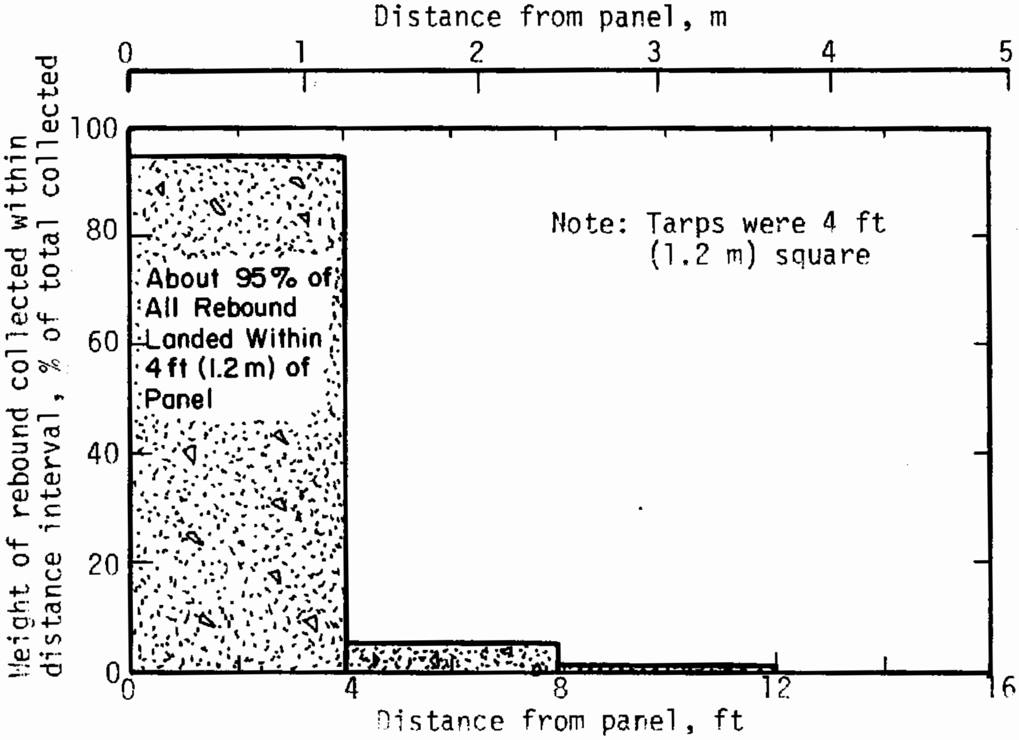
However, observations of the airstream made during the shooting process of different mixes, and detailed studies of airstream pictures taken with a high speed camera, indicate a much better mixing of the different shotcrete components (cement, fine and coarse aggregates, and water) when the long nozzle is used. Better mixing of the aggregates coming from the nozzle indicates, in general, an airstream consistency which sticks to the wall more readily and embeds incoming particles more easily, therefore, produces less rebound. In this respect, the use of a long nozzle should tend to reduce the average percentage of rebound and produce a more homogeneous material on the wall.

4.5.4 DISTRIBUTION OF REBOUND ON TARPS

The quilt-like pattern of small tarps used to collect rebound not only enabled simple and fast weighing but also enabled an assessment of the distribution of rebound on the ground at least within the accuracy of the 4-ft (1.2 m) square grid.

Generally, most of the rebound fell at the foot of the board. The distribution from side to side was more or less symmetrical about the centerline of the panel. The distribution of rebound with distance from the panel is illustrated in Fig. 4.15. Ninety-five percent (95%) of the rebound collected in all tests landed on the closest tarp which was within 4 ft (1.2 m) from the foot of the panel. Although not measured, it was observed that much of the rebound fell within 1 ft (0.3 m) of the panel and a high percentage of the 95 percent fell within the first 3 ft (0.9 m) of the panel. Usually the remainder of the rebound was collected on the second tarp away (4 to 8 ft; 1.2 to 2.4 m). Occasionally some landed on the third tarp away which extended to 16 ft (4.9 m). At the very beginning of shooting against a bare surface a few isolated pieces of coarse aggregate bounced as far away as 25 ft (7.6 m) but these are estimated to represent less than 0.5 percent of the total rebound collected; its effect on the magnitude of RAVE in a typical 4 in. (5 cm) test would be only about 0.25 percentage points.

For the conditions of these tests, a tarpaulin having overall dimensions of 16 ft wide by 12 ft deep (4.84 by 3.63 m) would have been sufficient for the bottom tarp. After establishment of the initial critical thickness a tarp 10 ft wide by 8 ft deep (3.0 by 2.42 m) would have been sufficient because particles do not bounce as far away.



a) Average distribution for all rebound tests

Layer	Thickness on wall at end of interval in. (cm)	Weight on tarp lb (kg) [%]	
		Within 4 ft (1.2 m) of panel	Between 4 and 8 ft (1.2 and 2.4 m)
Top tarp	4.2 (10.7)	76 (37) [93]	6 (3) [7]
Middle tarp	2.5 (6.2)	66 (30) [92]	6 (3) [8]
Bottom tarp	0.3 (0.8)	115 (52) [95]	6 (3) [5]
Grand total	4.2 (10.7)	257 (117) [93]	18 (8) [7]

b) Distribution for 3-tarp test of Mix 2

FIG. 4.15 DISTRIBUTION OF REBOUND AWAY FROM REBOUND PANEL

4.6 PRACTICAL APPLICATION OF REBOUND CONCEPTS

Several practical applications of the above concepts and results on the problem of rebound can be utilized immediately. These applications are presented in the following sections. First, since the numerical value of the rebound percentage normally reported by the industry has been shown to be highly dependent on the thickness shot, most of the data on rebound in the literature is misleading. The thickness of the layer, or layers, shot during the collection of rebound as well as other important documentary data should be reported when rebound is reported. Second, there is a need for a standardized method for reporting rebound. The concept of a "Standard Rebound Test", and especially a standard thickness to which rebound tests should be shot, will be discussed. The relationship between the volume, or weight, shot to that obtained on the wall is derived and utilized in examples to discuss various economic considerations about rebound. It should be recognized that there is an economic penalty in terms of added rebound when thick shotcrete linings are built up in multiple layers rather than a single layer. The economic implications of multiple layers as well as the savings associated with the reduction of the initial and final losses are evaluated.

4.6.1 SIGNIFICANCE OF PREVIOUSLY-REPORTED REBOUND DATA

INFLUENCE OF UNKNOWN THICKNESS EFFECT

Average rebound has been shown to be so highly dependent upon the thickness of the layer being shot that previously-reported rebound data on coarse aggregate shotcrete have limited or restricted value unless properly documented. This does not mean that all previous data are unreliable or useless. It merely implies that previously reported data may have an unknown bias due to the thickness effect and must be evaluated carefully before being used. Naturally, data on comparative studies of similar rebound tests with different conditions of shooting, or such as those reported by Studebaker (1939, or Kobler (1966), are less likely to be prone to bias from this thickness effect.

CORRELATION WITH REPORTED REBOUND RESULTS

Very few results reported in the literature are documented with the actual thickness shot during rebound tests. Most merely report an average value of rebound; sometimes a specified thickness is given or a wide range of thickness shot. Few reports give details such as percentage of time shooting overhead, etc. The few reported values of rebound that also have a corresponding thickness have been plotted in Fig. 4.16. Some of the reports have been confirmed by personal communications with the investigator to determine the details of the rebound tests.

Also shown in the figure is the range of RAVE values obtained from the tests on this project. This range should be expected to be lower than other results since the tests were conducted on regular vertical walls. The results from other projects often included some overhead shooting.

There is a great variety of conditions represented by the plotted results and considerable scatter may be expected. They include fine and coarse aggregate, wet- and dry-mix, wall- and overhead-shooting, etc. Nevertheless, there is a general tendency for this documented field data to show

Legend:

Project or Reference	No.	Thickness in.	Thickness cm	RAVE %	Shotcrete process	Overhead or wall
Hecla Mining (Hendricks 1969)	1a	4.8	12	22.5	dry	60% overhead
	1b	1-3	2.5-7.6	47	wet	mixed
IIT Research	2a	2	5	44-50	dry	overhead
(Bortz, et al., 1973)	2b	2	5	32-39	dry	wall
Waterways Experiment Station	3a	2	5	39	dry	wall
Research (Tynes and McCleese,	3b	2	5	35	wet	wall
1974)	3c	2	5	36	dry	wall
	3d	2	5	30	wet	wall
Bureau of Reclamation, Arrowrock Dam Restoration (Studebaker 1939)	4	3	7.6	19-29	dry	inclined wall
New Melones Tunnel (Corps, 1974)	5	2	5	30	dry	mixed
Washington Subway Unpublished (Blanck 1975)	6	4	10	22	dry	wall
Tehachapi Tunnel No. 1	7a	2-3	5-7.6	35	dry	mixed
(Evans, 1970) Unpublished	7b	2-3	5-7.6	45	dry	overhead
	7c	2-3	5-7.6	15	dry	wall
Arizona Mine	8a	2-3	5-7.6	30	dry	mixed
(Steenson, 1974)	8b	15	5-7.6	5-8	wet	mixed

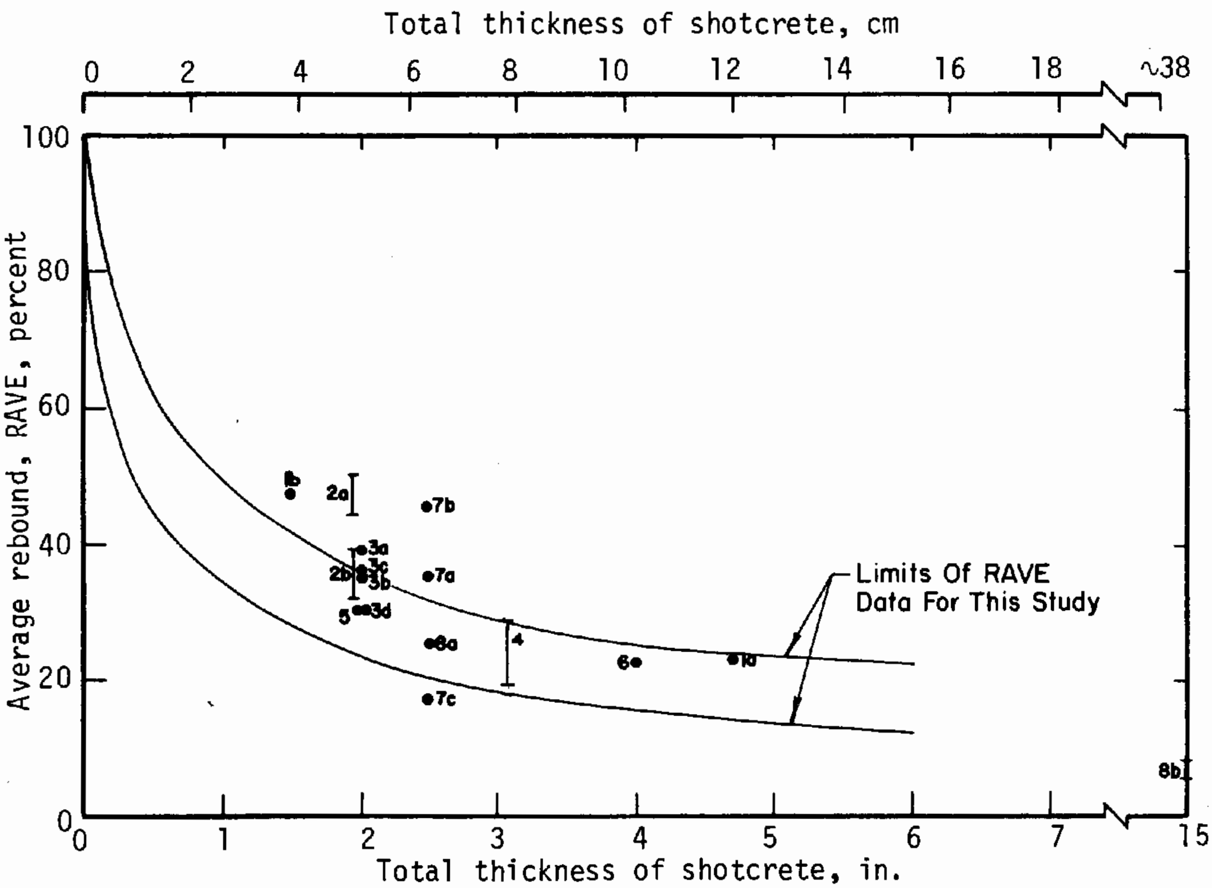


FIG. 4.16 CORRELATION OF RAVE WITH THICKNESS FOR DATA REPORTED IN LITERATURE

a decrease of RAVE with thickness that can be seen in the figure. There is also a general tendency for overhead shooting to result in higher rebound percentage (data sets 2 and 7). Wet-mix generally has a lower rebound and coarser material generally has higher rebound. If sufficient well-documented data becomes available in the future, bands or envelopes might be determined showing typical ranges for specific shooting conditions. For instance, a typical range for coarse aggregate dry-mix shotcrete might be differentiated from a band representing coarse aggregate wet-mix shotcrete. The data are too speculative and too sparse to permit such an interpretation at this time.

4.6.2 NECESSARY DOCUMENTATION OF REBOUND MEASUREMENTS

The state-of-the-art of shotcreting will advance fastest by relevant, truthful communications among users of shotcrete themselves. Thus, there is a need for a means of communication and for documenting the conditions under which various measurements were made.

It has been shown that the thickness of the fresh shotcrete affects the magnitude of the measured rebound in a way that cannot necessarily be controlled by the operator. Thus, it is recommended that the thickness of shotcrete be reported along with the other relevant factors affecting rebound. Some of these are listed in Table 4.12. Those particularly important items which should be reported with all rebound data are listed in capital letters.

4.6.3 DISCUSSION OF DESIRED THICKNESS FOR REBOUND TESTS

There are several reasons for conducting rebound tests. Two important reasons are 1) to compare different mix designs or shooting conditions

TABLE 4.12

FACTORS WHICH SHOULD BE CONSIDERED
AND REPORTED FOR REBOUND MEASUREMENTS

1. Nature of surface shot
    a. WALL OR OVERHEAD: APPROXIMATE PERCENTAGES OF EACH
    b. Roughness of wall
    c. Water conditions
    d. Type of rock
        1) Rock name
        2) Hardness of rock; (compressive strength)
        3) Type of jointing and joint-surface characteristics or filling material

2. Shooting conditions
    a. TYPE OF MIX: DRY OR WET
    b. Type of shotcrete machine, air and water pressures, length and diameter of hoses
    c. Type and internal diameter of nozzle, number and diameter of holes in water ring
    d. Material delivery rate, MDR, in weight per minute
    e. THICKNESS OF SHOTCRETE LAYER
    f. APPROXIMATE ESTIMATE OF WETNESS OF IN-PLACE SHOTCRETE
        1) Shooting condition for dry mix (i.e., glossy criterion, or wet or dry of glossy)
        2) Water rate added at nozzle for dry mix, estimate of water-cement ratio in-place
        3) Slump of wet mix shotcrete
    g. Temperatures of air, mix, and nozzle water
    h. TYPICAL DISTANCES AND ANGLE OF NOZZLE TO SURFACE
    i. MEASURED ACCELERATOR DOSAGE
    j. Age of dry mix before shooting

3. Mix conditions
    a. Mix design--batch weights
    b. Compatibility data between cement and accelerator at temperature and percent accelerator used
    c. Gradation and moisture of aggregates
        1) MAXIMUM SIZE
        2) PERCENTAGE GRAVEL-SIZED (No. 4 sieve, 4.75 mm)
        3) Grain-size curves
        4) Initial moisture content of fine and coarse aggregate
        5) Temperatures of raw materials: cement, aggregate, and water

Note: Factors listed in CAPITAL LETTERS are particularly important.

and, 2) to estimate actual rebound losses on a project. The influence of a variation in mix design or shooting condition on rebound if measured by RAVE can be determined if and only if all the mixes are shot to the same thickness. When there are significant differences in RAVE between mixes, shooting the same total batch weight for each mix will not result in the same thickness because the batch with a lower RAVE will result in a greater thickness on the wall. In any case, the surface area shot should be constant.

At the very least, rebound measurements should be made by shooting all tests to the same final thickness, that is, at least 4 to 5 in. (10.2 to 12.7 cm). The difference in the numerical value of average rebound by shooting to different thicknesses, all of which are greater than about 4 in. (10.2 cm), is not great since the RAVE curve is nearly asymptotic to a horizontal line.

A thickness of 10 cm (3.9 in.) is the recommended thickness for comparative evaluations of coarse aggregate shotcrete. This is a metric equivalent of a commonly used thickness of shotcrete linings used for temporary support. More importantly, it is a thickness at which RAVE is not changing rapidly since 4 in. (10 cm) is out on the near-horizontal portion of the RAVE curve as illustrated in Fig. 4.17. There is too much chance for error if rebound collection stops when the slope of the curve is still quite steep. Thus, it is recommended that rebound be reported on the basis of a standard 4-in. (10-cm) thick layer. Shooting all tests to this standard thickness should be adequate for rebound tests for evaluations of mix design or shooting conditions on rebound or for publishing results. Though the rebound behavior for wet-mix shotcrete may be different, rebound tests on wet-mix shotcrete should also be shot to the standard thickness to permit correlations with dry-mix shotcrete.

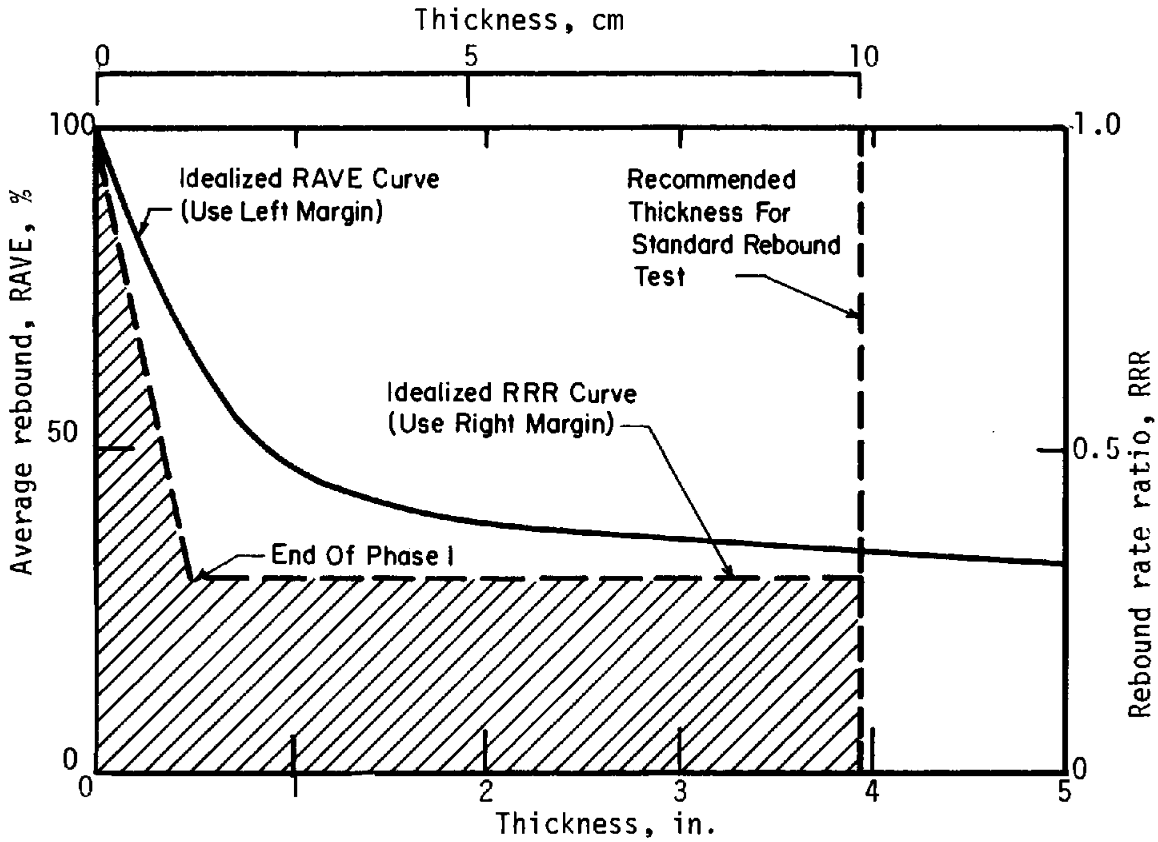


FIG. 4.17 CONCEPT OF STANDARD REBOUND TEST THICKNESS

However, actual rebound losses on a project can only be estimated in a rebound test by simulating the relevant conditions, especially the thickness actually to be shot for the project. Since there are Phase 1 losses at the beginning of each lift in a lining placed in multiple-lifts, the rebound test for estimating actual losses for a multiple-lift project is the thickness of one lift.

4.6.4 RECOMMENDED STANDARD REBOUND TEST

Because of the dominant effect of the final layer thickness on the measured value of average rebound, RAVE, it is proposed that a standard rebound test be developed in order that the relative influence of parameters affecting rebound can be investigated. Such a test can be used during pre-construction testing to evaluate the effect of variations in mix or shooting conditions on rebound. In addition it can be used for quality control and proficiency checks on the crew during construction. If adopted throughout the industry, such a standard rebound test would permit correlation of rebound information between jobs. Ultimately, data would be collected that could be used to determine typical ranges of RAVE and RRR values that might be expected with each of the various types of shotcrete (wet-mix, dry-mix, coarse or fine aggregate, etc.). Such a standard test should include a standard thickness to which rebound tests should be shot and reported. For the reasons discussed in the previous section the recommended thickness is 10 cm (3.9 in.).

The best method to make rebound comparisons between mixes is to determine rebound rate ratio, (RRR), for the entire test. In this way the effect of variables on the rebound rate during the establishment of the initial critical thickness as well as their effect on the subsequent rebound stages can be determined.

Based upon the experimental evidence collected in this program, it is believed that once the initial critical thickness is established (Phase 1), RRR during subsequent shooting (Phase 2) is approximately constant. This observation will be used to propose the following simple method to determine RRR for both Phase 1 and Phase 2 and to determine RAVE for the final thickness. With this information, a contractor can determine if changes in the mix design or shooting conditions will reduce the losses during Phase 1 and Phase 2 or both. The effects of even small changes in mix or shooting conditions should be able to be detected in the RRR values. Very little extra work is required to separate the losses during Phase 1 from those during Phase 2 since both proposed tests must be done in one shooting.

The suggested simple test consists of shooting at a specific area on two plywood test boards to specific thicknesses without interruption of shooting. After adjusting the nozzle, etc., on a practice board, the first test board is shot to a uniform thickness of 4 in. (10 cm). All rebound is collected on tarps; RAVE, to the standard thickness of 4 in. (10 cm), can then be calculated from the shooting of this first test board. Without stopping, a second nearby test board is shot to a uniform thickness that is judged by the nozzleman to be the thickness at which the material just begins to stick to the wall (end of Phase 1). Shooting of this second test board to such a small thickness uniformly will require a rapid movement of the nozzle all over the board. Naturally, it will be difficult for the nozzleman to judge this thickness. He should practice before actually running the test and he should note the behavior of the build-up on the first test board to guide him in shooting the Phase 1 portion of the test. The nozzleman, or an experienced observer, can also use the noise of the particles impacting on the board as a guide to the proper thickness at the end of Phase 1. The noise changes from a harsh raspy sound to a dull sound when the critical thickness is established. The critical thickness is probably 1/2 in. (1 cm) or less. It is better to shoot slightly thicker than the true end of Phase 1 than slightly thinner, since the errors are less if the thickness is greater. The test is complete when this second panel is shot to the critical thickness. The rebound collected while shooting this second board is used to calculate RRR for Phase 1. The measured thickness of shotcrete on this board is the experimental thickness of the critical layer.

The following calculations can be made from data determined during this two part test to determine the RAVE for the standard 4 in. (10 cm) and RRR for both phases. The net weight of rebound on the tarps for the first and second boards is designated as $RSUM_{10}$ and $RSUM_t$, respectively, where t is the measured thickness of the critical layer. After the tarps are weighed and cleaned, they can be put back on the ground and all material scraped off the boards onto the tarps. They can be weighed again to determine the weights of shotcrete on the first and second test boards, designated as $YSUM_{10}$ and $YSUM_t$, respectively. The total of the respective RSUM and YSUM equals SSUM for each test, designated as $SSUM_{10}$ and $SSUM_t$ (Mahar, Parker, and Wuellner, 1975). The calculations for $RAVE_{10}$, RRR_{10} and RRR_t are given in Table 4.13.

Based upon the results of this study, detailed procedures and equipment for a standard rebound test have recently been developed and are proposed by Mahar, Parker, and Wuellner (1975).

4.7 CONSIDERATIONS ON ECONOMICS OF REBOUND

There are several economic conclusions or implications resulting from this study of rebound. Some of the most important of these are presented and discussed in the following sections.

4.7.1 METHODS OF ESTIMATING MATERIAL QUANTITIES WHEN IN-PLACE THICKNESS IS THE CRITERION

Any volumetric term such as cubic yard or cubic meter has a limited or restricted usefulness in tunnel shotcrete work because material is usually batched by weight, and overbreak and rebound losses must be considered. Most tunnel specifications require a minimum thickness that must be placed on the

TABLE 4.13

SUGGESTED CALCULATIONS FOR TWO-PART STANDARD REBOUND TEST

1. RAVE Calculation

$$RAVE_{10} = \frac{RSUM_{10}}{SSUM_{10}} = \frac{RSUM_{10}}{RSUM_{10} + YSUM_{10}}$$

where $RSUM_{10}$ = Net weight of rebound collected during 4 in. (10 cm) thick test.

$YSUM_{10}$ = Net weight on test board after 4 in. (10 cm) thick test

$SSUM_{10}$ = Total weight shot during 4 in. (10 cm) thick test

2. Calculation of RRR during establishment of initial critical thickness (RRR for Phase 1)

$$RRR_{(0-t)} = \frac{RSUM_t}{SSUM_t} = \frac{RSUM_t}{RSUM_t + YSUM_t}$$

where t = actual average measured thickness of initial critical layer

$RSUM_t$ = Net weight of rebound collected after shooting only the initial critical layer

$YSUM_t$ = Net weight on test board containing only the initial critical layer

$SSUM_t$ = Total weight shot while establishing the initial critical thickness

3. Calculation of RRR subsequent to establishment of initial critical layer (RRR for Phase 2)

$$RRR_{(t-10)} = \frac{RSUM_{10} - RSUM_t}{SSUM_{10} - SSUM_t} = \frac{RSUM_{10} - RSUM_t}{(RSUM_{10} + YSUM_{10}) - (RSUM_t + YSUM_t)}$$

4. Material delivery rate calculation (MDR)

$$MDR = \frac{SSUM_{10}}{T_{10}} = \frac{RSUM_{10} + YSUM_{10}}{T_{10}}$$

where T_{10} = Net time to shoot the 4 in. (10 cm) test

5. Unit weight of material (γ)

$$\gamma_{10} = \frac{YSUM_{10}}{V_{10}} \approx \frac{YSUM_{10}}{(A_{10}) \times (t_{10})}$$

where: V_{10} = Actual volume of shotcrete on test board (Note, must account for wing walls or tapered edges or non-uniform-thickness

A_{10} = Surface area shot in 4 in. (10 cm) test wall. This thickness, perhaps modified by an average amount of overbreak, over a specified area of the tunnel is the average volume that must be placed. The volume can be converted to a weight in-place by multiplying by the unit weight of the material in place, γ. The relationships between the thickness and amount of material which must be shot are derived in Table 4.14.

It can be seen that the weight of material that must be shot exceeds the in-place weight (or equivalent volume) by the Overshoot Factor, OSF, defined as follows:

$$\text{Overshoot Factor} = \text{OSF} = \frac{1}{1 - \text{RAVE}}$$

The weight to be shot can be calculated according to Table 4.14. It is important to recognize that the RAVE used should be measured or estimated for a specific thickness that includes the estimated amount of overbreak and any tendency to shoot thicker or thinner than specified. Kobler (1966) states that 1.6 to 1.7 cu yd (1.2 to 1.3 cu m) of dry mix is required to produce 1 cu yd (0.8 cu m) of coarse aggregate shotcrete in-place underground. His "Overshoot Factors" would be 1.6 to 1.7. Hendricks (1969) reports a factor of 1.5 for dry-mix coarse aggregate shotcrete.

The Overshoot Factor is plotted in Fig. 4.18 against RAVE. The curve is concave upward with steepness increasing with RAVE. The nature of this curve is such that reductions in RAVE have different importance depending on the initial value of RAVE; the importance is greater with greater initial value. For instance, two zones on the curve are marked, both of which represent a reduction in RAVE of 10 percent. The magnitude of the Overshoot Factor reduces from 3.3 to 2.5, or a difference of 0.8, when the initial value is 70 percent. The magnitude of the factor reduces only from 1.4 to 1.2, or a

TABLE 4.14

FORMULAS FOR ESTIMATING WEIGHT THAT MUST BE SHOT TO OBTAIN A SPECIFIED THICKNESS IN-PLACE

$$YSUM = t \cdot A \cdot \gamma$$

where t = Actual thickness in-place (Includes overbreak and any tendency to shoot thinner or thicker than specified)

A = Area of tunnel to be shotcreted to thickness t

γ = Unit weight of material in-place

but,

$$SSUM = YSUM + RSUM$$

$$RSUM = RAVE \cdot SSUM$$

$$\therefore SSUM = YSUM + (RAVE \cdot SSUM)$$

transposing,

$$SSUM = YSUM \left(\frac{1}{1 - RAVE}\right)$$

Note: RAVE is expressed as a ratio not a percentage

The factor $\left(\frac{1}{1 - RAVE}\right)$ will be called the "Overshoot Factor", OSF

To obtain weight to be shot, for a desired weight in-place, multiply the weight in-place by the Overshoot Factor.

****

If underground shotcreting involves both shooting vertical walls and overhead, an adjusted Overshoot Factor can be used if a RAVE is known for shooting vertical walls and for overhead shooting according to the following formula:

$$SSUM_{o+w} = \gamma \cdot t \cdot A_{o+w} \left[\frac{(A_o \cdot OSF_o) + (A_w \cdot OSF_w)}{A_{o+w}} \right]$$

where:

subscript o represents value for overhead shooting
subscript w represents value for shooting vertical walls
subscript o+w represents total value for both overhead and vertical walls

Let $\left[\frac{(A_o \cdot OSF_o) + (A_w \cdot OSF_w)}{A_{o+w}} \right]$ = adjusted overshoot, OSF_{o+w} factor for both overhead and wall shooting

then:

$$SSUM_{o+w} = \gamma \cdot t \cdot A_{o+w} \cdot OSF_{o+w}$$

This formula will be satisfactory only if the thickness shot on the wall and on the overhead are equal. The formula can be revised in a similar manner to include different thicknesses.

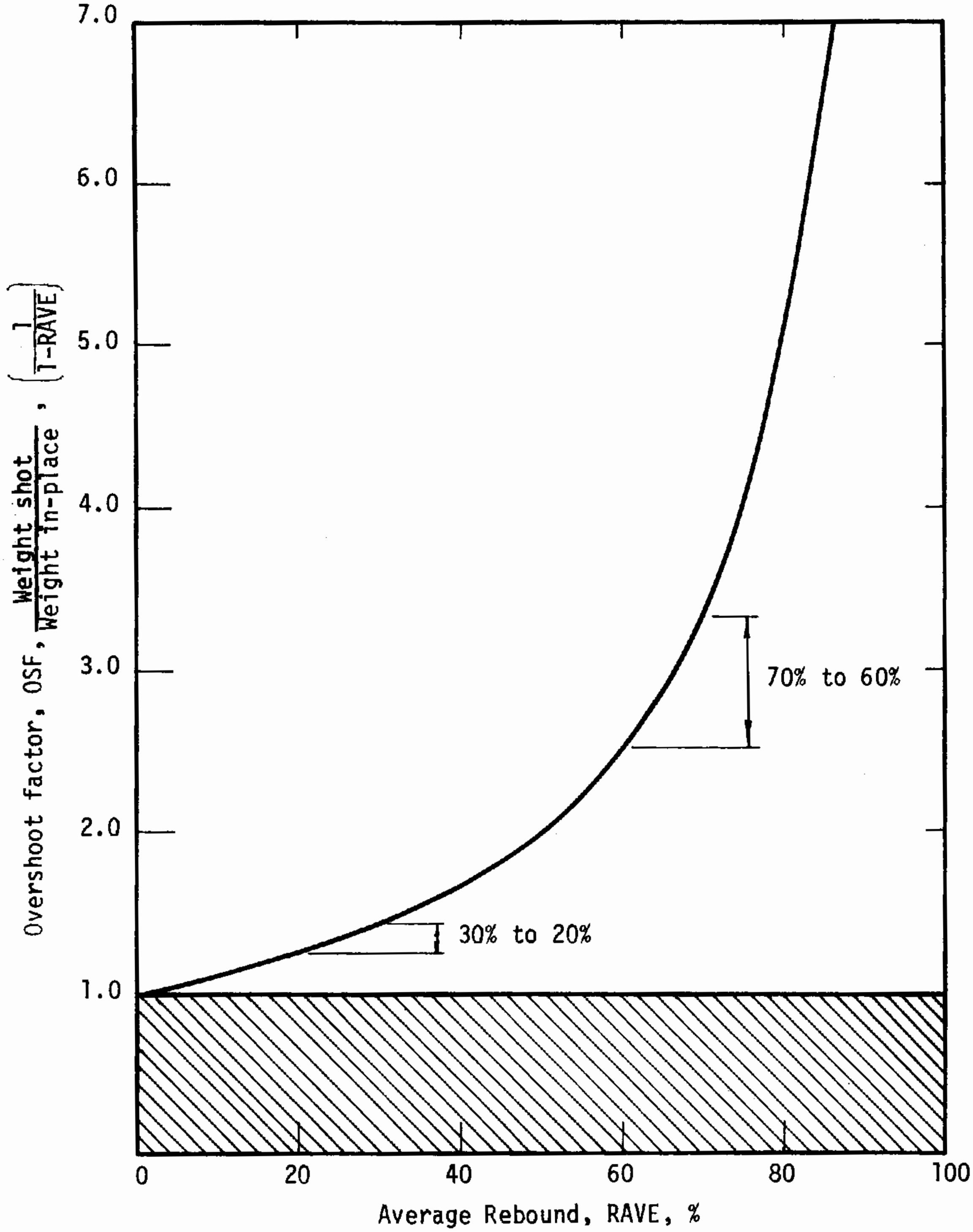


FIG. 4.18 RELATIONSHIP BETWEEN OVERSHOOT FACTOR, OSF, AND AVERAGE REBOUND, RAVE

difference of 0.2, when the initial value is 30 percent. This implies that the dollar savings are four times greater for an equal 10 percent reduction in RAVE when the reduction is from 70 to 60 percent than when the reduction is from 30 to 20 percent. It can be said that if RAVE is greater than about 50 percent, every effort to reduce rebound will bring great savings. Any unnecessary increase in RAVE, and especially any RAVE greater than 50 percent, should be unacceptable.

Figure 4.18 and Table 4.14 can be used to estimate the weight of material that must be shot to obtain a given weight in-place. Furthermore, if analyses are to be performed on the effect of certain improvements in mix or shooting conditions on cost, the comparison should be made on the basis of the respective overshoot factors and not on comparisons based solely on the respective values of RAVE as discussed in the next section.

4.7.2 ECONOMIC COMPARISONS AND THE OVERSHOOT FACTOR

Any numerical economic evaluation of rebound should be based upon RAVE data adjusted by the overshoot factor; interpretations based on unadjusted numerical values of RAVE will give the wrong impression unless converted to actual weights shot or adjusted by the overshoot factor. For instance, assume that, for the specified thickness, a certain set of mix and shooting conditions results in a RAVE of 30 percent. If improvements reduce RAVE to 20 percent, the improvement caused a 10 percent savings out of 30 percent or a reduction of rebounded material of about 33 percent, which sounds like a substantial savings. However, the overshoot factor changes from 1.43 to 1.25 for RAVES of 30 percent and 20 percent, respectively. Thus, the reduction in the total weight of material shot is 0.18/1.43 or only 12 percent. It can be seen that a significantly different impression of the relative economics of rebound is obtained, depending on how it is assessed.

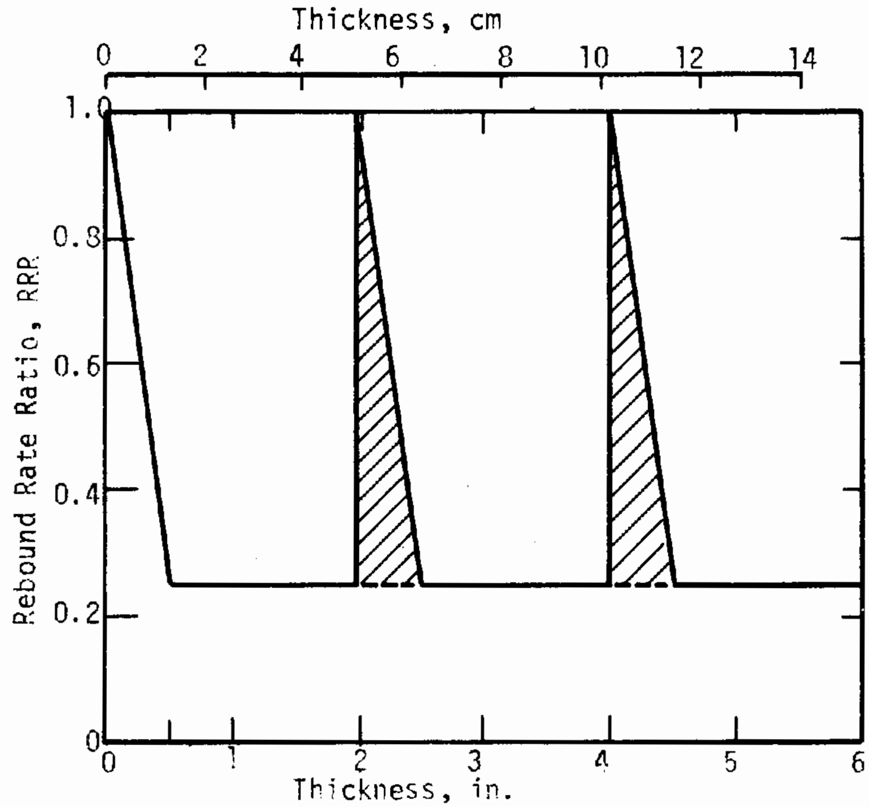
4.7.3 ECONOMICS OF REBOUND LOSSES ASSOCIATED WITH MULTIPLE LAYERS

Each time shooting begins against a hard surface, the rebound rates are initially very high as described in the previous sections. When a thick layer is placed in one lift, this high rebound rate occurs only once. When a layer is built up in multiple layers, extra phases of extra high rebound losses occur, as illustrated in Fig. 4.19a.

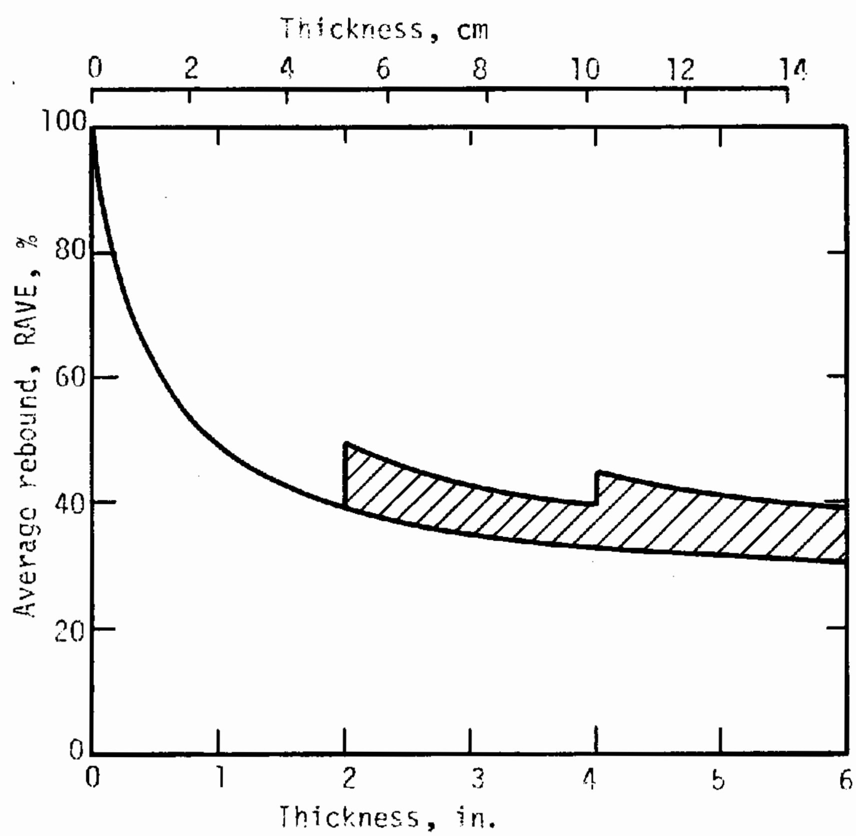
In this section, it will be shown that it is more economical to shoot one layer 6 in. (15 cm) thick than it is to shoot 3 layers 2 in. (5 cm) thick. A contractor may be faced with such a choice when shooting a final lining.

The time between lifts under consideration may be very short when accelerators are used. It is possible that, within a few minutes after shooting, depending upon the accelerator dosage, the surface may become hard enough to cause these very high rebound rates. General observations of shotcreting with fast-set accelerators indicate that the surface can become hard enough to exert an important influence on the behavior of the incoming shotcrete very quickly. The x-ray photographs of fiber shotcrete described in Chapter 7 show that, even when a panel was shot in less than one minute, significant layering occurred even though the nature of the layering was not that of a structural defect.

At each new layer, the RRR-versus-thickness curve is repeated as



a) Assumed RRR curve for multiple layers



b) Composite RAVE curve for multiple layers

FIG. 4.19 EFFECT OF MULTIPLE LAYERS ON REBOUND shown in Fig. 4.19a. Any rebound rate above the initial curve (shown shaded) represents unnecessary or at least extra losses. The effects of these extra losses have been converted with the equations given in Appendix F to the RAVE-versus-thickness diagram in Fig. 4.19b. Again, the shaded areas represent extra losses. The following paragraphs illustrate an example of the potential magnitude of these losses.

Assume that the rate of advance and the specified thickness of the lining requires a volume in-place represented by 100,000 lb (45,500 kg) (YSUM) each day. Assume that the rebound rate ratio, RRR, after the initial high losses, for overhead work is 0.25 and that the RRR curve shown in Fig. 4.19a is a straight line idealization of a realistic RRR curve. As seen in Fig. 4.19b, RAVE for an application in one layer would be 30 percent while the same thickness shot in 3 layers would result in a RAVE of 39 percent. Table 4.15 is a summary of the quantities and costs associated with these two methods of shooting assuming a cost of \$100/cu yd (\$130/cu m) through the gun and a weight of 3800 lb (1730 kg) per cu yd.

Table 4.15 illustrates that, for the assumed conditions, the amount that must be shot to obtain the specified volume in place would be reduced by 22,000 lb (10,500 kg) or by 13.3 percent if it is shot in one layer instead of three. The savings in cost through the gun would be around \$580 for the days work which, although only 13.3 percent of the total cost of shooting 3 layers, is still a worthwhile savings. These savings might be appropriate for a typical large subway or highway tunnel. If a final lining for a large underground opening or mine with several guns operating are considered, the daily savings in dollars might easily be doubled or tripled. In terms of rebound

TABLE 4.15

COMPARISON OF REBOUND LOSSES AND COSTS BETWEEN ONE- AND THREE-LAYER APPLICATIONS

	Average rebound for entire thickness, RAVE, %	Overshoot factor	Assumed weight in-place equivalent to 1 day's advance of final lining YSUM lb (kg)	Total weight shot to obtain in-place weight SSUM, lb (kg)	Total rebound losses, RSUM, lb (kg)	Cost of rebound $
One layer	30.3	1.43	100,000 (45,500)	143,000 (65,000)	43,000 (19,500)	1130
Three layers	39.3	1.65	100,000 (45,500)	165,000 (75,000)	65,000 (30,000)	1710
			Savings: (in terms of quantities for 3 layers)	22,000 (10,000) (13.3%)	22,000 (10,000) (33.8%)	580 13.3[1]

Note: [1] $580 = 13.3% of $4350, estimated total cost to shoot 3 layers (based on $100 per 3800 lb equivalent cu yd.)

losses, the single-layer application results in about 33.8 percent less rebound material to clean up. In addition, manpower costs are reduced and the potential for structural defects between layers is eliminated.

4.7.4 POTENTIAL FOR ECONOMY BY IMPROVEMENTS THAT REDUCE REBOUND

New nozzle designs or improved shooting techniques should be developed specifically to reduce both Phase 1 and Phase 2 rebound losses. Particular emphasis should be given to reducing losses during Phase 1, but it will be shown in this section the Phase 2 losses are also important. Recommendations of new equipment of specialized techniques that reduce rebound are beyond the scope of this study. However, rebound on any project can be reduced within the restraint of present technology by optimizing mix and shooting conditions and enforcing proper gun operation and nozzling practices. The potential for savings is illustrated by the following examples.

Costs are estimated for three cases. Case I might represent a condition in which rebound losses are moderately high; with an RRR for Phase 2 of 0.30, it might realistically represent a typical overhead shooting operation. Case II represents relatively low rebound losses with similar losses for Phase 1, but an RRR for Phase 2 of only 0.10. This case could represent losses that might result while shooting overhead after the operation in Case I was improved significantly, perhaps by the use of a highly efficient nozzle and good nozzling practice or other improvements. Cases I and II have similar Phase 1 losses. In Case III, Phase 1 losses have been eliminated altogether, by some improved method or equipment, and losses at all thicknesses occur at a Rebound Rate Ratio, RRR, of 0.20. It represents the case of a significant improvement in Phase 1 losses, but not quite as much as for Phase 2 losses as Case II.

Note that other relative interpretations might be given to these examples. For instance, a comparison between Cases I and II could be the difference between shooting an overhead or vertical wall. (Case II essentially represents the experimental data obtained during this study.) A third interpretation of relative conditions in Cases I and II might be of improved workmanship while shooting a vertical wall. Case I could be considered to be the result of poor workmanship, while Case II could be considered to represent good workmanship.

The assumed conditions are given in Table 4.16. The assumed idealized RRR curves are illustrated in Fig. 4.20, while the corresponding RAVE curves calculated from the assumed RRR curves are illustrated in Fig. 4.21. The values of RAVE were calculated from an equation relating time of shooting, RRR, RAVE, and thickness, discussed in Section 4.8 and derived in Appendix F.

A summary of the estimated quantities of material for each of the three cases is given in Table 4.17. Each case is analyzed at the critical thickness, 0.3 in. (7 mm), and at each inch (2.54 cm) out to a total of 6 in. (15.2 cm). The values in the table are based upon a square yard (0.83 sq m) of in-place material at the thickness shown and an assumed unit weight of 145 pcf (2320 kg/m^3). The table gives the weight of material in-place at the thickness shown, the RAVE calculated from the RRR curve, the corresponding overshoot factor, and the calculated weight of material that must be shot through the gun to build up the given thickness. The cost, time of shooting, and weight of material rebounded are summarized in Table 4.18. The values for time of shooting in Table 4.18 are based upon an assumed MDR of 400 lb/min (180 kg/min). The cost per square yard (0.83 m^2) for the amount needed

TABLE 4.16

SUMMARY OF CONDITIONS FOR EXAMPLE CASES

	Phase 1		Phase 2	Relative interpretation (read vertically)		
Case	RRR at zero thickness	Critical thickness t_c, in. (mm)	RRR	Overhead shooting only	Both overhead and vertical wall	Shooting vertical wall only
I	0.95	0.30 (7.5)	0.30	Typical losses.	Typical losses for overhead shooting.	Poor workmanship.
II	0.95	0.30 (7.5)	0.10	Significant improvement in Phase 2 losses only. Phase 1 losses similar to Case I.	Typical losses for shooting vertical wall.	Good workmanship.
III	0.20	0	0.20	Complete elimination of Phase 1 losses. Phase 2 losses reduced, but not as much as in Case II.		

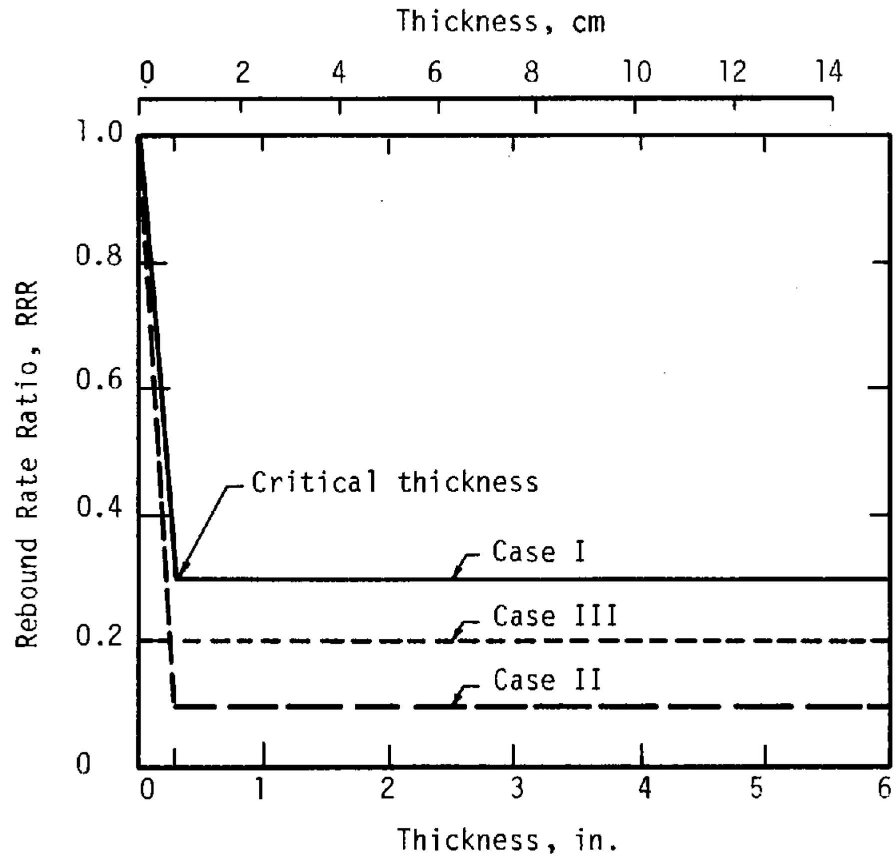


FIG. 4.20 ASSUMED RRR CURVES FOR EXAMPLE CASES

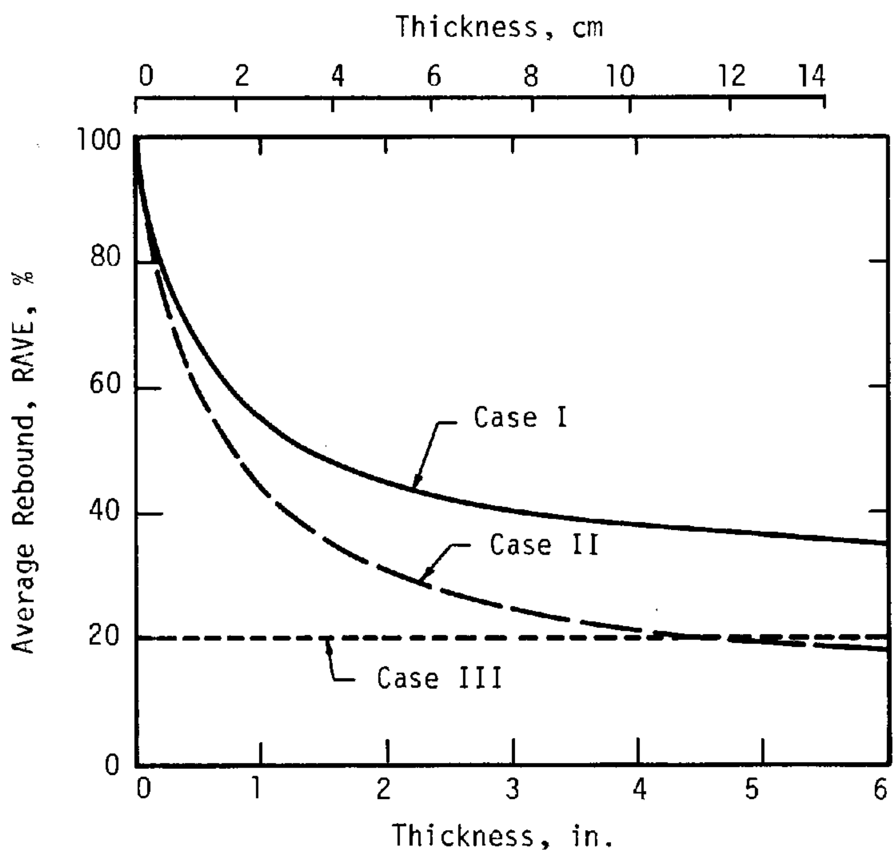


FIG. 4.21 RAVE CURVES FOR EXAMPLE CASES

TABLE 4.17

CALCULATED QUANTITIES FOR EXAMPLE CASES

Thickness in. (cm)	Weight of in-place material per sq yd, YSUM, lb (kg)	Average Rebound, RAVE, percent	Overshoot Factor, OSF	Weight of material through gun, SSUM, lb (kg)
Case I				
0.3 (0.76)	32.63 (14.8)	75.36	4.06	132.44 (60.2)
1.0 (2.54)	108.8 (49.4)	54.9	2.21	241.25 (109.7)
2.0 (5.0)	217.5 (98.9)	45.14	1.82	296.5 (180.2)
3.0 (7.62)	326.2 (148.3)	40.87	1.69	551.7 (250.8)
4.0 (10.1)	435.0 (197.7)	38.5	1.63	707.3 (321.5)
5.0 (12.7)	543.8 (247.2)	36.96	1.59	862.7 (392.1)
6.0 (15.2)	652.6 (296.6)	35.89	1.56	1018 (462.7)
Case II				
0.3 (0.76)	32.63 (14.8)	70.61	3.14	110.9 (50.4)
1.0 (2.54)	108.8 (49.4)	44.35	1.79	195.5 (88.9)
2.0 (5.0)	217.5 (98.9)	31.23	1.45	316.4 (143.8)
3.0 (7.62)	326.2 (148.3)	25.36	1.33	437.3 (198.7)
4.0 (10.1)	435.0 (197.7)	22.03	1.28	558.2 (253.6)
5.0 (12.7)	543.8 (247.6)	19.89	1.25	679.0 (308.6)
6.0 (15.2)	652.6 (296.6)	18.4	1.22	800.0 (363.5)
Case III				
0.3 (0.76)	32.63 (14.8)	20	1.25	40.8 (18.5)
1.0 (2.54)	108.8 (49.1)	20	1.25	136.0 (61.3)
2.0 (5.0)	217.5 (98.1)	20	1.25	272.0 (122.7)
3.0 (7.62)	326.2 (147.1)	20	1.25	407.8 (183.9)
4.0 (10.1)	435.0 (196.2)	20	1.25	543.8 (245.2)
5.0 (12.7)	543.8 (247.2)	20	1.25	679.8 (309.0)
6.0 (15.2)	652.6 (296.6)	20	1.25	815.75 (370.8)

TABLE 4.18

SUMMARY OF RELATIVE ECONOMICS OF EXAMPLE CASES

Thickness	Cost of material in place $/yd² ($/m²)			Total time build-up thickness min/yd² (min/m²)			Weight of material rebounded lb (kg)		
in. (cm)	Case I	Case II	Case III	Case I	Case II	Case III	Case I	Case II	Case III
0.3 (0.76)	3.48 (4.18)	2.92 (3.50)	1.07 (1.28)	0.33	0.27	0.10	99.81 (45.37)	78.27 (35.58)	13.58 (6.17)
1.0 (2.54)	6.35 (7.62)	5.14 (6.17)	3.57 (4.28)	0.60	0.49	0.34	132.45 (60.20)	86.70 (39.41)	27.2 (12.36)
2.0 (5.0)	10.43 (12.52)	8.33 (10.00)	7.15 (8.58)	0.99	0.79	0.68	179.0 (81.36)	98.90 (44.95)	54.5 (24.77)
3.0 (7.62)	14.52 (17.42)	11.51 (13.81)	10.73 (12.88)	1.38	1.09	1.0	225.5 (102.5)	111.1 (50.5)	81.6 (37.1)
4.0 (10.1)	18.61 (22.32)	14.69 (17.63)	14.30 (17.16)	1.77	1.40	1.36	272.3 (123.77)	123.20 (56.00)	108.8 (49.45)
5.0 (12.7)	22.70 (27.24)	17.87 (21.44)	17.9 (21.48)	2.16	1.70	1.70	318.9 (145.0)	135.20 (61.45)	136.0 (61.8)
6.0 (15.2)	26.78 (32.13)	21.05 (25.26)	21.46 (25.75)	2.54	2.00	2.04	365.4 (166.1)	147.40 (67.00)	163.15 (74.16)

to be shot through the gun at a cost through the gun of \$100 per cu yd (\$131/m^3) and 3800 lb/cu yd (2255 kg/m^3) is also shown. The costs, shooting times, and weights of rebound for the cases are presented graphically in Figs. 4.22, 4.23 and 4.24, respectively.

Interpretations of these data from a cost standpoint are complicated because of the practice of payment methods based upon amount of material through the gun. The costs in Fig. 4.22 are based on an assumed \$100 per equivalent cubic yard through the gun. If a contractor is paid in this manner, the curves indicate the relative magnitude of costs to the owner, i.e., payments to the contractor, and their variation with thickness for the three cases. Reductions in costs because of the improvements would then represent reduced costs to the owner and reduced payments for the contractor. On the other hand, if the contractor is paid by a lump sum or a unit price per foot basis, the owner's costs do not change and the savings are entirely the contractor's. The unit price to be used in such an analysis should not include profit because the savings, in this case, represent greater profits. The reductions in manpower in terms of time of shooting, Fig. 4.23, and the reductions in the amount of rebound to be removed, Fig. 4.24, are savings that go to the contractor whether he is paid through the gun or by a fixed price. The point is that someone saves by improvements to the shooting operations in either method of payment.

The curves in Figs. 4.22, 4.23 and 4.24 are similar because the cost through the gun, time of shooting, and rebound are related. The following discussion of the cost curves also applies, generally, to the time curves and rebound curves. The cost per sq yd increases rapidly to the critical

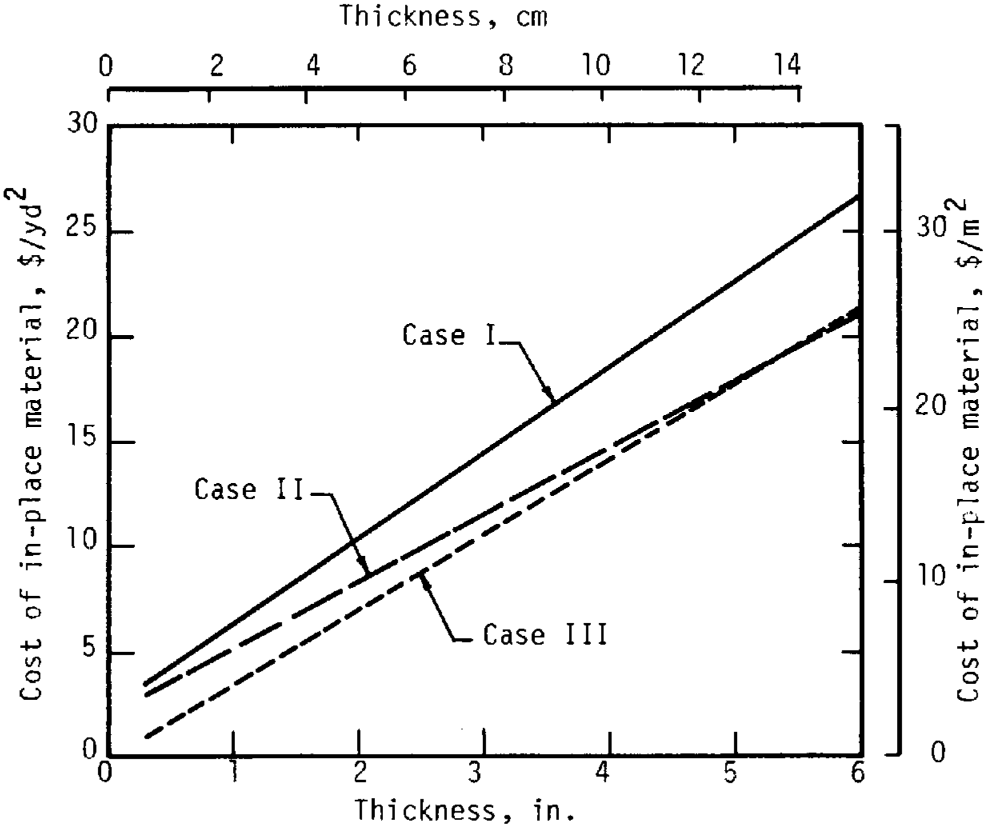


FIG. 4.22 COMPARISON OF COSTS FOR EXAMPLE CASES

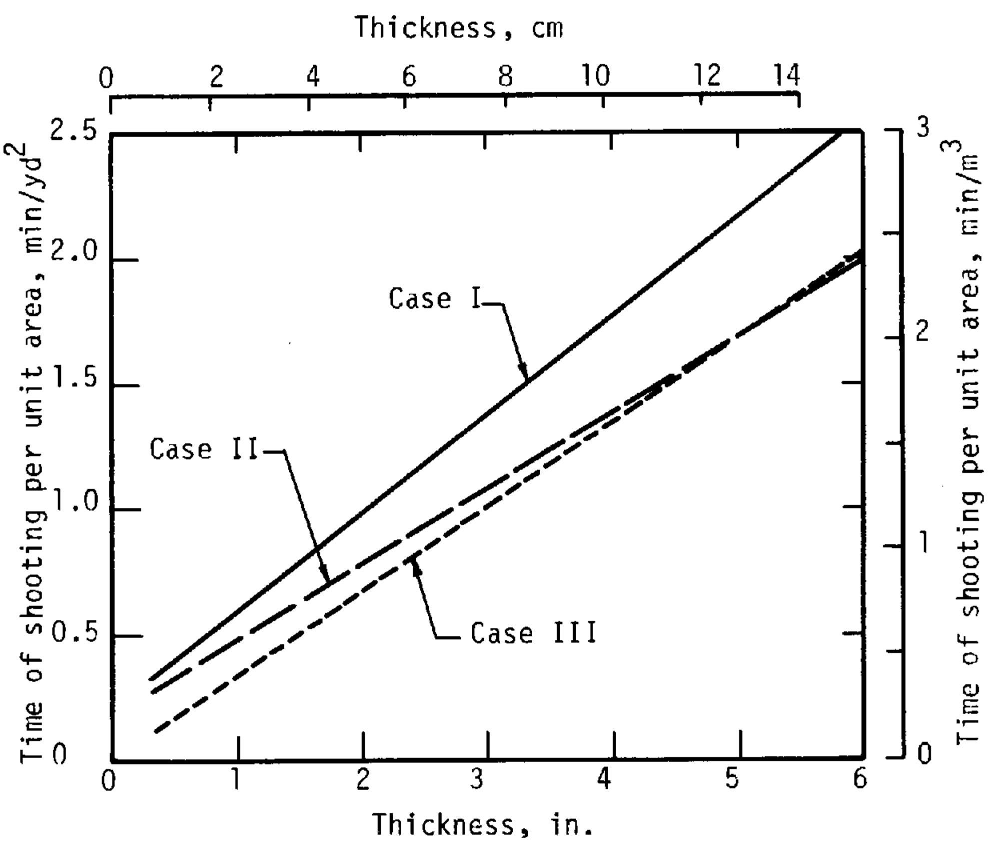


FIG. 4.23 COMPARISON OF SHOOTING TIMES FOR EXAMPLE CASES

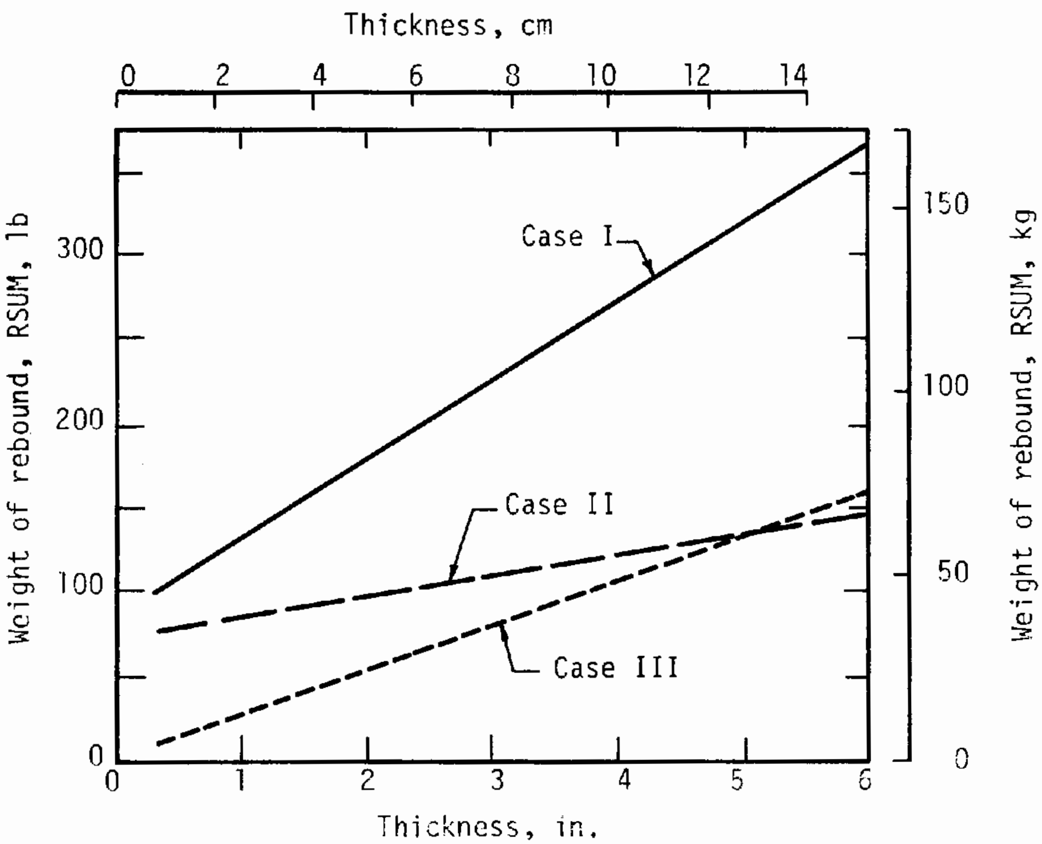


FIG. 4.24 COMPARISON OF REBOUND FOR EXAMPLE CASES

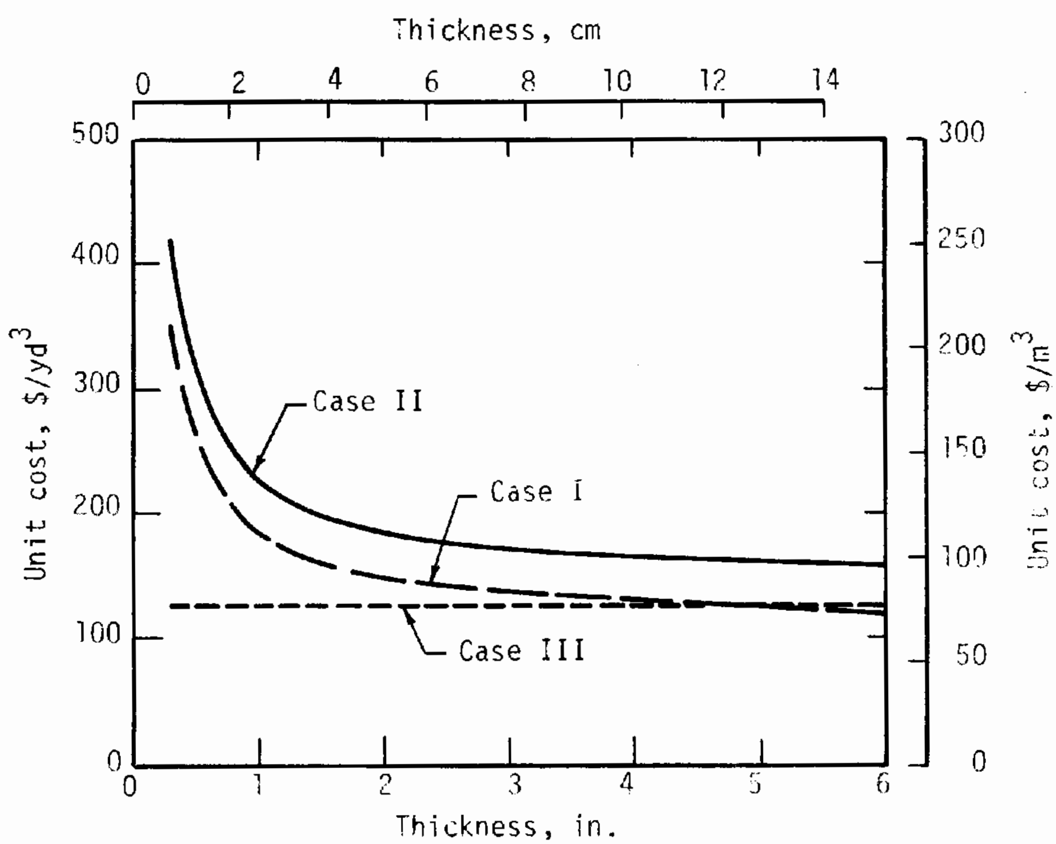


FIG. 4.25 EFFECT OF PHASE 1 LOSSES ON UNIT COSTS PER VOLUME IN PLACE: EXAMPLE CASES

thickness (the beginning of the curve), after which the rate of increase drops significantly, reflecting the lower RRR of Phase 2. Case III increases at a constant rate because there were no increased Phase 1 losses.

At the end of Phase 1, the cost per square yard of Case II is less by \$0.56 (\$0.68 per m^2), or about 16 percent of Case I. For a 6-in. (15-cm) thickness, the cost for Case II is \$5.73/yd^2 (\$7.13/m^2) less, about 21 percent cheaper than Case I. Accordingly, the dollar savings for reducing the rate of rebound during Phase 2 increases with thickness; for the assumptions made, it can be as much as \$6 per sq yd (\$7.23/m^2).

A comparison of Cases II and III affords an assessment of the effects of the relative magnitudes of RRR between Phase 1 and Phase 2. During Phase 1, Case II has the highest rebound rate since Case III has no increased losses. However, the conditions reverse for Phase 2 losses during which Case III has the highest rebound rate. The losses resulting from rebound in Phase 1 make the cost in Case II to be higher than Case III by \$1.85 per sq yd (\$2.23/m^2), or 173 percent higher; however, the trend reverses during Phase 2, and the cost differential reduces with thickness to the extent that the costs are equal at about 5 in. (13 cm). At thicknesses greater than about 5 in. (13 cm), Case II costs are less despite the high losses associated with Phase 1. Accordingly, it must be recognized that in making improvements to reduce the RRR associated with Phase 1, the improvement must not result in any substantial increase to RRR during Phase 2.

The time curves in Fig. 4.23 are given to indicate relative magnitudes of time of shooting for an assessment of manpower utilization. The general conclusions about time of shooting are the same as those for cost.

It can be seen, however, that it does not take as long to shoot from 2 in. (5 cm) to 4 in. (10 cm) as it does to shoot the first 2 in. (5 cm). In fact, in Case I, the time required to shoot the second inch (2.5 cm) takes only 64 percent of the time required to shoot the first inch (2.5 cm). However, with increasing thickness, the shooting time required to double a thickness tends to become nearly equal. Nevertheless, when shooting a thin shotcrete layer for support at the heading, it should be recognized that it does not take twice as long to place a lining twice as thick. Because of the geotechnical importance of providing substantial support as early as possible, consideration should be given to increasing the thickness of these initial layers. The cost penalty of added rebound associated with multiple-lifts has already been described; shooting added thickness at the heading might result in fewer lifts and a cheaper job.

In terms of manpower and equipment required to remove the rebound material, the relative positions of the curves in Fig. 4.24 are the same as those first discussed for cost and for time. However, at 6 in. (15 cm) the amount of rebound to be removed from the tunnel in the improved Case II is 62 percent less than the amount needed to be removed in Case I.

Another way to look at the economic implication of the high rebound losses associated with Phase 1 is that, if compared on a unit volume in-place, a thinner layer has a higher unit cost, as illustrated by a curve of unit cost (dollars per unit volume) in-place. These unit costs for the example cases are presented in Fig. 4.25. Accordingly, a job shot with the dry-mix process with a thin lining should not be estimated with the same cost per unit volume used for a thicker lining since the costs will be underestimated. Note that

Case III, without the extra loss during Phase 1, is exempt from this restriction. To some degree, wet-mix shotcrete should be less affected since the extra losses during Phase 1 are expected to be small with the wet-mix process. Rebound Rate Ratio, RRR, curves for wet-mix shotcrete should be determined experimentally to verify this assumption.

4.8 THEORETICAL EVALUATION OF THE RELATIONSHIP BETWEEN RRR, RAVE, TIME AND THICKNESS

The RRR and RAVE curves were introduced and plotted with respect to time in Section 4.2.2. The area under the RRR plot is directly related to RAVE only when both RRR and RAVE curves are plotted with respect to time. When they are plotted with respect to thickness, the area under the RRR curve is directly related to RAVE only if RRR varies incrementally, like a bar graph, and if RRR within the increment is constant. Any inclined or curved RRR-versus-thickness plot is not directly related to RAVE, as discussed in Appendix F. It was noted that these curves, when plotted to thickness, are related to the same curves plotted with respect to time by a non-linear function. However, the experimental RRR and RAVE curves were plotted with respect to thickness because the thickness-plots best represent the physical mechanisms involved in the rebound process. The experimental RAVE data were not obtained by determining the area under the RRR curve, but were determined directly from RSUM and SSUM.

It must be understood that the area under RRR curves plotted with respect to thickness is not always the ordinate of the RAVE curve plotted with respect to thickness unless the time of shooting is accounted for properly. It was not necessary to complicate the introductory concepts with a detailed discussion of the time-thickness function since RAVE was defined only by RSUM and SSUM. However, the relationship between time and thickness is important, and an equation relating these parameters with RRR and RAVE is derived in Appendix F on the basis of an idealization of the basic physical aspects of the problem. The time-thickness relationship is logarithmic for the simplified assumptions used in the derivation. The equations were used to calculate the RAVE curves for the example cases given in the last section based on the assumed RRR curves.

Figure 4.26 is a plot containing an idealized RRR-versus-thickness curve. It was assumed that 5 percent of the first material arriving at the

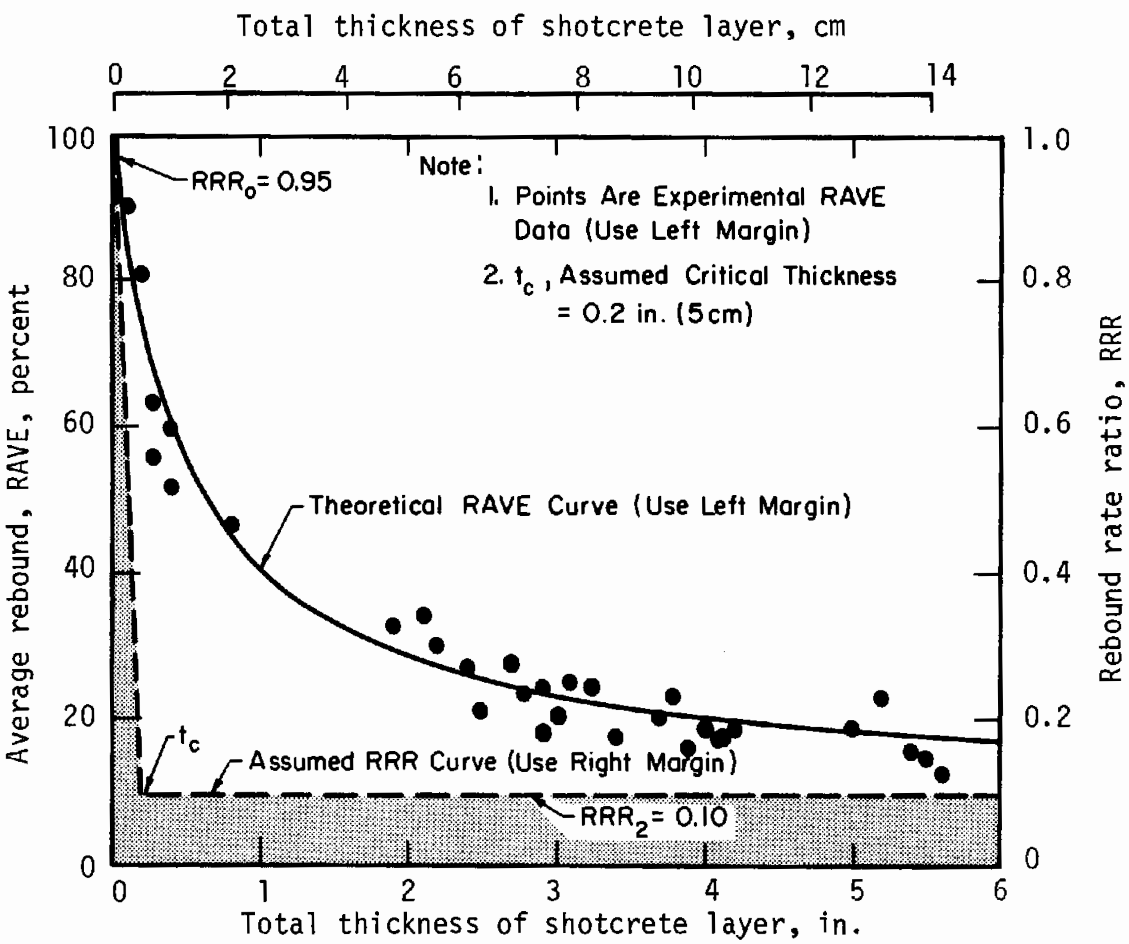


FIG. 4.26 COMPARISON OF THEORETICAL RAVE VERSUS THICKNESS CURVE WITH EXPERIMENTAL RESULTS

wall remains on the wall and that the constant magnitude of RRR during Phase 2 was 0.10. The critical thickness, t_c, was 0.20 in. (5 mm). These assumed data were used with the theoretical equation, derived in Appendix F, to calculate the RAVE curve (solid line).

The data points in Fig. 4.26 represent all the experimental RAVE data collected during this study. It can be seen that the theoretical curve fits the data reasonably well, considering the range of mix and shooting conditions included. The straight-line assumptions for RRR could be refined with more accurate experimental data to determine a more realistic non-linear RRR-versus-thickness curve. This new RRR curve could be used to derive a more accurate, but more complex, theoretical RAVE equation. For practical purposes, the present equation appears satisfactory for preliminary parameter studies to evaluate the effect of various conditions such as the magnitude of RRR for Phase 2 and the magnitude of the critical thickness, t_c. These parameter studies should be conducted, but should be verified with additional and more precise experimental studies of RRR. One useful study is the assessment of the effect of varying magnitudes of t_c, which is partly a function of the maximum size of aggregate. Such a parameter survey on t_c could be coupled with experimental results to evaluate the differences in rebound between mixes having different maximum-size aggregate.

4.9 MIX AND SHOOTING CONDITIONS THAT CAN REDUCE REBOUND

The high-speed photographic study (Chapter 5) and the observations and analyses for this chapter have resulted in an evaluation of the mechanisms leading to rebound and of an assessment of some of the factors affecting rebound.

The process of rebound during the establishment of the initial critical thickness (Phase 1) is believed to be different from the process of rebound during subsequent shooting into fresh shotcrete (Phase 2). Some of these factors are evaluated in Table 4.19. The table and this discussion primarily relate to factors within the present technology (1975). It is believed that new nozzle designs, gunning equipment, and special nozzling techniques can be developed easily to reduce rebound during both Phase 1 and Phase 2, but their development was not part of the scope of this study.

During Phase 1, anything that promotes adherence of material on the wall should reduce rebound. This includes the following mix conditions: a higher cement content, more fines in the mix (fly ash or very fine sand), smaller maximum size aggregate, proper wetness of aggregates so that particles are well-coated with cement, and a finer gradation.

Shooting conditions that are believed to be conducive to reduced rebound during Phase 1 include lower air pressure (i.e., lower particle velocity), lower MDR, better mixing of water at the nozzle (or other improved nozzle effects), higher accelerator dosage, higher nozzle-water temperatures, and the lowest water content above a threshold value at which the matrix is cohesive or paste-like. It is believed that shooting too wet will decrease the ability of the cement matrix to stick to the wall.

After the initial critical thickness is established, Phase 2 rebound is reduced by any condition or set of conditions that make the shotcrete on the wall softer or more plastic, at least until it tends to drop off. Thus, for maximum reduction of Phase 2 rebound, shooting as wet as possible (i.e., the wettest stable consistency) is one of the most beneficial and easiest conditions

TABLE 4.19

MIX AND SHOOTING CONDITIONS THAT REDUCE REBOUND

I. During establishment of initial critical thickness (Phase 1).

Any factor that makes the material in the airstream more coherent or cohesive.

Mix Conditions

A. More fines (cement, very fine sand, or fly ash).
B. Finer gradation; smaller maximum size; lower percentage coarse particles.
C. Proper moisture content of aggregate so that aggregate will be coated with cement.

Shooting Conditions

A. Shooting at optimum water rate; both too wet and too dry reduce tendency to stick.
B. Better mixing of water at nozzle.
C. Higher accelerator dosage.
D. Lower MDR and air pressure.
E. Warmer material and environmental temperatures.

II. During shooting into fresh shotcrete (Phase 2).

Any condition or set of conditions that make the material in the airstream more coherent and cohesive and the in-place shotcrete more plastic,up to the wettest stable consistency,will reduce rebound during Phase 2.

Mix Conditions

A. More fines (cement, very fine sand,or fly ash).
B. Finer gradation; smaller maximum size; lower percentage of coarse particles.
C. Proper moisture content of aggregate so that aggregate will be coated with cement.

Shooting Conditions

A. Shooting wetter up to the wettest stable consistency.
B. Increase in the following up to some optimum combination dependent on the interaction of the parameters:
   1. higher cement content
   2. higher accelerator dosage
   3. warmer materials and environmental temperatures.
C. Reduction in MDR and air pressure (not as important for Phase 2 as for Phase 1).
D. Better mixing of water at nozzle.
E. Reduced segregation of material in the material hose.

to control. Up to some optimum point, more cement, more accelerator, and warmer materials and environmental temperatures should make the material on the wall more plastic and more receptive to entrapment of particles. However, above some optimum combination, the stiffening of the in-place shotcrete takes place too fast and conditions become less favorable for reduction of rebound. Reductions in air pressure and MDR will also reduce rebound during Phase 2, but they are not as important as they are for Phase 1.

During both phases, proper nozzling techniques such as the optimum distance from the wall, perpendicularity to the plane of the surface of impact, and constant attention and adjustments by the nozzleman are of utmost importance.

Anything that will make the material being shot more coherent or cohesive will reduce rebound during both phases. More uniform gun operation or improved shotcrete equipment should reduce segregation of materials in the hose and, therefore, should reduce rebound. This is the value of the wet-mix process since material arrives at the wall as coherent mass. The dry-mix shotcrete particles, on the other hand, land independently, and each particle has a chance of either rebounding or adhering to the wall.

CHAPTER 5

EVALUATION OF AIRSTREAM AND OF REBOUND BY HIGH-SPEED PHOTOGRAPHY

5.1 INTRODUCTION

5.1.1 GENERAL

Many general observations have been made in the literature about the shotcrete airstream between the nozzle and the wall and about the characteristics of rebounding particles. The detailed behavior of the airstream is not easily seen by the naked eye, so high-speed photography was utilized on several mixes throughout the field program to study the behavior of the airstream and of the rebound. The objectives of this study were to learn as much as possible about the basic mechanisms leading to rebound, especially the rebound of the fibers, to determine the basic mechanisms of the buildup of shotcrete on the wall, and to gain information on the compaction of the shotcrete layer itself.

This chapter presents the results of this photographic evaluation of the shotcrete process. The geometric shape of the airstream and the velocity of the particles were determined. Observations have also been made on the segregation of particles in the airstream, details of the build-up of shotcrete on the wall, the disturbance to the topmost layer of shotcrete by the incoming material, the process of compaction, and the details of rebound of aggregate and fibers. It must be emphasized that this evaluation is confined to one particular set of conditions and that many more detailed studies will be necessary to truly understand the mechanisms involved and to evaluate the variations involved when equipment, mix designs, and shooting conditions change.

5.1.2 EQUIPMENT

CAMERA

The camera was a Fastax Model WF17 which accepts 100-ft (30.5 m) rolls of 16 mm film. The camera was mounted securely on a small steel stand to minimize vibrations and was protected from rebounding aggregate by a simple wooden box with the lens recessed behind a plain glass-covered hole in the box.

The camera was operated through an electronic control box called a "goose". Advance of the film begins when the shutter is tripped and the speed of the film increases very rapidly so that the entire 100 ft (30.5 m) of film is exposed in about one second. A rotating rectangular mirror-prism is geared to the film advance mechanism and, at maximum voltage to the "goose", the picture rate is as high as 7500 frames per second.

Since the film speed is variable, the speed of the film at any given instant is important. Two independent methods of calibration were used to measure the film speed. The camera has a built-in flashing lamp which exposes a light on the sprocket zone of the film 120 times per second. However, better results were obtained by placing a neon strobe spectrometer, which flashed at 120 Hertz, on the far side of the airstream in full view of the camera.

LIGHT

Tunnel lighting in the shooting area was supplemented by two 1000-watt mercury-vapor flood lamps mounted on a tripod. For the first two days of shooting, the area to be filmed was also lighted by an additional four 1000-watt quartziodide photographic lights but the total available light was still insufficient for proper exposure at 7500 frames per second.

On Days III and IV, a flash bulb, about as big as a 150 watt light bulb, and specially manufactured for high-speed-photography, was used in addition to the above lighting sources. This flashbulb was a Sylvania FF-33, rated at 140,000 Lumen-Seconds. The flashbulb burns for about 1-1/2 to 2 seconds. This lighting was satisfactory although the film still had to be pushed during processing. It appears that perhaps two of these high-speed-photography flash bulbs would have been sufficient.

FILM

All film was 16 mm film in 100-ft (30.5 m) rolls specially manufactured for high-speed-photography with larger sprocket holes to permit the fast film speeds without tearing; the pitch of the holes, however, is the same as 16 mm movie film.

Most of the films were "4X" black and white film (ASA 400); during processing the film was "pushed" to an equivalent ASA of about 1000. Two steel fiber mixes (33A and 45) were filmed with Ectachrome EK Tungsten color film (ASA/25) that was "pushed" during processing to an equivalent ASA of about 1000.

The image size on the film is about 8 by 12 mm with the long axis across the width of the 16 mm film; there are about 3 images per inch (13 images per decimeter).

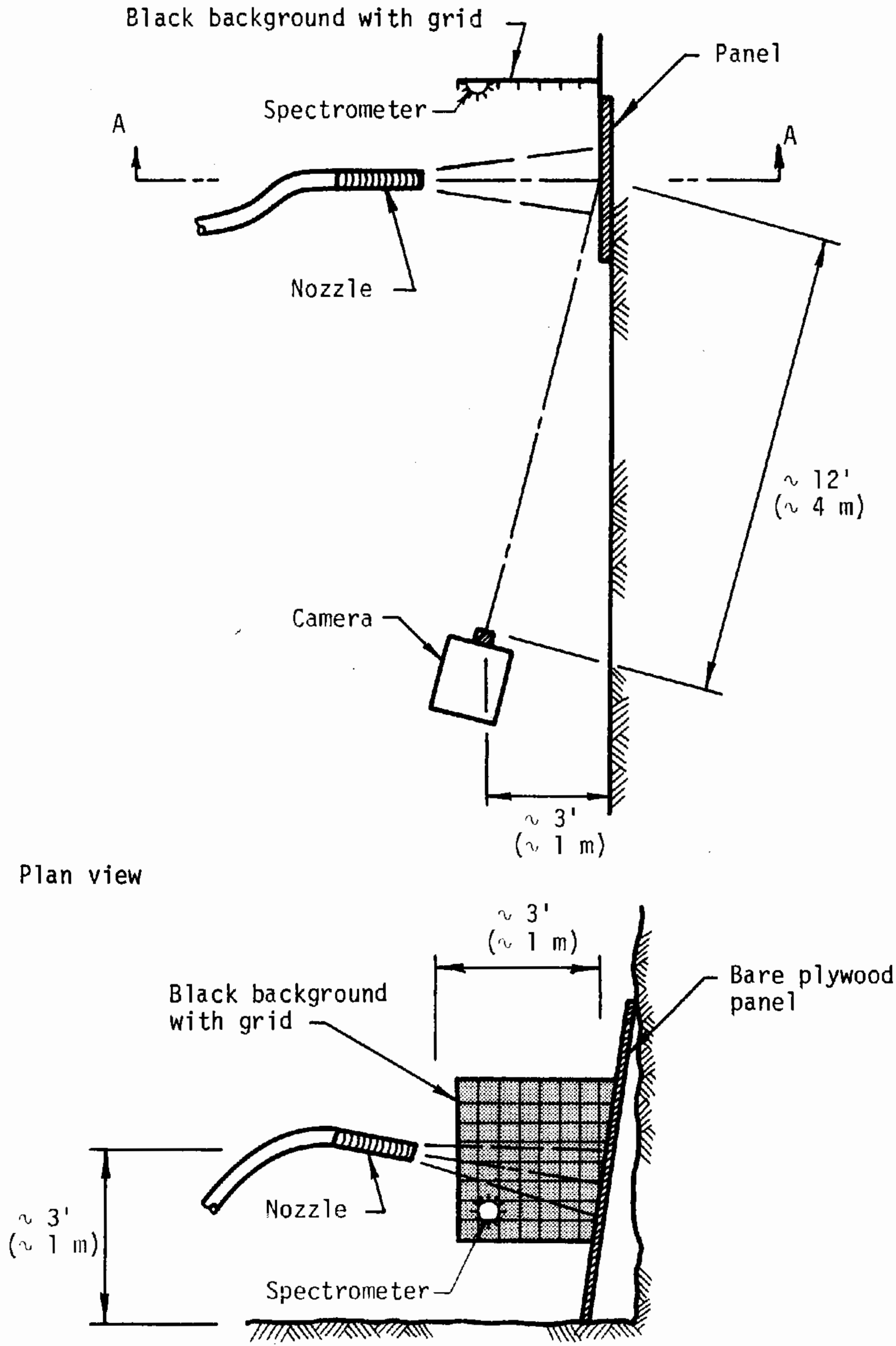
5.1.3 FIELD OPERATIONS

Planar and cross sectional views of the equipment layout are shown in Fig. 5.1. The camera was located approximately 12 ft (3.66 m) away from the shotcrete stream pointing nearly perpendicular to the direction of shooting. A slight angle was provided so that the build-up of the shotcrete layer on the wood panel could be photographed. For most of the photographs, a 4 ft x 4 ft (1.2 x 1.2 m) black backdrop (see Fig. 5.1b), with a 6 in. x 6 in. (15 x 15 cm) grid was located 3 ft (1 m) behind the airstream to provide background. A white backdrop was tried but the particles could not be seen as well as against a black background.

The photographic phase of the project was conducted in an area adjacent to the rebound testing area. As soon as rebound shooting was completed, the nozzleman directed the airstream toward a point on a nearby plywood panel. The camera had been focused on this point and filming began immediately. Each filming process lasted approximately 1 second.

5.1.4 METHOD OF EVALUATION

The processed film can be shown in an ordinary movie projector as a slow-motion movie. With a special movie projector, the film can be run at high or low speed in both forward and reverse and can be stopped. General observations and impressions were obtained by viewing each film numerous times. The film was also projected onto a large white sheet



a) Plan view

b) Profile, section A-A

FIG. 5.1 PHYSICAL LAYOUT FOR PHOTOGRAPHIC STUDY of paper and the details of the airstream traced directly. The axis of the airstream, the extreme limits of the cone, and buildup of the shotcrete layer on the wall were traced at various stages of shooting. In addition, locations of special features such as a heavy concentration of aggregate or a particular zone of low density were also traced. Photographic prints of selected frames of a few mixes were also obtained.

One serious drawback of single pictures of an airstream is the inability to determine if a particular particle was going toward or away from the wall. In moving pictures, a clear distinction can be made between incoming and rebounding particles.

A hand-operated editor-type projector was used to study the changes in the characteristics of the airstream from frame to frame and to obtain such parameters as velocity of the particles. A prominent particle was followed from the nozzle to the wall by looking at each successive frame. The number of frames required for the particle to traverse a given distance on the background grid was used as a measure of speed of the particle relative to the speed of the film at that particular instant.

The speed of the film varied from several hundred frames per second at the beginning, to 7500 frames per second at the end of the film. The exact speed of the film at any instant was calculated using the internal flashing light and external neon spectrometer. For instance, if there were 50 frames between successive flashes of the spectrometer at 120 Hz, the speed of the film was 6000 frames per second. The speed of particles was calculated as the distance traveled, as measured on the grid, divided by the real time it took to traverse the distance.

5.2 CHARACTERISTICS OF THE AIRSTREAM

5.2.1 DESCRIPTION OF AIRSTREAM

GENERAL DESCRIPTION

The airstream is roughly conical in shape. It generally consists of a central zone of high density surrounded by a less dense peripheral zone. The density of the particles within these zones and the contrast in density between the zones constantly changes.

The type of nozzle made a significant difference in the nature of the airstream. The long nozzle tended to produce a narrow cone with a sharply defined central zone of high density. The short nozzle tended to produce a relatively wide cone with a poorly defined central zone.

GEOMETRY

Particles exit the nozzle going various directions within the limits of the cone. In cross section, or in a two-dimensional photograph, the outline of the airstream is trapezoidal with its smallest base equal to the nozzle diameter.

Sketches of typical airstream cross sections are presented in Fig. 5.2. The stream axis is the axis of the dense central zone. The direction of those particles which have the maximum deviation from the stream axis determines the limits of the cone. The angles of deviation from the stream axis to the upper and lower boundary of the perimeter of the airstream define the size of the cone which appears to be an index of the efficiency of the nozzle and of the shooting operation. The angles measured for the mixes photographed are summarized in Table 5.1.

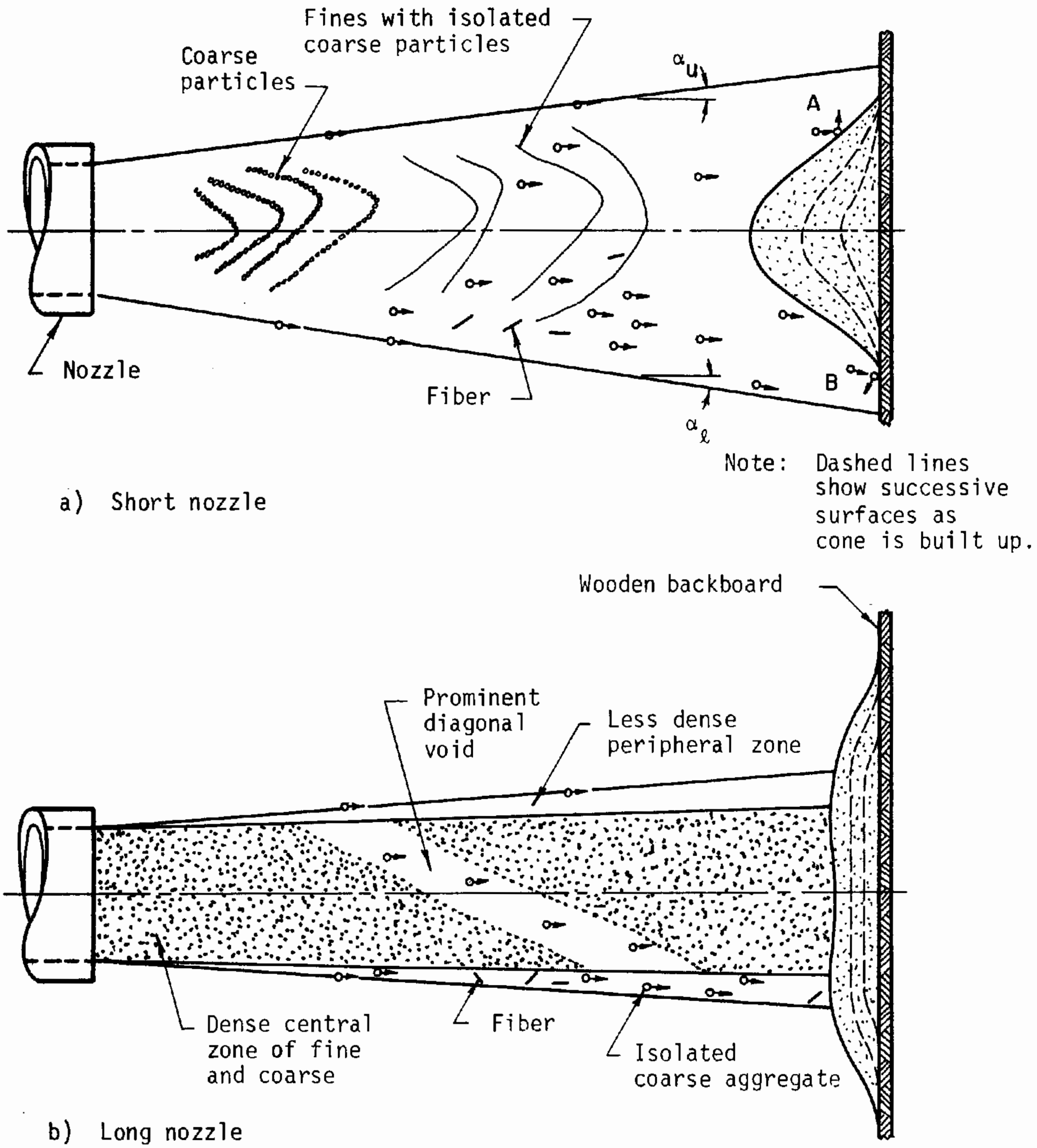


FIG. 5.2 CROSS SECTIONS OF TYPICAL AIRSTREAM AND SHOTCRETE ON WALL

TABLE 5.1

AIRSTREAM SCATTER ANGLES

Mix Description	Upper angle α_u, degrees	Lower angle α_ℓ, degrees	Central angle $\alpha_c = \alpha_u + \alpha_\ell$, degrees
Short nozzle			
22-7½I-60S	4.1	3.8	7.9
24-7½I-60S	7.1	8.3	15.4
33-7½I-60S IUS	7.9	9.0	16.9
34-7½I-60S-IUS-25CA	0	0	0
Long nozzle			
26-7½I-60L	6	6	12
26-7½I-100L	5.5	6	11.5
33A-7½I-100L-1US	7.3	10.2	17.5
38-8½I-100L-1US	6	6	12
40-7½I-100L-½US	1	1	2
42-10½R-100L-1US	0	0	0
45-7½I-100L-1NS	7.8	9.1	16.9
Mixes without cement			
43-0-0L (Dry aggregate only)	9.6	17.6	27.2
43-0-100L (Aggregate with nozzle water)	4.9	8.3	13.2

The data in Table 5.1 only describe the greatest scatter. They are not a measure of the number of particles or the distribution of particles straying from the stream axis. All visual observations indicated that the long nozzle produced a relatively concentrated airstream in a manner similar to a long-barrelled-shotgun or a shotgun with a choke. The maximum scatter angle, however, is not controlled solely by the type of nozzle.

The fact that many mixes exhibited a lower angle, α_{ℓ}, greater than the upper angle, α_u, is attributed to gravity (Fig. 5.2). Mix 43, consisting of aggregate without cement, was shot specifically to evaluate some of the factors affecting the scatter of the airstream. When aggregate was shot without adding water at the nozzle, the central angle, α_c, was 27°; adding water at the nozzle dropped α_c to 13°. The interaction of the water with the aggregate in the airstream appears to reduce the scatter of the particles as they leave the nozzle. The presence of cement and of accelerator may reduce the central angle further. Generally, those mixes which had very high cement contents or high accelerator dosages (Mixes 34 and 42) appeared to have concentrated airstreams; the peripheral zone of lower density was absent. It appears that anything that reduces segregation in the airstream tends to reduce the size of the cone. Fiber mixes tended to have greater scatter in the airstream.

BEHAVIOR OF AGGREGATE AND FIBERS IN AIRSTREAM

Many particles were observed to spin several times as they traveled to the wall. This spinning was particularly evident in the short-nozzle-airstream in which individual particles were plainly visible. The dense central zone in the long-nozzle-airstream did not appear to permit much spinning or it masked the spinning although spinning was still evident in the peripheral zone. Spinning of coarse aggregate was more evident with flat or elongated particles. Not only did their rotational motion show up better in the film but they appeared to be rotating faster than subrounded particles.

Fibers were not easily detected; most were in the peripheral zone of the airstream. This zone was responsible for the highest rebound so this may account for the low fiber retention. There appeared to be no interference between fibers and coarse aggregate, so the larger aggregate is not believed to be responsible for low fiber retention. Many of the fibers were oriented at some angle to the stream axis during their entire traverse to the wall. Those which did tumble or rotate, tended to tumble end over end once or twice before hitting the wall. The resolution of the film was not good enough to determine if the fibers were spinning around their longitudinal axis. It was also noticed that fibers have the capacity to follow the remnant air currents from the airstream after rebounding.

5.2.2 SPEED OF PARTICLES IN AIRSTREAM

COARSE PARTICLES

The measured average speed of the coarse aggregate in the airstream of 14 different mixes is summarized in Table 5.2. It ranged from 63 to 126 ft/sec (19 to 38 m/sec) and averaged about 75 ft/sec (23 m/sec) for all mixes. When present, steel fibers were determined to be traveling at about the same velocity as the coarse aggregate. The speed of coarse particles did not change substantially on their way to the wall. Most coarse particles travel at about the same speed as shown in Fig. 5.3, which shows a typical

TABLE 5.2

SPEED OF COARSE PARTICLES IN AIRSTREAM

Mix Designation	Measured Speed ft/sec (m/sec) Range	Average	Remarks
22-7-1/2I-60S	59-99 (18.0-30.2)	81 (24.7)	
24-7-1/2I-60D	53-103 (16.2-31.4)	70 (21.4)	
25-7-1/2I-60A	50.5-88 (15.4-26.8)	74 (22.6)	
26-7-1/2I-100L	55.5-82 (16.9-25.0)	68 (20.7)	
33-7-1/2I-60S-1US	113-152 (34.4-46.2)	126 (38.4)	Low MDR
33A-7-1/2-100L-1US	58-91 (17.7-27.7)	77 (23.5)	
34-7-1/2I-60S-1US-25CA	--	--	
38-8-1/2I-100L-1US	66-131 (20.1-39.9)	87 (26.5)	
40-7I-100L-1/2US	58-75 (17.7-22.9)	64 (19.5)	1/2 the fibers
42-10-1/2R-100L-1US	46-75 (14.0-22.9)	63 (19.2)	
43-0-0L (DRY)	56-90 (17.1-27.4)	73 (22.2)	Aggregate only , no nozzle water
43-0-100L (WET)	65-97 (19.8-29.6)	76 (23.2)	Aggregate only with nozzle water.
45-7-1/2I-100L-1NS	58-92 (17.7-28.0)	68 (20.7)	

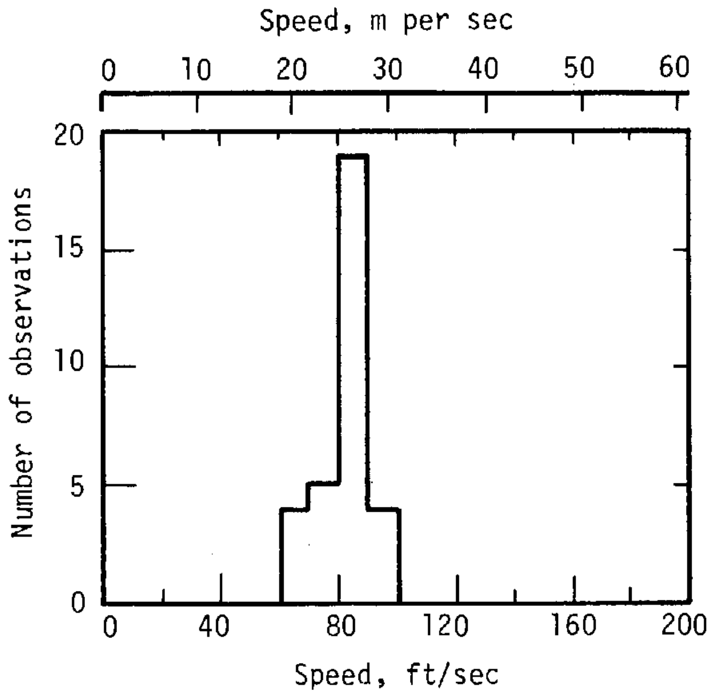


FIG. 5.3 HISTOGRAM OF SPEED OF COARSE PARTICLES, MIX 22

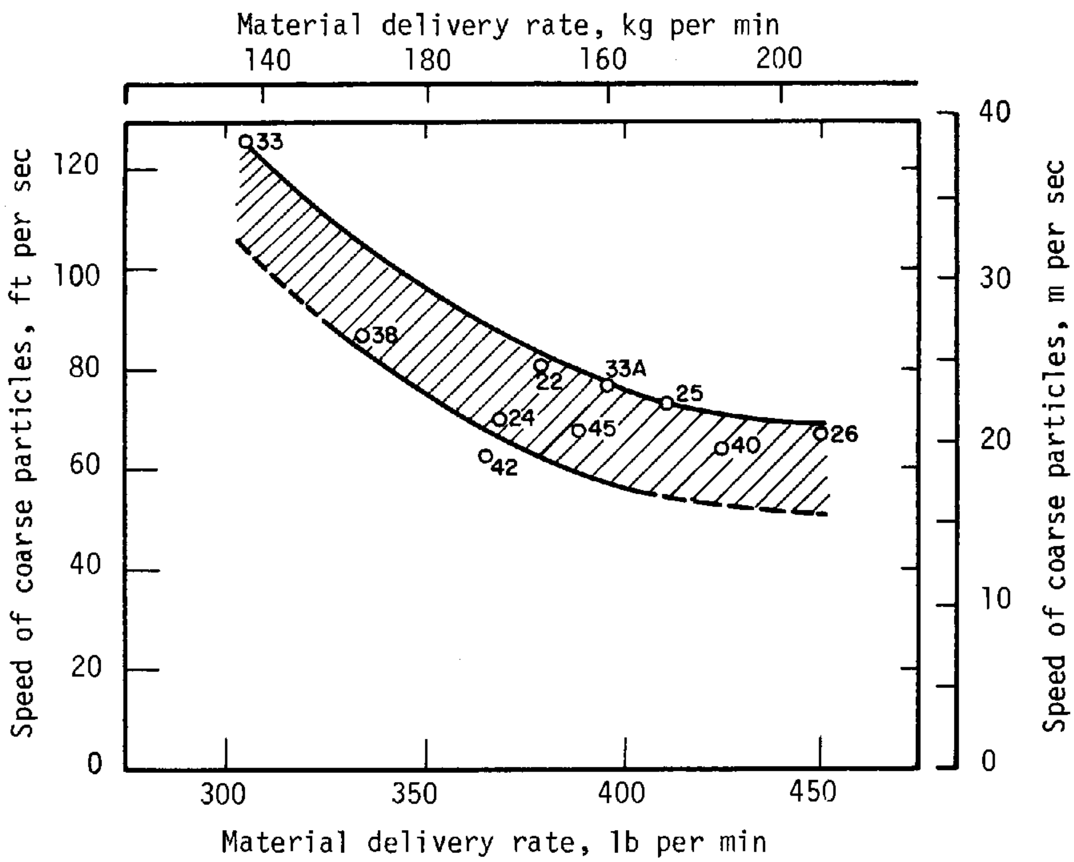


FIG. 5.4 RELATIONSHIP BETWEEN MATERIAL DELIVERY RATE
AND SPEED OF COARSE PARTICLES

histogram of the measured speed of 32 particles in Mix 22. The range was 60 to 100 ft per second (18 to 30 m/sec) with 60 percent of the particles between 80 to 90 ft/sec (24 to 27 m/sec).

The speed profile of the coarse particles was evaluated but showed no consistent trend. In general, the slower particles are in the peripheral zone.

The particles in Mix 33 were substantially faster than other mixes. This mix had a Material Delivery Rate of 297 pounds per minute (136 kg per min); the lowest of all the mixes. Particles were probably able to accelerate faster and reach a higher velocity with the lower interference. Figure 5.4 illustrates a tendency for higher speeds to be associated with low Material Delivery Rates.

The speeds are substantially lower than those given in the literature (Studebaker, 1939; Ryan, 1973; Valencia, 1974) and have been substantially higher than those found in this study. It is understood that most of the published data are based upon pressure measurements. The measurements given here are actual particle velocities. Calculations have shown that coarse particles in a hose under such conditions of temperature and pressure should have accelerated to a velocity similar to those measured.

FINE PARTICLES

Fines were difficult to separate from other particles in the concentrated air stream of the long nozzle; both coarse and fine particles moved toward the wall as a unit.

The segregation in the short-nozzle-airstream permitted an independent evaluation of the speed of the fines which appeared to come out of the nozzle in cyclic wave fronts, as sketched in Fig. 5.2a. The speed profile was similar to the wave front sketched and the measured speed of the center of the wave front of fines at the stream axis was about 1.4 to 1.8 times the speed of the coarse particles.

Thus the fine aggregate when traveling separately was traveling probably at speeds of about 90 to 160 ft/sec (27 to 49 m/sec) for most mixes.

5.2.3 VARIATIONS IN THE AIRSTREAM

GENERAL

The amount of material delivered by the shotcrete gun is not uniform with respect to time. The shotcrete gun used on this project discharged dry mix from the cylinders in the rotating barrel at a rate of about 2 cylinders per second; i.e., material was placed into the hose in 1/2-second-intervals. The character of particles in the airstream varies with each instant from sparse to dense and from segregated to well-mixed. Segregation and remixing occurs along the hose.

SEGREGATION OF WATER AND AGGREGATE

During field operations and other close visual observations of a shotcrete airstream, it was often noticed that some of the water added at the nozzle tended to travel on the outer periphery of the cone without ever mixing with the aggregate. This was especially true for short nozzles. At other times a stream of unmixed water could be seen in the lower portion of the airstream. It occasionally flipped back and forth between the lower and upper portions.

This segregation of unmixed water was seldom observed with the long nozzle which is indicative of the better mixing capabilities of this long nozzle. It appears that if water is not atomized or otherwise mixed in the nozzles, it does not get mixed on the way to the wall in the airstream. In this case, mixing of the water must take place by remolding or blending of the material in the wall; an inefficient operation. In addition, rebound of water itself could be significant.

Still photographs of shotcrete operations often show a whitish airstream. These are indicative of poor mixing in the nozzle. However, in the high-speed photographic studies, free water was never clearly identified; perhaps because the water did not photograph well or perhaps because the phenomenon did not occur during the one-second duration of photography.

SEGREGATION OF PARTICLES IN THE AIRSTREAM

SHORT NOZZLE: The short nozzle produced an airstream that consisted of coarse aggregate more or less uniformly distributed over the entire cross section of the cone. Typical short nozzle airstreams are shown in Fig. 5.2a. Generally there was little or no distinction between the central zone and the peripheral zone. Individual particles of coarse aggregate were easily seen in the photographs as they appeared to be traveling independently of fines at an ever decreasing density, as the cone width increased toward the wall. Clusters or groups of particles were not present although there was a tendency for more coarse aggregate particles to be in the lower portion. The fines seemed to travel in successive waves or pulses, also with a uniform density from top to bottom of the airstream.

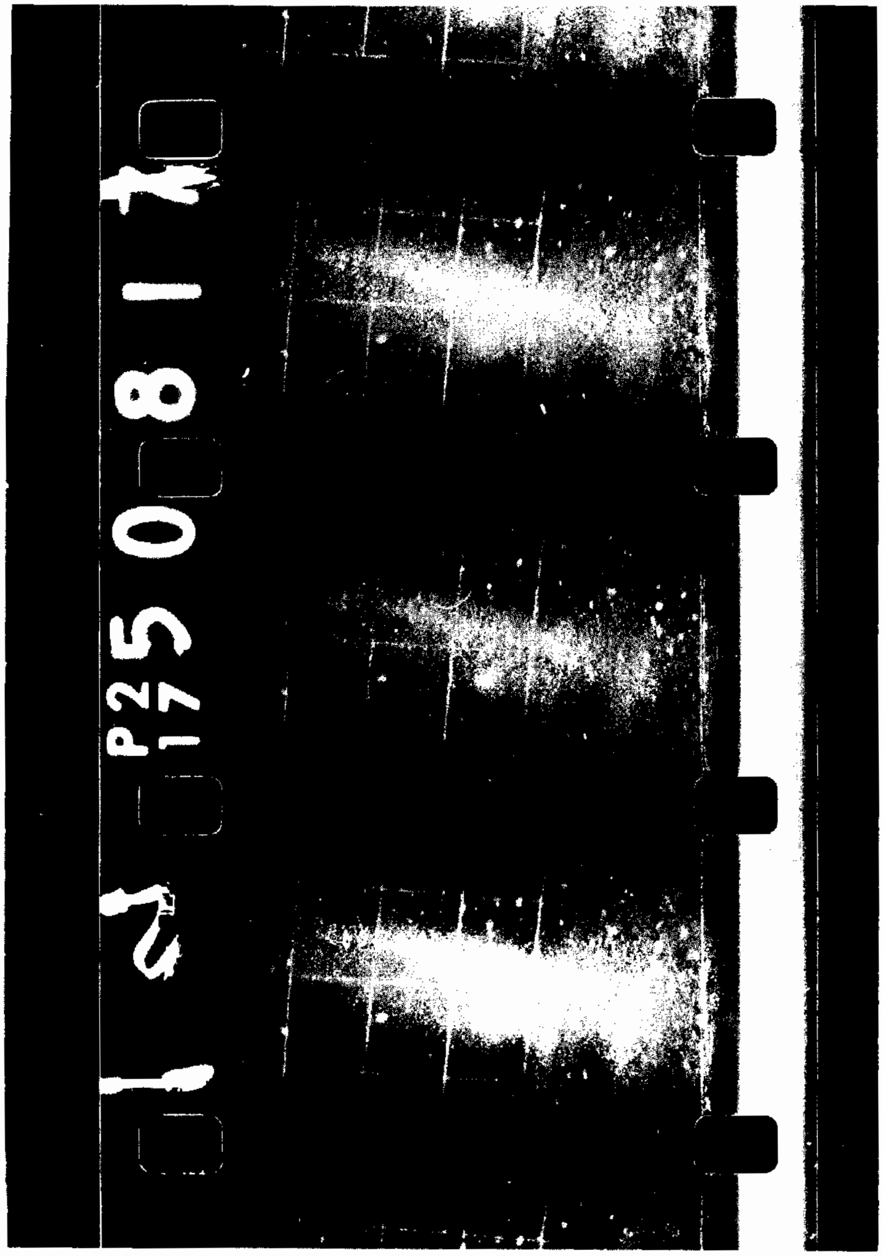
LONG NOZZLE: The long nozzle produced an airstream having a concentrated central zone distinctly separate from the peripheral zone as illustrated in Fig. 5.2b. The central zone consisted of groups or clusters of coarse and fine aggregate with only a few individual particles of coarse aggregate detectable; most of those were in the lower portion of the peripheral zone. Thus, the spread angle of the concentrated zone was very small and the longitudinal cross section of the central zone was nearly rectangular rather than trapezoidal.

The concentrated airstream is more desirable since the constituents of the airstream; cement, water, coarse and fine aggregates and, in some cases, fiber are in close proximity as they travel to the wall so they can blend together on the wall. Further, it appears that they are in close proximity because the ingredients are mixed better in the nozzle. The coarse particles in the scattered airstream of the short nozzle are so far apart that they tend to land independent of the matrix of cement and fines, so they tend to rebound rather than blend together.

SEGREGATION WITH TIME

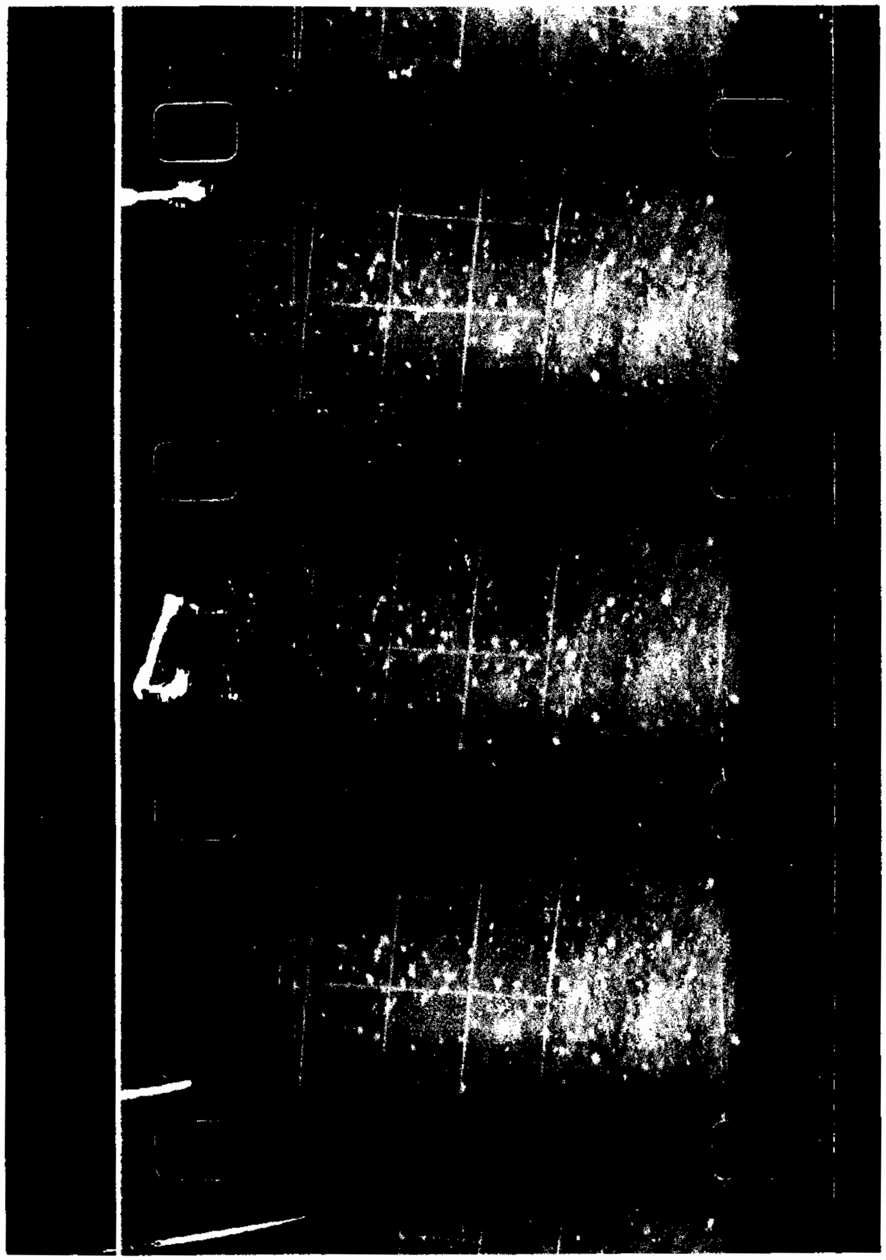
SHORT NOZZLE: Figure 5.5 illustrates the three basic types of segregation seen in the short nozzle. Figure 5.5a is predominantly fine, Fig. 5.5b is predominantly coarse and Fig. 5.5c is predominantly well-mixed. This cycle occurred twice during a one-second film, so the source of segregation is clearly associated with the rotation of the barrel which clears 2 cylinders per second.

This phenomena may be the result of fines being accelerated



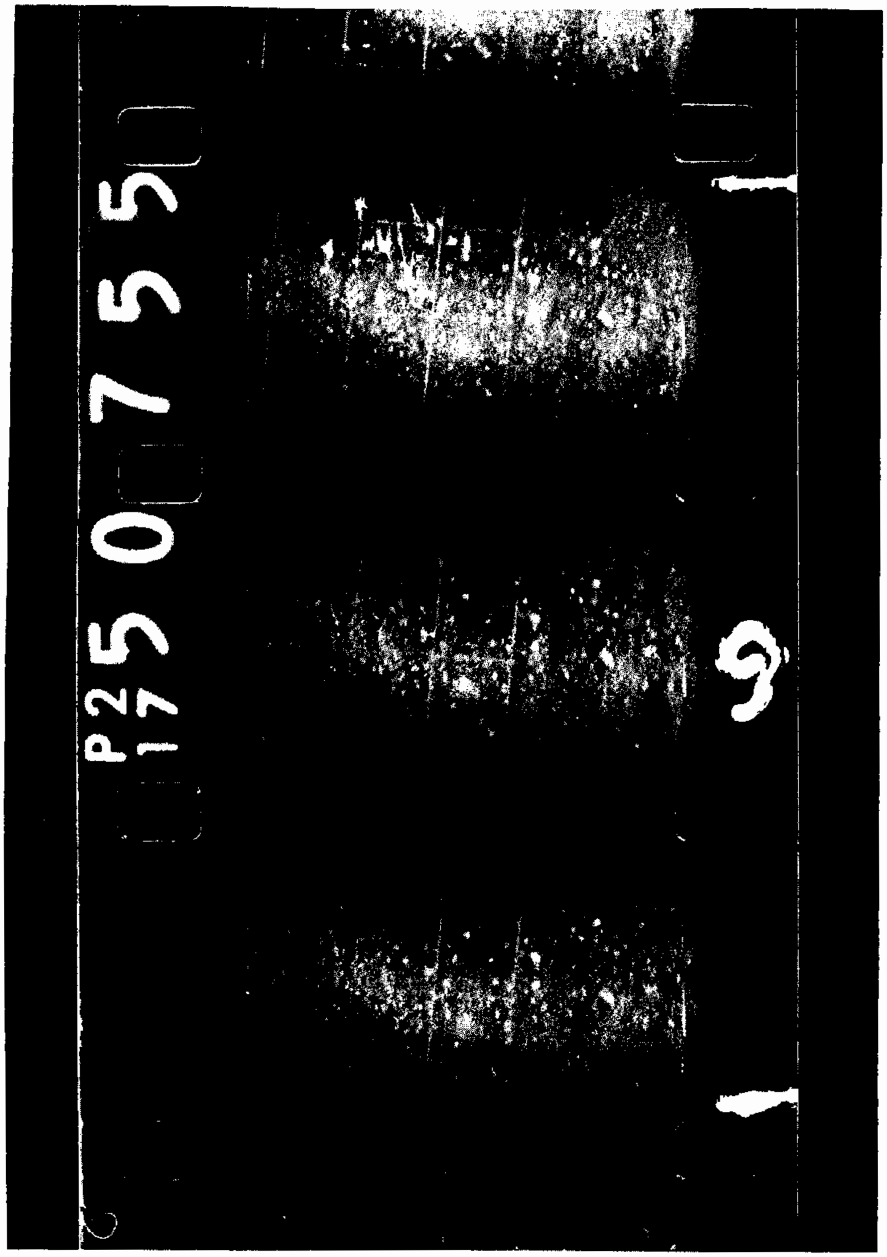
a) Predominantly fine airstream

FIG. 5.5 PHOTOGRAPHS OF TYPICAL SHORT NOZZLE AIRSTREAM



b) Predominantly coarse airstream

FIG. 5.5 (continued)



c) Predominantly well-mixed airstream

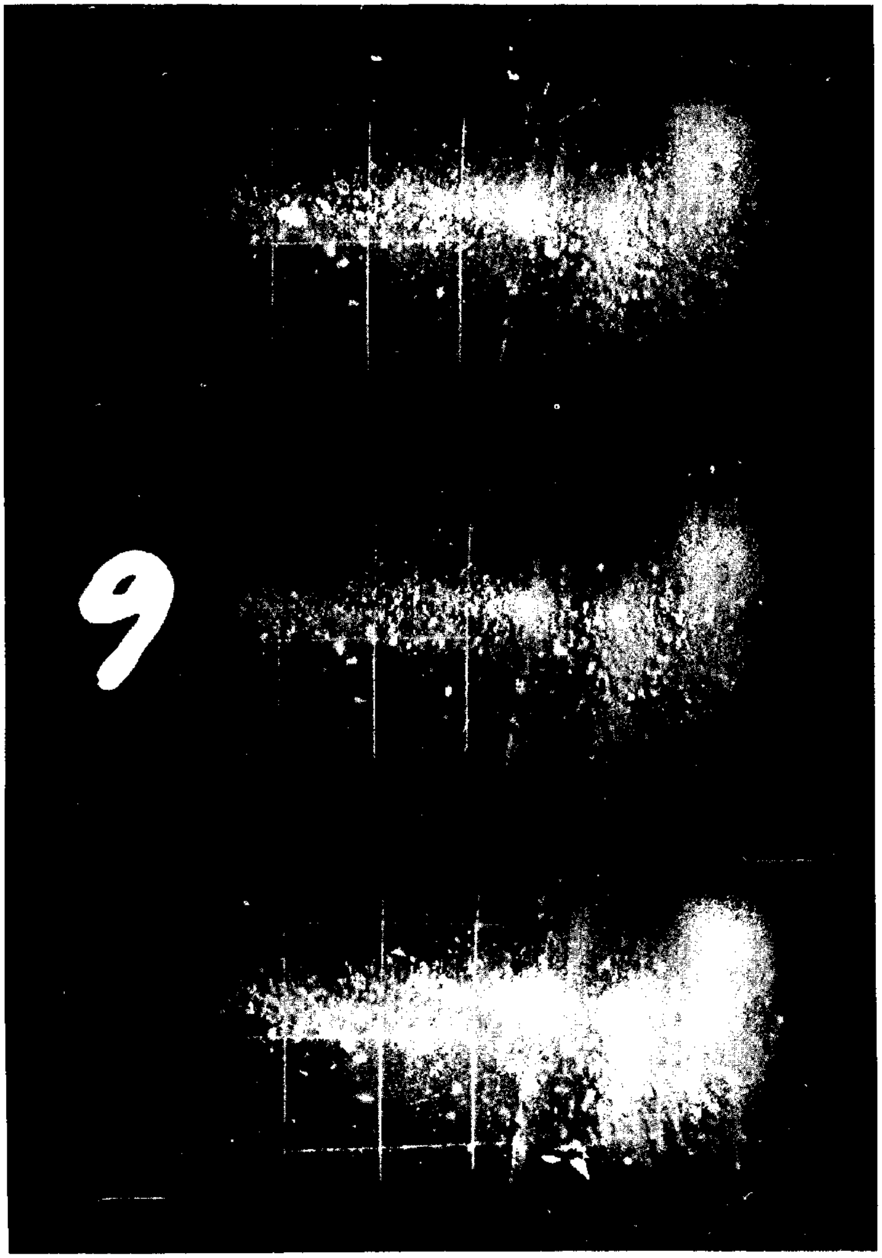
FIG. 5.5 (continued)

faster than the coarse particles. For any given discharge of one of the 9 cylinders in the rotating barrel, the fines would be seen in the airstream first, the more slowly accelerated coarse particles next, followed by the last of the coarse aggregate particles for the first cylinder discharge which have been overtaken by the faster-accelerated fines of the next successive cylinder discharge. It was noted that the duration of this well-mixed airstream was much shorter than the two other phases.

All of this phenomena is a function of the speed of rotation of the barrel, the length of hose, and the speed of the particles and air in the hose. Naturally, these effects would not be as cyclic in a double-pressure-pot type gun, but would be most evident in guns with the slowly rotating cylinder barrels such as those used for this program.

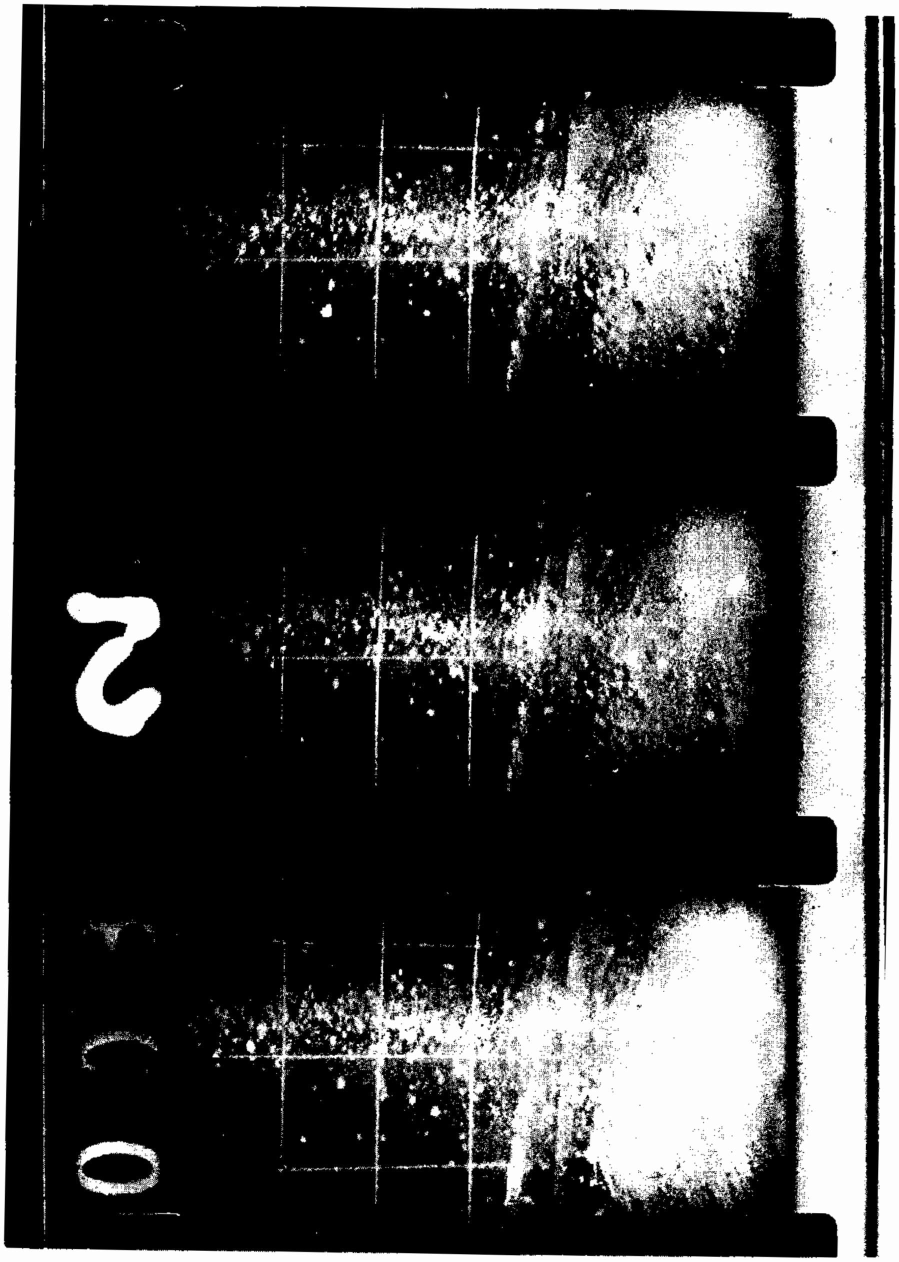
LONG NOZZLE: The airstream from the long nozzle appears to be less susceptible to time-dependent segregation caused by pulses of material along the hose since the nozzle tended to concentrate all the constituents into a cohesive-like mass going toward the wall. Only 2 stages of density were clearly evident; a dense well-mixed airstream shown in Fig. 5.6a and a light density airstream shown in Fig. 5.6b.

A special feature observed most prominantly in the long nozzle is that the longitudinal cross section appeared to be segregated diagonally. This is especially visible in Fig. 5.6c. Short-nozzle airstreams also tended to have similar phenomena as seen in Fig. 5.5c. The top of any given wave of material appears to be delayed with respect to the bottom. This could be the result of a longer hose path for the upper particles as the hose is



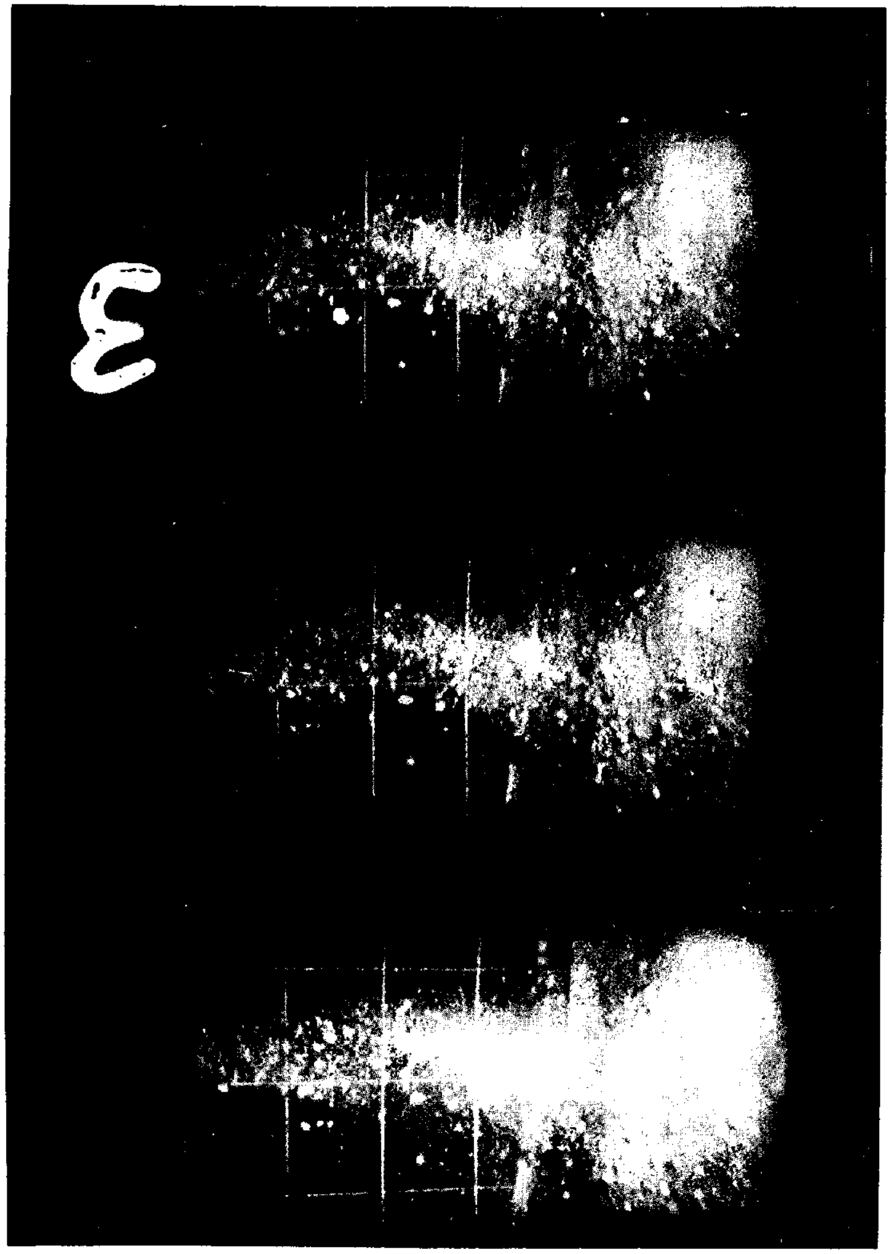
a) Predominantly dense and well-mixed

FIG. 5.6 PHOTOGRAPHS OF TYPICAL LONG NOZZLE AIRSTREAM



b) Predominantly light density

FIG. 5.6 (continued)



c) Illustration of diagonal segregation

Fig. 5.6 (continued)

bent over the nozzleman's shoulder, it is also possibly associated with a tendency for the long hose extension of the long nozzle to pulsate rapidly up and down.

5.3 PROCESSES OF BUILDUP OF SHOTCRETE ON THE WALL

5.3.1 GENERAL

This section discusses the build-up of the shotcrete layer on the wall as observed in the stop-action movies. It should be noted that this is the build-up of the first few pounds of material on a plywood surface as the nozzle was directed at one point on the wall for about 1 to 2 seconds without moving. Typically, a cone or prism of material was deposited on the wall with the apex of the cone at the stream axis with the height of the cone increasing with time. The short and long nozzles each resulted in a different type of build-up of material on the wall. For both nozzles there was a short period lasting a fraction of a second during which everything appeared to rebound off the wall.

5.3.2 SHORT NOZZLE

A typical cone of material build-up by the short nozzle was sketched in Fig. 5.2a. As soon as material began to stick to the wall a small cone was created. The height and the width of the base of the cone increased, maintaining a relatively sharp cone, with time as shown by the lines in the sketch. After about 1 or 2 seconds (the end of the filming), the height was about 4 in. (10 cm) and the base was as wide as the diameter of the outer perimeter of the airstream at the wall. An example of this type of cone buildup is illustrated by the dashed lines in Fig. 5.2a. The sharpness or steepness of this cone angle is believed to have some significance to rebound as will be discussed later.

The consistency of the material appeared stiff; it had a relatively dry appearance. Plastic deformation or remolding of in-place material did not take place as incoming material landed except for penetration of individual particles of coarse aggregate.

5.3.3 LONG NOZZLE

The nature of shotcrete build-up with the long nozzle has been sketched in Fig. 5.2b. The buildup was flat as opposed to the steep cone of the short nozzle. In cross section, the shotcrete on the wall takes the shape of a thin trapezoid with a wide base. The height-base ratio remains approximately constant throughout the buildup with time. At the end of one or two seconds of shooting, the height of this truncated cone was about 2 in. (5 cm). An example of this type of buildup is illustrated by the photographs of Fig. 5.6.

The consistency of the material on the wall appeared to be soft, wet and plastic. Considerable remolding of the in-place material took place as incoming material landed. Material in the cone appeared to flow radially from the impact location, enlarging the base of the cone.

5.3.4 EFFECT OF WALL ON SHOTCRETE

During early stages of shooting against the bare wall while the initial layers are being established, the hardness, rigidity, texture, etc., of the wall is important. Thus, the characteristics of the wall affect the nature of these initial layers.

However, after the initial layer is established, the photographs indicated that the incoming shotcrete is less and less affected by the wall, and eventually, except for providing a stable platform, the wall had no apparent effect on the incoming stream and on the material being deposited. The properties of the material being deposited were controlled by the properties of the material it hits, its own behavior, and on the remolding and compaction of it by subsequent incoming material.

In conclusion, the nature of the wall may have been overemphasized in the past. Perhaps this is one of the reasons why plywood test panels, if heavy enough, appear to give satisfactory results, despite the fact that they do not model the wall properties.

5.3.5 DISTURBED OR REMOLDED LAYER

The photographs clearly showed that the incoming shotcrete created a zone or layer of disturbance in the existing fresh shotcrete layer. This zone of disturbance or remolding varied for different consistencies of materials and for the different nozzles used.

Incoming shotcrete created a crater in the fresh shotcrete and, in doing so, remolded and pushed aside material already in place. Often, once a layer was built up, individual particles would enter the layer and become immediately embedded with a minimum of disturbance. At other times, large clusters of material would severely remold the adjacent in-place shotcrete. The depth of disturbance varied with the consistency but was estimated to be a few centimeters.

The remolding of shotcrete already on the wall can be either beneficial or detrimental depending on the setting characteristics of the shotcrete already on the wall and on the nozzle design. In poorly-designed nozzles, when the water and the dry mix arrive at the wall separately, this remolding or remixing is beneficial. When the accelerator dosage is so high that set occurs immediately, this disturbance, if significant, is bad. More research is needed on this problem of remolding as it relates to mix design, accelerator dosage, and nozzle design.

5.3.6 COMPACTION OF SHOTCRETE BY IMPACT

In accordance with Section 5.3.5 above, little or no compaction occurs in the upper few centimeters. All compaction occurs behind the zone of disturbance. Compaction is a function of the energy delivered or the sum of the force of the particles impacting per unit area of surface.

The photographs indicate that the particle speeds do not change very much between the nozzle and the wall. Thus, a change in speed or momentum with distance is not responsible for lower compaction with greater nozzle distances. Since the cone spreads out, the density of particles, and thus, the average force per unit area decreases with nozzle distance. Note, however, that the time variations in density of the airstream (Section 5.2.3) create significant variations in the force per unit area delivered to successive layers.

As the individual particles hit the fresh shotcrete and embed themselves, they impart an energy to the shotcrete in front of the particles. Larger, heavier, and faster moving particles have greater momentum and thus impart greater energy to the shotcrete. Further, the larger particles have a greater depth of influence from a stress distribution standpoint. Thus, compaction energy from wider particles extends to deeper layers and is more effective at shallower depths. Preliminary calculations tend to confirm these observations.

The consistency of the shotcrete already in place is an entirely separate variable which is just as important as the impact energy. The compaction of the layer depends upon its water content and its degree of hydration. Very likely an increase in water content up to some optimum will increase its susceptibility to compaction. Above this optimum, the material will be pushed around rather than compacted. So long as the shotcrete has not "set", it may be compacted with beneficial effects. Once the shotcrete has "set", compactive energy has a different effect on the shotcrete. On one extreme, after shotcrete has hardened (the case with multiple layers), additional compaction has no effect. On the other hand, compactive energy may destroy bonds of young setting shotcrete which have already formed, thus reducing the strength of the shotcrete. It is believed that high cement and high accelerator dosages may produce so "active" a mix that it loses initial and final strength.

5.4 PROCESS OF REBOUND

5.4.1 GENERAL

There are at least two stages of rebound. The first stage establishment of the initial critical thickness, was clearly evident in the photographs that showed many particles of all sizes rebounding for a fraction of a second until a very thin layer of cement-rich fines bonded to the surface. The number of particles rebounding dropped significantly after this initial layer was established. The mechanism of rebound during this first stage is strictly an impact problem. Though this is one of the major causes of rebound, quantitative information on impact could not be obtained from the photographs; however, the mechanism could be verified. The remainder of this chapter treats the second stage of rebound which occurred after the initial layer of fines was established.

Most of the rebounding material observed in the photographs were coarse aggregate and fiber. It was evident that the tendency to rebound was a function of the angle between the direction of particle travel and the plane of the surface at the precise point of impact. Particles that rebound tended to hit the wall in zones where only a very thin shotcrete layer existed so the impact energy was not absorbed by a cushion of shotcrete. Thus, most rebound occurred at the perimeter of the cone of buildup where the existing layer was thin and where the direction of movement of the particles was already at a critical angle to the stream axis as sketched at "A" in Fig. 5.2a.

Thus, many rebounding particles already have some radial component away from the point of impact at the center of the airstream. Consequently, there was a strong tendency for many rebounding particles to hit the wall and roll along the wall radially, away from the center of the impact of the stream. It is believed that most of the rebound of the fine aggregate occurs in this manner.

Also, when a particle impacted against a hard surface at an angle of incidence conducive to bouncing away from the wall, there was already a component away from the axis so the particle traveled away from the stream axis as it rebounded from the wall. Thus, they generally do not bounce back into the airstream. The airstream was also traveling outward, tending to carry rebounding particles along. Spinning of the particles on impact also tended to make them bounce away from the incoming airstream.

5.4.2 SPEED OF REBOUNDING PARTICLES

As expected, a considerable variation was found in the rebound speed of the coarse particles which ranged from near 0 ft/sec to as much as 1/3 of the incoming velocity (around 30 ft/sec; 9.1 m/sec). It is believed that the variation in the rebound velocity depends on four principal factors:

a. Incoming speed,

b. Thickness of the shotcrete layer on the surface of particle impact,

c. Hardness or consistency of rock surface of existing layer of shotcrete at precise location of impact,

d. Angle of deviation of the particle direction with respect to the surface at the location of impact.

The mechanisms explaining how these four factors interact will be explained in other sections.

Steel fibers usually rebounded at a low speed in a direction almost parallel to the wall surface, later falling mostly within a few feet of the wall; a few traveled as far as 8 to 10 feet from the wall. The fibers absorb a lot of energy through flexing of the fibers themselves at impact. Thus, their trajectory may be strongly influenced by the remnant air currents leaving the point of impact.

5.4.3 CAUSES OF REBOUND

The photographic technique is particularly effective in an evaluation of the causes of rebound. From other observations on this program, it has been shown that coarse aggregate is the primary constituent of rebound. This discussion will basically treat the rebound of coarse aggregate with selected comments about the rebound of steel fiber.

The various factors of rebound cannot be separated from each other in any simple manner because of their interaction; the relative importance of these factors is not known. Nevertheless, it is helpful to discuss the various factors independently to simplify the explanation.

The photographic study resulted in the identification of the following factors as being important to the mechanism of rebound.

ESTABLISHMENT OF INITIAL CRITICAL THICKNESS

There is a certain amount of "inevitable rebound" that must occur during the establishment of the initial critical layer. This amount of inevitable rebound will vary for different mix and shooting conditions. Any nozzle, combination of nozzles, or multi-pass shooting procedures that are more efficient in establishing the initial layer will be most valuable in reducing rebound. The establishment of the initial thickness is discussed in detail in Chapter 4.

HARDNESS OF SURFACE BEING SHOTCRETED

The characteristics of the wall being shotcreted have importance primarily during the first stage of rebound. However, while the initial layer is being established, some 80 to 100 percent probably rebounds irrespective of the characteristics of the wall within the range of hardness of normal rock or plywood surfaces. Thus, the hardness of the wall may not have much effect on the rate of rebound but it may determine how far the rebound bounces. These are safety and nuisance factors to the nozzle crew rather than economic factors.

However, the hardness of the wall may influence the length of time required to establish the initial layer. For instance, the relative hardness of the particle and wall may affect the amount of the cement matrix on the particle which is deposited on the wall at impact. Much more information is required on this aspect.

THICKNESS AND STIFFNESS OF FRESH IN-PLACE SHOTCRETE

Obviously, if the in-place shotcrete has become hard prior to another application, the comments of the previous section applies. However, with accelerators, shotcrete gains a certain stiffness almost as soon as it is placed, especially at high accelerator dosages. The stiffness of previously placed shotcrete is one of the factors determining the amount of energy lost as the particle hits and penetrates the existing shotcrete layer. This stiffness also determines the depth of penetration. It also determines whether the particle will rebound back out of the layer. A 1 cm particle will not lose much energy by penetrating an existing 3 mm layer. Thus, the thickness of the layer and the relative thickness to particle size is important to rebound.

PENETRATION INTO FRESH SHOTCRETE

This factor is the relative penetration of a particle or cluster of particles into an existing fresh shotcrete layer. The question of importance to rebound is mainly how much energy is absorbed when a particle impacts. The following particle-surface interaction was observed in the photographs. The particle may impact, penetrate only a small amount and bounce off. Or it may penetrate an amount sufficient to have enough of its momentum absorbed so that its rebound energy was less than the sum of the forces holding the particle in the shotcrete (bond, friction, etc.). Finally, a particle or a cluster of particles would often penetrate completely into a thick soft layer of fresh shotcrete so that the soft walls of the crater formed by penetration would collapse behind and entrap the particles.

One other mechanism of rebound noticed in the photographs occurred when a particle impacted at a low angle of incidence on a steep slope of a cone. Sometimes the particle would hit the slope and penetrate sufficiently to cause a slope failure which kicked some material already in place out of the wall. Usually this material was re-entrapped by subsequent incoming material.

LOCAL ANGLE OF INCIDENCE

It has been observed that less rebound occurs if the nozzle is perpendicular to the surface being shotcreted. This is true not only on the macro-scale for which it was intended (i.e., the direction of the nozzle itself), but the results of this photographic study indicated that on the micro-scale, a particle was less likely to rebound if it hit the existing surface of fresh shotcrete at right angles to the surface at the point of impact.

This effect is illustrated at point "A" in Fig. 5.2a. It was observed that rebound for both nozzles tended to be more likely near the perimeter where there was only a thin layer of shotcrete anyway, where the particles in the airstream were acting independently, and where the angle of incidence to the wall of the cone was at its maximum.

However, for the steep conical surface generated by the short nozzle, the angle of incidence at the precise point of impact deviated considerably from 90°. The greater the deviation from the perpendicular to the surface of the precise point of impact, the greater the chances for rebound.

Thus, by observation between Fig. 5.2a and 5.2b, one can see that the long nozzle should be likely to have less rebound because the angle of incidence of a particle to the flat surface produced was more favorable.

DISCUSSION OF CONSISTENCY OF MIX

It is possible that the cones of the short nozzle were steeper because the nozzleman may have unknowingly shot on the dry side of optimum with the short nozzle and on the wet side with the long nozzle. However, the measured water contents of the fresh shotcrete do not indicate a consistent trend. It is likely that the water mixes better in the long nozzle with the dry mix and the result is a more uniform and wetter consistency.

Regardless of these considerations, it can be said that the wetter the consistency, the flatter the existing surface, and the lower the angle of incidence of incoming particles, consequently, the lower the rebound. Thus, a revival of the term and of the practice of shooting at the "wettest stable consistency" advocated by Studebaker (1939) can be recommended for a reduction of rebound. Any effect of this shooting criterion on other physical properties must also be considered. Studebaker concluded that rebound was minimized when placed at the wettest stable consistency. Wettest stable consistency, WSC, was defined as the wettest consistency possible without sloughing of the shotcrete. This WSC will obviously be less for overhead work than for walls and, in terms of water-cement ratio, WSC will necessarily vary with different accelerator contents.

EFFECT OF SUBSEQUENT INCOMING MATERIAL

Since shotcreting is a continuous process, incoming material occasionally collided with rebounding particles. Sometimes these collisions re-entrapped the rebound. At other times the collisions scattered both particles so that neither stuck to the wall. Thus, from this standpoint the effects are random but it can be seen that the process of rebound is complicated by this factor.

However, it was also noticed that some material just hitting the surface was quickly covered by the incoming material right behind it. This burial appeared to enhance retention of shotcrete on the wall. This burial factor is particularly important when the airstream is concentrated such as produced by the long nozzle. The concentrated airstream has a higher burial rate and, thus, should reduce rebound.

EFFECT OF MOVING THE NOZZLE

The nozzle was held in a constant position while the photographs were taken. Hence, the effect of moving the nozzle, as done in practice, either in a translation or rotary motion was not directly observed. Nevertheless, the effect of moving the nozzle can be estimated from the observations made.

The effect of moving the nozzle is to continually move the airstream into areas where the initial layer of shotcrete does not exist or where the existing shotcrete layer has already gained some stiffness. In practice, there are portions of a given shotcrete airstream that are rebounding at say 80 to 90 percent and adjacent portions rebounding at only 10 or 20 percent. Further, movement of the nozzle tends to put the center of the airstream on the slope of the existing cone rather than directly into the center of the cone of buildup. This effect is believed to be minimal, however.

The rotary motion used by many shotcrete nozzlemen appears to be sound from several standpoints, but the size and rate of build-up of the cone must be judged in determining the size of the rotary circles. It appears the perimeter areas of the airstream, observed to be high in rebound, should be maintained in zones where soft fresh shotcrete already exists. This is a practical impossibility. However, the most important feature is the establishment of the initial layer which has to be established at some time or other.

SIZE AND SPEED OF THE PARTICLES

The size and velocity of the particles govern their energy at impact. The greater the velocity, the greater the energy available for rebound and the greater the energy that must be absorbed by the existing layer for a particle to stick. Also, the larger the particle, the larger the mass and, thus, the energy. So an increase in either size or velocity increases the tendency for rebound. The photographs clearly indicated that the coarse particles were the most prominent particles rebounding. This is also confirmed by the grain size distribution of the rebound. The particle velocity for most mixes were quite similar so the effect of velocity on rebound could not be measured.

ROTATION OF PARTICLES

Many particles rotated about their axis considerably while traversing from the nozzle to the wall. Other factors being equal, it was clear from the photographs that rotating particles had a greater tendency to rebound.

PARTICLE SHAPE

The flat elongated particles tended to be more susceptible to rotation in the airstream. Further, when these rotating elongated particles hit the surface, they disturbed a larger area than would have been disturbed by a subrounded particle of similar size. In some instances, platy particles also removed material already in place as they hit and disturbed the surface.

NOZZLE DISTANCE

This was not significantly changed in the field program. The geometry of the airstream shown in a previous section clearly indicates that the closer the nozzle, the more concentrated the stream. Though not studied, the nozzle distance has also been shown by others to be an important factor to rebound (Kobler, 1966).

5.5 CONCLUSIONS

1. High speed photographic studies are effective in evaluating nozzle design, mechanisms of rebound, etc.
2. The airstream is roughly conical, consisting of a central zone of high concentration of particles surrounded by a less dense peripheral zone. The density of particles in these zones constantly changes with time.
3. Pulsations of the material delivered to the airstream appears to be directly related to continuity of discharge from the nozzle. Within a fraction of a second, the mix particles in the airstream change from mostly coarse, to mostly fine, to well-mixed.
4. The long nozzle produced a more concentrated and better-mixed airstream. It was judged to be superior to the short nozzle in every respect observed in the photographs.

However, the long nozzle has a greater tendency to plug and, thus, may be a greater safety hazard.

5. Most coarse particles traveled at a rate of about 65 to 75 feet per second (20 to 23 meters/second). Many coarse aggregate particles, especially elongated ones, tended to spin about their axis at a high rate. The velocity of the particles was not as high as reported in the literature. The air speed that is usually reported in the literature is not the same as the particle speed since the particles are still accelerating.
6. Fines appeared to travel in successive wave fronts at speeds of about 1.4 to 1.8 times the speed of coarse particles.
7. The speed of rebounded particles is about one-third of the speed of incoming particles. Most of the rebounded material was coarse particles and fiber (i.e., not as much fine material). This is discussed in detail in Chapter 6.
8. After the initial layer of shotcrete is established, observed as only a few tenths of an inch in this study, the incoming shotcrete is affected very little by the wall, and eventually, except for providing a stable platform, the wall had no apparent effect on the incoming stream and on the material being deposited.

The properties of the material being deposited were controlled by the properties of the material it hit, its own behavior, and the remolding and later compaction of subsequent incoming material. This may explain why plywood test panels appear to give satisfactory results, even though they do not exactly model the rock surface.

9. Two basic types of shotcrete build-up were observed. A sharp relatively stiff cone of dry appearance was formed by the segregated stream of the short nozzle. A flat soft shotcrete cone of wet appearance was formed by the long nozzle.
10. Incoming particles created a zone or layer of disturbance in the existing fresh shotcrete. In some cases the disturbance remixed and thus improved the shotcrete, whereas, in other cases it tended to disturb the existing shotcrete.
11. Compaction also must occur behind the zone of remolding. Compaction is a function of the nature of the impacting shotcrete and of the consistency of the shotcrete being compacted. The compaction depends on the energy of impact and the efficiency of the impact. Shotcrete that has not "set" can be compacted; after initial set it can be disturbed. An increase in water content, up to an optimum, may enhance compaction but above this optimum it is only pushed around. Active mixes with high dosages of cement and accelerators

are disturbed rather than compacted. Treatment of this subject from the standpoint of strenqths is given in Section 9.8.

12. The tendency to rebound was a function of the angle between the direction of particle travel and the plane of the surface at impact.

13. The high-speed photographic evaluation tends to confirm the idea that rebound is reduced when the mix is shot at the wettest stable consistency.

14. Fibers tended to be located in the peripheral zone where conditions are most conducive for rebound. They also appeared to be affected by the remnant air currents, a condition that would tend to increase rebound. These observations confirm the high fiber rebound rates and low fiber retentions. Mixes with high cement or accelerator content which tended to have sharply reduced cone angles or which moved toward the wall as a more or less coherent mass would be expected to have higher fiber retentions. Coarse aggregate did not interfere with fibers and, thus, the presence of coarse aggregate is not believed responsible for low fiber retention.

15. Rebounded fibers do not appear to be missile hazards any more than coarse aggregate; the trajectory of rebounded coarse particles confirms the fact that most rebound is located within a few feet of the wall. Goggles should be mandatory for any shotcrete operation.

CHAPTER 6

FRESH SHOTCRETE SAMPLES

6.1 INTRODUCTION

One of the reasons shotcrete has become an accepted structural support is because the industry has been able to shoot high quality shotcrete fairly consistently. Yet the operations involved in shotcreting tend to create a somewhat variable material compared to structural concrete. A comprehensive program of sampling and testing fresh shotcrete was undertaken during this study to evaluate the potential variability and to provide documentation for other phases of this project.

Samples of fresh shotcrete were collected from the mix hopper, from the wall, and from the rebound pile. Each sample was stored and transported in a bottle containing methyl alcohol to inhibit hydration. Subsequently, samples were analyzed to determine such parameters as water, cement, and gravel contents.

Although discussed somewhat throughout this report, it is important to note that there are abundant reasons why shotcrete, especially with the dry-mix process, can be a moderately variable material. For the conditions on this project, material was discharged from the rotating barrel into the air hose about two times per second while at the end of the hose the nozzle provided water at a constant rate as illustrated schematically in Fig. 6.1. This process leads to a variable water-cement ratio in-place in spite of the fact that the material is remixed on the wall by subsequent incoming material.

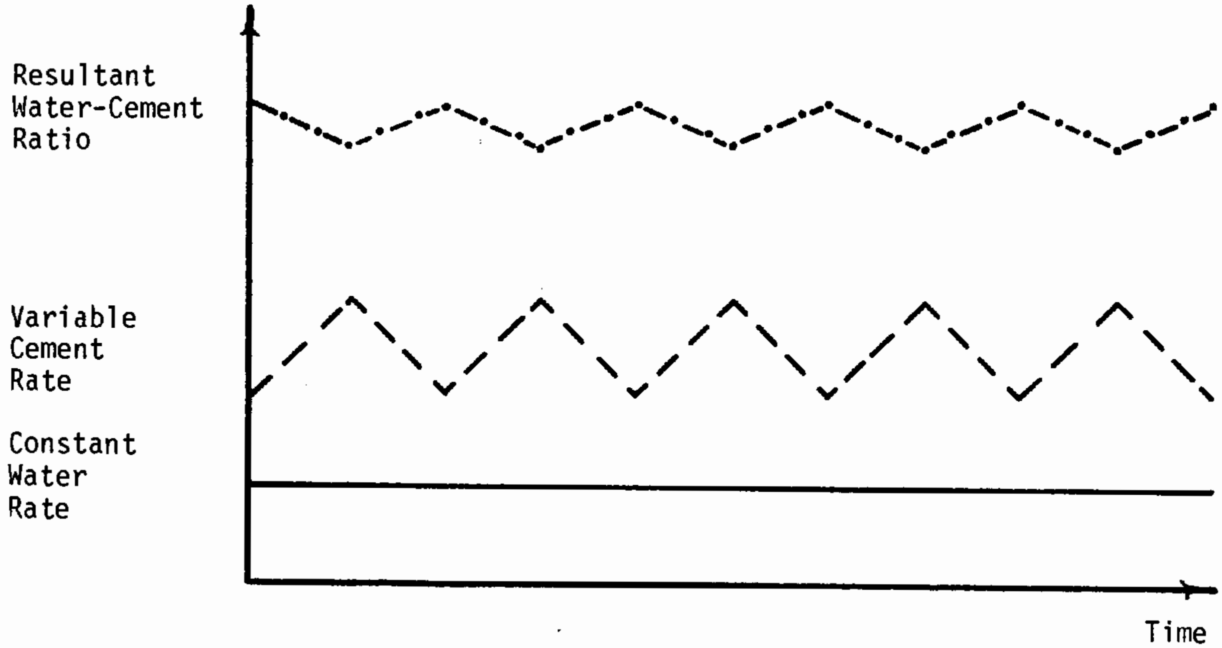


FIG. 6.1 SCHEMATIC ILLUSTRATION OF POTENTIAL VARIATION OF WATER-CEMENT RATIO IN DRY-MIX PROCESS

For dry process shotcrete, adjustments made by the nozzleman can contribute either to more uniform shotcrete or to more variable shotcrete. Nozzling techniques can cause the product to be completely variable by entrapping rebound, by overcorrecting and shooting alternatively too wet or too dry by too wide a margin, or by not correcting the water at all. On the other hand, a qualified nozzleman can keep the proper distance, maintain perpendicularity, and adjust his water timely and properly to account for variations in the mix as well as variations of the wall being shotcreted. However, there is some small time lag in these adjustments and evan a good nozzleman shoots a good part of the time either slightly wet or slightly dry.

The data in this chapter are evaluated in terms of variability between mixes, between panels in the same mix, and within the same panels.

The batch weights and moisture conditions were known and the amount of water added at the nozzle was also known. From these field conditions, water and cement content are calculated and compared to the fresh-sample data. These comparisons were made for several reasons. For example, the comparison proves that the fresh-sample technique provides reasonable results. Once confidence is gained with the results from fresh samples, they, in turn, provide a check on the batching operation. Reasons why there should be general but not exact agreement between the fresh samples and the calculated data are discussed.

6.2 SAMPLING PROGRAM

Sampling of fresh shotcrete during Day I and Day II was rather limited, consisting generally of about one or two samples from each mix. The purpose of this limited program was to determine any problems in the methods used to collect, store, and analyze the samples, and to give an indication of whether useful results could be achieved by a more extensive program of sampling. As a result, a much more comprehensive sampling program was planned for Days III and IV. This included taking a larger number of samples from each mix so that a more accurate reading on variation from mix to mix could be obtained. Data reported in this chapter are based on from 2 to 6 good samples of in-place shotcrete and about 1 to 2 good samples of dry mix and rebound material. Five mixes (Mixes 23, 25, 26, 39 and 45) were sampled even more extensively (up to 18 samples of in-place shotcrete) so that variations in shotcrete with depth and location on individual panels could be assessed.

Three types of samples were collected: samples representative of a) the dry mix in the holding hopper, b) the in-place shotcrete on the wall, and c) the rebounded material. These types of samples will be referred to as dry mix, in-place, and rebound samples, respectively.

Dry mix samples were gathered by scooping a representative portion of shotcrete mix from the discharge of the auger. In this respect, the term "dry mix" is somewhat a misnomer since the aggregate in the bins was quite wet. The primary purpose of the dry mix sample was to serve as a check on whether the mix after batching and transporting to the holding hopper was still representative of the design mix.

The in-place samples were collected by scooping shotcrete from panels immediately after shooting. Samples of in-place shotcrete were taken from the edges of compression test panels, from special test panels, and from the panels which were shot for rebound tests. The latter is designated as "Rebound Wall" and is not to be confused with samples of rebounded material called "Rebound".

A known amount of about 400 to 500 g of methyl alcohol was added to each sample bottle. The alcohol served a dual purpose by inhibiting the hydration process, and by providing a combustible fluid for drying. Immediately after placing the shotcrete in the bottles, securing the caps and recording the sample number, the samples were shaken vigorously to disperse the alcohol throughout the sample to inhibit hydration most effectively. They were shipped back to the laboratory at the University of Illinois in Urbana, Illinois for testing. Burning off the alcohol in the field for on-the-spot analysis was possible but it was found to be impractical because of the precision required and because of the large number of samples.

6.3 SAMPLE ANALYSIS

6.3.1 WATER CONTENT

The total weight of shotcrete, alcohol, and bottle were weighed to the nearest 0.1 g upon arrival at the laboratory and then reweighed immediately prior to testing. To determine the moisture contents, each bottle containing the shotcrete-alcohol-water mixture was emptied carefully into a bowl and ignited to burn off the water and alcohol. The weight of water in the sample was simply the difference between the loss of weight on burning and the weight of alcohol in the bottle. Visual examination and more extensive absorption tests indicated that the condition of the aggregate-cement combination after burning was equal to or only slightly less than the saturated, surface-dry condition so the aggregate was considered to be saturated, surface-dry for practical purposes. The water content was obtained by dividing the calculated weight of the evaporated water by the total dry weight of the sample (including any fibers).

In some cases the caps were not securely fastened on the bottles and some alcohol vaporized or leaked; however, these were identified by the reweighing program. Corrections were performed which accounted for this possible source of error and those samples that experienced significant weight losses were discarded.

6.3.2 CEMENT CONTENT

After the water and alcohol were burned off, each sample was sieved to determine the cement content and gradation. It was assumed that all material passing the No. 200 sieve was cement with only minor corrections necessary to account for any fines in the aggregate which may also have passed the sieve. This procedure worked well with the small number of samples taken during the first two days of sampling. However, due to the considerably greater number of samples taken during Days III and IV, some delay occurred before the water and alcohol were burned off. Consequently, hydration proceeded to a greater extent than in the earlier samples and as a result a small amount of cement coated the sand and gravel particles after burning. Therefore all but the portion of the sample which passed the No. 200 was washed in a 3N solution of hydrochloric acid (HCl). The loss of weight during washing was assumed to be cement since the effect of a similar washing of clean aggregate was negligible. The value of cement content, the sum of the weight which passed the No. 200 sieve and the weight loss from HCl washing, is expressed as a percent of the total dry weight of the sample, including any fibers.

6.3.3 WATER-CEMENT RATIO

Because it was determined that the burning process evaporated only water that would have entered into the hydration process, no further transformations were required to calculate the water-cement ratio: the water content was simply divided by the cement content.

6.3.4 GRADATION

The dried contents of every bottle were sieved through a No. 4 sieve (4.76 mm), a No. 40 sieve (0.42 mm), and a No. 200 sieve (0.074 mm) to determine the gravel and cement content and the shape of the gradation curve. Selected samples were also sieved through intermediate sieves to obtain the typical shape of the grain size curves more accurately. All material retained on the No. 4 sieve was denoted as "gravel", usually expressed as a percentage by weight of the total dry sample, including fibers.

6.3.5 FIBER CONTENT

Unlike other physical properties, the fiber contents of the samples were determined by two independent methods of sampling. In addition to the samples of fresh in-place shotcrete, a measure of fiber content was also obtained by crushing sawed portions of test panels, thereby removing the fibers from cured, intact shotcrete specimens. Values for fiber content are expressed as percents of the total dry weight of either the fresh sample or the sawed specimen.

6.4 RESULTS

6.4.1 BASIC FINDINGS

The basic results are contained in Appendix C. There is scatter but not as much as one might anticipate. The average values appear reliable and agree well with other data collected.

Two independent methods were used to evaluate the constituents of the dry mix and in-place materials. In addition to the fresh samples, average values for the percentages of each constituent were calculated from the actual batch weights. The water in the dry mix was calculated directly from the batch weights and known water contents of the aggregates. Average water contents in the airstream were computed by adding the measured amount of water added at the nozzle to the water in the aggregate and dividing the total weight of water by the total dry weight of the batch. Any moisture in the compressed air supply was neglected. Whenever appropriate, the measured values from the fresh samples are compared to the calculated values as a check of the methods. Good comparisons imply both methods are giving satisfactory results and give confidence in the methods employed. In one case, the comparisons did not agree and it was quite apparent the batch weights were in error.

As far as absolute values are concerned, they agree well with reported values for coarse aggregate dry-mix shotcrete. If anything, the values for water and cement content may be slightly low; however, it will be seen that they agree well with the calculated values obtained independently. Regardless of the absolute values the samples were all treated in the same way, so a relative comparison of the average values between mixes is considered appropriate.

To put the data in perspective before the details are discussed, the following trends were observed. The water content of the dry mix was about the same as the water content of the rebound while the water content of the in-place shotcrete was several percent higher. There was a higher percentage of cement in-place than batched while rebound contained much less cement. The water-cement ratio of the in-place shotcrete varied from 0.26 to 0.37 but was close to 0.30 for most mixes. Rebound losses for fibers were very high. Only about one-half to two-thirds of the fibers in the dry mix were retained in the wall. More gravel rebounded than was retained on the wall.

The results and discussion presented in the following sections are those obtained for samples taken on Days III and IV; there were an insufficient number of samples obtained during the limited sampling program on Days I and II to warrant detailed analyses and presentation but similar trends were observed.

6.4.2 WATER CONTENT

The average results from fresh samples are compared with calculated values for the dry mix and for in-place shotcrete in Tables 6.1 and 6.2 respectively. There is scatter as one might expect from a limited sampling program but for the dry mix, the fresh sample data varies by only 1.3 percentage points from calculated values at the most with an average difference for all mixes of only 0.18 percentage points. From this close agreement, it is concluded that satisfactory data were obtained by the fresh sample technique. As expected, the average results from fresh samples of in-place shotcrete (Table 6.2) are slightly higher than the calculated batch weight values. It will be shown in Section 6.5.2 that since more dry material rebounds than water, the in-place water content should be slightly higher than the water content in the airstream. Stewart (1931) reports the same effect. However, it will be shown later that the water-cement ratio on the wall is less than that in the airstream. The overall average difference shows the measured in-place values to be about 1 percentage point higher than the calculated.

The average values for water content of samples taken on Days III and IV are regrouped for relative comparison between mixes and between type of sample in Table 6.3. They are summarized below:

Dry Mix	≃	4%
In-Place	≃	7-1/2%
Rebound	≃	4-1/2%

TABLE 6.1

COMPARISON OF MEASURED AND CALCULATED WATER CONTENTS: DRY MIX

Mix	Calculated value, %[1,2]	Average measured value from fresh samples, %[1]	Difference
23	4.2	4.3	+0.1
24	4.1	5.4	+1.3
25	4.1	3.7	-0.4
26	4.1	4.8	+0.7
28	4.1	3.4	-0.7
29	4.3	3.4	-0.9
30	4.0	4.2	+0.2
31	4.1	3.6	-0.5
33	4.0	-	-
33A	4.0	4.3	-0.3
34	5.1	-	-
38	3.9	4.2	+0.3
39	4.0	3.8	-0.2
40	4.1	3.2	-0.9
42	4.0	3.0	-1.0
45	4.0	-	-
Average	4.13	3.95 Average difference	-0.18

[1] Percentages based upon dry weight of all constituents in mix.

[2] Based upon water content of aggregates in batch.

TABLE 6.2

COMPARISON OF MEASURED AND CALCULATED WATER CONTENTS: IN-PLACE SAMPLES

Mix	Calculated value, %[1,2]	Average measured value from fresh samples, %[1]		Difference
23	5.6	6.2		+0.6
24	5.6	7.3		+1.7
25	6.7	7.2		+0.5
26	7.8	6.7		-1.1
28	6.9	7.5		+0.6
29	6.3	7.5		+1.2
30	8.6	7.4		-1.2
31	-	7.7		-
33	6.5	7.4		+0.9
33A	6.2	8.5		+2.3
34	7.4	-		-
38	5.6	7.2		+1.6
39	5.7	8.5		+2.8
40	6.3	7.4		+1.1
42	8.8	10.3		+1.5
45	5.6	6.3		+0.7
Average	6.64	7.54	Average difference	+0.94

[1] Percentages based upon dry weight of all constituents in mix.

[2] Based upon water content of aggregates in batch and water added at the nozzle.

TABLE 6.3

AVERAGE MEASURED WATER CONTENTS: DAYS III AND IV

Mix designation	Type of sample		
	Dry mix	In-place	Rebound
23-7-1/2I-60S	4.3	6.2	4.6
24-7-1/2I-60D	5.4	7.3	4.8
25-7-1/2I-60L	3.7	7.2	3.8
26-7-1/2I-100L	4.8	6.7	3.6
28-7-1/2R-100S	3.4	7.5	4.8
29-6-1/2R-100S	3.4	7.5	-
30-8-1/2R-100S	4.2	7.4	-
31-7-1/2R-60S	3.6	7.7	5.6
33-7-1/2I-60S-1US	-	7.4	4.1
33A-7-1/2I-100L-1US	4.3	8.5	4.4
34-7-1/2I-60S-1US-25CA	-	-	4.2
38-8-1/2I-100L-1US	4.2	7.2	4.1
39-7-1/2I-100L-1US	3.8	8.5	-
40-7I-100L-1/2US	3.2	7.4	6.2
42-10-1/2R-100L-1US	3.0	10.3	5.0
45-7-1/2I-100L-1NS	-	6.3	3.8
Range	3.0-5.4	6.2-10.3	3.6-6.2
Average	3.95	7.54	4.54

NOTE: Water content is expressed as a percent of the total dry weight of the sample

For the field conditions, the dry mix was already quite wet. Water added at the nozzle and differential rebound effects resulted in the in-place shotcrete having a water content roughly double that of the dry mix. Note that the water content of the rebound was about the same as the dry mix.

The in-place water content varies somewhat from mix to mix. The nozzleman had to adjust the water for each of these mixes and the averages also include any sampling errors and variations in homogeneity. Yet, most of the mixes had an average water content of 7-1/2 percent, an indication of good nozzle work. The 10.3 percent value for Mix 42 was a result of maintaining the water-cement ratio for a high cement content.

6.4.3 CEMENT CONTENT

Cement contents measured in the fresh samples are compared to calculated cement contents for both dry mix and in-place samples in Table 6.4. The agreement between batched and measured cement contents of the dry mix samples is excellent with the exception of Mix 42. With this exception the maximum difference is +2.3 percentage points for Mix 30 and the average difference is only +0.36 percentage points. Thus it may be concluded that the batch closely approximated the desired mix except perhaps Mix 42. Moreover, the techniques of sampling and evaluating cement content by means of the fresh samples appear to be quite satisfactory.

The method of batching the regulated-set cement of Mixes 27 through 31 and Mix 42 was not by the weight hopper from bulk storage as was the case in the other mixes using Type I cement. Regulated-set cement was furnished in 94 lb (43 kg) bags and was batched manually by bag count. Thus, there

TABLE 6.4

COMPARISON OF MEASURED TO CALCULATED CEMENT CONTENTS

Mix	Calculated from batch weights, %[1]	Dry mix		In-place	
		Measured %[1]	Difference, measured to calculated	Measured %[1]	Difference, measured to calculated
23	19.3	--	--	22.4	+3.1
24	19.3	18.2	-1.1	25.7	+6.4
25	19.3		--	24.0	+4.7
26	19.3	19.5	+0.2	22.4	+3.1
28	19.3	19.2	-0.1	24.3	+5.0
29	16.7	18.2	+1.5	22.3	+5.6
30	21.9	24.2	+2.3	27.8	+5.9
31	19.3	20.7	+1.4	26.1	+6.8
33	19.5	--	--	29.0	+9.5
33A	19.5	18.6	-0.9	25.7	+6.2
34	19.5	--	--		
38	21.6	22.0	+0.4	25.4	+3.8
39	19.5	19.1	-0.4	24.8	+5.3
40	18.3	18.6	+0.3	19.4	+1.1
42[2]	19.5	26.3	+6.8[2]	31.0	+11.5[2]
45	19.5	--	--	20.2	+0.7
	Average difference (excluding Mix 42)		+0.36		+4.8

[1]Percentages based upon dry weight of all constituents in mix.
[2]See text for explanation of unusually high cement content in Mix 42.

are some reasons for the differences in the batching of Type I and the batching of regulated-set cement as shown in the averages. Mix 42 is a special case since all evidence points to the fact that a miscount of bags was made and about 10-1/2 bags were batched instead of 7-1/2 bags. Other evidence besides the dry mix, such as the in-place cement content, the in-place water content, and the amount of cement in the rebound also indicate an extraordinarily high cement content. Further, this was the only mix that began to hydrate significantly before it could be shot. This and the fact that every fresh sample tested had extraordinarily high cement contents leads to the conclusion that there were about 10-1/2 bags instead of 7-1/2 bags in Mix 42. The other possibilities could be that 7-1/2 bags were batched into substantially less aggregate, or that cement for 1-1/2 cu yd could have been batched with aggregate sufficient only for 1 cu yd; however, the material delivery rate does not confirm this possibility. Thus the fresh samples served as a valuable check on the batching operation and the Mix Designation Code 42-10½R-100L-1US reflects the actual nominal bag count of 10-1/2 bags.

It has been observed in the literature that the cement content in the wall is richer than as batched (Studebaker, 1939; Zynda, 1966; Litvin & Shideler, 1966; Lorman, 1968). This phenomenon is shown clearly in the comparison of batched to in-place cement contents in Table 6.4. Neglecting Mix 42, the average increase in cement content in-place above the calculated batched cement content was about 5 percentage points for all mixes. Mix 42 also experienced a 5 percentage point increase when in-place cement content is compared to the measured cement content in the dry mix.

Thus the cement content of in-place shotcrete is, as expected, about 5 percentage points higher than the cement content as batched. This enrichment is attributed to the fact that the rebound rate of cement is less than the rebound rate of aggregate. Physically, those particles that are well-coated with cement and water tend to stick on the wall while those that are not covered or bound together by a cement matrix are more likely to rebound, particularly during the first few seconds of shooting against a bare wall.

The effect of the above phenomenon is to have different rebound rates for the different constituents in the mix, a phenomenon that will be discussed in more detail in Section 6.5; it can also be seen in Table 6.5, where the averages for all mixes for the dry mix, in-place, and rebound samples are shown. The overall average cement contents are summarized below:

	% of Dry Weight
Dry Mix	~ 19% Cement
In-Place	~ 24% Cement
Rebound	~ 12% Cement

From these rough figures it can be seen that for a given batch most of the cement stays on the wall, while the total weight of other constituents in the wall is reduced substantially through rebound. The net result is a higher percentage of cement in-place even though the total weight of cement on the wall has actually decreased slightly. This effect of differential rebound rates is evaluated quantitatively in Section 6.5.

The measured cement contents of the dry mix reflect the batched percentages. Thus the measured cement content in-place of mixes with high batched cement contents have correspondingly high measured in-place cement contents. The cement contents follow the anticipated trends.

TABLE 6.5

AVERAGE MEASURED CEMENT CONTENTS: DAYS III AND IV

Mix designation	Type of sample		
	Dry mix	In-place	Rebound
23-7-1/2I-60S	--	22.4	12.7
24-7-1/2I-60D	18.2	25.7	13.8
25-7-1/2I-60L	--	24.0	9.7
26-7-1/2I-100L	19.5	22.4	11.0
27&28-7-1/2R-100S	19.2	24.3	13.4
29-6-1/2R-100S	18.2	22.3	--
30-8-1/2R-100S	24.2	27.8	--
31-7-1/2R-60S	20.7	26.1	15.0
33-7-1/2I-60S-1US	--	29.0	10.6
33A-7-1/2I-100L-1US	18.6	25.7	10.1
34-7-1/2-60S-1US-25CA	--	--	10.4
38-8-1/2I-100L-1US	22.0	25.4	11.4
39-7-1/2I-100L-1US	19.1	24.8	--
40-7I-100L-1/2US	18.6	19.4	9.2
42-10-1/2R-100L-1US	26.3	31.0	14.2
45-7-1/2I-100L-1NS	--	20.2	9.4
Range	18.2-26.3	20.2-31.0	9.2-15.0
Average cement content of mixes with a nominal 7-1/2 bags/cu yd	19.21	24.46	11.61

NOTE: Cement content is expressed as a percent of the dry weight of the sample or batch.

All parameters in this chapter have been normalized as a percentage of the dry weight of the entire sample rather than the wet weight. Thus, these percentages are independent of the amount of water in the sample. Since it is customary to quote cement content in terms of total weight, such as used in the term "bags per cubic yard," a small conversion is necessary. Basically, for the conditions in these tests, the cement content in terms of total weight of in-place shotcrete is about 1 to 1-1/2 percentage points less than the percentages based on dry weight. To put these percentages into perspective of more customary terms, Fig. 6.2 illustrates an approximate relationship

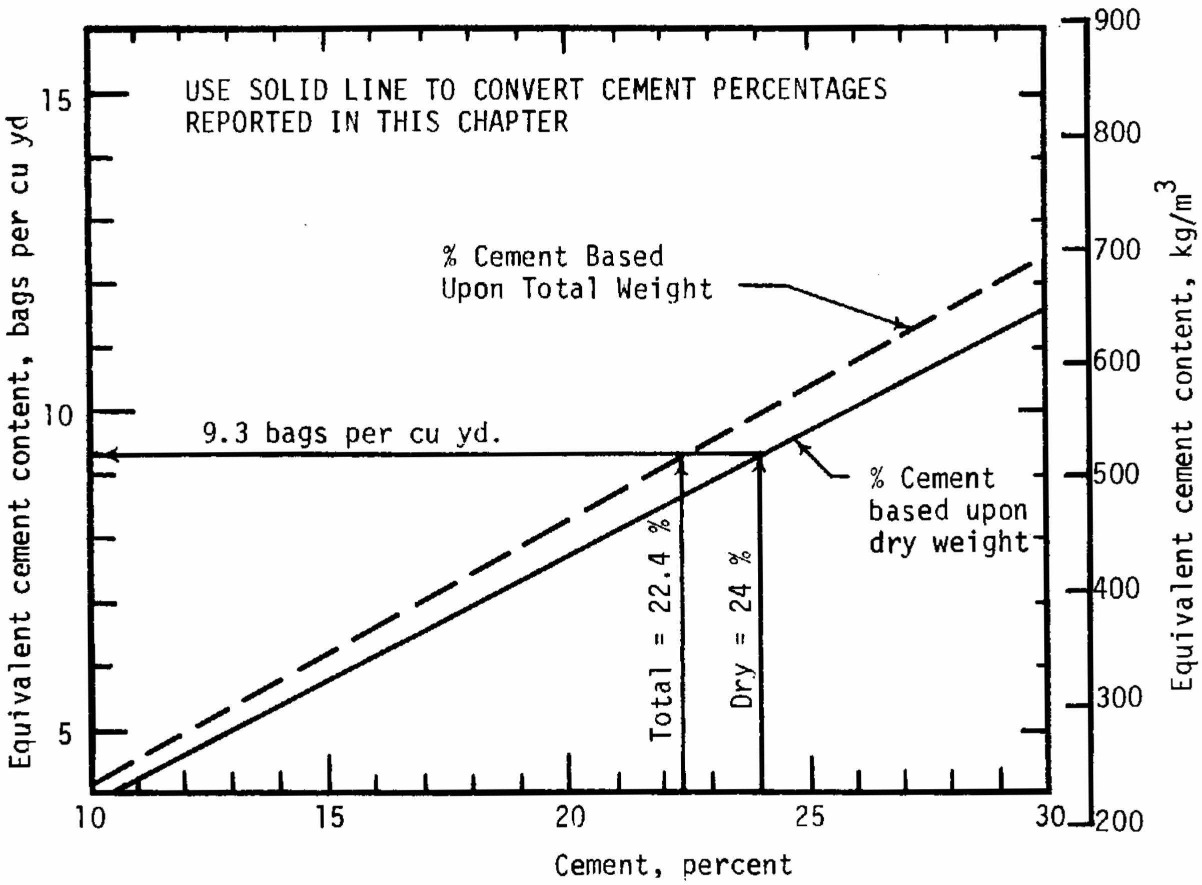


FIGURE 6.2 RELATIONSHIP BETWEEN CEMENT CONTENT IN PERCENT AND BAGS PER CUBIC YARD

between percent cement by dry weight, percent by total weight and bags per cubic yard (94 lb or 43 kg per bag). It can be seen that the average of in-place cement content of 24 percent by dry weight is equivalent to 22.4 percent by total weight or an equivalent 9.3 bags per cubic yard. Hence, the enrichment is the equivalent of about 2 bags per cu yd (110 kg/m^3) and the in-place cement content is very high by concrete mix design standards.

6.4.4 WATER-CEMENT RATIO

Average water-cement ratios, both calculated and measured, are summarized in Table 6.6. A wider variation in this comparison should be expected since any errors in either water content or cement content will accentuate errors in the ratio itself. Yet, the range of measured water contents is rather narrow, from 0.26 to 0.37, with many of the samples close to the average of 0.31. This does not mean that all the shotcrete placed for a given mix was at the same water-cement ratio because, as will be shown later, there were noteworthy variations. This reflects the inherent variability of shotcrete, a subject discussed in Section 6.4.7. The fact that many mixes had water-cement ratios close to the average implies that there was a strong tendency for the nozzleman to shoot consistently at an average water-cement ratio in-place of around 0.30. It can be seen that the water-cement ratio calculated from batch weights and measured nozzle water was higher than the measured in-place values (.333 and .305 respectively). A similar trend has been observed by others and in an analysis given in Section 6.5.3.

It should be noted that since the aggregate used on this project was extremely wet, the water-cement ratio of the dry mix was already as high as

TABLE 6.6

COMPARISON OF CALCULATED AND MEASURED WATER-CEMENT RATIOS

Mix	Average water-cement ratio for entire mix			Water-cement ratio while shooting panels			Water-cement ratio while shooting rebound tests		
	Calculated[1]	Measured[2]	Difference	Calculated[1]	Measured[2]	Difference	Calculated[1]	Measured[2]	Difference
23	.29	.29	0	.27	.27	0	.37	.37	0
24	.31	.29	-.02	.34	.28	-.06	.37	.30	-.07
25	.34	.29	-.05	.36	.29	-.07	.30	.28	-.02
26	.41	.30	-.11	.41	.28	-.13	.40	.31	-.09
27	.30	.30	0	.31	---	----	.28	.30	+.02
28	.36	.30	-.06	.36	---	----	---	---	----
29	.38	.34	-.04	.38	.34	-.04	---	---	----
30	.39	.27	-.12	.39	.27	-.12	---	---	----
31	---	.30	----	---	.32	----	---	.29	----
33	.33	.26	-.07	.33	.26	-.07	.32	---	----
33A	.32	.32	0	.32	.33	+.01	.31	.32	+.01
34	.38	---	----	.38	---	----	.38	---	----
35	.31	---	----	.31	---	----	---	---	----
38	.26	.28	+.02	.26	.28	+.02	.26	---	----
39	.30	.34	+.04	.30	.34	+.04	---	---	----
40	.35	.36	+.01	.31	.34	+.03	.38	.37	-.01
42	.35	.33	-.02	.35	.32	-.03	.34	.34	0
45	.29	.31	+.02	.29	.31	+.02	.29	.33	+.04
Averages	.333	.305		.333	.302		.333	.321	

Notes: 1. Calculated from following data known or measured in field: batch weights, moisture in aggregates, and water added at nozzle.

2. Average of measured values from fresh shotcrete samples.

about 0.2 which is unusual for dry mixes on most projects. In fact, the general rule of thumb for satisfactory moisture conditions of aggregate is to have about 5 percent moisture in the sand. The sand for these results had a water content of about 8 percent above saturated, surface-dry. It is well known that high moisture contents in aggregates cause excessive plugging of hoses.

Finally, the water-cement ratio of the rebound has little significance since there was not enough cement to make the determination reliable and thus it is not reported.

6.4.5 GRADATION OF MIXES

The design mix was basically cement plus equal weights of fine and coarse aggregate. This mix was modified somewhat for steel fiber mixes by reducing sand by 85 lb (39 kg) and gravel by 110 lb (50 kg). One mix, Mix 34, was shot with 25 percent coarse aggregate and 75 percent fine aggregate to evaluate the effect of the reduced coarse aggregate on the rebound of steel fiber.

Each of the fresh shotcrete samples were sieved through the No. 4 (4.76 mm) and the No. 200 (0.074 mm) sieves. A few samples were sieved through intermediate sieve sizes to obtain the typical shape of the gradation curve. Gradation curves were also determined for both aggregates; Fig. 6.3 is a composite gradation curve for a typical design mix of cement and 50 percent fine and 50 percent coarse aggregate. Though the design mix changed slightly for steel fiber mixes, this curve for practical purposes is satisfactory for all mixes except Mix 34. Since there is no data from fresh samples for Mix 34, its design mix gradation will not be shown.

Figure 6.4 contains idealized envelopes of gradation curves for

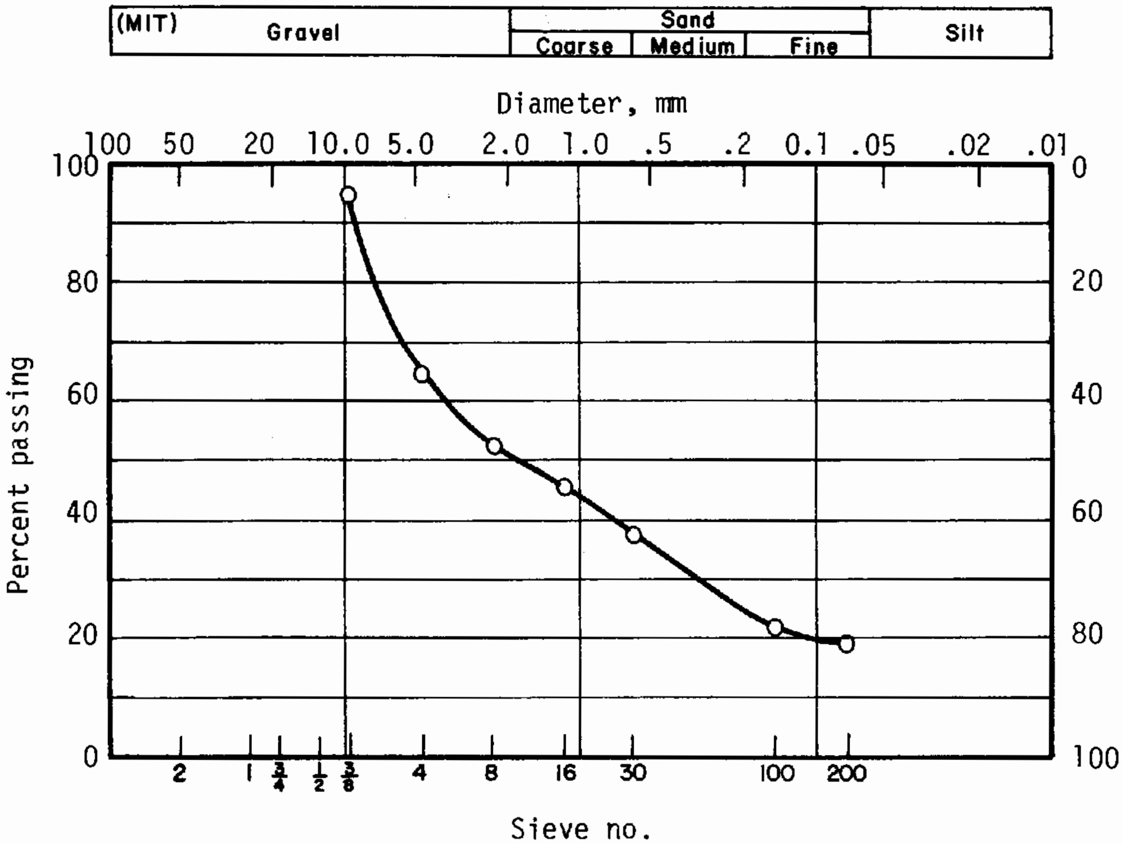


FIG. 6.3 COMPOSITE GRADATION CURVE FOR ALL INGREDIENTS IN STANDARD DESIGN MIX

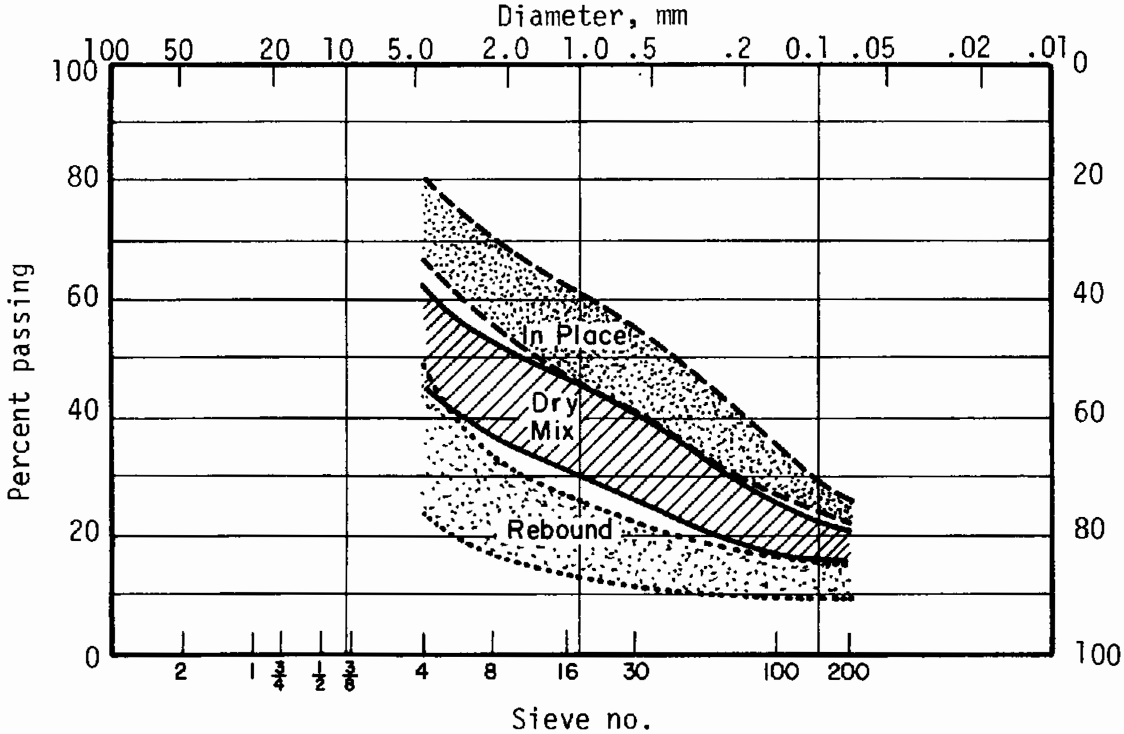


FIG. 6.4 ESTIMATED ENVELOPES OF GRADATION CURVES FOR IN-PLACE, DRY-MIX, AND REBOUND

dry mix, for in-place, and for rebound samples. The end points at the No. 4 and No. 200 sieves represent the measured ranges for the gravel content and cement content respectively. The shapes of the curves are estimated from a few samples with intermediate sieve data.

The measured gradation data were expected to agree fairly closely with the calculated data from the design mix, but for reasons yet unexplained the average measured percentage of coarse aggregate (No. 4 sieve) in the dry mix was about 10 to 15 percentage points coarser than the calculated data in Fig. 6.3 predict. Yet, about 200 tests on 15 mixes were used to establish end points of the envelopes. Many hypotheses have been considered to explain this anomaly including incorrect aggregate gradations, errors in batching causing excessive coarse aggregate, bias in taking samples of dry mix and fresh shotcrete, and errors in the determination of the gradation of fresh samples. None of these hypotheses adequately explain the differences, especially since the scales had been calibrated, there was a full-time inspector at the batch plant, and a good correlation between batched and measured percentages has already been demonstrated with the water and cement contents. The effect of mixing was not measured directly but is not expected to make the mix coarser; Studebaker (1939) reported breakdown of aggregate making the mix finer.

Because the bands for dry mix, in-place, and rebound are narrow and in the absence of a satisfactory explanation other than errors in the original gradation curve, gross errors in batching, or segregation of the dry mix before shooting, the measured samples will be assumed to be satisfactory at least for purposes of the following discussion.

Figure 6.4 illustrates that the in-place shotcrete is not as coarse as the dry mix and that the rebound is much coarser than both dry mix and in-place shotcrete. Gravel is defined as material that will not pass the No. 4 sieve (4.76 mm). The gravel contents for dry mix, in-place, and rebound samples of all mixes are summarized in Table 6.7.

The scatter of all of the dry mix, in-place, and rebound samples was about 20 percent within each category. The average gravel contents are summarized below:

Dry Mix	$\simeq$	44%
In-Place	$\simeq$	32%
Rebound	$\simeq$	66%

It can be seen that in terms of percentage the in-place shotcrete had less gravel while the rebound material contained considerably more gravel compared to the dry mix.

These trends are consistent with observations by others (Studebaker, 1939; Kobler, 1966; Litvin and Shideler, 1966), and with present models for the mechanisms of rebound. Clearly the coarser particles are more prone to rebound, especially during the initial stage of shooting against a bare rock wall. The gradation of the rebound samples confirms this observation. Several samples were taken at various locations of the rebound pile (near and far, and bottom and top tarps) but there were too few samples and too much scatter in those samples obtained to establish any clear trends. Almost total segregation of the mix occurs during rebound of the particles since they bounce off individually at different speeds and directions.

TABLE 6.7

GRAVEL CONTENT IN FRESH SHOTCRETE SAMPLES

Mix	Gravel content, %[1]		
	Dry mix	In-place	Rebound
23	54	36	64
24	46	29	59
25	45	38	76
26	49	36	71
28	52	26	64
29	44	36	--
30	43	39	--
31	33	27	51
33	--	19	67
33A	39	28	69
34[2]	--	21	58
38	44	34	70
39	43	29	--
40	44	41	75
42	41	27	70
45	--	38	62
Range	33-54	19-41	51-76
Average (excluding Mix 34)	44.4	31.5	65.8

[1] Gravel content is defined as percentage of total dry weight of sample, including cement and fibers, that was retained on No. 4 sieve. It should not be confused with % coarse aggregate.

[2] Mix 34 batched with reduced % coarse aggregate.

6.4.6 FIBER CONTENT

Substantial rebound losses of steel fiber were noticed during shooting. Fiber was batched at a calculated rate of about 3.6 percent by total dry batch weight in all fiber mixes except one. This 3.6 percent by weight corresponds closely to about 1 percent by total volume. To determine the effect of lower percentage of fiber, Mix 40 was batched with only 1.8 percent by weight which is a nominal 1/2 percent by volume.

The measured fiber contents of the fresh samples of dry mix, in-place, and rebound samples are compared with the calculated fiber contents in Table 6.8. This data will be evaluated in detail together with other data assembled about steel fiber shotcrete in Chapter 7. Nevertheless, it is important to note that during the time the shotcrete was built up, only about 2/3 of the batched fibers were retained in the wall and the remaining 1/3 rebounded. Even a larger number of fibers are lost before the initial critical thickness is established, but these losses cannot be evaluated by in-place sampling.

TABLE 6.8

AVERAGE FIBER CONTENT--DAYS III AND IV

Mix designation	Type of sample			
	Batched	Dry mix	In-place	Rebound
33-7-1/2I-60S-1US	3.5	-	2.4	2.5
33A-7-1/2I-100L-1US	3.6	2.4	1.2	3.9
34-7-1/2I-60S-1US-25CA	3.6	-	1.9	3.8
38-8-1/2I-100L-1US	3.5	3.6	2.5	2.6
39-7-1/2I-100L-1US	3.6	2.2	2.6	-
40-7I-100L-1/2US	1.8	2.3	1.1	1.6
42-10-1/2R-100L-1US	3.6	3.0	3.1	2.0
45-7-1/2I-100L-1NS	3.8	-	2.0	5.0
Average (excluding Mix 40)	3.60	2.70	2.24	3.30

NOTE: Fiber content is expressed as a percent of the total dry weight of the sample or batch.

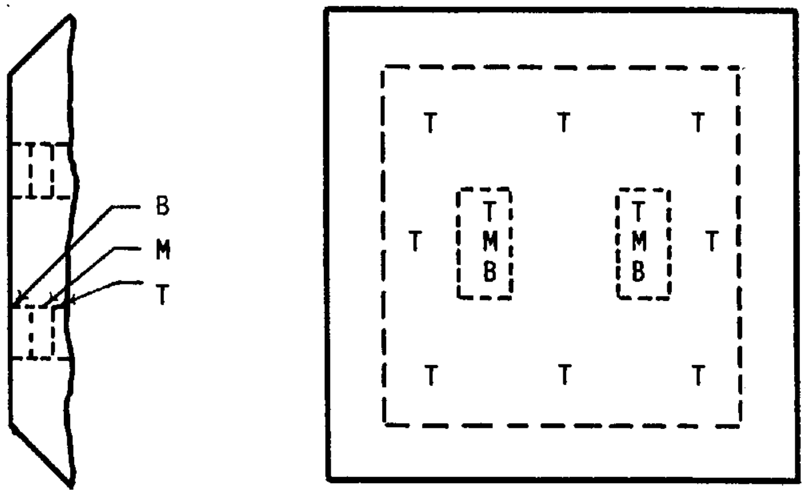
There are many reasons for substantial scatter in the determination of fiber content by the fresh samples. Fibers tend to clump together and thus when looking at any small sample there may be either an excess or a depletion of fibers, though the distribution on a larger scale may be fairly uniform. The relative weight of the fibers and their behavior in a mix are such that they tend to segregate from the rest of the mix. Finally, there are relatively few fibers in each bottle and the percentages are small fractions of larger quantities. All the above phenomena lead to scatter.

The fresh samples also proved very useful in tracking down the cause of the severe bending of fibers. At first it was thought that the bending was caused by the shooting operation. However, it was found that the fibers in the fresh samples of dry mix were also bent so that the cause was either associated with mixing or transporting the fibers. It has been concluded that fibers were bent by the paddle wheels of the pug-mill mixer.

6.4.7 VARIATIONS OF PHYSICAL PROPERTIES

Selected mixes were subjected to a comprehensive sampling program to determine possible variations in the physical properties of fresh in-place shotcrete. One panel from each of Mixes 23, 25, 39 and 45 was sampled as illustrated in Fig. 6.5a. Fourteen samples were obtained from each of these panels; 10 from the outer 1/3 of the thickness of the panel, 2 from the middle 1/3 of the thickness, and 2 from the bottom 1/3 of the thickness.

No locational trends were evident other than general scatter and variation. Results from Mix 25 are presented as a typical example in Fig. 6.5b.



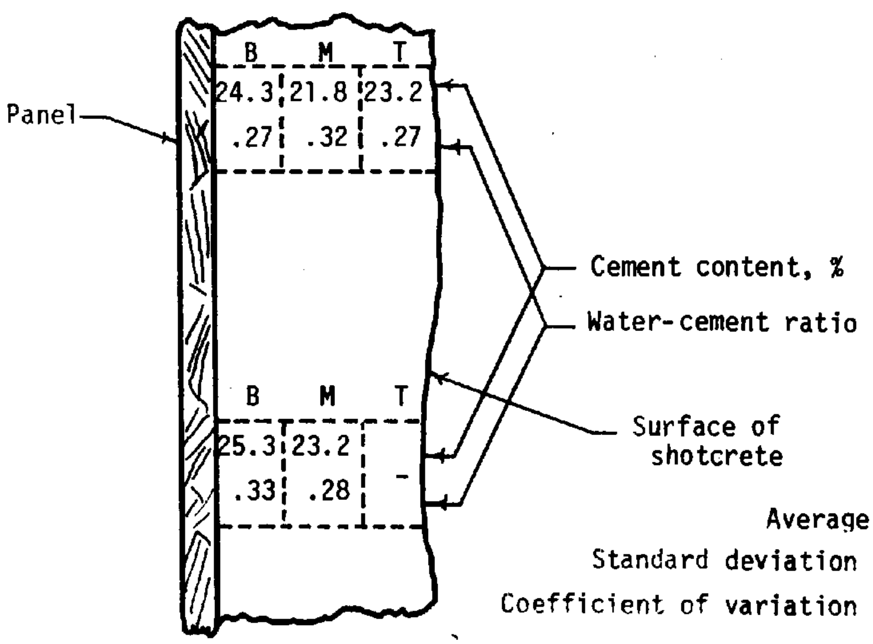
Legend:

T: Sample from outer third of thickness

M: Sample from middle third

B: Sample from bottom third

a) Locations of fresh samples on comprehensive panels



Tabulation of all samples from outer third of thickness of one panel

	Cement, %	Water-cement ratio
	24.9	.28
	25.7	.28
	25.3	.26
	24.4	.32
	23.6	.32
	24.7	.30
	23.8	.28
	23.2	.27
Average	24.45%	0.289
Standard deviation	± 0.87	±0.023
Coefficient of variation	3.56	7.96

b) Results from comprehensive sampling of mix 25

FIG. 6.5 TYPICAL RESULTS OF COMPREHENSIVE SAMPLING OF SINGLE PANEL

The water cement ratio for all 10 samples taken from the outer one third of the panel ranged from 0.26 to 0.32; the average was 0.29 with a standard deviation of ±0.023. Its coefficient of variation is 8 percent. Such variations should be expected in dry mix shotcrete but these variations are no greater than one might expect from field tests since they include both variations in material properties and test errors.

The cross section through the thickness of the panel illustrates the variations of the cement and water-cement ratio with thickness. No consistent trends were observed. Much more precise sampling would be required to delineate the thin cement-rich layer at the interface between the panel and the shotcrete.

6.5 ILLUSTRATION OF CONTINUITY CONCEPT IN DRY-MIX SHOTCRETE

6.5.1 INTRODUCTION

The basic purpose of this section is a better understanding of the magnitudes and percentages of each constituent at the four stages of shooting: 1) dry mix in the hose, 2) airstream after the addition of water, 3) in-place, and 4) rebound. A hypothetical mix will be analyzed and discussed in terms of each constituent of the mix at each of these four stages of shooting. The analysis assumes that the total weight of each constituent in the dry mix can be accounted for in all subsequent stages of shooting. It has been shown in Fig. 6.1 that, in actuality, the material in the hose and thus in the airstream is a pulsating quantity. To simplify this illustration the material delivery rate is assumed to be constant and uniform. Although, in reality, there are losses, such as the atomization of water in the airstream and in the collection of rebound, they will not be considered here since the discussion is primarily to illustrate the concept. However, the concept could be modified to include losses at any or all stages.

6.5.2 HYPOTHETICAL MIX

A hypothetical mix which behaves during shooting in a manner similar to the mixes shot for this program will be used for illustration. The batch weights for this hypothetical mix are shown in Table 6.9 which also presents the entire example problem. Table 6.9 presents a reasonable assumption for the distribution of the constituents in the mix at each of four stages of shooting as follows:

I Batch Weights and Dry Mix in Hose

II Airstream

III In-Place

IV Rebound

In addition to its hypothetical weight, each constituent at each stage also is expressed first as a percentage of the total batch weight on line 2 and then as a percentage of the dry weight of the batch on line 3. Each constituent at each stage is expressed in these three ways. Up to now, all parameters have been in terms of a percentage of the dry total weight (line 3) but it is helpful in this case to also look at the percentages in terms of total weight.

In section I of Table 6.9, the batch weights and aggregate moisture conditions are the exact weights batched for the standard mix during Days III and IV. Although the mix used fine aggregate and coarse aggregate in equal proportions, some of the fine aggregate was retained on the No. 4 sieve

TABLE 6.9

ILLUSTRATION OF CONTINUITY CONCEPT

	Dry constituents				Water			
	Cement	Sand	Gravel	Total dry wt	In aggregate	Added at nozzle	Total	Total Weight
I. Batch Weights (Also Assumed = Distribution in Hose)								
Wt, lb	705	1305	1644	3654	151	0	151	3805
% Total Wt	18.5	34.3	43.2	96.0	4.0	0	4.0	100
% Dry Wt	19.3[1]	35.7	45.0[2]	100	4.1	0	4.1[3]	104
II. Airstream								
Wt, lb	705	1305	1644	3654	151	92	243	3897
% Total Wt	18.1	33.5	42.2	93.8	3.9	2.4	6.2	100
% Dry Wt	19.3[1]	35.7	45.0[2]	100	4.1	2.5	6.6[3]	107
III. In-Place (Assume 25% Rebound)								
Wt, lb	625	1119	989	2733	--	--	190	2923
% Total Wt in Wall	21.4	38.3	33.8	93.5	--	--	6.5	100
% Dry Wt in Wall	22.9[1]	40.9	36.2[2]	100	--	--	6.9[3]	107
IV. Rebound (Assume 25% Rebound)								
Wt, lb	80	186	655	921	--	--	53	974
% Total Wt of Rebound	8.2	19.1	67.2	94.6	--	--	5.4	100
% Dry Wt of Rebound	8.7[1]	20.2	71.1[2]	100	--	--	5.7[3]	106
III + IV = II								
Wt, lb	705	1305	1644	3654			243	3897

[1] Called "cement content" in this chapter.
[2] Called "gravel content" in this chapter.
[3] Called "water content" in this chapter.

(definition used for gravel size), some of the coarse aggregate passed the No. 4 sieve, and each had different moisture contents. When everything is accounted for, there was 1305 lb (592 kg) of sand-sized material passing the No. 4 sieve and 1644 lb (746 kg) of gravel-sized material retained on the No. 4 sieve. The water shown is that which is actually present in the total amount of aggregate batched. Thus, section I of Table 6.9 represents an actual distribution as it was shot and as such they are real, not assumed values. It is assumed that there are no losses after batching and the same average distribution is valid for the dry mix in the hose.

Those values with the number 1 footnote represent the "cement content" as has been defined and used in this chapter; footnote 2 represents gravel content, and footnote 3 represents water content in a similar manner. Section II of Table 6.9 reflects only the addition of an amount of water typically added at the nozzle so that it includes all material in the airstream.

Sections III (In-Place) and IV (Rebound) were calculated from the data in section II by assuming typical water contents, cement contents, and gravel contents, that are approximately the average values measured on this project. In every category, the sum of the value in III and IV adds up to the weight in the airstream and reflects the idealized condition of no losses. It was further assumed in this calculation that 25 percent rebound of the 3897 lb (1768 kg) in the airstream results in 2923 lb (1326 kg) on the wall and 974 lb (442 kg) in the rebound pile. Next, various values close to the measured averages for this project were assumed for water, cement, and gravel contents and adjusted by trial and error until all values satisfied continuity of flow from the airstream to the wall and into the rebound pile.

6.5.3 DISCUSSION

While it is true that the numbers will change if a different average rebound percentage is assumed and that losses will affect the absolute and relative magnitudes of the various constituents shown in sections III and IV of Table 6.9, it has been demonstrated that by using typical values for cement, water, and gravel contents, etc., the weights of each constitutent can be accounted for at all stages in the shooting process. The fact that continuity of weight can be maintained throughout these calculations, not just for one but for all constituents in the airstream, while still using values for rebound percentage, cement contents, water contents, and gravel contents which are close to the average values measured on this project, lends credence to the values themselves and the analyses and conclusions of this chapter. Thus, it has been shown that the values measured are not just independent measurements, but they are also related to each other in about the proper proportions as shown by the continuity calculation.

The results of this continuity analysis are illustrated graphically in Figs. 6.6 and 6.7. The weights of each constituent are drawn to linear scale for each stage of shooting in Fig. 6.6. Thus, the total length of each bar represents the total material at that stage and the length of each subdivision for a given constituent represents the actual weight of that constituent and can be compared by linear scaling to any other subdivision in the figure. Figure 6.7 illustrates the same data in terms of percentages of total weight at each stage. Thus, the total length of each bar represents 100 percent, and is the same for each stage. The relative lengths of each subdivision in each bar represents the weight of the constituent in terms

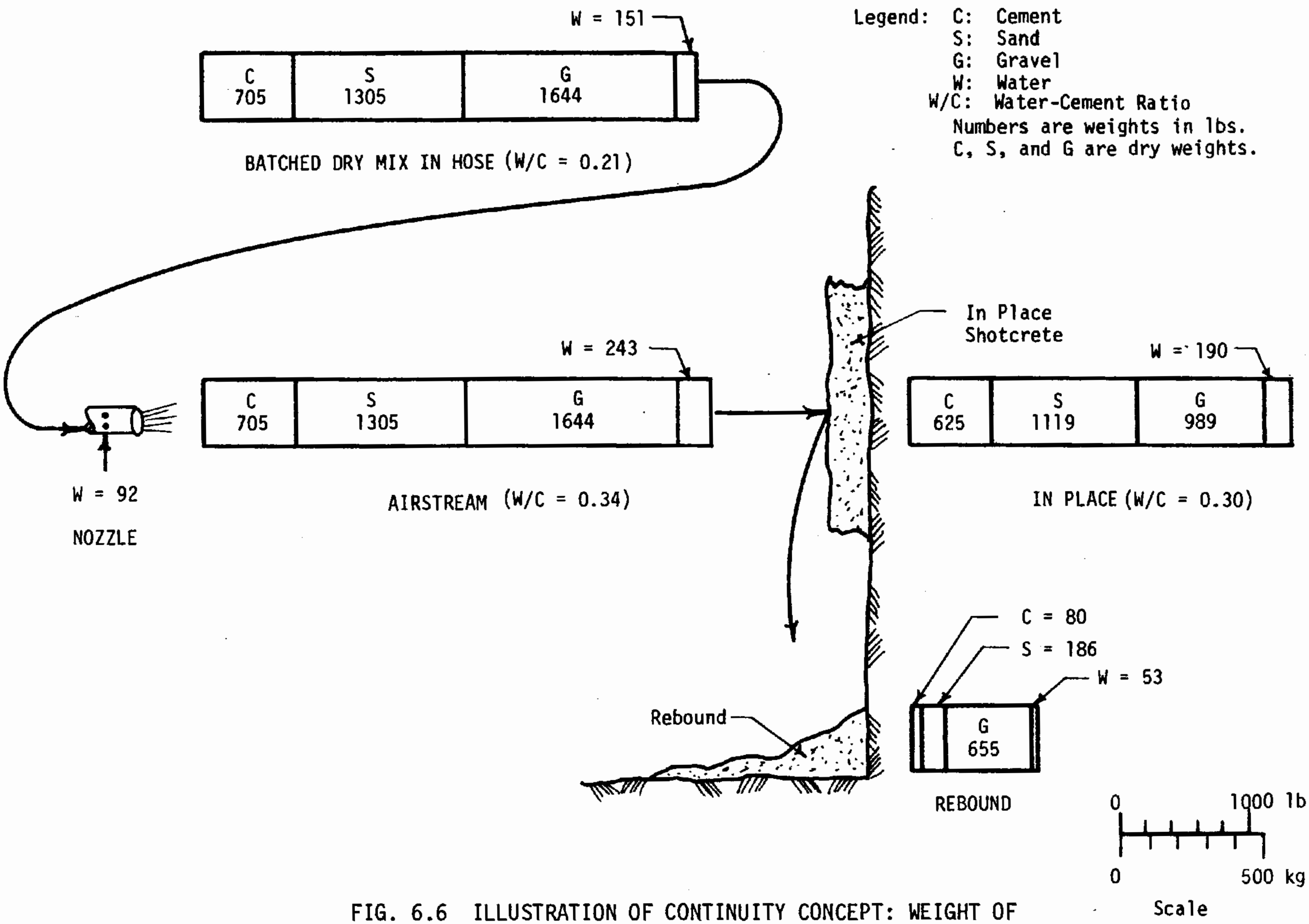


FIG. 6.6 ILLUSTRATION OF CONTINUITY CONCEPT: WEIGHT OF CONSTITUENTS AT EACH STAGE OF SHOOTING PROCESS

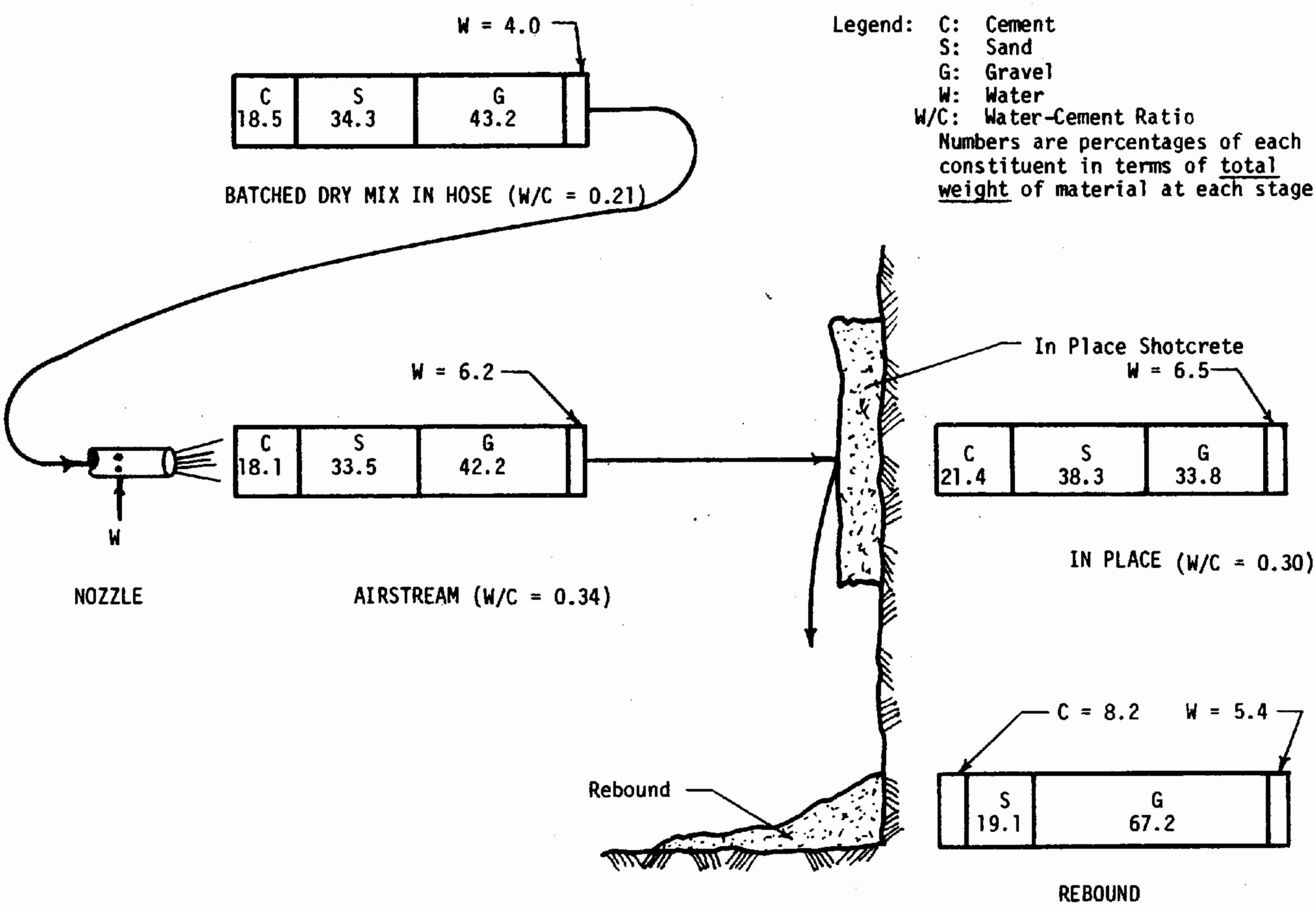


FIG. 6.7 ILLUSTRATION OF CONTINUITY CONCEPT: PERCENT OF CONSTITUENT WEIGHTS AT EACH STAGE OF SHOOTING

of a percentage of the total weight of the stage only. The length of one subdivision at one stage cannot be compared directly to another subdivision in another stage.

The study shows that, for the conditions assumed, the water-cement ratio in the airstream was higher than the water-cement ratio of the in-place shotcrete (0.34 and 0.30 respectively). The same trend was actually observed in the fresh sample results and has been observed by others (Smith and Hannant, 1970). The difference is caused by the fact that water rebounds at a greater rate than cement and this phenomenon should be considered when evaluating reported values of water-cement ratio in the literature.

A clear distinction must be made between the percent content of any constituent at any given stage (dry mix, airstream, wall or rebound pile) and the rate of rebound as given by the rebound rate ratio, RRR, of the constituent. The percent content of any constituent at any stage is the percentage of the total of all materials in that particular stage while the RRR is the ratio of the weight of the constituent at any given stage to the weight of that constituent in the airstream. The constituent gravel in the hypothetical example (Table 6.9 and Figs. 6.6 and 6.7) will be used to illustrate the difference. Gravel is 33.8 percent of a large amount of material that stays on the wall and 67.2 percent of a much smaller amount of material that rebounded. However, the 33.8 percent gravel content on the wall is 33.8 percent of three-fourths of the total of all material in the airstream, not 33.8 percent of the gravel in the airstream. In fact, 60.2 percent of the gravel in the airstream stays in the wall (YRR = 0.602, Table 6.10). The 39.8 percent (YRR = 0.398, Table 6.10) of the gravel in the airstream that rebounds is sufficient to become 67.2 percent of the relatively small total amount of materials in the rebound pile. The following discussion is concerned with the rate of rebound, RRR, of each constituent, i.e., how much of it lands in the rebound pile compared to how much of it was in the airstream.

Another useful product of this continuity analysis is the calculation of the rebound rate ratio, RRR, and yield rate ratio, YRR, for each constituent of the mix. Rebound rate ratio is the ratio between the rate of material rebounding and the rate of material being shot at any given instant. Yield rate ratio, YRR, is the comparable ratio for the material adhering to the wall (see Section 4.2.1). Table 6.10 contains the values of RRR and YRR for the individual constituents of the mix calculated from the hypothetical example of Table 6.9. These values represent the RRR and YRR after the initial critical thickness is established (see Section 4.2.2).

For this example, water rebounds at about the same rate, RRR, as the total average rate while cement and sand-sized particles rebound at a rate of about one-half the total average rebound rate. As expected, the gravel rebounds at a very high rate; about 40 percent of the gravel shot at the wall rebounds.

In conclusion, gravel has the highest rebound rate since 40 percent will become rebound; in terms of yield, only 60 percent of the gravel shot will end up in the wall. The rebound rates of individual constituents is also discussed in Chapters 4 and 5. It has been known for years that the reduction of rebound of gravel-sized particles is an important goal.

It should be remembered that this analysis is for conditions after the critical initial layer is established as discussed in Chapter 4. At the beginning of shooting, 100 percent of nearly every constituent rebounds, then the rebound rate ratio for each constituent drops to values approximating those in Table 6.10.

TABLE 6.10

AVERAGE YIELD AND REBOUND PERCENTAGES
OF EACH CONSTITUENT: HYPOTHETICAL EXAMPLE

	Cement	Sand	Gravel	Dry weight	Water	Total weight
Weight in airstream,						
lb (kg)	705 (320)	1305 (592)	1644 (746)	3654 (1658)	243 (110)	3897 (1768)
Weight in rebound						
lb (kg)	80 (36)	186 (84)	655 (297)	921 (418)	53 (24)	974 (442)
Rebound rate ratio, RRR						
	0.113	0.142	0.398	0.252	0.218	0.250
Yield rate ratio, YRR						
	0.887	0.858	0.602	0.748	0.782	0.750

Notes: 1) Ratios (RRR and YRR) are based upon weight of each constituent in airstream
2) Rebound Rate Ratio, RRR, and Yield Rate Ratio, YRR, are applicable only after the initial critical thickness is established (see Section 4.4.2).

6.6 DISCUSSION AND CONCLUSIONS

Procedures for analysis of fresh samples of shotcrete have been developed which appear to work well. Methods of analysis of constituents in shotcrete are not new, Studebaker (1939) used the familiar Dunagan test to analyze fine aggregate shotcrete. Also the test was used to evaluate the studies reported by Litvin and Shideler (1966). A major variation from the Dunagan test procedure (Dunagan, 1931) is the use of the methyl alcohol to inhibit hydration so that the analysis need not be performed immediately after collection of the sample.

The use of methyl alcohol did inhibit most of the tendency of the cement to hydrate but a moderate amount of cement still adhered as a surface coat on individual sand and gravel particles. This made an extra step of washing in hydrochloric acid necessary to determine cement contents accurately.

Furthermore, the accuracy of the water content determinations are affected since the calculation of the water content is a function of the difference of two relatively large numbers. In view of these problems other methods of analysis should be tried or improvements should be made in these techniques. Several new techniques have been developed or improved recently for the concrete industry and may be applicable to shotcrete.

Despite these problems the tests and methods worked well in the field and reasonable results were obtained. Differences between the average values of mixes were observed and explained and an apparent error in batching was discovered.

Absolute values of the percentage of each constituent were determined at each stage of the shotcrete operation. These measured values were shown to be reasonable by a continuity analysis. The numerical values from this study verify and quantify conclusions and observations made over the years by those in the industry such as, for example, that there is an enrichment of cement on the wall and that most of the rebound is coarse aggregate.

The average or typical values of the parameters measured in the fresh-sample study are summarized in Table 6.11. The average water-cement ratio was 0.30 for the conditions of this test. Many mixes had a water-cement ratio close to this average despite wide variations in mix design and shooting conditions. This is partly due to the fact that the nozzleman was consistent in his shooting and partly due to the facts that shooting and mix conditions are not only interrelated, but they are also self-compensating. Water-cement ratio appears to be a dependent variable. Data from this study are compared to the water-cement ratio reported in the literature in Table 6.12.

Average cement content increased from 19 percent in the dry mix to 24 percent in-place, an equivalent increase of about 2 bags per cu yd (110 kg/m^3). Only 12 percent of the rebound was cement. Gravel content decreased from an average of 44 percent in the dry mix to about 32 percent in-place while about 66 percent of the rebound was gravel-sized particles. Only about two-thirds of the batched fibers were retained in the wall. Additional fibers are lost in rebound before the initial critical layer is established. A large number of samples were obtained from a single panel to evaluate the variability of shotcrete. The coefficients of variations of the parameters were typically 5 to 10 percent, which indicates good control for field-type operations and indicates that in spite of the tendency for dry mix shotcrete to be variable, good quality shotcrete is not as variable as expected.

A continuity analysis of a typical mix was conducted assuming that the total weight of each of the constituents can be accounted for throughout all stages of shooting. The analysis confirmed the results of the

TABLE 6.11

SUMMARY OF AVERAGE MEASURED VALUES FOR THIS PROJECT

	Water content	Cement content By dry wt	Cement content Equivalent bags/yd^3	Cement content Equivalent kg/m^3	Water-cement ratio	Gravel content
Dry mix	4.0%	19%	7.5	(420)	0.2	44%
In-place	7.5%	24%	9.3	(520)	0.30	32%
Rebound	4.5%	12%	4.5	(250)	---	66%

NOTE: Percentages based upon dry weight of all constituents in mix.

TABLE 6.12

SUMMARY OF REPORTED VALUES OF WATER-CEMENT RATIO FOR COARSE AGGREGATE DRY-MIX SHOTCRETE

Source	Water-cement ratio
Reported Ranges	
Kobler (1966)	0.32-0.40
Reading (1966)	0.35-0.50
Brekke (1972)	0.35-0.50
Measured Data	
Litvin and Shideler (1966)[1]	0.26-0.38
Bortz, et al., (1973)[2]	0.34-0.46
Corps (1974)	0.35-0.66
This Project	
Measured in fresh samples[1]	0.26-0.34
Calculated from batch weights and metered water[2]	0.26-0.41

[1] Measured in fresh-samples of coarse aggregate shotcrete.

[2] Calculated from batch weights and metered nozzle water for mixes containing 7 to 8 bags of cement/yd^3 (390-445 kg/m^3).

fresh-sample study and permitted reasonable numerical estimates to be made of the rate of rebound of each constituent. For the example given, total rebound of all constituents was assumed to be 25 percent and the rebound rate ratio, RRR, was calculated to be 0.11 for cement, 0.14 for sand, 0.40 for gravel, and 0.22 for water. Because water rebounds at a greater rate than cement, the water-cement ratio in place is less than the water-cement ratio in the airstream (0.30 vs 0.34 respectively for this example), a phenomenon that should be considered when estimating water-cement ratio from metered nozzle water data.

CHAPTER 7

FIBER RETENTION AND ORIENTATION

7.1 INTRODUCTION

Steel fiber shotcrete is a relatively new material, so there are few studies that document its physical properties and the customary variations in those physical properties. Data on steel fiber shotcrete is contained in papers by Poad and Serbousek (1972), Kaden (1974a, 1974b), Chrionis (1974), Poad et al., (1975), Henager (1975) and Ryan (1975). However, they treat fine aggregate steel fiber shotcrete rather than the coarse aggregate shotcrete, the subject of this study. This chapter contains an evaluation of those physical properties peculiar to steel fiber shotcrete; particularly the amount, distribution and orientation of the fibers. Strength of steel fiber shotcrete is evaluated and compared to the strength of other mixes in Chapters 9 through 13.

Some aspects, such as the amount of fiber in the samples and the distribution of fiber within the samples, are relatively obvious and easy to evaluate. Other aspects such as the orientation of fibers, shrinkage or corrosion potential, and the potential interference the fibers themselves cause to the compaction process are not as obvious nor as easy to evaluate. Shrinkage and the corrosion potential of the fibers was not a part of this study; indeed, very little data exists for these subjects, even for steel fiber concrete.

Because of the presence of the fibers, the physical properties of the mix are more anisotropic and have a greater variation than ordinarily observed for shotcrete. Batching of steel fiber shotcrete is very difficult since usual procedures cause many of the fibers to entangle themselves into small balls. The high specific gravity of the fibers and their very different kinematic behavior compared to subrounded sand and gravel tend to promote segregation of the fibers. For the same reasons, the shooting of steel fibers tends to cause uneven distribution and anisotropic physical properties. On this project, many of the fibers were bent by the fast rotating blades of the pug-mill mixer. This bending reduced the effectiveness of the fibers in modifying the physical properties of the shotcrete.

Unless otherwise specified, all measured fiber contents in this report are in terms of dry weight of the sample. However, customary American practice for steel fiber concrete is to report fiber content as a percentage by volume rather than weight. All steel fiber mixes for this project were batched with steel fiber at about 3.6 percent by weight which corresponds to an equivalent nominal 1 percent by volume, a very common fiber content in the steel fiber concrete industry. Mix 40 was the only mix batched with half as many fibers, 1.8 percent by weight (nominal 1/2 percent by volume).

7.2 AMOUNT OF FIBER RETAINED IN THE WALL

7.2.1 MEASUREMENTS OF FIBER CONTENT FROM IN-PLACE SAMPLES

Fiber mixes were subjected to three independent methods for determining fiber content: 1) counting fibers exposed on cut surfaces; 2) recovering all fibers from pulverized samples of hardened shotcrete of known weight and volume; and 3) analysis of fresh shotcrete samples.

Counting of fibers exposed on cut faces is a relatively easy means for qualitatively evaluating relative fiber contents; selected results are

TABLE 7.1

SELECTED FIBER COUNT RESULTS

Mix No.	Sample # 1	2	3	4	5	6	Weighted Mix Average No./in.^{2}	(No./cm^2)
			Fiber Count Per Unit Area					
I	MIXES BATCHED WITH ONE PERCENT USS FIBER BY VOLUME							
5	12.7	8.1	8.6	9.4	11.3	10.6	10.1	(1.6)
33	13.8	11.4	11.2	13.8	16.0	15.4	13.8	(2.1)
33A	13.0	8.6					10.8	(1.7)
34	15.5	14.5	10.6				13.5	(2.1)
38	10.2	10.5					10.4	(1.6)
39	17.4	15.2					16.3	(2.5)
42	10.5	10.7	14.0	12.2			11.9	(1.8)
						Average	12.4	(1.9)
II	MIX BATCHED WITH ABOUT ONE PERCENT NSS FIBER BY VOLUME							
6	13.4	15.7	16.0	20.3	16.0	14.9	16.0	(2.5)
III	MIX BATCHED WITH ONE-HALF PERCENT USS FIBER BY VOLUME							
40	7.7	7.4			6.6		7.6	(1.2)

given in Table 7.1. An illustration of this fiber count program is given in the discussion of fiber orientation in Section 7.4. Only fiber counts from side or end cuts of the samples are reported here since fiber counts on the top of samples are much lower because of their preferred orientation in the plane of the wall.

The range of average fiber counts was considerable. For USS fibers batched at 1 percent by volume, fiber counts range from 10.1 to 16.3 fibers per in.^{2} (1.6 to 2.5 per cm^2) with an average of 12.4 per in.^{2} (1.9 per cm^2). Mix 40, shot with half the fibers, had about half the fiber count. The NSS fibers are slightly finer and lighter than the USS fibers so there are more fibers per unit weight. For any given weight of fibers, there should be about 10 percent more NSS fibers.

The fiber counts can be related in a general way to a percentage of fiber in the in-place shotcrete. This relationship was found by subjecting 18 samples whose cut faces were already counted to the following procedure: 1) weigh and measure intact sample; 2) pulverize sample carefully with lead hammer; 3) remove fibers from debris with magnet and weigh; 4) calculate ratio between weight of fibers and total weight; and 5) correlate to fiber count. The results of this program are contained in Table 7.2. The average fiber content of all the pulverized samples (except Mix 40 which was batched with only half as many fibers) was 2.2 percent by weight; the batched percentage was about 3.6 percent by weight (1 percent by volume).

The number of fibers per square inch that corresponds to 1 percent fiber content by weight shown in the last column of Table 7.2 was obtained by dividing the average fiber count by the percent fiber measured upon pulverizing. The number of fibers per square inch per one percent fiber content varied considerably between mixes ranging from 3.94 to 7.21 (0.61 to 1.12 per cm^2); the average was 5.5 fibers per square inch (0.86 per cm^2). Other correlations are necessary for the NSS fibers which are lighter. These correlations are considered to be estimates for conditions in this project only; other projects should make similar correlations in the future.

TABLE 7.2

FIBER CONTENT OF PULVERIZED SAMPLES

Mix Designation	Average Measured Fiber Content in Pulverized Samples, % by weight	Average Fiber Count of Pulverized Samples, No./in.^{2} (No./cm^2)	Average No. Fibers for 1% by Weight	
			No./in.^{2}	No./cm^2
33	2.30	13.7 (2.1)	5.96	0.92
33A	1.88	10.8 (1.7)	5.74	0.89
34	2.08	15.0 (2.3)	7.21	1.12
38	2.20	10.3 (1.6)	4.68	0.72
39	2.82	16.3 (2.5)	5.78	0.89
40*	1.43	7.6 (1.2)	5.34	0.82
42	2.82	11.1 (1.7)	3.94	0.61
Average of all mixes except Mix 40	2.22	Average of all mixes	5.52	0.86

* Batched with half as many fibers.

The factor between fiber counts and fiber content generally ranged from 5 to 6 fibers per in.^{2} (.8 to .9 fibers/cm^2) per 1% fiber content. However, the factors were substantially different for 2 mixes; Mix 34 and Mix 42. Mix 34 had a factor of 7.21 fibers per square inch (1.12 fibers per cm^2) for 1% fiber. This implies that a greater percentage of fibers were exposed on the cut faces. This mix had high accelerator content and was batched with only 25% coarse aggregate. Most likely the low percentage of coarse aggregate was responsible for the high factor. It is physically impossible for fibers to occupy the same space as aggregates. When there is a lower percentage of coarse material, there is a better chance for fibers to be exposed on cut surfaces.

Mix 42 had a factor of 3.94 fibers per in.^{2} (0.6 fibers per cm^2) for 1% fiber. This mix was shot with regulated-set cement at a very high cement content. It was also the mix which retained the highest percentage of fibers.

Fiber counts were made on several other samples in addition to those pulverized. The averages of fiber counts and the corresponding estimated fiber content for each mix, based upon the correlation for that specific mix established in Table 7.2, were calculated (see Table 7.3). Finally, fiber content was measured in the fresh shotcrete samples. These data were presented in Section 6.4.6 and will be evaluated in Section 7.2.2.

7.2.2 DISCUSSION OF FIBER RETENTION

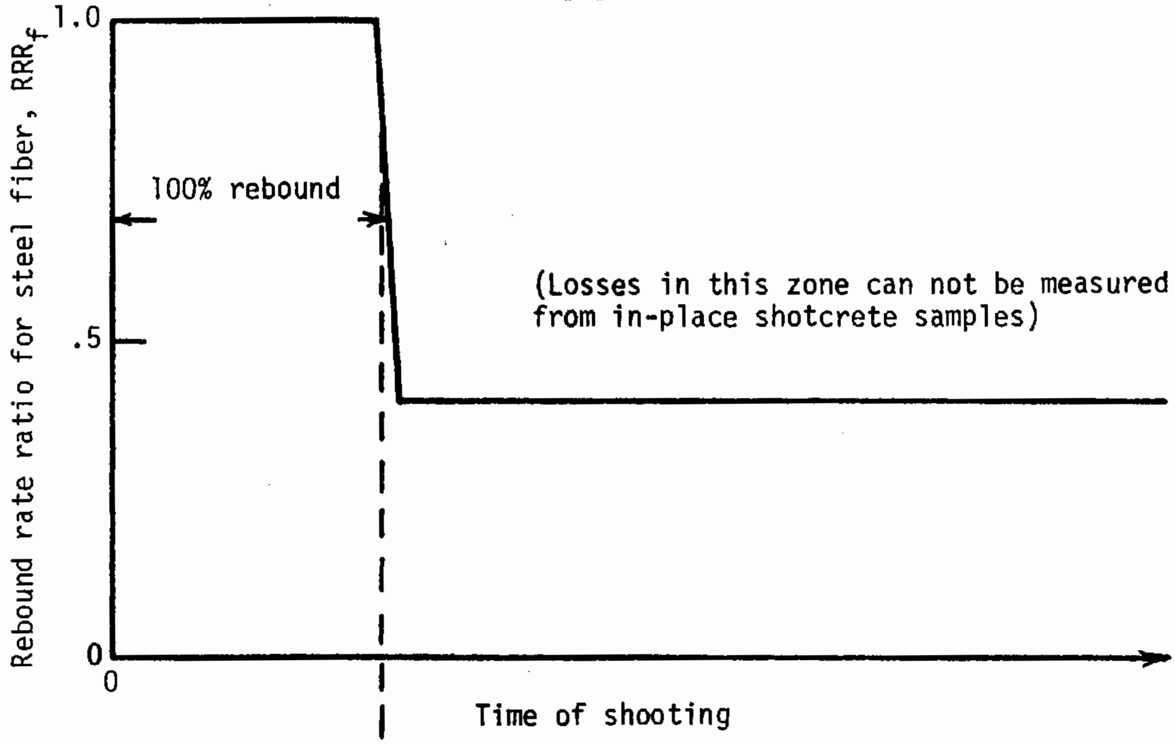
GENERAL

There are two major related consequences of fiber loss. First, there must be a certain minimum fiber content so that the fibers can provide the desired crack-arrest mechanism and post-crack resistance. Second, such high losses of about 50 percent of steel fiber pose a severe economic problem for the practical use of steel fiber shotcrete. The purpose of this chapter is to evaluate the physical characteristics of steel fiber shotcrete. However, excess rebound of fiber affects the physical properties significantly and it is important to determine what factors tend to increase fiber retention.

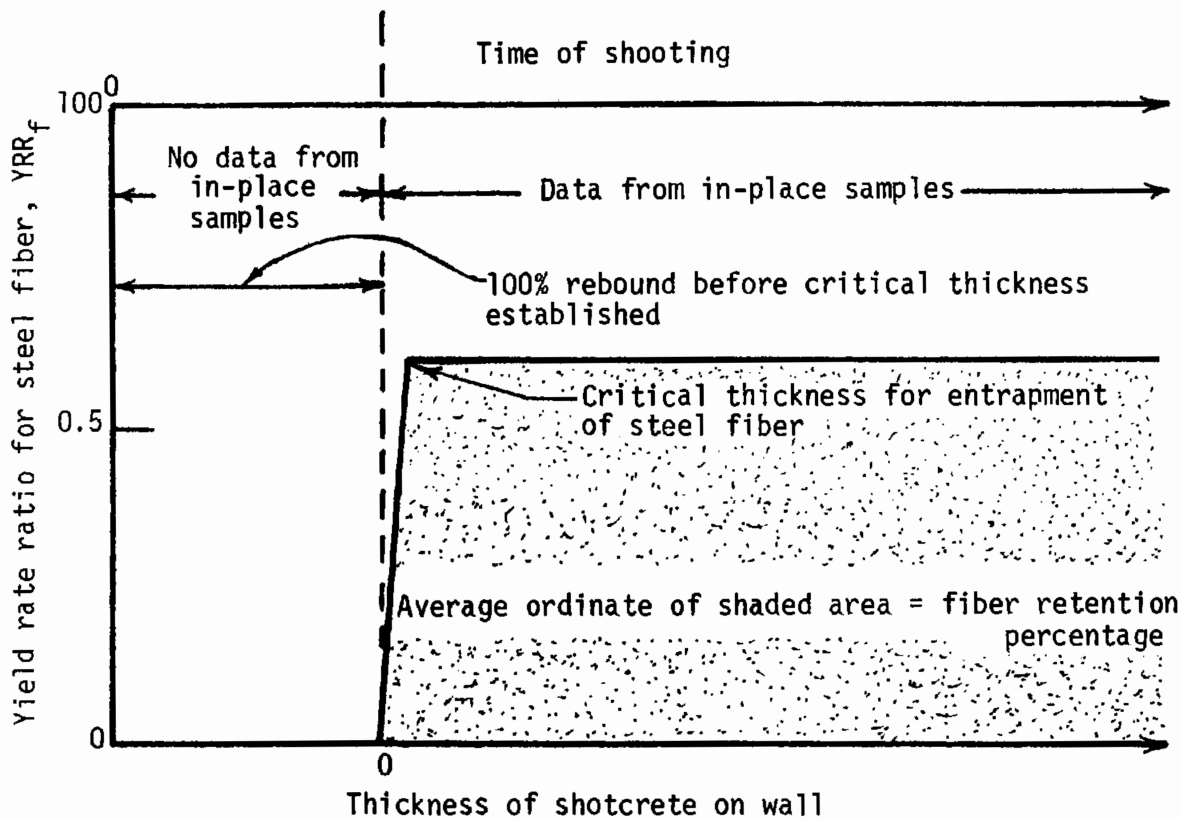
DIFFERENT METHODS OF EVALUATION

When evaluating fiber retention, two different problems must be considered, 1) the total economics associated with all losses, and 2) the losses that affect the physical properties. These must be treated separately. For the economics of fiber shotcrete, total losses, including those before the critical thickness is established, are important. For consideration of the physical properties, only those losses that occur after the critical thickness is established are important since they affect the strength of the shotcrete.

The rebound characteristics of fiber probably have a similar behavior to the rebound characteristics of the entire mix. Probably all of the fibers rebound during the first few seconds of shooting against a bare rock wall until the critical thickness of paste is established as shown in Fig. 7.1a. Once the critical thickness is established, the Rebound Rate (RR_f) and Rebound Rate Ratio (RRR_f) of the fibers probably reduce significantly; a corresponding increase in the Yield Rate Ratio (YRR_f) results. A detailed discussion of this phenomenon is contained in Chapter 4.



a) Idealized rebound of steel fiber vs time of shooting



b) Composite idealized yield rate rate for steel fiber vs time of shooting and thickness

FIG. 7.1 IDEALIZED REBOUND BEHAVIOR OF STEEL FIBERS

It is important to recognize that these high fiber losses at the beginning of shooting were not measured directly because there was an important difference between the way fiber retention was measured and the way total rebound was measured. The total rebound measurements were made by collecting all materials that rebounded during the total time of shooting, including the time of exceptionally high rebound before establishing the critical layer. On the other hand, the fiber retention was measured from in-place specimens and, thus, they represent a direct measurement of the number of fibers present in the in-place shotcrete after the critical thickness was established. They do not include the losses that occurred while the critical thickness of paste was being established. The fiber percentage in-place described in this section is relevant to the physical properties of the shotcrete. A percentage loss can be calculated from these data but the actual losses from an economic standpoint can be expected to be 10-20% higher.

GENERAL REBOUND BEHAVIOR

It appears that only a very thin layer of paste is necessary to entrap fibers, probably because the fibers have a relatively low "effective thickness". Following the establishment of the critical layer thickness, the rate of entrapment is probably more or less constant with thickness, provided the shotcrete is built up in one pass. To put the critical thickness into perspective, it is believed to equal only a tenth of an inch, (2.5 mm) or less. Thus, the YRR_f versus thickness curve probably has a steep initial portion and a more or less flat top as shown idealized in Fig. 7.1b.

FIBER RETENTION PERCENTAGE

Data from three methods of estimating fiber content are summarized in Table 7.3. The first column of data is the estimated fiber content based upon average fiber counts and the correlation established for each mix in Table 7.2. The second column of data contains fiber contents determined by pulverizing hardened specimens; the average results of fiber contents in the fresh shotcrete samples are presented in the third column of data. The average of the results of the pulverized samples and fresh shotcrete samples is given in the next column. This average measured fiber content is divided by the calculated fiber content from batch weights to obtain the Fiber Retention Percentage, FRP. Note that the estimated fiber content from the fiber counting program was not utilized for the determination of FRP because of the large variations in fiber counts. Fiber contents should not be based solely on estimates from fiber counts. The Fiber Retention Percentage, FRP, is the average percentage of steel fiber measured in samples divided by the percentage of steel fibers batched.

$$\text{FIBER RETENTION PERCENTAGE, FRP} = \frac{\text{Percentage of Fibers in Samples}}{\text{Percentage of Fibers Batched}}$$

where:

$$\text{Percentage of Fibers in Samples} = \frac{\text{Weight of Fiber in Sample}}{\text{Total Weight of Sample}}$$

$$\text{Percentage of Fibers Batched} = \frac{\text{Weight of Fibers Batched}}{\text{Total Dry Weight of Batch}}$$

The magnitude of FRP is an indication of the effectiveness of the mix design and shooting conditions in embedding the fiber. Mix designs and shooting conditions which have a low FRP are uneconomical. For a lower FRP more

TABLE 7.3

SUMMARY OF FIBER CONTENTS IN-PLACE

Mix Designation	Estimated Fiber Content by Fiber Counts %	Measured Fiber Content, %			Calculated Batched Fiber Content, %	Fiber Retention Percentage FRP
		Pulverized Samples	Fresh Shotcrete Samples	Average of Pulverized and Fresh Samples		
5-7½I -45S-1US		-	1.8	1.80	3.1	58%
6-7½I -45S-1NS	-	-	1.8	1.80	4.1	44%
33-7½I -60S-1US	2.4	2.2	2.4	2.30	3.6	64%
33A-7½I -100S-1US	1.5	1.7	1.2	1.45	3.6	40%
34-7½I -100L-1US	2.9	2.1	1.9	2.0	3.6	56%
38-8½I -100-1US	1.9	2.2	2.5	2.35	3.5	67%
39-7½I -100L-½US	2.8	2.8	2.6	2.7	3.6	75%
40-7 I -100L-½US	1.4	1.4	1.1	1.2	1.8	67%
42-10½R-100-1US	3.0	2.8	3.1	2.9	3.3	88%
45-7½I -100L-1NS	-	-	2.0	2.0	3.6	56%
			Average Fiber Retention Rate for All Fiber Mixes			61.8%
			Average Fiber Losses as a Percentage of That Batched			38.2%

fiber must be batched to obtain a given percentage fiber in-place. Once the minimum desired fiber content in-place is determined, the amount which must be batched to obtain this desired fiber content is a function of FRP.

It can be seen in Table 7.3 that the FRP was disappointingly low. After the critical thickness was established, only 62% of the fibers in the airstream became embedded to perform a useful function. The mixes encompassed a wide range of mix designs and shooting conditions, however, and FRP ranged from 40 to 88 percent. In addition, a lot of fibers rebounded while establishing the critical thickness of paste necessary to embed and retain fibers.

HIGHEST FIBER RETENTION PERCENTAGE

Mix 42 achieved the highest fiber retention percentage of all mixes with 88%. Three factors of Mix 42 set it apart from the other mixes: 1) it used regulated-set cement instead of Type I, 2) the cement content was exceptionally high, and 3) the dry mix had begun to hydrate before shooting. The mix was batched with an estimated 985 lb (450 kg) of regulated-set cement (see Section 6.4.3), and the dry mix reached a temperature of 98°F (36.7°C before shooting. The relative roles of these factors in the high fiber retention rate is unknown. It is believed, however, that the high cement content and the high amount of nozzle water added may be major factors in the higher retention.

EFFECT OF MIX DESIGN

The cement content of the steel fiber mixes ranged from 7 to 10 1/2 bags (18 to 25% by weight). The mix with the highest cement content, Mix 42 at 25%, did have the highest FRP. Within the range of 7 to 8 1/2 bags (18 to

21%) there is no consistent trend indicating a strong dependence of FRP on cement content. The combination of high accelerator percentage (8.4%) and only 25% coarse aggregate in Mix 34 did not significantly improve the FRP either. It is possible that the mix was too active (see Chapter 9) and set too fast, thus making the mix less capable of embedding fibers. This may have masked any trends associated with lower percentage coarse aggregate.

The amount of fiber batched is generally reflected in the amount of fiber found in the wall. Mix 40, batched with one half the amount of fibers, had about one-half the amount of fibers in-place than were found in other mixes. Its FRP of 67% was comparable to other mixes.

One mix was batched with fine aggregate only (zero percent coarse aggregate) to determine if the presence of coarse aggregate significantly affected fiber retention. Unfortunately, the mix could not be shot because excess moisture in the sand would have plugged the hose.

EFFECT OF SHOOTING CONDITIONS

There was considerable scatter in the results, indicating that the detailed shooting conditions may have been more important than mix design. Three mixes, Mix 33, 33A, and 39 had identical mix designs but the FRP were 64%, 40%, and 75% respectively. In fact Mixes 33A and 39 were shot on the same day using the same nozzle, nozzle water temperature, etc. However, Mix 33A was one of the first mixes shot on Day IV and other physical properties, strength, (etc.) did not compare well with other mixes either. The implication is that the detailed shooting conditions, nozzle distance, nozzle direction, water usage, etc. are probably the important controlling factors in FRP. There appears to be some relation between nozzle type and FRP; FRP for the long nozzle was an average of about 10% higher than the FRP for the short nozzle. The long nozzle not only mixed better but also generally had higher water contents.

High moisture conditions on Day IV in the dry mix prevented lowering the air pressure to evaluate the effects of air pressure on fiber retention. On Day II, Mixes 5 and 6 were shot with 40 psi (0.28 MPa) with no significant differences in FRP noted.

EFFECT OF TYPE OF FIBER

Although the two NSS fiber mixes had the lowest retention rates, there were not enough NSS fiber shotcrete mixes to test this fiber adequately. Furthermore, there are several USS fiber mixes which have an FRP about as low as the NSS fiber mixes. The NSS fiber is stiffer and it appeared to the nozzleman to bounce back more energetically, but this may not be governed by the same factors that govern retention. There are no compelling reasons to prefer one fiber over another.

SUMMARY OF FIBER RETENTION

Although several mix and shooting conditions were changed during this project, none of these changes, except a possible substantial increase in cement content, appeared to be responsible in any consistent manner for the measured in-place fiber contents.

The Fiber Retention Percentage, FRP, ranged from 40 percent to 88 percent of the batched fiber content with an average of 62 percent.

The parameters listed below were changed in attempts to increase the fiber retention rate.

Parameter	Range
Water temperature	60 to 100°F (16 to 38°C)
Batched cement content	7 to 10 1/2 bags/cu yd (18-25%)
Batched fiber content	1.8 to 4.1% by weight
Percentage coarse aggregate	25 to 50%
Accelerator percentage	3.0 to 8.4%
Nozzle type	Long and Short
Type of fiber	USS and NSS
Air pressure	40 psi (0.28 MPa) with 50 ft (9 m) hose to 75 psi (0.5 MPa) with 150 ft (46 m) hose

Pertinent values for each mix are summarized in Table 7.4. It appears that the specific details of nozzling (angle, distance, water content, etc.) may be the controlling factors in fiber retention. This may mean that nozzlemen may have to be trained to spot and correct for excessive rebound of fibers. The mixes with higher cement content and higher water-cement ratio were generally those with higher FRP, but no consistent trend was observed. From the results of the photographic studies (Chapter 5) and other studies, it appears that anything which makes the material in the airstream more coherent or more plastic, i.e., more cement and higher water-cement ratio, should improve chances for fiber retention. There was no evidence in the photo study that coarse aggregate interferred with fiber retention. Thus, higher cement content, improved nozzle designs or shooting at the wettest stable consistency all should improve FRP. Fly ash could be substituted for some cement for economy. It is believed possible for a mix to set too fast if it contains too much cement and/or too much accelerator. Such a mix may not retain fibers well because it will not be plastic and will not be receptive to embedment of fibers.

TABLE 7.4

SUMMARY OF FACTORS AFFECTING FIBER RETENTION RATE

Mix No.	FACTORS						Fiber Retention Percentage
	Batched Fiber Content %	Measured Cement Content In-Place, %	Water-Cement Ratio	Accelerator %	Type of Fiber	Water Temp. and Nozzle °F	
I MIXES BATCHED WITH NOMINAL ONE PERCENT FIBER BY VOLUME							
5	3.1	-	-	∿ 3	USS	45S	58
6	4.1	-	-	∿ 3	NSS	45S	44
33	3.6	29.0	.26	4.9	USS	60S	64
33A	3.6	25.7	.32	3.0	USS	100L	40
34*	3.6	-	-	8.4	USS	60S	56
38	3.5	25.4	.28	3.2	USS	100L	67
39	3.6	24.8	.34	3.5	USS	100L	75
42	3.3	31.0	.33	0	USS	100L	88
45	3.6	20.2	.31	3.1	NSS	100L	56
II MIX BATCHED WITH NOMINAL ONE-HALF PERCENT FIBER BY VOLUME							
40	1.8	19.4	.36	3.0	USS	100L	67

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* Only mix with 25% coarse aggregate.

7.3 DISTRIBUTION OF FIBERS

7.3.1 INTRODUCTION

The distribution of fibers throughout the in-place shotcrete is very important if they are to be effective in improving the structural capacity. It is important to know the range of fiber contents in a given structural component, i.e., the maximum and minimum fiber contents, so that strength and post-crack resistance can be related not only to the average but also to the minimum statistically important fiber content.

The degree of uniformity in fiber distribution was determined by making numerous saw cuts through selected 2 ft x 2 ft x 3 in. (61 x 61 x 8 cm) shotcrete panels. The exposed cut surfaces were then examined to determine the uniformity of the severed fibers exposed on these faces. Figure 7.2a shows a typical set of saw cuts made through such a panel. A one-inch (2.54 cm) square grid, shown superimposed on a cut face in Fig. 7.2b, was used to divide each face into equal areas. The number of severed and exposed fibers in each unit area was then counted. It was found that fiber counts were not reliable unless the surface to be counted was a saw cut. These counts were then plotted in the form of bar charts showing the fiber counts for each inch across the cut face. In this way trends in numbers of severed fibers and thus the character of the distribution could be seen.

From this data, trends within particular samples, among samples from different panels of equal batched fiber content, and among panels from different batches were investigated. Trends observed within individual

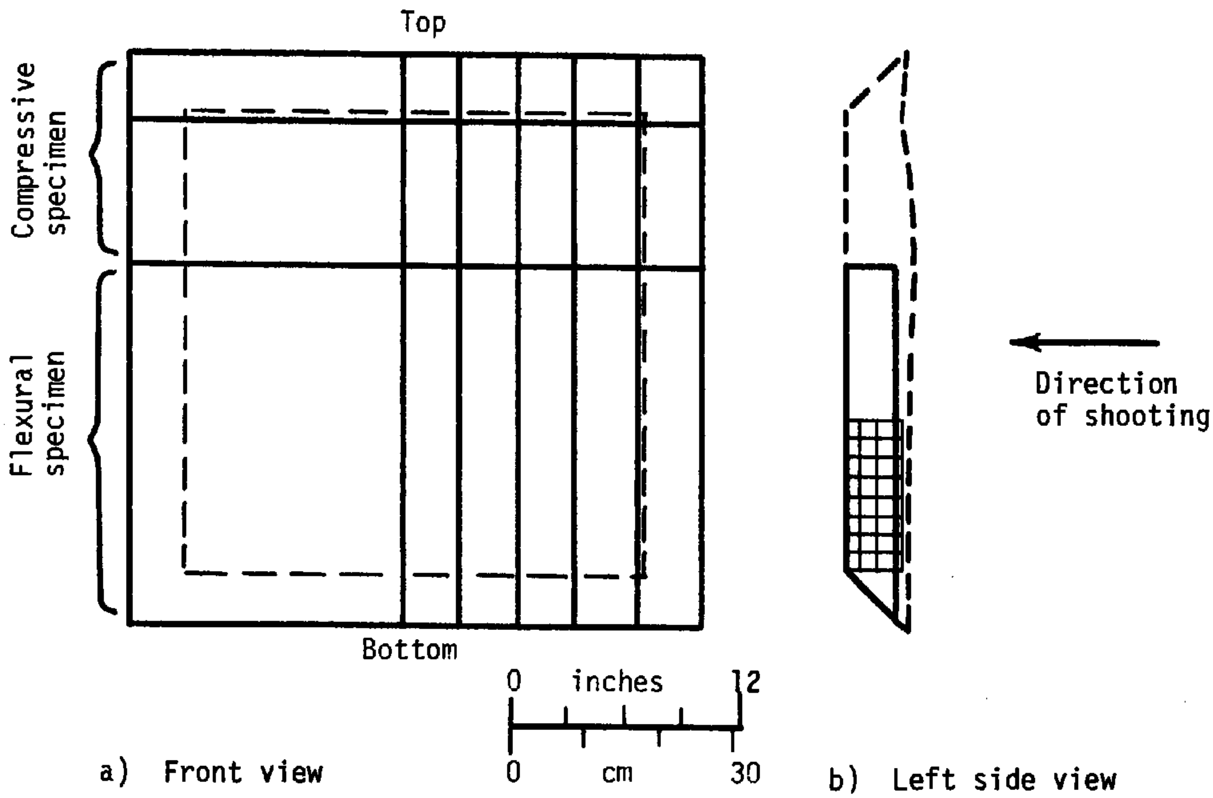


FIG. 7.2 TYPICAL SAW CUT AND GRID FOR FIBER COUNTING

samples and among samples from varying batches were considered in determining the fiber distribution in shotcrete as a material. Any trends in fiber counts among panels from shotcrete batches of differing mix proportions but identical initial fiber content were sought to determine what factors, if any, in mix proportioning would affect the percentage of retained fiber.

7.3.2 VARIATION OF FIBER DISTRIBUTION

DISTRIBUTION WITHIN A SINGLE SAMPLE

Fairly wide variations in the fiber counts are commonly found from one unit area to the next along most cut faces. Typical fiber count results are shown in Figs. 7.3 through 7.5. The square grids and the number of fibers in each grid are shown for the top, left side and end views of the samples. Figures 7.3 and 7.4 have grids with one inch (2.54 cm) dimensions while Fig. 7.5 illustrates a 1/2-inch (1.27 cm) high by 1 inch (2.54 cm) long grid. Figure 7.4 is for sample 40-1-1 which has one-half the fibers of other mixes. The average fiber counts per unit area along continuous lines along or across the grid are plotted graphically in some of the views to illustrate aspects of fiber distribution.

It was found that distribution appeared quite nonuniform when comparing fiber counts in specific adjacent unit areas of the grid. As an example, in one of the grids counted, 25 fibers were found in one unit area adjacent to a unit area with as few as 5 fibers. Occasionally, a unit area would not have any fibers, but instead had a cluster of several pieces of

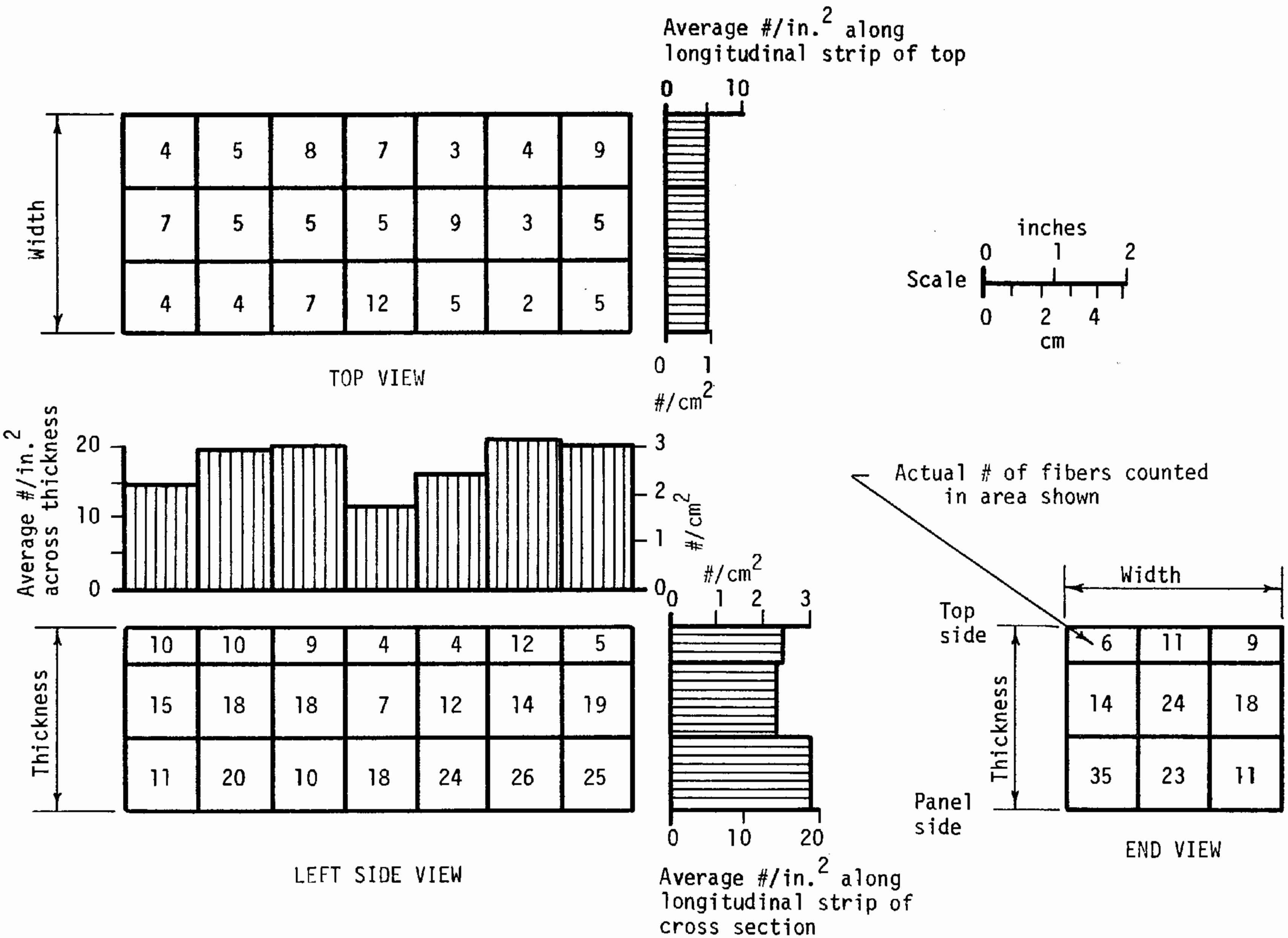


FIG. 7.3 FIBER COUNT RESULTS: SAMPLE 39-2-3

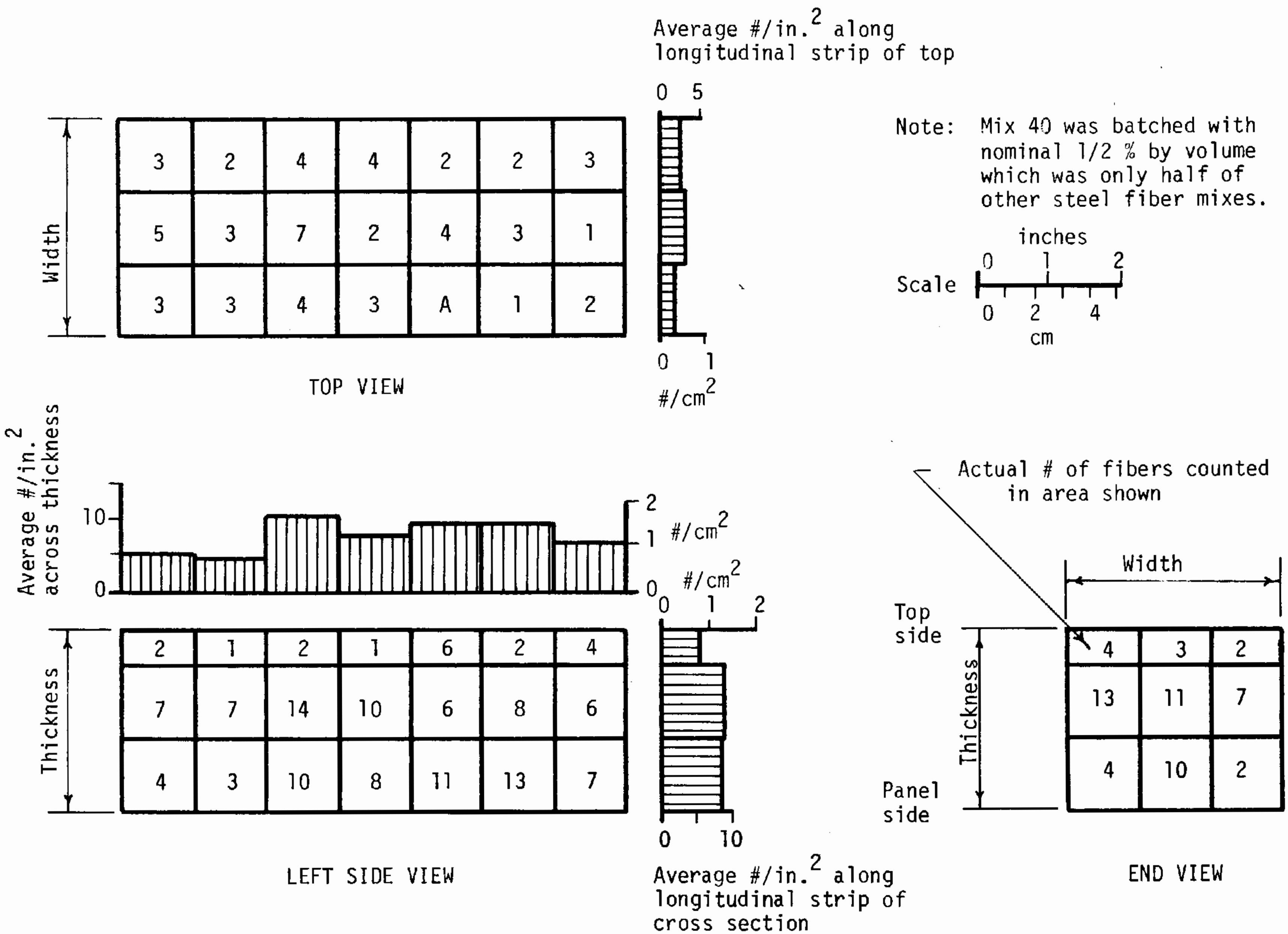


FIG. 7.4 FIBER COUNT RESULTS: SAMPLE 40-1-1

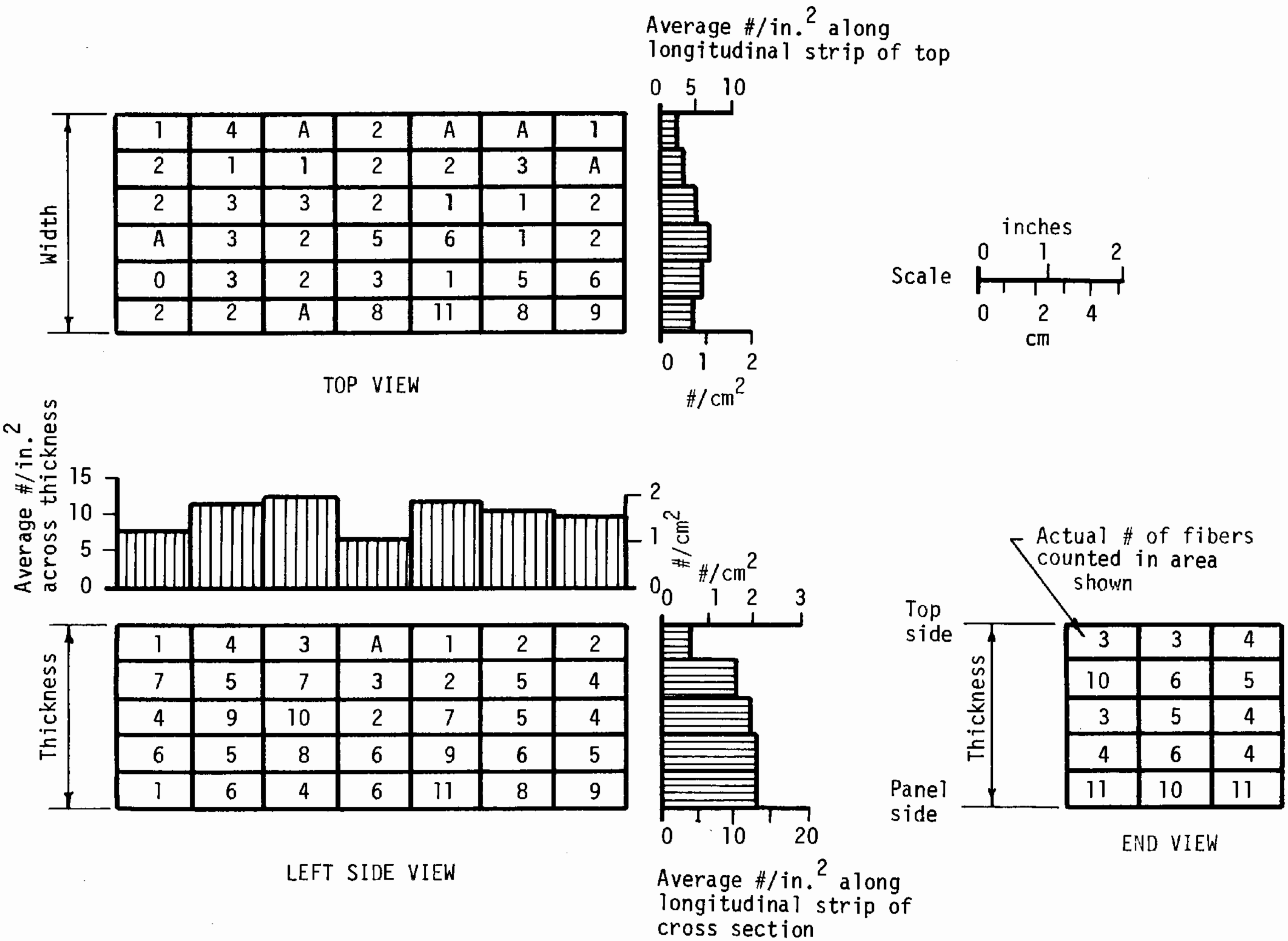


FIG. 7.5 FIBER COUNT RESULTS: SAMPLE 42-3-1

coarse aggregate. These unit areas are denoted by the letter "A" in the box. There were no unit areas without fibers that did not also have the excess aggregate. Though fiber counts in adjacent unit areas varied appreciably, the average fiber count along lines within the sample were much more uniform.

The top view of sample 39-2-3 in Fig. 7.3 is a good example in which fiber counts vary from 2 to 12 per unit area while the averages along the lines are very uniform at about 5 to 6 counts. Thus, on a small scale of an inch or a few centimeters, there were large differences in fiber counts while on larger areas the variations were less important.

Another trend sometimes evident in the fiber count study was lower fiber count for the top inch or so, even when normalized on an area basis as done in the graphical displays. As sketched in Fig. 7.2b, these samples were trimmed to remove the irregular top one-quarter to one-half inch, so the counts shown in the figures do not extend to the shooting surface. Counts in samples that were not trimmed often showed the same trend. This phenomenon could be interpreted to mean that one mechanism for fiber retention occurs through embedment from subsequent incoming shotcrete, possibly in the zone of disturbance remixing observed in the high-speed photographic study.

VARIATION IN FIBER COUNTS ACCORDING TO ORIENTATION OF SURFACE

The fiber counts on the top view of all specimens were substantially lower than the side or end views since the fibers were oriented mostly in the plane of the panel and fewer fibers are exposed on surfaces parallel to the panel. Thus fiber counts from top cut surfaces should not be averaged with those cutting through the thickness. This aspect of fiber orientation is discussed in Section 7.4.

VARIATION BETWEEN SAMPLES OF THE SAME MIX

The variation in average fiber count between samples of the same mix or panel is not great as can be seen in Table 7.2. For example, six samples were counted in both Mixes 5 and 33. Differences in fiber counts of the 6 samples from these mixes were low; standard deviations were 1.7 and 2.0 fibers/in.^{2}. Although the variation may be fairly great on a unit-area basis throughout the material, it is far less variable on the macroscopic scale. Potential cracks must encounter areas of both high and low fiber content.

VARIATION BETWEEN MIXES

On a mix to mix basis for Days III and IV, Mixes 33 through 42 (not including Mix 40 which was batched with only 1/2 the fibers), the average fiber count of all mixes was 12.4 fibers/in.^{2} (1.9 per cm^2) and the standard deviation between mixes was only 2.2 fibers/in.^{2} (0.34 per cm^2).

7.3.3 EVALUATION OF FIBER DISTRIBUTION BY X-RAY METHODS

A very impressive clear indication of fiber distribution is shown by x-ray photographs made of fibrous shotcrete samples that had already been subjected to fiber counts. To avoid seeing too many fibers in the x-ray photographs specimens were trimmed down to a thickness of one inch (2.5 cm) before being x-rayed. X-ray photographs of several samples are presented in Figs. 7.6 through 7.11. Figures 7.9, 7.10 and 7.11 are x-rays of the same samples whose fiber counts are shown in Figs. 7.3, 7.4 and 7.5, respectively. Because of trimming, the orientation of the specimen in the x-ray may not be the same as the orientation in the figures with fiber count grids; the counted cut surface may have been removed or it may be the mirror image of the counted surface.

Some fibers are not their full length in these photographs since they were cut off. Some may have an orientation in the direction the x-rays were taken which reduces the apparent length and reduces the apparent angle of inclination. Thus a fiber that appears straight up and down is likely to be inclined at some angle to the vertical which can not be portrayed in these 2-dimensional photographs.

The x-rays were originally made to give a visual impression of fiber orientation, but their contribution to the understanding of the distribution of fibers is also important because visual evaluation of relative fiber content is possible. Areas of high and low fiber concentration are vividly portrayed. Clearly, fibers are not randomly dispersed. Often, fiber bands can be seen to be concentrated along surfaces that probably were previously-shot, temporarily-exposed surfaces. These fiber bands are particularly evident in Figs. 7.7 and 7.8. It is important to note that the surfaces were not extremely hard because the total time to shoot the panels was a minute or so. Thus, they existed only a few seconds, but that was long enough to affect the local air stream currents and thus the orientation

FIG. 7.6 X-RAY PHOTOGRAPH OF SAMPLE 33-3-1

FIG. 7.7 X-RAY PHOTOGRAPH OF SAMPLE 34-3-2

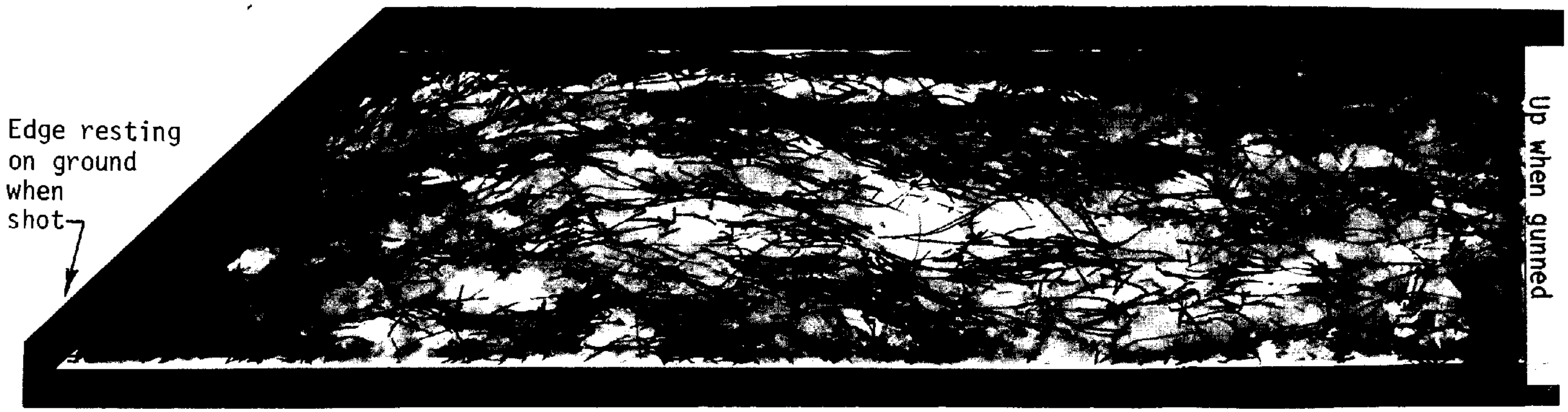


FIG. 7.8 X-RAY PHOTOGRAPH OF SAMPLE 39-2-5

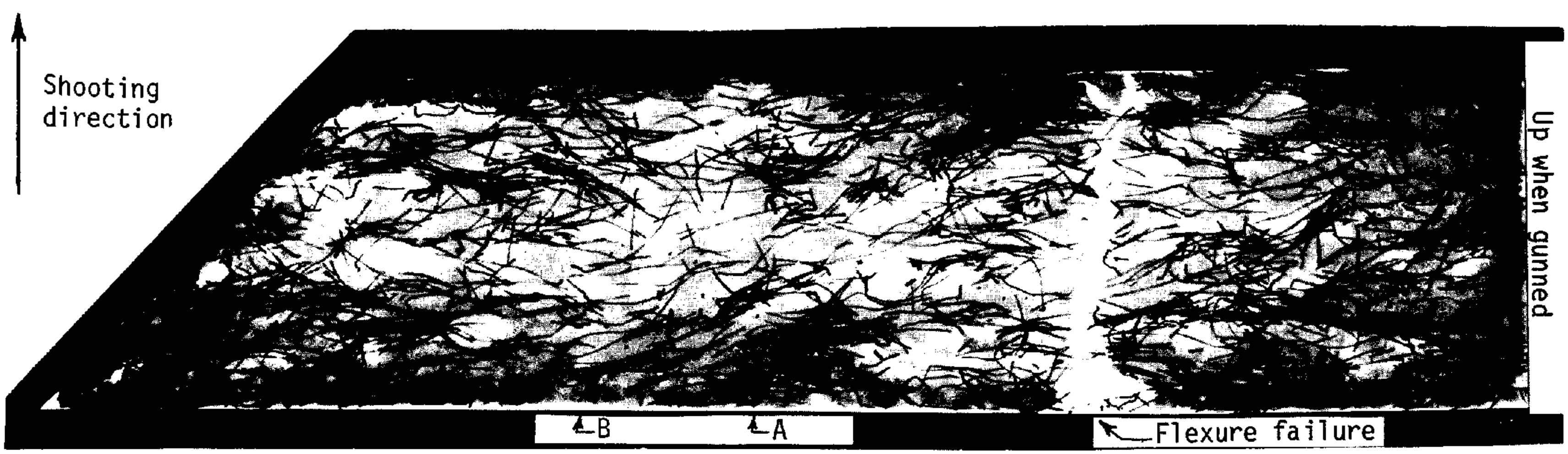


FIG. 7.9 X-RAY PHOTOGRAPH OF SAMPLE 39-2-3

FIG. 7.10 X-RAY PHOTOGRAPH OF SAMPLE 40-1-1

FIG. 7.11 X-RAY PHOTOGRAPH OF SAMPLE 42-3-1

and distribution of fibers. However, the same pattern could also be obtained by a sudden burst of increased fiber concentration; a phenomenon known to occur. The nozzleman usually built up the shotcrete on the panels from the bottom upward, with the shotcrete thicker at the bottom tapering thinner at the top just as the fiber bands show in the x-rays. The photographs also show how laminations might form and be oriented in non-fibrous shotcrete. Generally, there was also a concentration of fibers at the shotcrete panel interface.

Some samples did not exhibit prominent fiber bands. The sample of Mix 33 shown in Fig. 7.6, the sample of Mix 40 with low fiber content shown in Fig. 7.10, and the steel fiber regulated-set sample of Mix 42 in Fig. 7.11 all lack prominent fiber-rich bands. Mix 40 (Fig. 7.10) however does not have many fibers and this may be the cause of the absence of the concentrated bands. The fibers in most x-rays are oriented in the same directions as the bands.

The effect of fiber distribution on sampling and analysis of fresh shotcrete samples is illustrated by the areas A and B in Fig. 7.9 which could have been sampling areas of fresh shotcrete samples. The fiber content of a fresh sample from area A would have been higher than the average, and the fiber content of area B would have been lower than the average. Thus, significant differences in fiber content from fresh samples should be expected.

Some of the x-rays were made on failed beam specimens. The effect of fiber distribution on properties such as flexural strength are illustrated by the fact that the flexural cracks in the figures appear to have occurred at one of the several points of minimum fibers across the width of the specimen. Thus a direct link between fiber distribution and other properties such as flexural strength or at least the location of the failure crack are indeed probable and are a good subject for future research. Flexural cracks in steel fiber beams were always sinuous cracks governed by the least concentration of fibers at each level throughout the thickness. The x-ray technique should be a powerful tool in studies of the strength of fiber shotcrete.

Finally, the fact that many of the fibers were bent "U" or "V" shaped (see Chapter 3) is clearly evident in the x-rays. This bending is believed to be responsible for lower than expected flexural strengths.

7.4 ORIENTATION OF FIBERS

Fiber orientation affects the isotropy of the shotcrete. Most fiber concrete mix designers assume that fibers are randomly dispersed and randomly oriented. Since the method of shotcrete placement tends to lead to a laminated product, a study of fiber orientation was undertaken to determine if there was a preferred direction of orientation for the fibers.

Four techniques were used to study orientation: 1) visual observations of samples during cutting and testing, 2) comparing fiber counts on cut faces in the three planes, 3) critical examination of the cross section of severed fibers exposed on cut faces, and 4) x-ray photographs of samples of shotcrete.

Even a casual visual observation of the samples of fibrous shotcrete samples will show that the fibers tended to lie in the plane of the surface being shot. It was observed that if the axis of a fiber was nearly perpendicular to a cut surface, the cross section of the severed fiber would closely resemble a right section of the fiber. On the other hand, if the axis of the fiber was nearly parallel to the cut surface then the severed fiber would look long and thin, much like a longitudinal section of the fiber.

A program of special fiber counts was undertaken in which the number of "end fibers" and the number of "flat fibers" were counted in each unit area on each of 3 mutually perpendicular cut surfaces. Results obtained from this study indicated a strong tendency for fibers to be subparallel to the wall, but the method was based on indirect evidence and when it was found that fibers were bent out of shape, the program was suspended. The method should work when fibers are straight however.

The preferred orientation also can be obtained from other indirect evidence obtained from fiber counts. It was found that average fiber counts per unit area on surfaces parallel to the panel (perpendicular to shooting direction) were substantially lower than fiber counts on side or end cuts. This is clearly seen in Figs. 7.3, 7.4, and 7.5 where the fiber counts of the top views are roughly one-half of the counts on the sides or ends. Such a distribution of fiber counts implies that on the average, substantially more fibers lay in planes parallel or subparallel to the surface of shooting.

As mentioned before, the x-ray photographs were originally intended to be used for fiber orientation studies. Indeed the fibers are clearly shown in the x-ray photographs to be oriented subparallel to the surfaces of shooting.

Examination of the x-ray photographs shows that many of the fibers in the shotcrete are bent to varying degrees. This phenomenon also appears to disrupt the parallel orientation of fibers. The principal portion of the bending of fibers occurs during dry mixing prior to shooting. The effect of this bending on the engineering properties of fibrous shotcrete is considered in Chapter 10.

Fig. 7.11 of Mix 42 illustrates some disarray of fibers at the wing walls, and, to a certain extent, at the panel surface, both of which are points of expected disturbance. Of all the panels that were shot on this program, none appeared to have fibers sticking out of the back when the plywood forms were removed. It appears that for these shooting conditions, no fibers stuck into the soft plywood forms, even though in some of the x-ray photographs it may appear that it occurred.

CHAPTER 8

DESCRIPTION OF STRENGTH TESTING PROGRAM

8.1 TEST SCHEDULE

Shotcrete with accelerators and shotcrete with regulated-set cement begin to gain strength immediately after placement and should develop a strength greater than 500 psi (3.45 MPa) in a few hours. Early strength is extremely important when shotcrete is used for initial or temporary support in difficult tunneling ground so this strength testing program was planned specifically to evaluate early strength characteristics of fresh shotcrete. The methods developed for obtaining and testing samples were directed toward rapid and accurate determination of relatively low-strength shotcrete. Three compression tests and one flexural test were planned to be conducted within the first hour for Mixes 23, 28, 39, and 45. More comprehensive studies were planned for these mixes since they served as control mixes for specific types of shotcrete. The pullout test program was planned to supplement the compressive strength results. In reality, the strength of the shotcrete did not develop as rapidly as anticipated because of the very low temperatures. Therefore early testing was not necessary except for some of the regulated-set cement mixes.

Generally, several compression tests were made on samples from each mix at some time less than 4 hours, and then again at one day; flexural testing for most mixes began at about one day. Subsequently, testing was conducted at ages of about 7 days, 28 days, 42 days and 6 months.

The earliest tests were conducted as follows:

Compressive Test	39 minutes
Flexural Test	4.2 hours
Pull-Out Test	
First Attempt	5-10 minutes
First Useful Data	3.3 hours

8.2 MEANING OF REPORTED STRENGTHS

The strength testing program was developed to evaluate the in situ strength of a thin shotcrete lining typically applied at a tunnel heading. Since the first application of shotcrete is usually on the order of 3-in. (7.6 cm) thick, panels were shot to this thickness. Right rectangular prisms were sawed from the panels and the early tests were conducted on specimens without any other treatment except for capping. The samples were thus about 3 in. (7.6 cm) square with 2 sawed sides, one formed side (the back of the panel) and one rough shotcrete surface. Specimens tested at an age greater than one day were soaked 24 to 48 hours immediately prior to testing.

The strength testing program was developed to evaluate relative differences in strength between mixes. The shotcrete industry does not have a standard test specimen analagous to the 6 in. x 12 in. (15 x 30 cm) cylinder in the concrete industry. Thus, there is no standard design strength parameter analagous to f'_c. The recommendation of standard test specimens to obtain standardized strength parameters was not in the scope of work, but the methods of collecting, preparing, and testing on this project were developed toward such a goal.

In the absence of standard strength parameters and in anticipation of anisotropic strength behavior, especially in steel fiber shotcrete, new methods of testing were developed specifically for this project. The strengths reported herein were obtained on samples that were prepared in a special way. Since all samples were prepared in the same manner, the value of the strength of one sample or set of samples has meaning relative to another sample, but not necessarily to strength data from a different type of sample in another test program. The magnitudes of strength and moduli obtained with these test procedures certainly fall within the range of reported values from other projects using different test methods. Nevertheless, correlations between these test results and those of others would be necessary just as correlations are necessary between the cube-test results and results from 6 in. x 12 in. (15 x 30 cm) cylinders.

To avoid confusion with f_c' or any other standardized parameter, the test results will be designated as shown in Table 8.1. No special significance is given to any particular age at time of test (such as 28-day strength for f_c'). Because shotcrete requires high strength within a few hours for success, research emphasis was on early strength. Strength tests were made at about 28 days simply to follow customary practice. The strength at various ages will be designated as shown in Table 8.1.

8.3 COLLECTION AND PREPARATION OF SAMPLES FOR STRENGTH TESTING

8.3.1 COLLECTION OF SAMPLES

Obtaining a good sample from a large piece of fresh shotcrete is

TABLE 8.1

TERMINOLOGY FOR STRENGTH RESULTS

σ_c	Compressive strength defined as maximum compressive stress
σ_f	Flexural strength defined as maximum flexural stress (Modulus of Rupture)
σ_p	Pull-out strength defined as maximum pull-out stress on shear surface

NOTES:

1. Units are in psi or MPa
2. Age at testing can be denoted by subscripts
   Examples: σ_{c28} would be compressive strength at 28 days

   σ_{c2h} would be compressive strength at 2 hours

difficult even under ideal conditions. Since the whole purpose of the program was to conduct the test program under typical field conditions, conditions were not ideal.

The criteria set for the method of obtaining specimens of shotcrete were that the method had to be practical, speedy, and at the same time provide samples representative of in-place shotcrete shot against typical rock surfaces. Preliminary shooting tests were made with various kinds of wire-baskets but the wire-basket method was abandoned because the samples were laminated and not representative.

More strength data has been collected by shooting into plywood panels of various forms than any other method of collecting samples. It was believed originally that shooting against a soft plywood surface could not produce the same quality shotcrete as that obtained by shooting against a hard rock surface. Other practical means of collecting representative samples were sought without success. After carefully observing shotcrete build-up on rock walls, it was concluded that once a thin layer of shotcrete was established on the wall, all subsequent material became embedded in this first layer that is even softer than plywood. Subsequent layers of shotcrete did not appear to be affected significantly by the nature of the surface being shot. Thus, for practical purposes, the hardness and other features of the surface is primarily important only for a few seconds or until a layer somewhat less than 1/2 in. (12.7 mm) thickness is established. Therefore the importance of one objection to plywood panels was reduced by this observation. It was believed that another objection of panels, that of sampling too small an area, could be avoided by shooting a large area such as a 4 x 8 ft (1.22 x 2.44 m) panel all at once and cutting it into smaller, more manageable, pieces in a manner similar to that described by Bortz, et al., (1973).

Two large frames were constructed of heavy steel angle to hold a 4 x 8-ft (1.22 x 2.44-m) plywood sheet in a vertical position as rigidly as possible. The plywood panel had been cut up into 2 x 2-ft (0.61 x 0.61-m) squares and the pieces assembled on the frame into a 4 x 8-ft (1.22 x 2.44-m) mosaic. Each small panel consisted of two 3/4 in. (19 mm) sheets nailed together for added rigidity. Figure 8.1 is a photograph of one of the frames in use. These frames were used for the collection of samples for mixes 14 and 21 on Day II. However, they were difficult to disassemble and remove from the tunnel each day and the individual panels were difficult to remove for rapid testing. The frames were abandoned in favor of small 2 x 2-ft

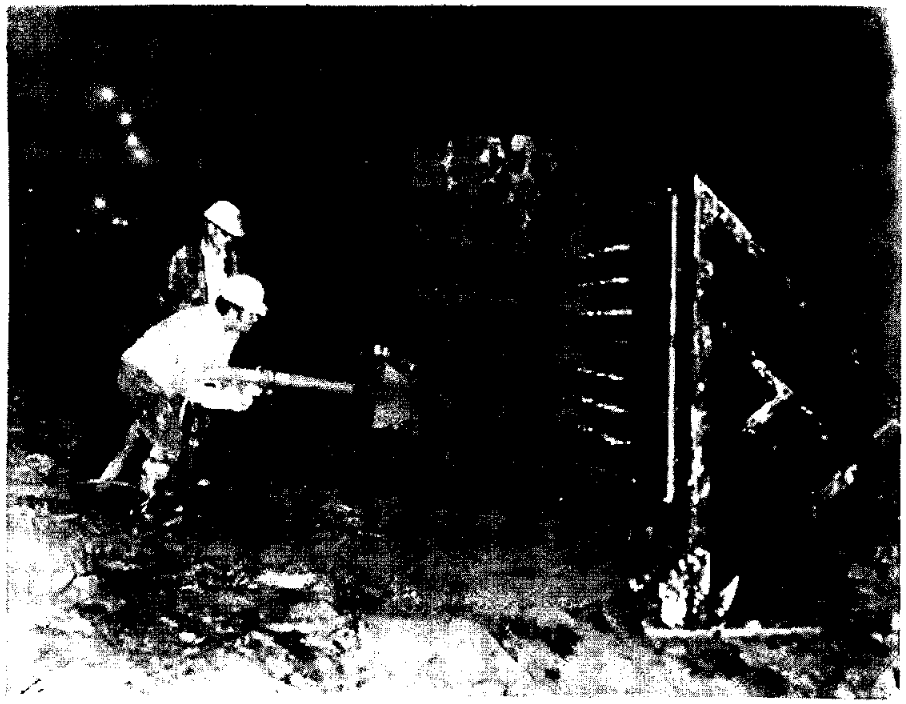


FIG. 8.1 SHOOTING AGAINST LARGE FRAMES WITH INDIVIDUAL 2 FT X 2 FT (0.61 X 0.61 m) PLYWOOD PANEL ATTACHED

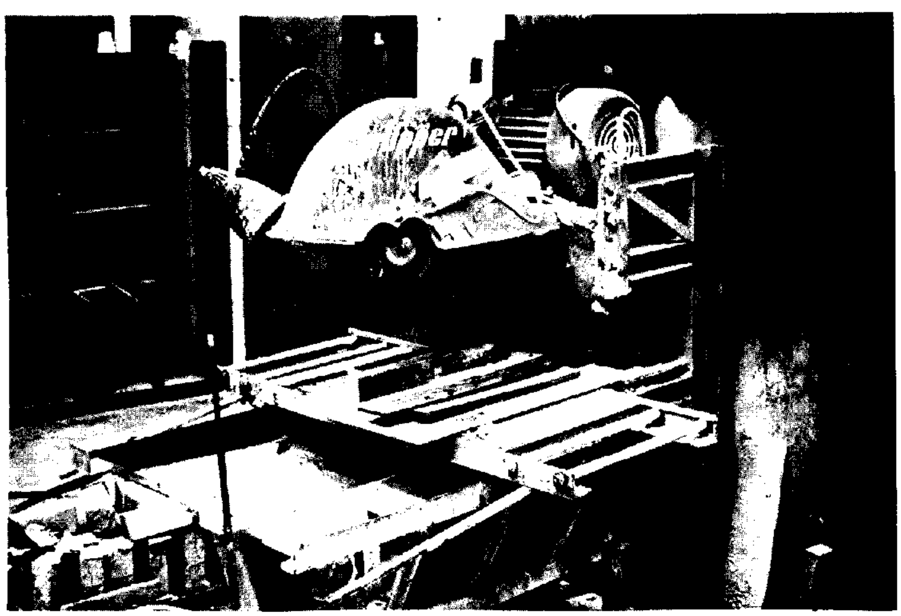


FIG. 8.2 MASONRY SAW WITH CARRIAGE MODIFIED FOR SHOTCRETE PANEL CUTTING

(0.61 x 0.61-m) individual plywood panels made from 2 pieces of 3/4 in. (19 mm) thick plywood nailed together to form a rigid back with 45° wingwalls on all four sides.

Most of the strength tests were made on specimens sawed from these smaller individual panels. On Days III and IV as many as 20 of these individual panels for each mix were leaned against the tunnel wall and filled with shotcrete. The mix number, the sequence number of shooting the panel, and the top of the panel (or direction up) were marked on the plywood and on the shotcrete itself with bright red spray paint immediately after shooting. Thus panel 23-4 refers to the 4th panel shot of Mix 23. Each of the approximately 200 pound (90 kg) panels were loaded onto a two-wheeled hand cart and moved to the testing area.

8.3.2 SAMPLE PREPARATION

At least one panel of each mix was sawed into prisms immediately after shooting while the shotcrete was still fresh and weak. The saw is a table-type concrete saw modified to provide added strength. The carriage assembly was modified to permit easy translation front to back and left to right and to permit rotation of the sample so that perpendicular saw cuts could be made easily. A 14-in. (35-cm) diameter diamond saw blade was used. The saw is shown in Fig. 8.2. Sufficient specimens for all testing up through 7 days were cut from the panels the same day they were shot. All specimens for testing at 28 days and older were cut from panels as needed. The top of the panels had been marked so that the prisms would be cut in the proper orientation as shown in Fig. 8.3a. Cuts were first made from top to bottom

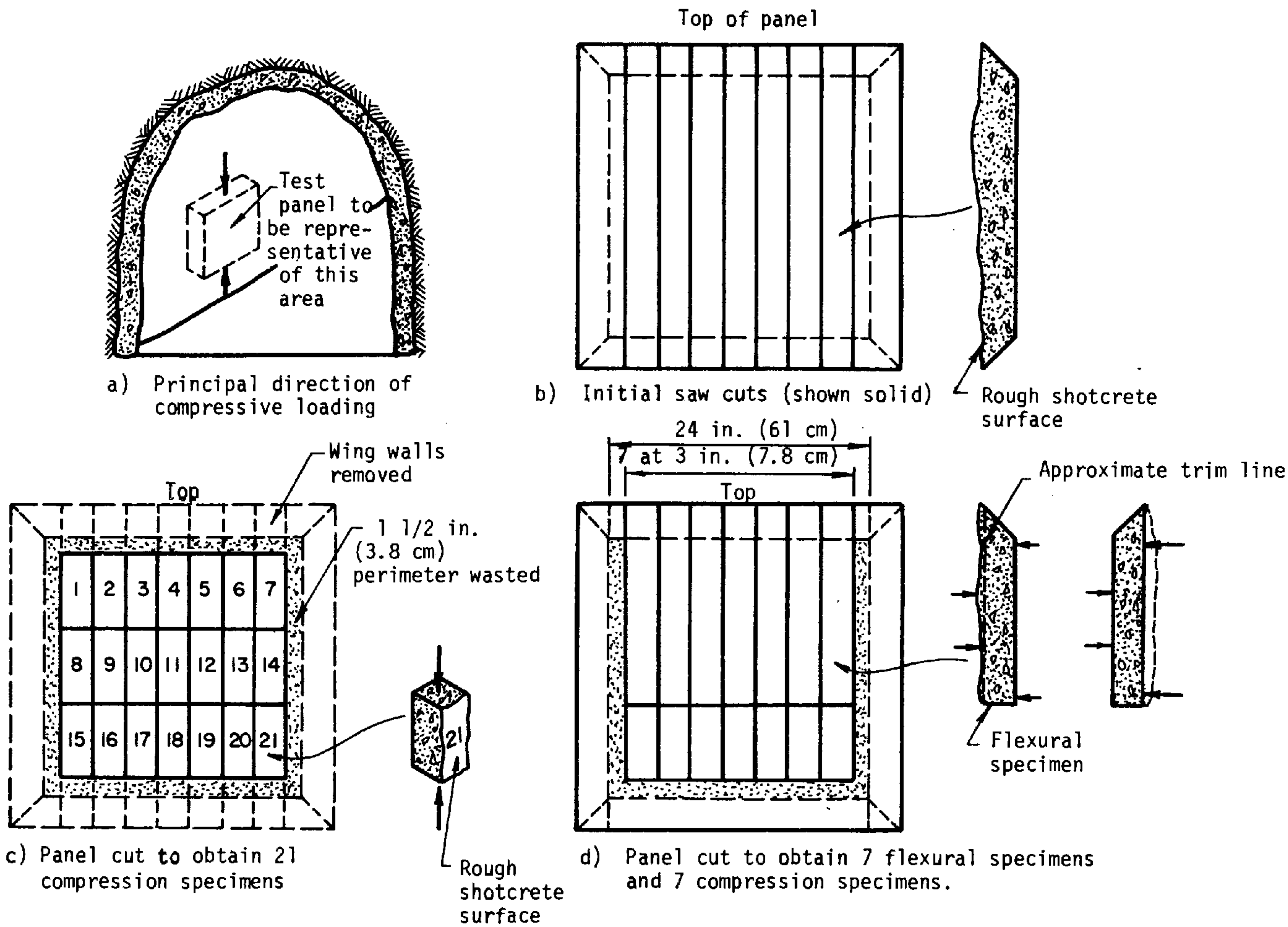


FIG. 8.3 CONFIGURATION OF PANEL CUTS TO PRESERVE RIGHT SIDE UP

to make long beam-like prisms 3 x 3 x 24 in. (7.5 x 7.5 x 61 cm) long as shown in Fig. 8.3b. These prisms were then cut either into 21 prisms about 3 x 3 x 7 in. (7.5 x 7.5 x 17.8 cm) for compression specimens as shown in Fig. 8.3c, or into the combination 7 beams 3 x 3 x 15.5 in. (7.5 x 7.5 x 39.4 cm) for flexural tests and 7 compression specimens as shown in Fig. 8.3d. The proper orientation of all specimens was known and maintained throughout testing. For instance, the axial load on compressive specimens was always applied in a direction perpendicular to the direction of shooting (parallel to any potential laminations) with the specimen sitting upright with the top platen on the top of the specimen.

Brown masking tape was wrapped around each specimen and the specimen number and an arrow indicating the direction "up" was marked on the masking tape with industrial-type wide felt marking pens. As a precaution, specimens themselves were also marked with marking pens on the fresh shotcrete after the surfaces dried. This dual marking system was satisfactory. The numbering system is shown in Fig. 8.3c. Thus specimen 23-1-2 was the second specimen cut from panel 1 of mix 23.

Each sample was weighed to the nearest ounce (28 grams), and measured to the nearest 0.1 in. (2.5 mm).

The rough shotcrete surface on most samples was not trimmed. Thus, one side was the rough shotcrete surface. This rough surface was trimmed for a few special tests conducted at 42 days and 6 months and for a few other samples that were too thick to fit into the testing machine. Trimming has some implications on the apparent strength which are discussed in Section 9.6.2.

8.3.3 CURING

The wooden panels had been treated with two coats of polyurethane varnish sealer prior to shooting to minimize loss of water through the wood forms. All mixes except 10 and 21 were cured in a similar manner and all panels within each mix were treated similarly. Mixes 10 and 21 were cured in the tunnel for about 1 day and then transported to the University after which they were cured at 70°F (21°C) in a wet fog room.

All samples of Days III and IV remained in the tunnel until testing or up to a maximum of about one month, whichever was shorter. The temperature of the storage area was about 50°F (10°C) and the relative humidity was about 85%. These panels were essentially air dried in this environment until tested at 7 days or until about 28 days, when they were shipped to the University of Illinois where they were stored in a temperature-and humidity-controlled environment. The temperature ranged between 70° to 80°F (21° to 27°C) and the humidity was about 50%. Pull-out panels were cured in the same manner as other test specimens.

8.3.4 SATURATION OF SAMPLES

Samples less than 3 days old were not saturated. All other samples were immersed in lime water for 24 to 48 hours immediately prior to testing. However, many of the specimens did not appear to be saturated throughout, especially those tested at 6 months. The interior of many of these specimens was drier than the edges. Special specimens tested at 42 days were soaked 10-12 days prior to testing. Pull-out panels were never soaked.

8.3.5 TESTING TEMPERATURES

Compression and flexural samples up through the 7-day test were tested in a cold environment (about 35°F; 1-1/2°C). Pull-out panels were tested at about 35°F (1-1/2°C) up through one day tests, 50°F (10°C) through 28 days, and 70° to 80°F (21 to 27°C) beyond 28 days.

8.4 COMPARATIVE STRENGTH PROGRAM

The comparative strength program was carried out in the following manner. The standard mix was selected to be the same mix design routinely used by the contractor for shotcrete support of the Dupont Circle Station. This is a nominal 7-1/2 bag mix with 50% sand and 50% 1/2-in. (1.25 cm) maximum size coarse aggregate. A control mix of standard proportions and conventional shooting procedures was shot at the beginning of each of the last two days of shooting, Day III and Day IV. The comparative strength program was conducted on mixes from Days III and IV with only 2 exceptions from Day II. For comparative purposes, it was intended that the physical properties, rebound characteristics, and the strength of subsequent mixes be compared to the control mix for that day. The two control mixes for the comparative strength tests are Mix 23, which was shot with a conventional nozzle and 60°F (16°C) water on Day III, and Mix 26, which was shot on Day IV with the "long nozzle" and 100°F (38°C) water. Subsequent mixes during these two days of comparative strength testing were selected to have only one simple variation in the mix design or in the shooting conditions so that the effect of this single variation could be determined and compared to the results obtained from the control mix or from another similar mix. The various comparisons desired were summarized in Table 2.6

together with remarks about the validity of the comparison after all data have been reviewed.

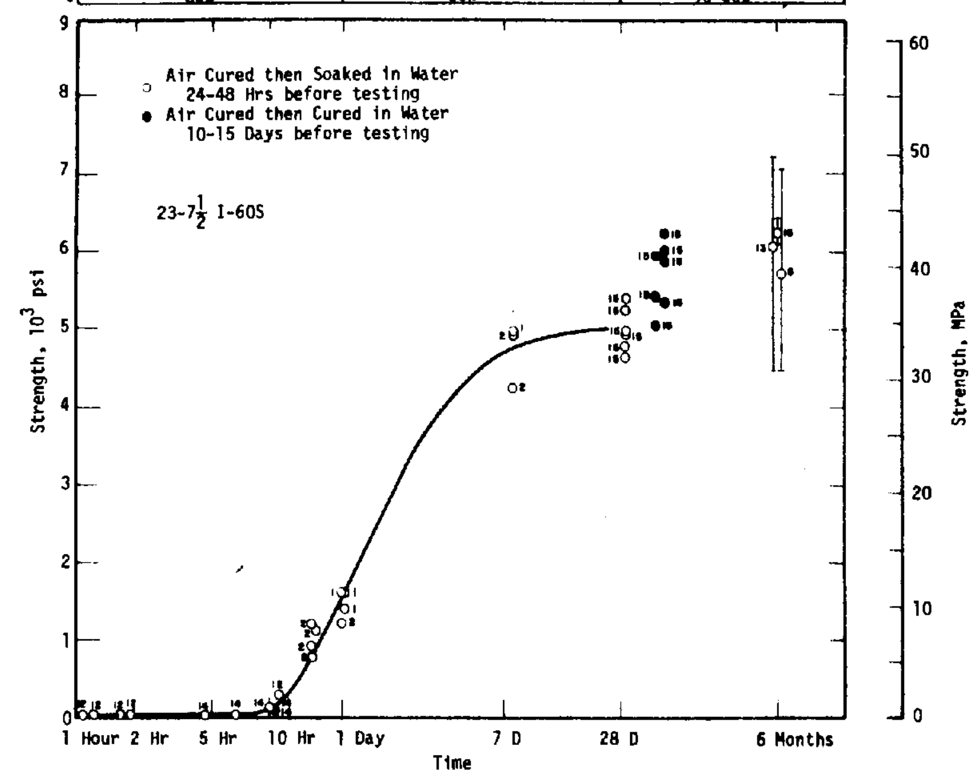
In a few cases these comparisons were achieved without interference of some extraneous parameter. In other cases, more conditions changed than just the single variation intended. The documentation program (precise timing, water records, etc.) was invaluable in explaining apparently anamalous results.

8.5 STRENGTH-TIME PROPERTIES

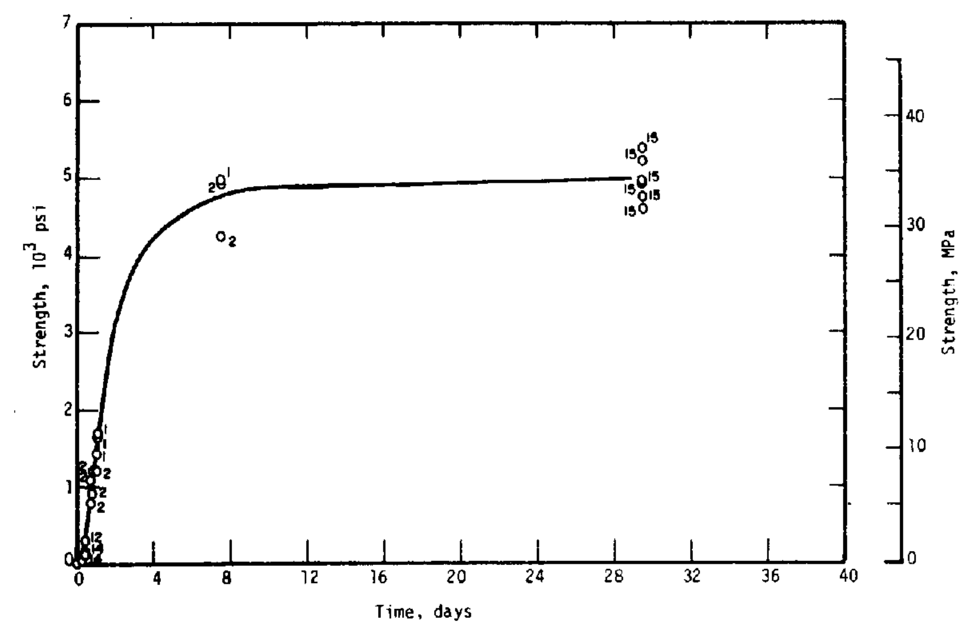
8.5.1 BASIC NATURE OF STRENGTH VERSUS TIME CURVES

Shotcrete with accelerator sets almost immediately and then begins to increase strength rapidly at rates depending upon such factors as the compatibility between the cement and the accelerator, the dosage of the accelerator, the temperature of ingredients, etc. Because the strength tests were shot under adverse temperature conditions, the rate of gain of strength was relatively slow as illustrated in Fig. 8.4a which is a typical plot of compressive strength, σ_c versus the logarithm of time. Superimposed on the figure is a description of typical curing conditions. Semi-logarithmic plots such as in Fig. 8.4a distort the time scale so that the details of the increase in strength during the first 24 hours can be seen as clearly as the long-term strengths. However convenient it may be to see both early and long term strength behavior on one plot, the time scale does mask the true rate of gain in strength. For comparative purposes, the same data up to only 40 days is replotted in Fig. 8.4b to an arithmetic time scale in which the slope of the line is always the rate of gain in strength. This is not the case for semi-logarithmic plots.

Location	At shooting and testing area near portal	In storage in tunnel away from tunnel portal	Inside CE shop at University of Illinois
Temperature	30 to 35°F (-1 to 2°C)	50 to 55°F (10 to 12.5°C)	70 to 80°F (21 to 27°C)
Relative Humidity	85%	85%	40-60%



a) Semi-logarithmic plot



b) Arithmetic plot

FIG. 8.4 TYPICAL COMPRESSIVE STRENGTH-TIME CURVES AND CURING CONDITIONS

8.5.2 METHOD OF PRESENTATION OF RESULTS

Because the very-early-strength behavior (less than 8 hours) is more important than the 28-day strengths, most strength data has been plotted with respect to the logarithm of time, which shows the early strength behavior more clearly. Arithmetic plots to about one day are used occasionally to demonstrate early strength gain. In some cases, strength data were obtained only up through an age of 28 days. After 28 days, curing conditions changed markedly as shown in the upper legend of Fig. 8.4a. Thus, two sets of strength-time curves have been prepared. The first series consists of one plot for each mix containing all strength data for σ_c, σ_f, and σ_p up through 28 days on 3-cycle log paper. These curves are presented in Appendix E. Each test is represented by a point on the plot; the Arabic numeral beside each point is the number of the panel from which the test specimen was cut. Therefore, the reader can visually evaluate interpanel (between panels) and intrapanel (within panel) variations at a glance. Curves have been drawn to represent our best judgment of the strengths based upon our knowledge of strength-time relations, stress-strain characteristics, mode of failure, and nature of failure surfaces. The curve for the compressive strength, σ_c, is solid; the flexural strength, σ_f, curve is dashed, and the pullout strength curve, σ_p, is dotted. These plots will be used to discuss strength behavior up through 28 days and the relationships between compressive, flexural, and pull-out strength by superimposing various plots or by reproducing individual plots in the next few chapters in order to clarify conclusions.

The second series of strength-time curves extend only the compressive strength data to an age of six months on 4-cycle log paper. Those mixes which have no 6-month data were not replotted. Since the curing changed so drastically, the best fit curves have not been extended to 6 months. Still the scatter and the effects of the new curing conditions are quite evident. These curves are contained in Appendix E.

The data have been evaluated statistically also and tabulated in Appendix D. These tables contain statistical averages by panel and by mix for each of the three types of strength, σ_c, σ_f, and σ_p. Separate tables have been prepared for each of the 4 ages at which most tests were made, 7 days, one month, 42 days, and 6 months. A table of estimated compressive strength at one day is also presented.

The statistical average and the value from the best fit strength time curves at the same ages may not agree exactly since the data have been treated differently. The statistical average depends only upon the data for that narrow time period, whereas the best fit curve accounts for the previous and subsequent strength results, and a personal weighted evaluation of the scatter of the data in general.

8.6 DISCUSSION OF SAMPLE COLLECTION AND PREPARATION

The method of sawing prisms and beams from small panels worked extremely well and is recommended for consideration by the industry as a standard method of collecting and preparing samples for testing. The method is fast, simple, inexpensive and it provides an oriented sample with an appropriate length-to-width ratio. Also, they can be lifted up to the table of a masonry saw and cut with a diamond blade within minutes after shooting.

Specimens for this study were cut from panels that were less than 15 minutes old and at a time when the compressive strength was only about

20 psi (0.14 MPa). No other sample preparation method permits an accurate direct measurement of strength of weak shotcrete. The orientation of the sample is known at all times. The direction of force during testing in compression is parallel to the potential laminations and parallel to the anticipated principal compressive stresses in situ. Accordingly, these oriented samples provide the information necessary for quality control; the test strength is governed either by the strength of the matrix or by the strength of the structural defects, whichever is least. The same advantages apply to flexural specimens. A comparative test program of shotcrete prisms of various lengths and widths could identify the optimum dimensions of samples so that a standard specimen and panel size can be adopted by the industry.

The small test panels can be stored in small areas, possibly leaning against the tunnel wall in the location they were shot. Hence, curing conditions for the panels will be similar to in situ conditions. Duplication of curing conditions is essential in strength testing. If the ground water can keep the shotcrete saturated, the panels should be maintained moist during curing. If the tunnel is dry, air drying of panels may duplicate the conditions best. In any event, air drying in the tunnel results in a reasonable, conservative estimate of strength.

CHAPTER 9

COMPRESSIVE STRENGTH

9.1 INTRODUCTION

The primary emphasis of the testing program was on determination of the entire compressive strength-time curve through an age of six months and on the comparison of these strength curves between mixes. The earliest compressive strength was obtained at an age of 39 minutes. However, with the exception of regulated-set shotcrete mixes, the strength did not develop very fast because of the cold environment and only a few early compressive strength tests during the first 6 to 8 hours were required to define the strength-time curve.

The general strength-time relationships have been discussed in Chapter 8 and the detailed test data and plots are contained in Appendices D and E, respectively. Stress-strain relationships and modes of failure are discussed in Chapter 11. Relationships between the compressive strength of selected mixes and major groups of mixes are evaluated in this chapter. The influence of various shooting conditions on compressive strength is also treated. Some of the expected trends are substantiated by the data, but some of the data do not fit the expected trends, probably because several parameters affected the results to be undetermined degree. The influence of the various factors is estimated in these cases.

The overall variation in the test data as measured by the coefficient of variation is relatively small and the test results are considered good for the conditions. Nevertheless, there was noticeable variation in strength from panel to panel, within each panel, and even through the thickness of the specimen. The effects of these and other variations are discussed.

9.2 TEST PROCEDURES

9.2.1 GENERAL

Where possible, the applicable portions of the following ASTM test methods were followed: C39, C42 and C116. The methods were modified only as necessary to accomodate the type of specimen and the low strength of some of the specimens.

9.2.2 PREPARATION OF SPECIMEN

Considerable care was taken during sample preparation to maintain the proper orientation of the samples and to maintain an adequate thickness-to-length ratio. Compression specimens were right-rectangular prisms, 3 x 3 x 7 in. (7.6 x 7.6 x 17.8 cm), cut from the panels so that their orientation in space with respect to vertical and to the direction of shooting was always maintained. The back of the panel provided a smooth side and the two cut sides of the specimen also provided smooth sides. However, except in a special series of tests, no attempt was made to trim off the rough shotcrete surface since the purpose was to evaluate the strength of shotcrete in situ, not just the strength of the material itself. Figure 9.1 is a photograph of typical rough and trimmed compression specimens. When the rough surface of the specimens was trimmed, no more was trimmed off than necessary to provide a smooth side parallel to the back consisting totally of sound shotcrete. Thus, a variable amount of the outer surface was trimmed off.

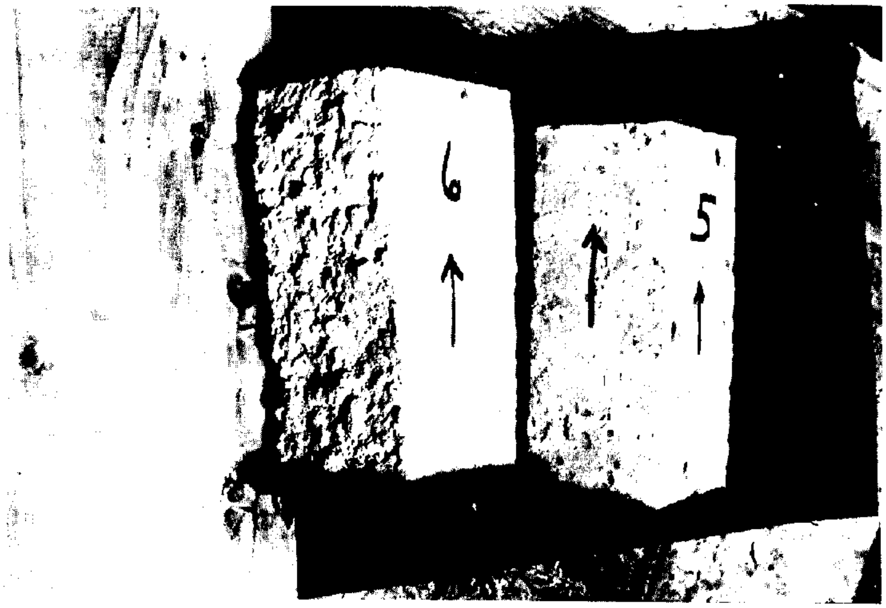


FIG. 9.1 TYPICAL PRISMATIC ROUGH AND TRIMMED COMPRESSION SPECIMENS

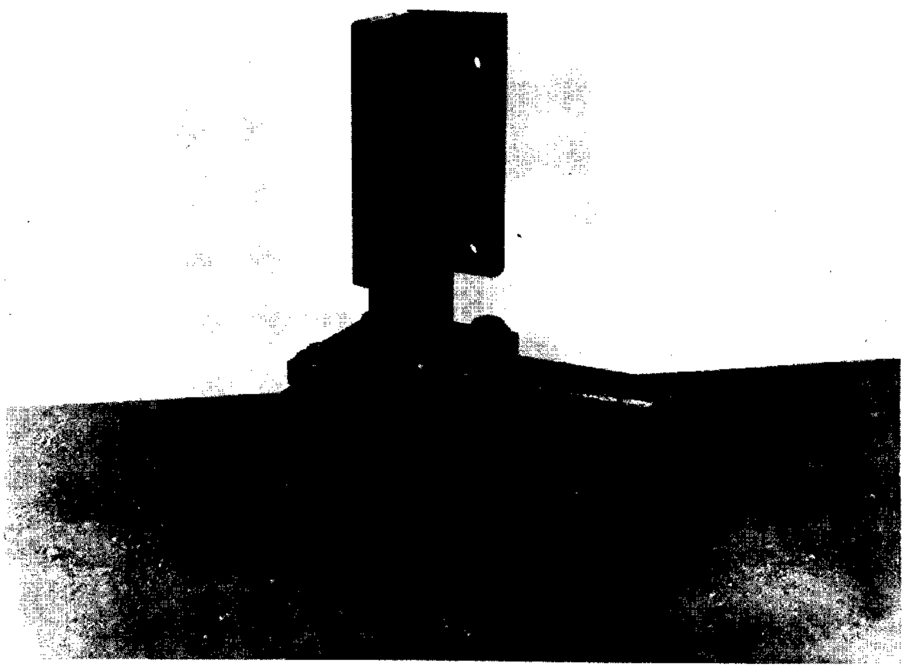


FIG. 9.2 CAPPING DEVICE FOR PRISMATIC SPECIMENS

After specimens were cut from the panels, they were soaked in lime water for about 24 to 48 hours. Before testing, the dimensions and weight of the the specimens were determined. Measurements in the field were made using a ruler graduated in tenths of an in. (2.5 mm); weight measurements were made using a scale graduated in ounces. In the laboratory, measurements of dimensions were made with a ruler graduated in 0.02 in. (0.5 mm). A spring scale sensitive to ± 0.1 gram was used to determine the weight in air. A Dunagan balance apparatus sensitive to ± 0.5 gram was used to determine the submerged weight of specimens.

Each specimen was capped with a thin layer of sulfur-based capping compound that hardened to a compressive strength in excess of the strength of the shotcrete. The special capping device shown in Fig. 9.2 was designed to accommodate the prismatic samples. Another special apparatus was used to check that the ends of the capped sample were parallel and perpendicular to the sides of the specimen.

Just before loading, one reusable clip-on-type strain gage with a 1 in. (2.5 cm) gage length was attached to each of the two sawed sides of the specimen at mid-height. The gages are illustrated in Fig. 9.3. The knife-edges of the strain gages were held tightly against the sample by rubber bands that surrounded the specimen and the gages. The gages were connected to an x-y recorder that automatically plotted load against the average of the measured strains throughout the time of loading.

9.2.3 TEST PROCEDURE

An effort was made to center and align the specimen in the testing

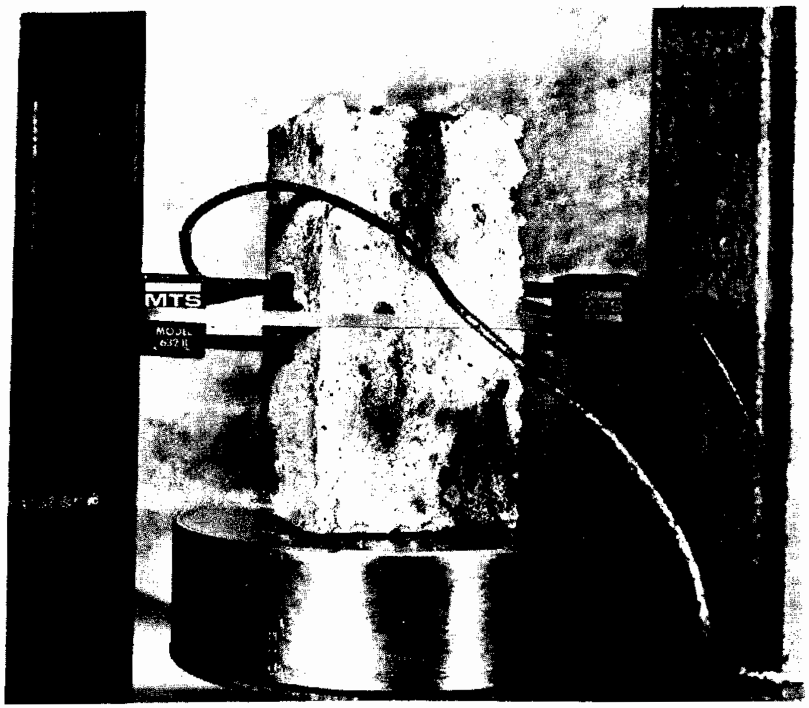


FIG. 9.3 REUSABLE CLIP-ON STRAIN GAUGE

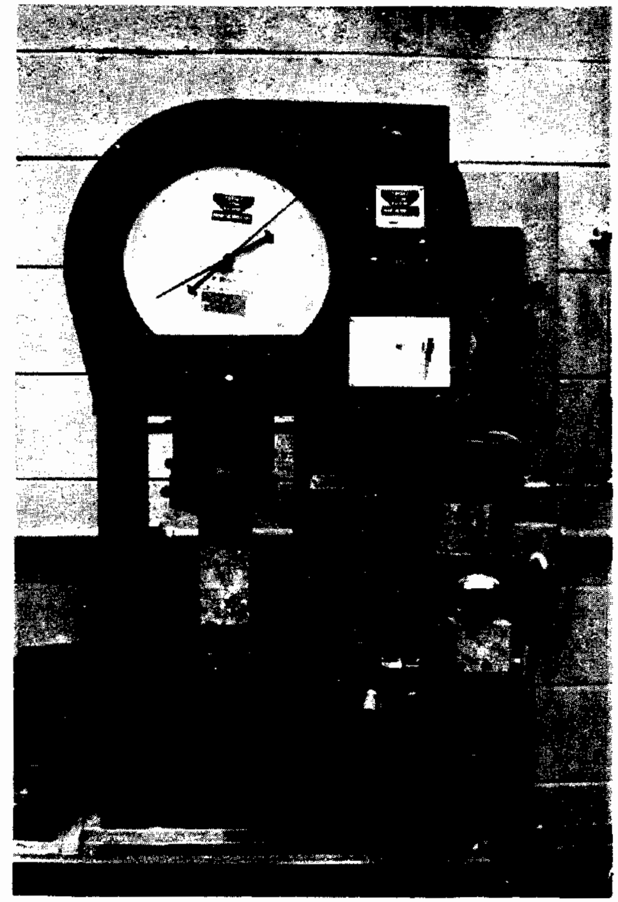


FIG. 9.4 COMPRESSION TESTING MACHINE

machine within 0.1 in. (2.5 mm). In every case the direction of loading duplicated the anticipated direction of loading in the field by loading in a direction perpendicular to the direction of shooting (parallel to potential laminations). The specimen was loaded slightly to position and seat the head. An LVDT (Linear Variable Differential Transducer) was then positioned so the movement of the testing machine head was recorded. This movement was also recorded automatically as a function of load with an x-y recorder.

Load was applied at a rate within the range specified by ASTM C 39 until the specimen exceeded maximum load. The vertical scale of both x-y recorders was connected to calibrated electronic load cells. The follower needle on the 10 in. (25 cm) diameter dial on the Bourdon gage of the testing machine was recorded as an independent check on the plots. After testing, a sketch was drawn showing the locations of the failure surfaces; in some cases a photograph of the specimen was taken. Any unusual phenomena that occurred during the test, observations of the failure surface, and differences in the mode of failure were also recorded.

Figure 9.4 shows the compression testing machine; Fig. 9.5 is a diagram of it and its associated instrumentation. Figure 9.6 is a photograph of the x-y recorder console. For the field tests, all this equipment was temporarily mounted in a station wagon as shown in Fig. 9.7.

9.3 COMPUTATION OF COMPRESSIVE STRENGTH AND METHOD OF PRESENTATION

The maximum compressive stress (compressive strength) was computed in the usual manner. The maximum load was divided by the average cross sectional area of the specimen to obtain compressive strength, σ_c. Through the

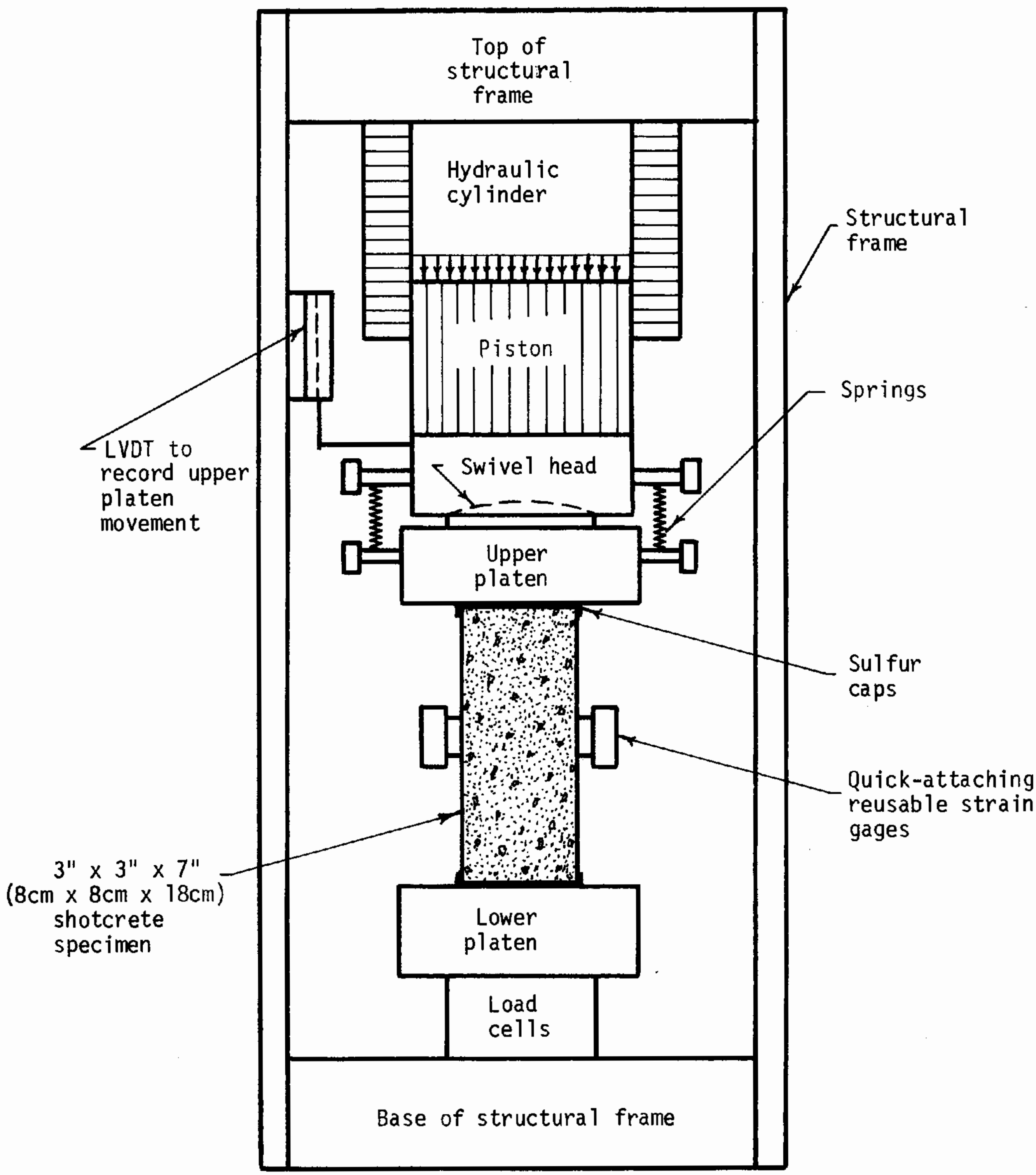


FIG. 9.5 SKETCH OF COMPRESSION TESTING ARRANGEMENT

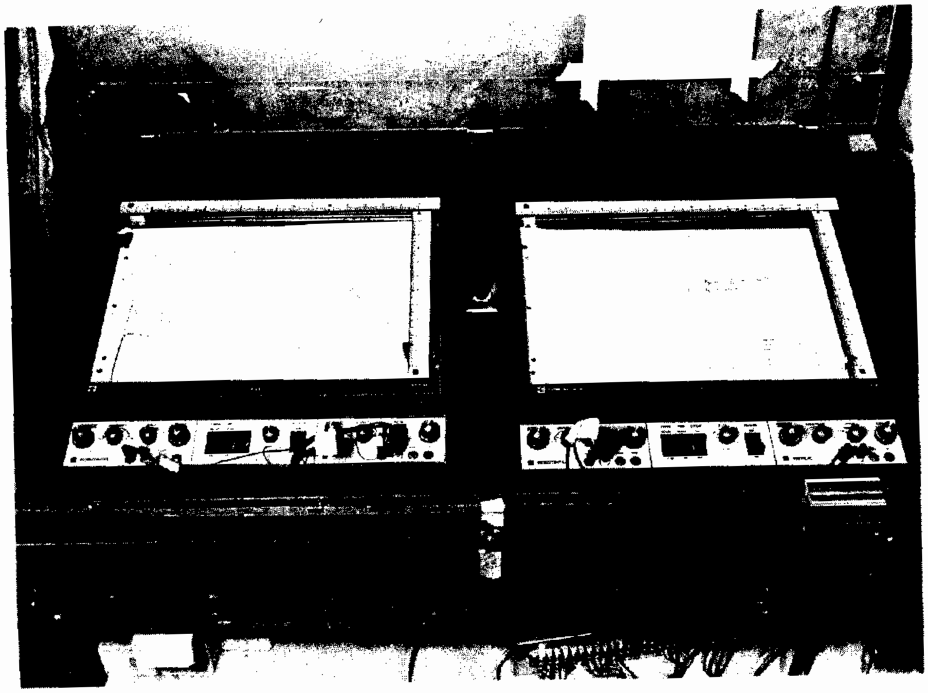


FIG. 9.6 X-Y RECORDER CONSOLE

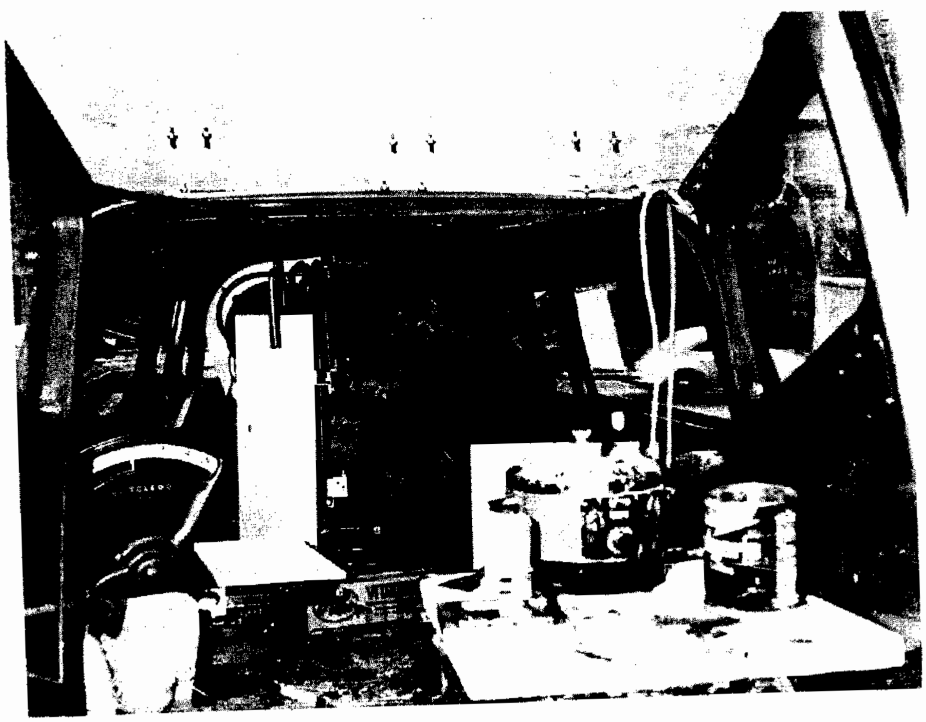


FIG. 9.7 FIELD TEST LAB IN STATION WAGON

42 day tests, the average of the areas of the top and bottom was used. For the six-month tests, the average cross-sectional area was also determined by dividing the total weight of specimen in air by the product of the length of specimen and the unit weight determined by Dunagan test method (Dunagan, 1931). Both methods of determining the average area were compared frequently and since there was no substantial difference between the two methods, the area determined by the Dunagan test method was used for the results at six months.

The results are presented and evaluated in the subsequent sections. First, the results through about one day will be presented and discussed. Next, the results through six months will be treated. Many of the factors affecting early strength also will be shown to have a different effect or an effect to a different degree than found for strength at later ages. Hence, Section 9.7 summarizes, compares, and relates the findings on the strength of "young" shotcrete and on the strength of shotcrete at intermediate and long-term ages. Young is defined as less than about one day old. Generally data for young shotcrete are plotted against an arithmetic time scale while data for older shotcrete are plotted against the logarithm of time. Hence, some of the early strength data are shown both to arithmetic and to logarithmic time scales.

Three major groups of shotcrete were tested; 1) conventional non-fibrous with Type I cement, 2) non-fibrous regulated-set cement shotcrete, and 3) steel fiber shotcrete with Type I cement. The one steel fiber regulated-set cement mix (Mix 42) falls either in group 2 or 3 depending on the parameter considered. Each of these three major groups had a control mix. The control mixes all had a similar mix design except for the one major variable which designates its major group. In the following sections the results from these control mixes will be compared. However, it is possible that any panel tested for a control mix may not be representative of the entire mix or may have considerable scatter statistically; the averages of all the mixes in each of the major groups are also compared to see if they show the same trends as those given by the individual results of the control-mixes. Finally, the data within each group will be evaluated to determine the trends resulting from variations within each major group.

9.4 EVALUATION OF COMPRESSIVE STRENGTH RESULTS OF YOUNG SHOTCRETE

9.4.1 GENERAL FINDINGS

Because of the cold temperatures the rate of gain of strength during the first 6 to 8 hours was minimal with only a few exceptions. The range of compressive strength at 5 hours for typical conventional shotcrete mixes was only 25 to 130 psi (0.2 to 0.9 MPa). It was found that both fibrous and non-fibrous shotcrete with Type I cement and accelerators behaved similarly during these early ages. Hence, in some of the following comparisons, data from the shotcrete mixes with Type I cement and accelerators can be considered as one group whether fibrous or non-fibrous. In contrast to these low strengths, the regulated-set shotcrete mixes and two mixes with exceptionally high dosages of accelerator developed considerable strength very quickly.

9.4.2 ANTICIPATED BEHAVIOR

Shotcrete for temporary support of underground openings requires the highest strength attainable as early as possible consistent with economy and long-term strength requirements. At normal temperatures and with acceptable compatibility between the cement and accelerator, shotcrete with accelerator sets and gains strength quickly so that it achieves a compressive strength of 500 psi (3.45 MPa) by about 3 hours, and 1000 psi (10.34 MPa) by about 5 hours as shown by the band in Fig. 9.8. The band represents a composite of strength-time data assembled from the various sources shown. The dashed curve in Fig. 9.8 represents a composite curve for shotcrete without accelerators.

Regulated-set shotcrete even without accelerators also can be expected to set and gain strength quickly. The expected strength-time relationship of regulated-set shotcrete, shown by the solid curve of Fig. 9.8, was derived from data on regulated-set shotcrete presented by Bortz, et al. (1973).

9.4.3 COMPRESSIVE STRENGTH OF YOUNG CONVENTIONAL AND FIBROUS SHOTCRETE

GENERAL RELATIONSHIPS

The low temperature was expected to retard gain of strength some unknown amount. Conventional shotcrete with normal dosages of accelerator tested in this program appeared to set quickly enough, but gained strength slowly during the first 6 to 8 hours. The earliest compressive tests conducted on conventional shotcrete with about 3 percent accelerator resulted in a σ_c of about 20 psi (0.14 MPa) at an age of 39 minutes. By about 5 hours, σ_c was only about 30 psi (0.21 MPa). The strength remained at these very low levels to ages ranging from 7 to 12 hours depending on the mix and shooting conditions. Then strengths began to develop rapidly, strengths ranging from 1600 to 1900 psi (11.0 to 13.1 MPa) had developed by the end of one day. At ages less than one day, the compressive strength curves of fibrous mixes

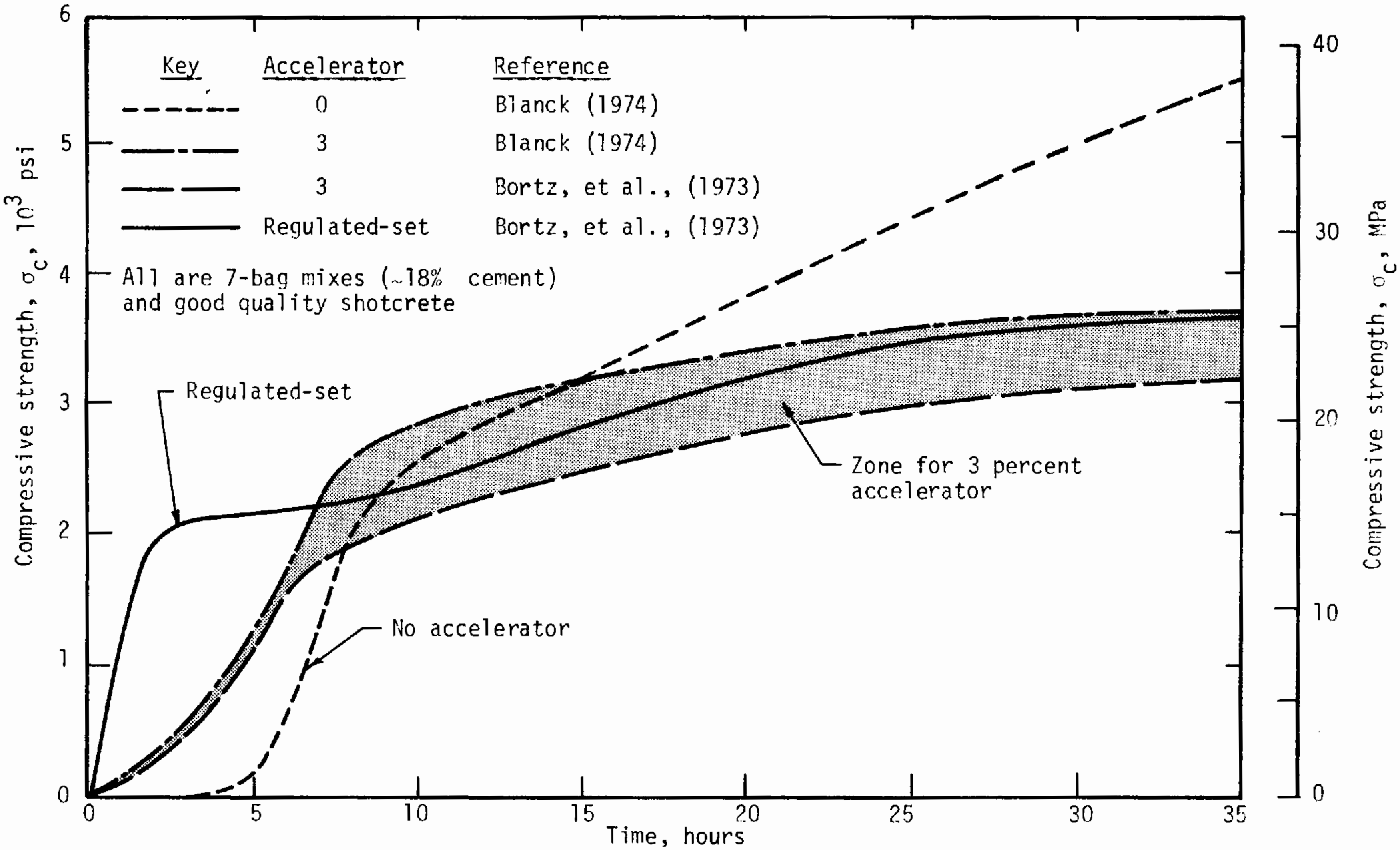


FIG. 9.8 TYPICAL COMPRESSIVE STRENGTH-TIME RELATIONSHIPS FOR YOUNG SHOTCRETE REPORTED IN THE LITERATURE

correspond closely to non-fibrous ones so this discussion of young shotcrete is applicable to both fibrous and non-fibrous mixes. The range of average strength-time curves for all conventional non-fibrous mixes with about 3 percent accelerator is shown by the cross-hatched area in Fig. 9.9. For comparison the average of the composite strength-time curves for 3 percent accelerator in Fig. 9.8 is shown dashed in Fig. 9.9. All evidence indicates that the primary reason for the slower development in strength was the extremely low temperatures.

EFFECT OF ACCELERATOR DOSAGE

Evidently the cold environment made the accelerator nearly ineffective as far as strength gain is concerned. Gillmore Needles test results on cold materials are summarized from the tables in Appendix B and from Chapter 3 in Table 9.1. It can be seen that the cement and accelerator were compatible at normal room temperatures yet were not compatible when tested cold. Much more accelerator would be required to produce the desired set times at a low temperature. This is especially true for the final set time. On the other hand, less accelerator seems to be required for higher than normal temperatures.

Slow material delivery rates for two mixes inadvertently resulted in high dosages of accelerator. Mix 33 had an accelerator dosage of 4.9 percent while Mix 34 had a dosage of 8.4 percent. Both were steel fiber mixes, but the early strength behavior of other steel fiber mixes was similar to that of non-fibrous mixes, so a comparison of early strength of these 2 mixes with non-fibrous mixes in Fig. 9.10 appears to be appropriate. The early strength

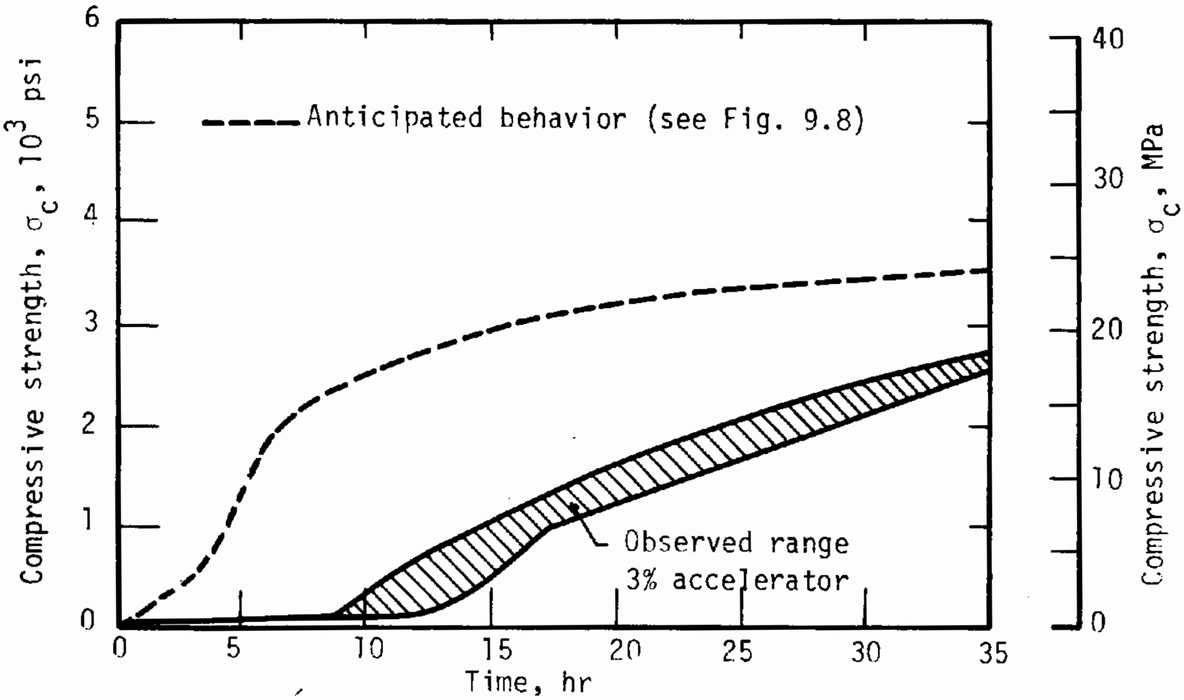


FIG. 9.9 RANGE OF COMPRESSIVE STRENGTH-TIME CURVES FOR YOUNG CONVENTIONAL NON-FIBROUS SHOTCRETE

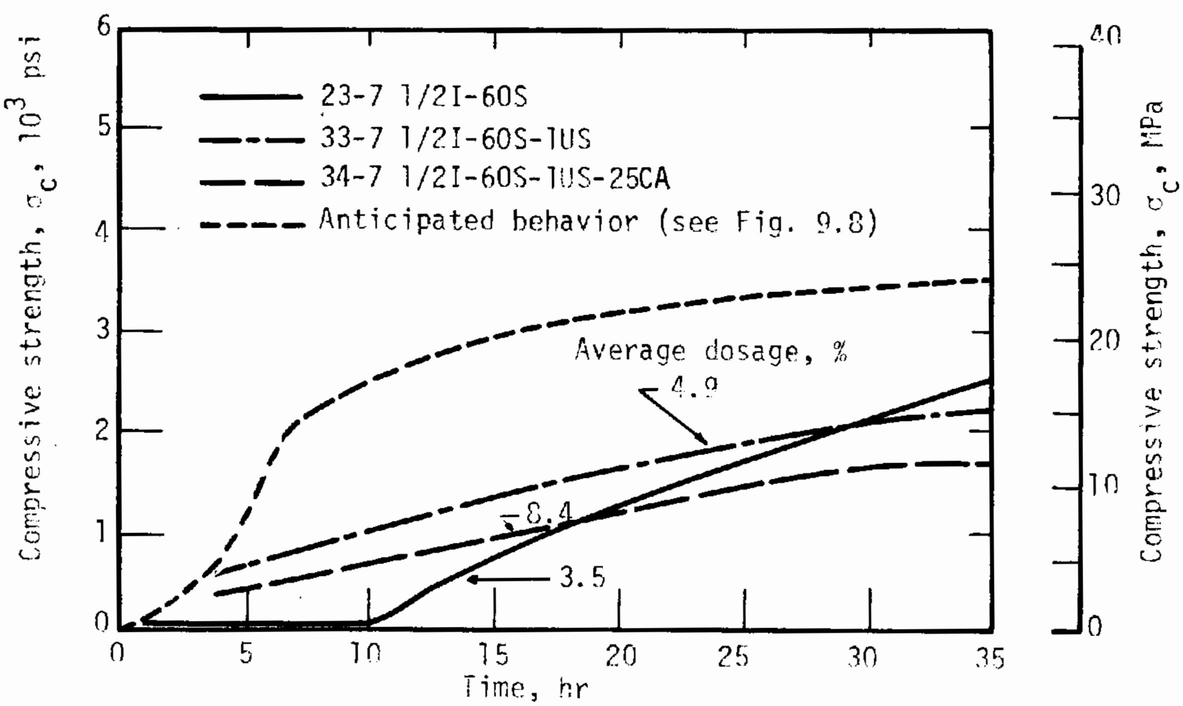


FIG. 9.10 EFFECT OF ACCELERATOR DOSAGE ON COMPRESSIVE STRENGTH-TIME CURVES OF YOUNG SHOTCRETE

TABLE 9.1

EFFECT OF TEMPERATURE ON SETTING TIME[1]

Temperature	Gillmore Needles setting time, min-sec			
	Type 1 cement[2]		Regulated-set cement[3]	
	Initial set	Final set	Initial set	Final set
Results at room temperature	3-00	10-30	1-30	7-00
Results at 42°F (5.5°C)	4-30	33-00	34-00	160-00

[1] Detailed results are presented in Chapter 3. Desired set times are 3 minutes in initial set and 12 minutes for final set.
[2] Accelerator dosage: 4 percent by weight of cement.
[3] Accelerator not required.

was enhanced markedly by the high accelerator dosages. There appears to be an optimum accelerator dosage above which additional accelerator results in lower early strength. The average of the composite strength-time curve for 3 percent accelerator in Fig. 9.8 is again shown dashed in Fig. 9.10 for comparison. It can be seen that even the best results are lower than what might be anticipated under ideal conditions.

It is concluded that much higher accelerator dosages are required for cold weather shotcreting than for normal-temperature operations to produce similar early-strength. Unfortunately, high dosages produce substantially lower long-term strength; the effect of the accelerator on strength after one day will be discussed later.

EFFECT OF THICKNESS OF SHOTCRETE ON STRENGTH GAIN OF YOUNG SHOTCRETE

The effect of the thickness of the shotcrete layer on the rate of gain of strength was not specifically studied but indirect data is available. It has been observed during routine construction of thick final linings that shotcrete 1 ft (30 cm) or more thick gets very hot during curing. The 3-in. (7.6 cm) thick panels used in these studies and the thin shotcrete linings they represent are so thin that they dissipate their own heat of hydration very quickly while thick shotcrete cannot. Table 9.2 gives data comparing the build-up of temperature of thin and thick shotcrete specimens shot for another research project at the Dupont Circle construction site (Brierley, 1975; Jones, 1976). Also shown are selected temperatures measured in 3-in. (7.6 cm) thick panels shot for this project.

The internal temperature of shotcrete is higher with increasing layer thickness. It is known that the early rate of gain of strength of concrete is enhanced by higher temperature (Troxell, et al., 1968) and there is every reason to believe that similar behavior exists for shotcrete. Hence, it may be concluded that the rate of gain of strength of shotcrete in thick layers is higher than for thin layers. This factor is probably more critical at lower temperatures. The thicknesses used for temporary support of underground openings are usually thin.

INFLUENCE OF NOZZLE-WATER TEMPERATURE ON STRENGTH OF YOUNG CONVENTIONAL AND FIBROUS SHOTCRETE

Mix 25 shot with 60°F (16°C) water may be compared with Mix 26 shot with 100°F(38°C) nozzle-water to evaluate the influence of nozzle-water

TABLE 9.2

OBSERVED TEMPERATURES IN THICK AND THIN SHOTCRETE LAYERS

	Thickness, in.	(cm)	Approximate air °F	(°C)	Maximum Temperature, °F	(°C)	Age at Maximum Temperature, hrs
Measurements made June 27, 1973 during WMATA study for construction of Dupont Circle Station (Brierley, 1975)							
Large test box (2x2x4 ft) (61x61x122 cm)	24	(61)	75	(24)	150	(66)	~6 to 8
In situ shotcrete lining	~30	(76)	75	(24)	130 to 150 (54) to (66)		~10 to 14
Small test panel (12x4x4 in.) (30x10x10 cm)	4	(10)	75	(24)	84	(29)	4
Test panels shot for this study							
Typical test panel shot on Day III	3	(7.6)	40	(4)	61	(16.1)[1]	0 to 0.2
Typical test panel shot on Day IV	3	(7.6)	30 to 40 (-1 to 4.5)		63	(17.2)[2]	0 to 0.2

Note: [1]) Temperature of regulated-set Mix 28 built up to a maximum of 80°F (26.7°C) at 2 hours after shooting.

[2]) Temperatures of regulated-set Mix 42 was 86°F (30°C) at 0.7 hours after shooting.

temperature on early strength since all other conditions were nearly the same. It appears that the mix shot with hot water gained strength earlier and faster. Significant gain of strength began at about 8-1/2 hours for the mix with hot water and at about 12 hours for the mix shot with cold water. At 12 hours, the compressive strength of the mix shot with hot water was about twice that of the one shot with cold water. However, the strengths of both mixes at 12 hours were quite low, the difference was only 300 psi (2.1 MPa), and the data are meager.

It is tentatively concluded that hotter nozzle-water can accelerate the initial rate of gain of strength. Evidence to be presented later indicates there is reason to believe that the combination of high water temperature and high accelerator dosage could result in lower initial strengths. Thus, there probably is an optimum water temperature for early strength.

INFLUENCE OF CEMENT CONTENT ON STRENGTH OF YOUNG CONVENTIONAL AND FIBROUS SHOTCRETE

Mixes 38, 39 and 40 would seem to provide this comparison since the batches were shot with 8-1/2, 7-1/2 and 7 bags (475, 418 and 390 kg/m^3) of cement, respectively. However, no early tests were made on Mix 40. The earliest strength tests for the 8-1/2 bag (475 (kg/m^3) Mix 38 was 145 psi (1 MPa) at about 2-1/4 hours. Mix 39, a 7-1/2 bag (418 kg/m^3) mix, attained only about 50 psi (0.34 MPa) at about 1-1/4 hours. Since the strength-time curves were approximately flat at these ages, the comparison of the two mixes appears appropriate. The higher cement content may have caused the higher early strength, but strengths were comparable at 1/2 day and one day so the advantage of the high cement content was subsequently lost. The data are very meager and the higher strength at early ages could result from other factors than cement content.

INFLUENCE OF TYPE OF NOZZLE ON EARLY STRENGTH OF CONVENTIONAL SHOTCRETE

Mix 25 shot with the long nozzle can be compared with Mix 23 shot with the short nozzle the day before. If compared, the early portions of these two strength-time curves would plot almost on top of each other. The type of nozzle apparently had little effect on the early strength.

9.4.4 STRENGTH OF YOUNG REGULATED-SET SHOTCRETE

GENERAL

The compressive strength of young regulated-set shotcrete was often much higher than conventional mixes but it was also erratic and spotty. Some mixes achieved the anticipated very high strength, while others achieved strengths that were only a few times that of the conventional control mixes.

The cold environment was expected to restrict the early development of strength of the regulated-set mixes too. The Gillmore Needles results given in Table 9.1 indicate regulated-set cement is even more sensitive to temperature than Type I cement. Above a certain temperature (about 80 to 100°F) (27 to 38°C) an apparent false set was observed in Gillmore Needles tests (Fig. 3.2) apparently because the true initial set occurred in the mixing bowl. It is believed that this same phenomenon occurs in the nozzle and airstream. Therefore, higher nozzle-water temperatures are considered beneficial up to an optimum temperature above which higher temperatures result in a loss of early strength.

COMPARISON OF REGULATED-SET TO CONVENTIONAL SHOTCRETE

The data in Table 9.3 allows a comparison of the compressive strength of selected regulated-set mixes with their respective control mix of conventional shotcrete. After 2 hours, various regulated-set shotcrete mixes had gained compressive strength that ranged from about 1.0 to 27 times its respective control mix. Contrary to expectations the mix shot with the coolest water (60°F, 16°C) developed the highest early strength.

TABLE 9.3

COMPARISON OF COMPRESSIVE STRENGTH OF YOUNG REGULATED-SET SHOTCRETE WITH YOUNG CONVENTIONAL SHOTCRETE

Mix No.	Description	Compressive strength, σ_c psi (MPa)		
		2 Hours	5 Hours	10 Hours
28	Control mix for regulated-set with 100°F (37.8°C) water	45 (0.31)	1000 (6.9)	3000 (20.7)
31	Regulated-set with 60°F (15.5°C) water	1350 (9.3)	1500 (10.3)	2200 (15.2)
23	Conventional control	50 (0.35)	30 (0.21)	120 (0.83)
42	Regulated set steel fiber mix (high cement content)	350 (2.4)	400 (2.8)	1000 (6.9)
39	Conventional steel fiber control	60 (0.41)	100 (0.69)	700 (4.8)

Figure 9.11 is a comparison of the strength-time curve of regulated-set Mix 31, shot with cool water, with the curve for Mix 33, the conventional shotcrete with 4.9 percent accelerator that achieved the highest strength of all conventional mixes during the first 10 hours. The superiority of the

regulated-set shotcrete is clear. Figure 9.12 is a comparison of the strength-time curves of two mixes similar except for temperature and cement type. The Type I cement control mix was accelerated with about 3.4 percent accelerator while the regulated-set cement was accelerated with hot water.

The upper envelope of all the average strength-time curves for regulated-set mixes is compared to the upper envelope of all the conventional control mixes in Fig. 9.13. The shaded area in each of these figures highlights the increase in σ_c over the conventional control mixes. The strongest regulated-set mix at any given time exceeded the strongest control mix by the

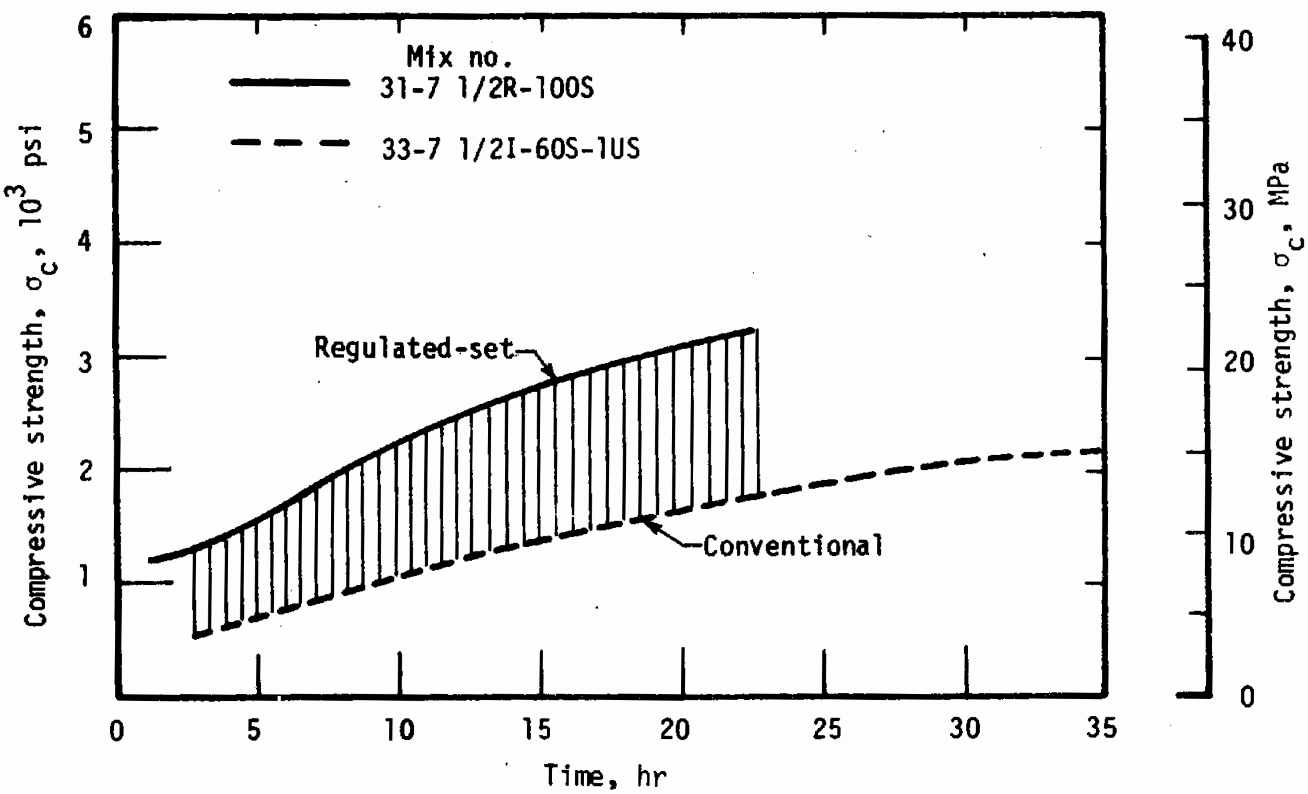


FIG. 9.11 COMPARISON OF COMPRESSIVE STRENGTH-TIME CURVES OF YOUNG SHOTCRETE: STRONGEST REGULATED-SET MIX VS STRONGEST CONVENTIONAL MIX

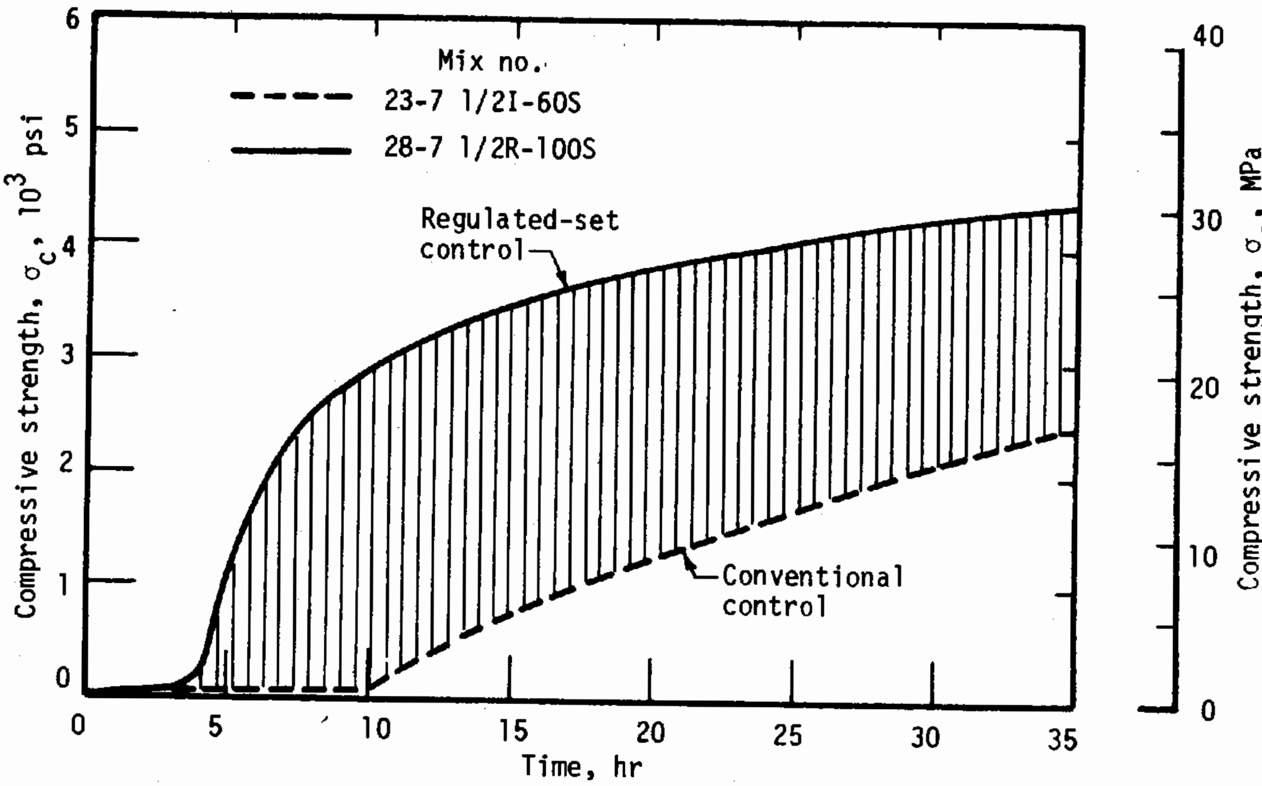


FIG. 9.12 COMPARISON OF COMPRESSIVE STRENGTH-TIME CURVES OF YOUNG CONTROL MIXES FOR REGULATED-SET SHOTCRETE AND CONVENTIONAL SHOTCRETE

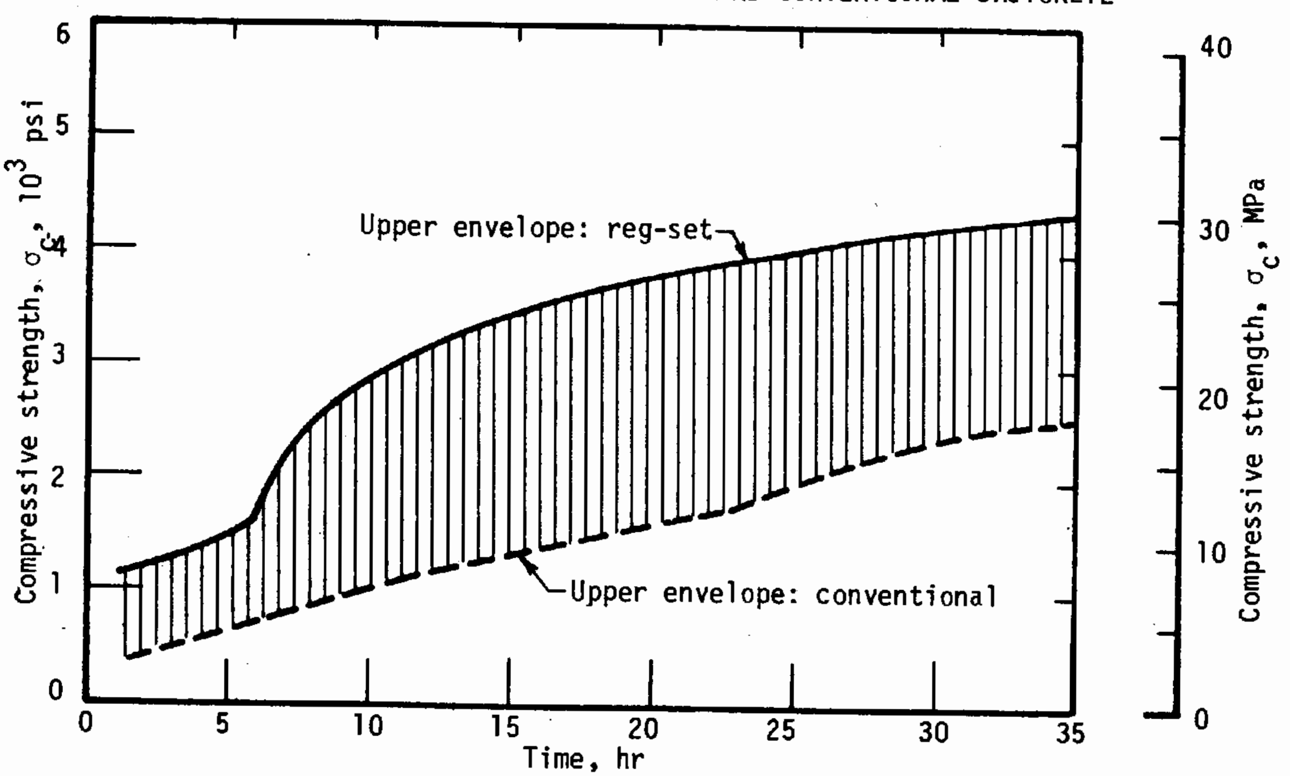


FIG. 9.13 COMPARISON OF UPPER ENVELOPE OF YOUNG REGULATED-SET AND OF CONVENTIONAL SHOTCRETE COMPRESSIVE STRENGTH-TIME CURVES

ordinate of the shaded area. In particular the increased strength within the first few hours indicates that regulated-set shotcrete could be extremely important in poor ground requiring immediate support.

In all comparisons, regulated-set shotcrete developed substantially higher strengths than conventional shotcrete.

EFFECT OF NOZZLE WATER TEMPERATURE ON YOUNG REGULATED-SET SHOTCRETE

The nozzle water temperature of 100°F (38°C) was selected on 1) the basis of results for initial set in compatibility tests, 2) a visual observation of shooting of regulated-set shotcrete within the range of water temperatures from 60 to 120°F (16 to 49°C) (Mixes 17 to 20), 3) previous experience by others (Bortz, et al. 1973), and 4) general knowledge of the behavior of regulated-set concrete with various mixing-water temperatures. The data in Fig. 9.14 indicates that the 100°F (38°C) temperature was too hot for optimum early-compressive-strength development. The figure compares two mixes identical in every respect but nozzle-water temperature. Mix 31, shot with 60°F (16°C) water, developed substantially more early strength, faster than Mix 28 shot with 100°F (38°C) water. Unfortunately, only a few panels of Mix 31 were shot and strength results do not extend beyond 21 hours. It is believed that the high nozzle-water temperature with high regulated-set cement content tended to promote initial setting before or as soon as the material reached the wall. All subsequent incoming material acted to disturb rather than to compact the material. The test data appear to substantiate this hypothesis. A similar phenomena is believed responsible for the comparatively low strength of Mix 34 at early ages; the 8.4 percent accelerator made the mix too "active".

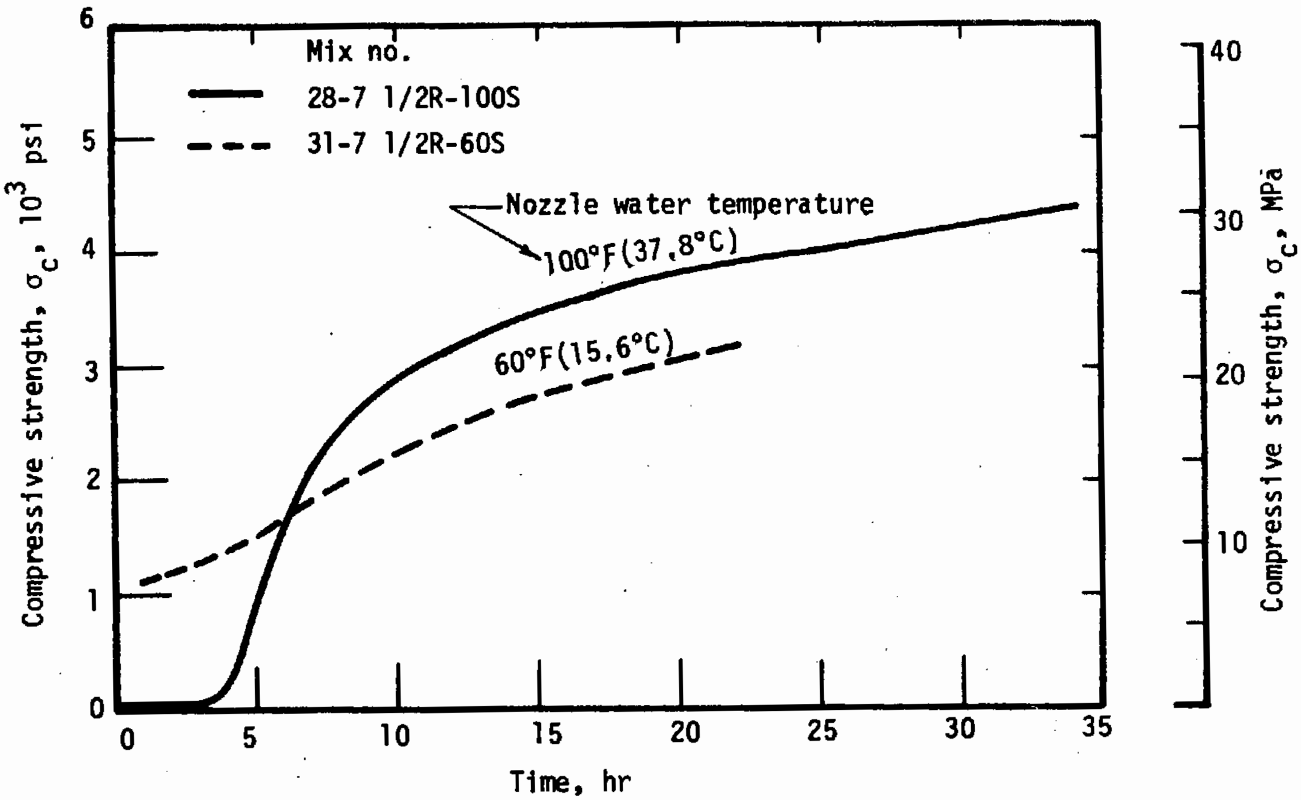


FIG. 9.14 EFFECT OF NOZZLE-WATER TEMPERATURE ON COMPRESSIVE STRENGTH-TIME CURVES OF YOUNG REGULATED-SET SHOTCRETE

EFFECT OF CEMENT CONTENT: YOUNG REGULATED-SET CEMENT

The cement content of regulated-set shotcrete mixes varied between 6-1/2 and 10-1/2 bags per cu yd (360 to 580 kg per cu m). Of these mixes only 29, 28, and 30 have similar conditions. Their actual cement contents were 22.3 percent, 24.0 percent and 27.8 percent, respectively. The early-strength behavior of these mixes is compared and related to the water cement ratio in Table 9.4.

It can be seen that Mix 29 had the lowest cement content and the highest water-cement ratio. Both factors tend to delay setting so it is impossible to

TABLE 9.4

EFFECT OF CEMENT CONTENT AND WATER CEMENT RATIO ON COMPRESSIVE STRENGTH OF YOUNG REG-SET SHOTCRETE

Mix no.	No. bags cement batched	Measured cement content in-place %	Measured water-cement ratio	Age at beginning of rapid strength gain hrs	Age when 1000 psi (6.9 MPa) obtained hrs
29	6-1/2	22.3	0.34	12	24
28	7-1/2	24.0	0.30	3	4
30	8-1/2	27.8	0.27	6	9

evaluate the relative roles of the two factors. Mix 28 was intermediate and exhibited the quickest strength gain.

Mix 30 had the highest cement content and the lowest water-cement ratio, both of which should promote faster setting. However, this mix did not gain strength as quickly as Mix 28. It is believed that the poor strength-gain of Mix 30 resulted because incoming shotcrete disturbed in-place shotcrete that had already set. The conditions were very favorable for ultra-quick setting (hot water, low water-cement ratio, and high cement content). The mix can be considered too active. The previous section described the same phenomenon in Mix 28. Credence to this disturbance phenomena for Mix 30 is given by the fact that the one-month strength of Mix 30 was lower than the other regulated-set mixes even though it had the highest cement content. This lower long-term strength would also result from such disturbance.

9.5 INTERMEDIATE AND LONG-TERM COMPRESSIVE STRENGTH

9.5.1 GENERAL FINDINGS

This section includes the results of compressive strength tests from one day through six months. Some of the trends expected in the long-term strength results began to show up in the seven-day strengths. At seven days and later, the steel fiber mixes had lower compressive strengths than the non-fiber control mixes. Also, the increase in strength shown by regulated-set mixes over control mixes was not as spectacular as seen at early ages because their strength advantage over conventional mixes decreases with age. Mixes with high accelerator dosages also tend to have lower strength. The data in this section are presented and discussed by individual control mixes and by the following major groups: 1) non-fibrous conventional, 2) regulated-set, and 3) steel fiber mixes. Data will be grouped and tabulated according to these major groups so that broad trends between the major groups can be observed more easily and so that major variations within each group may be identified. The average strength shown for each major group includes the effects of all variations of mix design and shooting conditions within the group unless otherwise noted. For example, the average strength shown for the regulated-set group would include the strength of mixes containing 6-1/2, 7-1/2 and 8-1/2 (360, 418, and 470 kg/m^3) bag mixes. Where major variations exist in the strength results within a group, an average excluding the strength of the variant mix is also shown.

Because variations of parameters within each group are of interest, the mixes are discussed individually also. There was one control mix in each major group that had mix design and shooting conditions similar to the conventional shotcrete control mix in as many ways as possible.

In the following paragraphs, the relations between the control mixes are first described. Then the average strengths of each group are evaluated to see if the same relationships hold. Finally, variations of mixes in each group are discussed.

9.5.2 COMPRESSIVE STRENGTH AT ONE DAY

Because of testing schedules and breakdown of testing equipment strengths were not determined precisely at one day. The strengths, σ_{c1}, reported in this paragraph have been estimated from the strength-time curves in Appendix E, so the strengths can only be considered approximate.

The estimated compressive strengths of the control mixes at one day, σ_{c1}, are compared in Table 9.5. The strength of regulated-set shotcrete is 2.5 times its conventional shotcrete control while the strength of steel fiber shotcrete is approximately the same as its control within the accuracy of the results.

TABLE 9.5

COMPARISON OF ESTIMATED COMPRESSIVE STRENGTH OF CONTROL MIXES AT ONE DAY

Mix number	Description of mix	Strength, σ_{c1} psi (MPa)	Remarks
Regulated set shotcrete			
28	Reg-set control	4000 (27.6)	Regulated-set shotcrete is 2.5 times stronger
23	Conventional control	1600 (11.0)	
Steel fiber shotcrete			
39	Steel fiber control	2100 (14.5)	Within accuracy of results about the same
26	Conventional control	1900 (13.1)	

Table 9.6 is a summary of the estimated compressive strengths at one day by group. The averages for the group follow the same trends as the control mixes, i.e., the strengths of conventional and steel fiber mixes are similar and the strengths of the regulated-set mixes are about double the control. Looking at the individual mixes, the compressive strengths of the conventional mix shot on Day II (Mix 14) is significantly greater than those shot on Days III and IV. However, a different brand of cement was used on Day II and all the improvements in strength should not be attributed completely to the higher temperature on Day II. Nevertheless, it is believed the warmer environment played an important role.

The steel fiber mix with the highest accelerator dosage (Mix 34) had the lowest compressive strength of the group at the age of one day. The low strength of Mix 24 is attributed to poor shooting conditions and the low strength of Mix 29 is attributed to the low cement content (only 6-1/2 bags) (360 kg/m^3) and a relatively high water-cement ratio of 0.34 compared to other regulated-set mixes.

9.5.3 COMPRESSIVE STRENGTH AT SEVEN DAYS

Table 9.7 provides a comparison of the strength, σ_{c7}, of the control mixes at 7 days. The variation in strength between the mixes is evident although the data for this age are both meager and variable; the regulated-set mix is somewhat stronger than its conventional shotcrete control (10 percent) while the steel fiber mix is somewhat lower than its control. This trend for lower compressive strength of fibrous shotcrete has been observed by other researchers (Poad, et al., 1975).

TABLE 9.6

SUMMARY OF ESTIMATED COMPRESSIVE STRENGTH AT ONE DAY

Conventional shotcrete		Regulated-set shotcrete		Steel fiber shotcrete	
Mix number	Strength, σ_{c1} psi (MPa)	Mix number	Strength, σ_{c1} psi (MPa)	Mix number	Strength, σ_{c1} psi (MPa)
MIXES SHOT ON DAY II					
14	2500 (17.3)	21	3400 (23.5)		
MIXES SHOT ON DAYS III AND IV					
23	1600 (11.0)	28	4000 (27.6)	33	1800 (12.4)
24	800 (5.5)	29	1200 (8.3)	33A	1900 (13.1)
25	1800 (12.4)	30	3200 (22.1)	34	1400 (9.7)
26	1900 (13.1)	31	3500 (24.1)	38	1700 (11.7)
				39	2100 (14.5)
				42	2300 (15.9)
				45	2000 (13.8)
AVERAGES FOR DAYS III AND IV					
	1525 (10.5)		2975 (20.5)		1885 (13.0)
Excluding Mix 24		Excluding Mix 29		Excluding Mix 34	
	1770 (12.2)		3570 (24.6) 200% of control		1970 (13.6) 111% of conventional

TABLE 9.7

COMPARISON OF COMPRESSIVE STRENGTH OF CONTROL MIXES AT SEVEN DAYS

Mix number	Description of mix	Strength, σ_{c7}, psi (MPa)	Remarks
Regulated-set shotcrete			
28	Reg-set control	5220 (36.0)	Reg-set has 510 psi (3.5 MPa) greater strength (10%)
23	Conventional control	4710 (32.4)	
Steel fiber shotcrete			
39	Steel fiber control	3890 (26.8)	Steel fiber has 560 psi (3.9MPa) lower strength (12%)
25	Substitute conventional control*	4450 (30.7)	

*Note: Samples of actual conventional control, Mix 26, were not available for testing at 7 days. Mix 25 is identical to Mix 26 except that it was shot at 60°F (15.6°C) instead of 100°F (37.8°C).

Similar trends are observed when evaluated by group as shown in Table 9.8. Within the steel fiber group, the strength of the mixes with high accelerator (Mixes 33 and 34) are quite low compared to mixes with the normal dosage of about 3 percent accelerator. Mix 34 with about 8 percent accelerator has a strength of 2280 psi (15.7 MPa) compared to the average of other steel fiber mixes of 3640 psi (25.1 MPa), a 37 percent difference.

TABLE 9.8

SUMMARY OF COMPRESSIVE STRENGTH AT SEVEN DAYS

Conventional shotcrete		Regulated-set shotcrete		Steel fiber shotcrete	
Mix number	Strength, σ_{c7} psi (MPa)	Mix number	Strength, σ_{c7} psi (MPa)	Mix number	Strength, σ_{c7} psi (MPa)
MIXES SHOT ON DAY II					
14	3720 (25.7)	21	5190 (35.8)		
MIXES SHOT ON DAYS III AND IV					
23	4710 (32.4)	28	5220 (36.0)	33	2940 (20.2)
25	4450 (30.7)	29	5240 (36.1)	33A	3300 (22.7)
		30	4820 (33.2)	34	2280 (15.7)
				38	3530 (24.3)
				39	3890 (26.8)
				40	4460 (30.7)
				42	3540 (24.4)
				45	3120 (21.5)
AVERAGES FOR DAYS III AND IV					
	4580 (31.5)		5090 (35.1)		3380 (23.3)
				Excluding 33 and 34*	
					3640 (25.1)

*Mixes 33 and 34 contained high dosages of accelerator

9.5.4 COMPRESSIVE STRENGTH AT ONE MONTH

Table 9.9 summarizes the compressive strength of the control mixes at one month. Again the same trends hold, the regulated-set mix was 25 percent stronger than the conventional shotcrete control mix and the steel fiber mix was 11 percent weaker than its control. A summary of compressive strength by group is given in Table 9.10. The same general trends are observed.

Interestingly, all the reliable conventional mixes (Mixes 14, 23, 25, and 26) had a compressive strength very close to 5000 psi (34.5 MPa) despite varied shooting conditions. Again, the strength of Mix 34, that had an accelerator dosage of about 8 percent, was quite low, 2800 psi (19.3 MPa) compared to the 4030 psi (27.7 MPa) average for the other steel fiber mixes.

TABLE 9.9

COMPARISON OF COMPRESSIVE STRENGTH OF CONTROL MIXES AT ONE MONTH

Mix number	Description of mix	Strength σ_{c28} psi (MPa)	Remarks
<u>Regulated-set shotcrete</u>			
28	Reg-set control	6220 (42.9)	Reg-set is 25% stronger than control
23	Conventional control	4980 (34.3)	
<u>Steel fiber shotcrete</u>			
39	Steel fiber control	4450 (30.7)	Steel fiber is 11% weaker than control
26	Conventional control	5020 (34.6)	

TABLE 9.10

SUMMARY OF COMPRESSIVE STRENGTH AT ONE MONTH

Conventional shotcrete		Regulated-set shotcrete		Steel fiber shotcrete	
Mix number	Strength σ_{c28} psi (MPa)	Mix number	Strength σ_{c28} psi (MPa)	Mix number	Strength σ_{c28} psi (MPa)
MIXES SHOT ON DAY II					
14	4910 (33.9)	21	5200 (35.8)		
MIXES SHOT ON DAYS III AND IV					
23	4980 (34.3)	28	6220 (42.9)	33	4040 (27.9)
24	4300 (29.7)	29	5870 (40.4)	33A	3560 (24.5)
25	5330 (36.7)	30	5080 (35.0)	34	2800 (19.3)
26	5020 (34.6)			38	3950 (27.2)
				39	4450 (30.7)
				40	4260 (29.3)
				42	3900 (26.9)
AVERAGES FOR DAYS III AND IV					
	4910 (33.8)		5720 (39.5)		3850 (26.5)
Excluding Mix 24				Excluding Mix 34	
	5110 (35.2)				4030 (27.7)

These data are presented graphically in Fig. 9.15 where similar mixes are placed in the three basic groups. The heavy solid vertical line in the figure is at 5000 psi (34.5 MPa) which is the average of the two control mixes (Mix 23 for Day III and Mix 26 for Day IV). The one-month compressive strength for all other mixes might be compared to this strength. In addition there was a control mix for regulated-set mixes (Mix 28) and steel fiber mixes (Mix 39). The average strength for each of these is shown by a dotted line within the group of mixes for which the control mix is applicable. The maximum, the minimum and one standard deviation is shown for each mix so that the scatter in the results can be appreciated visually. Thus, the horizontal length of the lines is proportional to the amount of scatter in the strength data.

9.5.5 COMPRESSIVE STRENGTH AT FORTY-TWO (42) DAYS

Prisms suitable for compression testing were sawed from the uncracked ends of all the beams tested in flexure for the one-month tests in the manner illustrated in Fig. 8.3. Thus the rough portion of these specimens was trimmed off; this trimming has strength implications as discussed in Section 9.6. These specimens were not only about 2 weeks older than the one-month compression specimens but also had been soaking and curing in water at room temperature for the extra 2 weeks. The one-month specimens had only been soaked at room temperature for about 40 hours. All previous curing had been air dry at about 55°F (12.8°C). The results of this special series of compression tests at 42 days are summarized by group in Table 9.11. These data indicate that the combination of trimming the specimens and of more favorable curing conditions resulted in an apparent increase of compressive strength of about

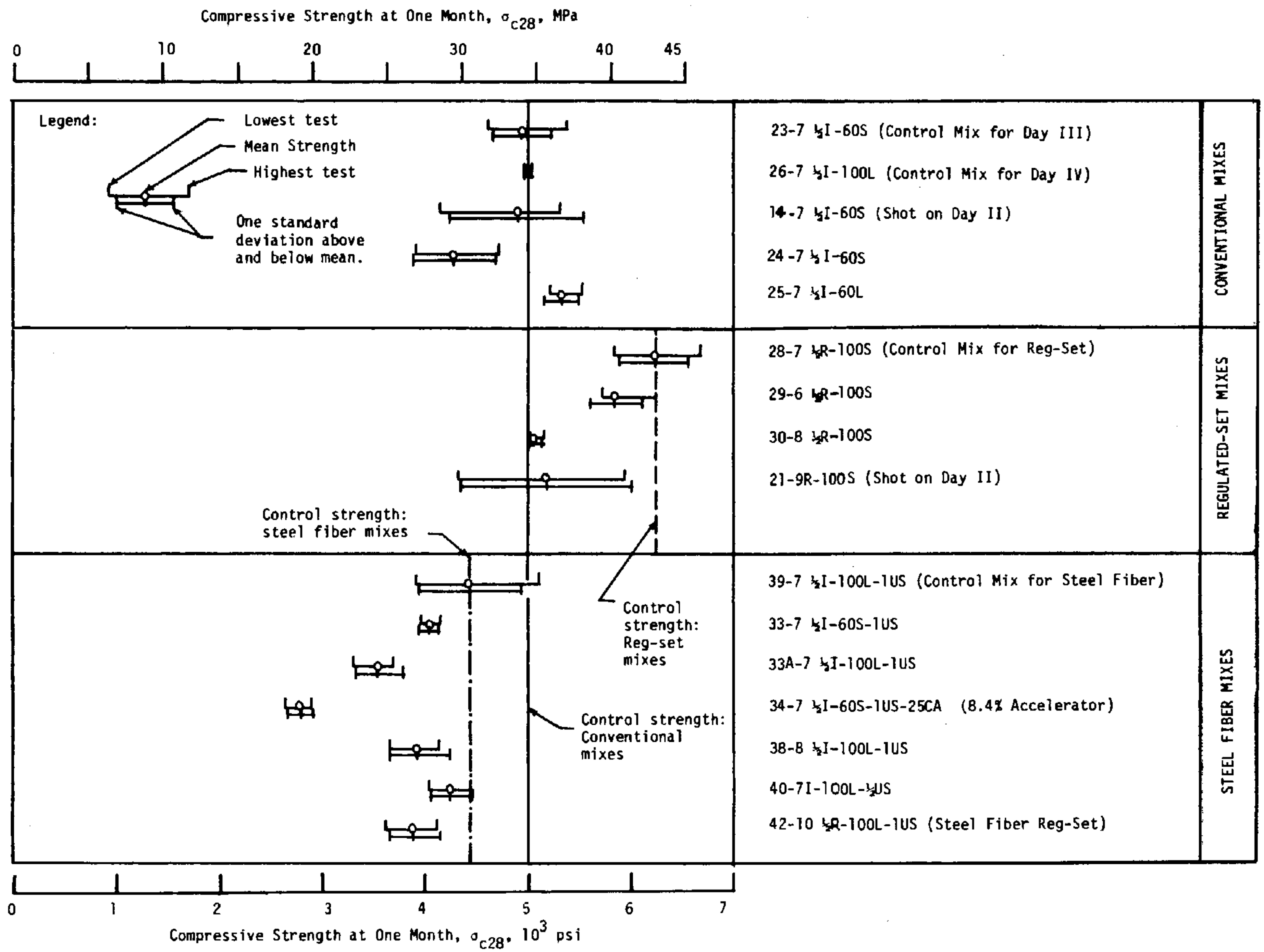


FIG. 9.15 COMPARISON OF COMPRESSION TEST RESULTS AT ONE MONTH

TABLE 9.11

SUMMARY OF COMPRESSIVE STRENGTH
AT FORTY-TWO DAYS

Conventional shotcrete		Regulated-set shotcrete		Steel fiber shotcrete	
Mix number	Strength, σ_{c42}, psi (MPa)	Mix number	Strength, σ_{c42}, psi (MPa)	Mix number	Strength, σ_{c42}, psi (MPa)
23	5700 (39.3)	28	6820 (47.1)	33	4380 (30.2)
24	4630 (31.9)	29	6630 (45.7)	33A	4400 (30.3)
25	6120 (42.2)	30	5700 (39.3)	34	4210 (29.0)
26	5780 (39.9)			38	4790 (33.0)
				39	5650 (38.9)
				40	5430 (37.4)
				42	4280 (29.5)
AVERAGES, σ_{c42}					
Exluding mix 24				Excluding Mix 34	
	5870 (40.5)		6380 (44.0)		4820 (33.2)
AVERAGE FOR THESE GROUPS AT 28 DAYS, σ_{c28} (FROM TABLE 9.10)					
	5110 (35.2)		5720 (39.5)		4030 (27.7)
INCREASE OVER 28 DAY STRENGTH σ_{c28}					
	760 (5.2)		660 (4.6)		790 (5.5)
PERCENT INCREASE OVER 28 DAY STRENGTH GAINED OVER 2 WEEK CURING PERIOD AND BY TRIMMING					
	15%		11%		20%

660 to 790 psi (4.6 to 5.5 MPa) as discussed in more detail in Section 9.6. It is believed that the 11 percent increase seen in the regulated-set mixes is due primarily to trimming while the more porous steel fiber samples demonstrate 20 percent increase probably because of a combination of trimming and additional curing. Changes in curing conditions of concrete specimens results in a similar increase in strength (Troxell, et al., 1968).

9.5.6 COMPRESSIVE STRENGTH AT SIX MONTHS

At the age of six months, panels had been cured air dry at about 85 percent humidity and 70°F (21.1°C) since the one-month long cool curing period. Many tests were conducted at this time to evaluate a number of factors including expected variations in strength within any given panel and the effects of trimming and soaking.

The results of compression tests on the control mixes are summarized in Table 9.12. Regulated-set shotcrete is about 25 percent stronger than its conventional shotcrete control mix. Steel fiber Mix 39 has a strength 15 percent lower than the strength for its control, Mix 26. However, the strength of Mix 26 is believed unusually high, possibly because of test error or possibly due to particularly wet curing conditions. If Mix 26 is accepted as representative of the conventional mix, the steel fiber control mix was 16 percent weaker that its control mix. However, most of the evidence indicates that the strength of this particular panel of Mix 26 is not representative. Only 4 specimens tested from Mix 26 were from one panel while 22 tests were made on Mix 23, another control mix but shot with the short nozzle. Compared to Mix 23, the six-month strength σ_{c180} of steel fiber is about equal to the control.

TABLE 9.12

COMPARISON OF COMPRESSIVE STRENGTH OF CONTROL MIXES AT SIX MONTHS

Mix number	Description of mix	Strength, σ_{c180}, psi (MPa)	Remarks
Regulated set shotcrete			
28	Reg-set control	7250 (50.0)	Reg-set is 24% stronger
23	Conventional control	5880 (40.5)	
Steel fiber shotcrete			
39	Steel fiber control	5880 (40.5)	Steel fiber is 15% weaker than control Mix 26 but very close to strength of control Mix 23
26	Conventional control*	6950 (47.9)	

*Observed strength of Mix 26 as shown believed excessively high for several reasons. Believe control mix strength should be closer to Mix 23 at 5880 psi (40.5 MPa)

The six-month-strengths are summarized by group in Table 9.13 and are presented graphically in Fig. 9.16.

9.6 OBSERVED VARIATIONS IN COMPRESSIVE STRENGTH

9.6.1 GENERAL COMMENTS

There are many reasons why shotcrete under routine construction conditions of placement is a moderately variable material. Some of the reasons for the variability are; 1) the improper and inadequate blending of the accelerator before it reaches the wall, 2) the pulsating nature of the material

TABLE 9.13
SUMMARY OF COMPRESSIVE STRENGTH
AT SIX MONTHS

Conventional shotcrete		Regulated-set shotcrete		Steel fiber shotcrete	
Mix number	Strength, σ_{c180}, psi (MPa)	Mix number	Strength, σ_{c180}, psi (MPa)	Mix number	Strength, σ_{28}, psi (MPa)
23	5880 (40.5)	28	7250 (50.0)	39	5880 (40.5)
		29	6770 (46.7)	40	6260 (43.1)
26	6950 (47.9)	30	5560 (38.3)	42	4910 (33.8)
				45	5410 (37.3)
AVERAGES					
	6415 (44.2)		6530 (45.0)		5615 (38.7)
Excluding Mix 26					
	5880 (40.5)		11% stronger than conventional		4% weaker than conventional

coming through the line, 3) the variations in the dry mix itself, 4) the variations that occur at the nozzle and at the wall during impact, and 5) the many variable factors associated with the nozzleman. Other factors were enumerated and discussed in Chapter 6.

Variations in the strength results can be seen in the strength-time plots in Appendix E. The scatter between specimens from the same panel is most obvious from these plots, but in a few cases specimens from two or more panels were tested and in these plots panel-to-panel differences can be

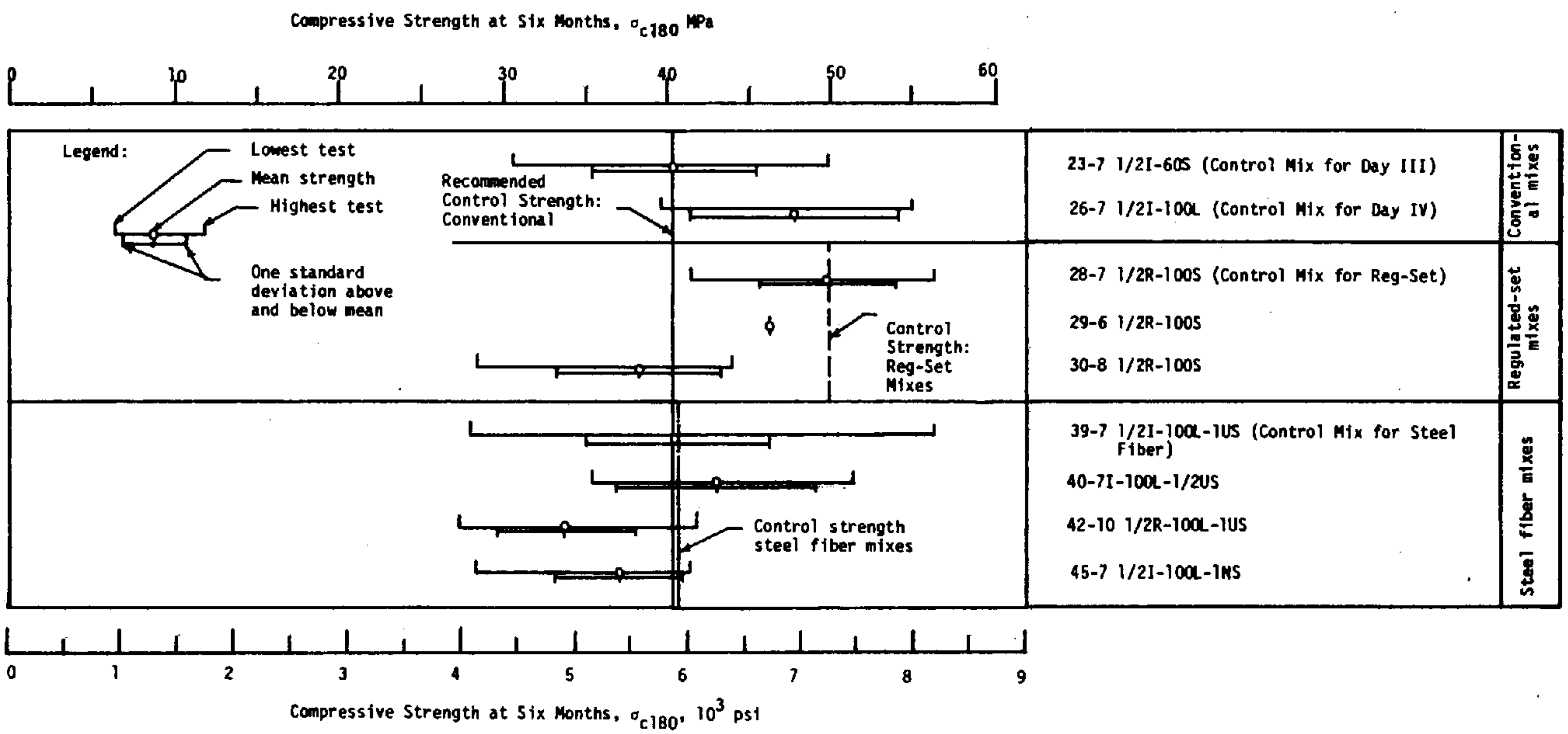


FIG. 9.16 COMPARISON OF COMPRESSION TEST RESULTS AT SIX MONTHS

observed. Figure 9.17 is reproduced from Appendix E to illustrate typical scatter in the results. Although standard ASTM procedures for testing were followed, and care was taken in the preparation, testing, and interpretation of the results, it is well known that the testing equipment and procedures are responsible for some of the scatter. It should be emphasized that the basic data came from tests using equipment customarily used in field testing. Further differences in the laminar build-up of the shotcrete at different locations of the panel and the normal variability of water, cement, and aggregate contents described in Chapter 6 are responsible for some of the differences in strength within a panel. Slight differences in nozzle distance and angle,

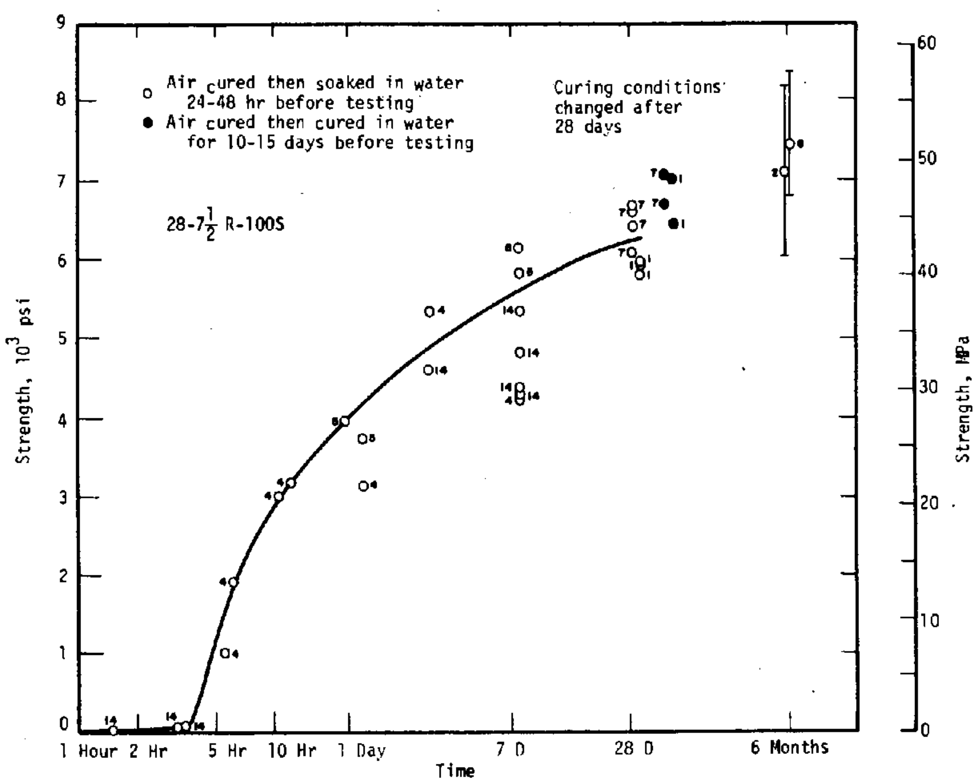


FIG. 9.17 TYPICAL STRENGTH-TIME CURVE ILLUSTRATING SCATTER IN RESULTS

or variations in material delivery rate between panels are responsible for some of the observed scatter. Differences in curing conditions within each panel could be responsible for some variation.

Despite all the scatter observed and discussed in the next sections, the coefficient of variation was surprisingly low; it varied from 0 to 18 percent for the averages of the strength results from all the mixes tested from 7 days through 6 months. The average of all the coefficients of variation throughout this time period was only 9 percent.

Nevertheless, the following sections will serve to illustrate the scatter of results inherent in quality control for shotcrete. Further, it should give limits to the confidence of strength data which might be considered in design and in routine quality control. Strength was observed to vary 1) within the thickness of shotcrete layer, 2) within a panel, and 3) between panels.

9.6.2 EFFECTS OF TRIMMING OFF OUTER ROUGH SURFACE

Compression specimens tested at 42 days were cut from the uncracked ends of failed flexural test beams. These beams had been trimmed to provide a more uniform specimen for flexural testing. Only the rough outer front surface had been trimmed off. These tests indicated a substantial *apparent* strength difference over the 28-day tests. The interpretation of these data was complicated by the fact that they were not only trimmed but also had been cured in water for two weeks longer than the 28-day specimens.

The outer rough 1/2 in. (13 mm) or so of shotcrete does not get compacted by incoming shotcrete. Further, it is subjected to significantly different microcuring conditions in that this outer layer is exposed to all temperature and humidity variations. The outer layer most likely dries out even in relatively humid tunnels since curing compounds or other curing methods are not customarily used. In the case of these panels, the temperatures at mid-thickness was never below 35°F (2°C) but the outer 1/4 in. (6 mm) or so could even have frozen because of the low temperatures.

The significance of this problem of an apparent weaker outer zone in practical design terms is that since total thicknesses are customarily specified, its existence should be recognized and appreciated by designers and contractors. If a liner 1-1/2 to 2 in. (3.8 to 5 cm) thick is specified, this weaker layer could become a substantial portion of the total thickness. In this case, quality control tests on just the intact portion of much thicker panels may be unrealistic.

A special series of tests was conducted at six months to evaluate the magnitude of the apparent strength differences between trimmed and untrimmed specimens. Two complete 2 x 2 ft (61 x 61 cm) panels were cut into twenty-one (21) 3 x 3 x 7 in. (7.5 x 7.5 x 17.8 cm) compression specimens as shown in Figs. 9.18 and 9.19. Eleven specimens from each panel had their rough outer surface trimmed off (designated T in the figures). Specimens designated R were not trimmed. Figure 9.1 is a photograph of a rough and a trimmed specimen.

Considering all 21 samples of panel 23-6 (Fig. 9.18), the average strength of the trimmed specimens exceeded that of the rough specimens by 270 psi (1.9 MPa); the trimmed specimens were 660 psi (4.6 MPa) stronger for panel

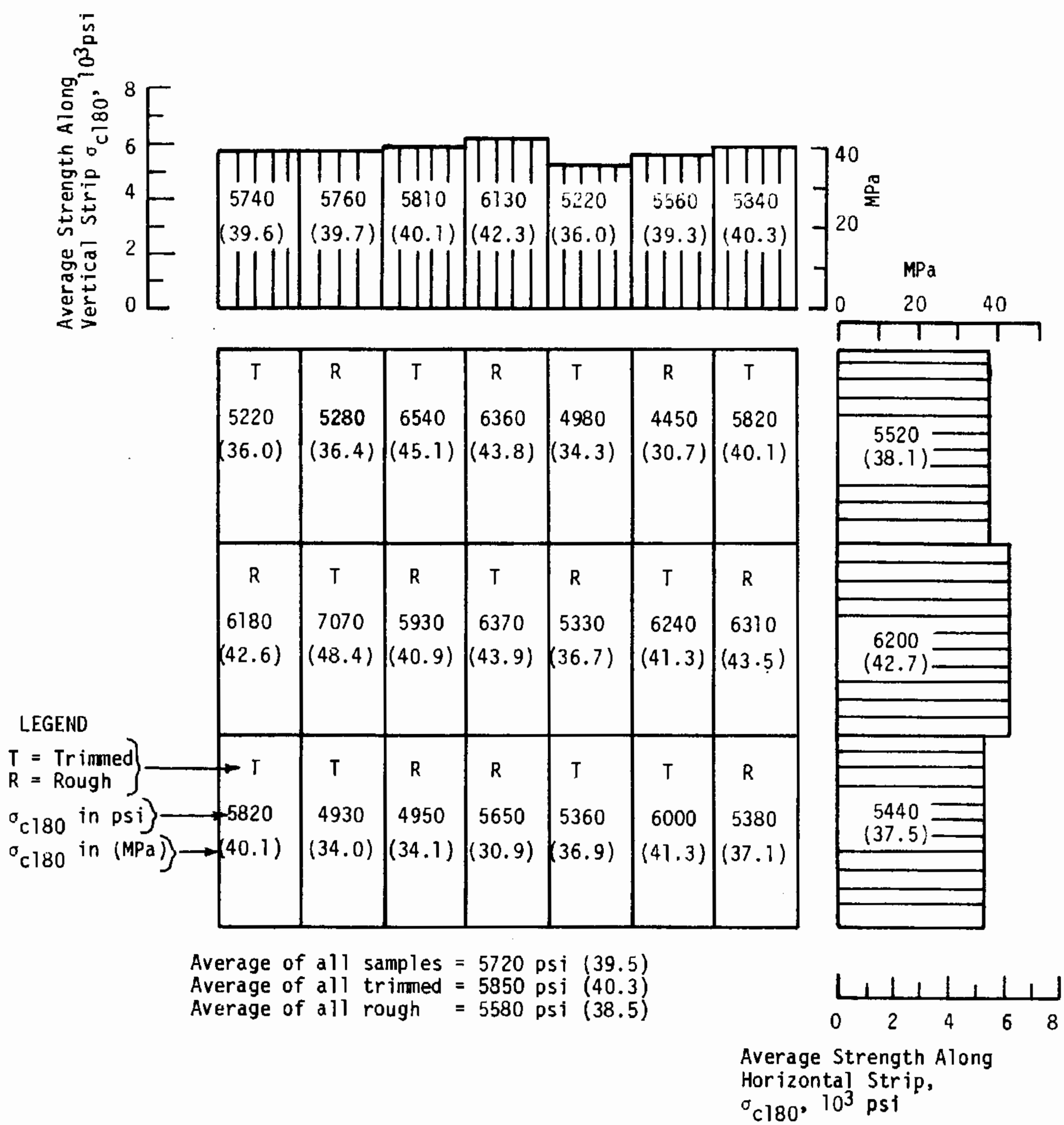


FIG. 9.18 VARIATION IN COMPRESSIVE STRENGTH, PANEL 23-6

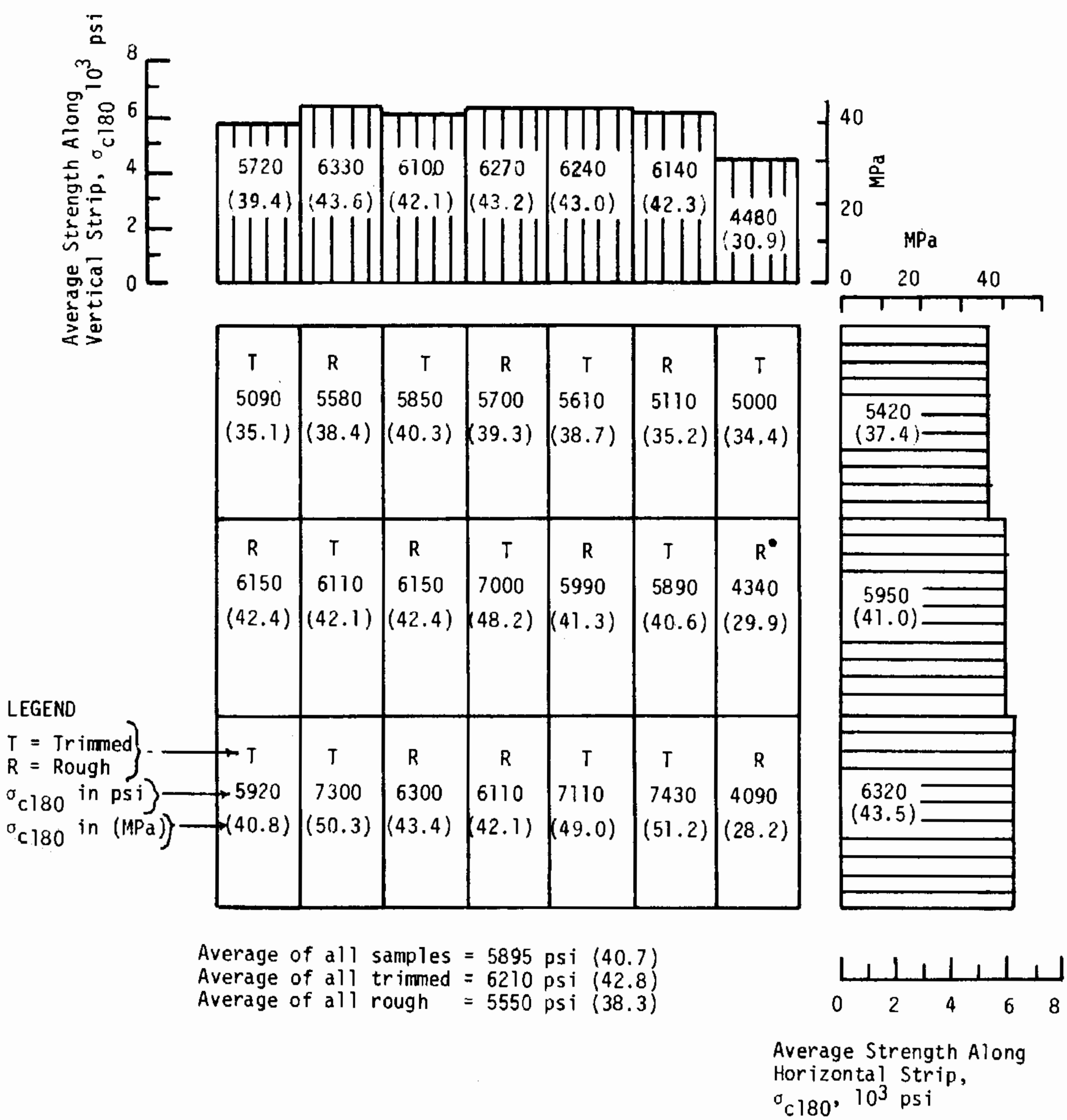


FIG. 9.19 VARIATION IN COMPRESSIVE STRENGTH, PANEL 39-1

39-1 (Fig. 9.19). Table 9.14 is a summary of the results of this special series of tests averaged in various ways. Depending upon how the results are grouped, the trimmed specimens were stronger by 10 to 930 psi (.07 to 6.4 MPa) but generally within 300 to 700 psi (2.1 to 4.8 MPa) or about 5 to 12 percent.

It is concluded that trimming specimens resulted in an *apparent* increase in strength of about 500 psi (3.4 MPa) at six months. Naturally the material didn't get stronger; in reality a weaker zone was removed and the *average* strength is *apparently* higher by an amount generally less than 10 percent. The total load carried by a trimmed sample would be close to the total load that could be carried by the rough specimen. With the exception of these two panels and the 42-day tests, all other compression tests were conducted on rough specimens since the purpose of the program was to evaluate the in situ strength of shotcrete.

9.6.3 VARIATIONS IN STRENGTH WITHIN A SINGLE PANEL

Figures 9.18 and 9.19 and Table 9.14 also summarize the variation in strength within a single panel. As might be expected there is a slight tendency for the center of the panel to be stronger than the exterior. This tendency can be seen in the graphical display in the figures of the average along vertical and along horizontal strips. There are exceptions however.

For panels 23-6 the average strength of the interior specimens was 610 psi (4.2 MPa) stronger than that of all perimeter specimens; this value for panel 39-6 was 440 psi (3.0 MPa). It is indicated that interior specimens

TABLE 9.14

SUMMARY OF VARIATIONS OF COMPRESSIVE STRENGTH WITHIN PANELS

	Number of specimens	Panel 23-6			Panel 39-1		
		Average strength psi (MPa)	Standard deviation	Coeff. of variation %	Average strength psi (MPa)	Standard deviation	Coeff. of variation %
All specimens	21	5720 (39.4)	653	11	5895 (40.6)	877	15
All trimmed specimens	11	5850 (40.3)	682	12	6210 (42.8)	867	14
All rough specimens	10	5580 (38.5)	623	11	5550 (38.3)	789	14
All perimeter specimens	16	5580 (38.5)	605	11	5790 (39.9)	962	17
All trimmed perimeter specimens	8	5580 (38.5)	557	10	6160 (42.5)	983	16
All rough perimeter specimens	8	5570 (38.4)	688	12	5420 (37.4)	838	15
All interior specimens	5	6190 (42.8)	636	10	6230 (42.9)	444	7
All trimmed interior specimens	3	6560 (45.2)	446	7	6330 (43.6)	588	9
All rough interior specimens	2	5630 (38.8)	*	*	6070 (41.8)	*	*
All corner specimens	4	5560 (38.3)	307	6	5025 (34.6)	748	15

Note: Refer to Figs. 9.18 and 9.19.
* Sample population too small.

are on the order of 500 psi (3.4 MPa) stronger than perimeter specimens. This strength differential results from the interference of the wing walls of the panel and other end or boundary effects including shrinkage and curing differences. However, it must be recognized that except for some foliation surfaces, blasted rock surfaces are generally very rough, often rougher than 45° wing walls on panels simulate. Thus, wing walls are not considered objectionable for all quality control testing because they model typical rock conditions reasonably well.

The coefficient of variation of all samples from the conventional shotcrete panel 23-6 was 11 percent, it was 16 percent for the steel fiber shotcrete panel 39-1. This reflects slightly more variation for steel fiber panels as should be expected but the magnitude of the coefficient of variation for both types of shotcrete can be considered good. Averages for other mixes at other ages generally demonstrated similar low coefficients; although the range was from 0 to 30 percent, the average was 9 percent.

It can be seen that there are substantial variations in the strength results for shotcrete, but they are not excessive considering the nature of the material itself. A coefficient of variation of 10 percent is considered good for results of field tests of 6 x 12 in. (15 x 30 cm) cylinders of ordinary concrete at 28 days (Troxell, et al., 1968). Thus, these panels compare favorably as far as the variation of strength tests is concerned.

In spite of these coefficients of variation, considerable difference in adjacent specimens prepared in the same manner can be expected. In these two panels, the strength of adjacent specimens prepared identically often varied by as much as 500 to 1000 psi (3.4 to 6.9 MPa); the maximum difference for an interior and a perimeter specimen in panel 23-6 was 2140 psi (14.7 MPa).

9.6.4 VARIATIONS BETWEEN PANELS

There are more reasons for variation between panels than for variations within panels. This is particularly important at ages less than one day when the shotcrete is curing and gaining strength rapidly.

An evaluation of differences in strength from panel to panel can be made at six months when a large number of tests were conducted on different panels, the results of which can be seen from the tables in Appendix D. The maximum difference between the average strength of individual panels of the same mix at six months was 1330 psi (9.2 MPa) or about 20 percent. The average difference between the strengths of individual panels of the same mix for all test times was only 700 psi (4.8 MPa), less than 15 percent.

9.6.5 EFFECT OF SIZE OF SPECIMEN

Because compression specimens were sawed from panels of various thicknesses, the compression specimens were not all the same thickness. In general, the untrimmed panels were about 3 in. (7.6 cm) thick. At each test period the thickest and best available panel was selected for testing. This meant that the six-month-tests were performed on specimens that were somewhat poorer quality than those of the earlier tests. A few of the six-month-test specimens were only 2.5 to 2.75 in. (6.4 to 7.0 cm) thick. In no case were the specimens so thin that buckling became a problem, but it is believed that some very small specimens showed lower than normal compressive strengths due to the effects of size. The greater the ratio of specimen height to thickness, the lower the strength indicated by the compression test. Slightly greater variability in the results at six months occurred because these specimens were, on the average, thinner than the total group of specimens. Panels that were particularly thin are denoted by a "**" in Appendix D and an average has been computed neglecting these results. An idea of the size effect can be obtained by comparing the six-month results from panel 39-16 with the average of Mix 39, excluding panel 16 as shown in Table 9.15. The difference was 960 psi (6.6 MPa) or about 16 percent lower for the samples that were only 2 in. (5 cm) thick.

TABLE 9.15

TYPICAL EFFECT OF SIZE OF SPECIMEN

	Six-month compressive strength, σ_{c180}, psi (MPa)	Remarks
Average of panel 39-16	4920 (33.9)	16% lower than average for Mix 39
Average of all panels of Mix 39 except 39-16	5880 (40.5)	
Range of other panels of Mix 39	5550 (38.3) to 6770 (46.7)	

9.6.6 EFFECT OF MOISTURE CONTENT OF SPECIMENS AT TIME OF TESTING

The ASTM specification requires that all specimens be soaked at least 40 hrs immediately prior to the compression test (ASTM C 42). All specimens tested at 3 days or older were soaked; it was impractical to soak compression specimens tested at earlier ages. During the six-month tests, a special series of tests was conducted in conjunction with the pullout tests to evaluate the effects of soaking. Compression specimens were cut from the perimeter of all the pullout panels. Normally 10 compression specimens were obtained from each panel; to determine the effect of soaking, 5 specimens were soaked for at least 40 hrs immediately prior to testing, and 5 were not. Results of these tests, shown in Chapter 13, indicate that there was no consistent trend in the difference in strength at six months between soaked and unsoaked specimens. Some of the soaked specimens had higher strengths and some had lower strengths. The average of all dry specimens was 6120 psi (42.2 MPa) while the average of all soaked specimens was 6000 psi (41.4 MPa). When specimens were broken open to observe the failure surface, only about 0.25 in. (6 mm) around the perimeter could be considered soaked. Hence, there is no physical reason to anticipate that soaking for the limited time specified will affect the strength significantly. This also attests to the low permeability and low absorptive capacity of the shotcrete.

9.7 SUMMARY AND DISCUSSION OF RESULTS FOR ALL AGES

9.7.1 GENERAL COMMENTS

The results of compressive strength tests have been presented and discussed in terms of specific age groups in the previous sections. This section consists of a recapitulation of those results in broader terms of their overall strength-time behavior. This is accomplished by interpreting the effects of each of several parameters with time. Some parameters exhibit more and sometimes a different influence on strength at one age than at other ages. The change in strength with time is discussed; some of the factors believed to increase strength at an early age have an opposite effect as the shotcrete gets older, and vice versa. More importantly, it appears that many factors affecting the strength of shotcrete have an optimum magnitude individually and that there is an optimum combination of factors collectively.

9.7.2 ANTICIPATED BEHAVIOR

The anticipated behavior of young shotcrete has already been discussed in Section 9.4.2. Basically, conventional shotcrete with accelerator sets and gains as much as 1000 psi (6.9 MPa) strength by about 5 hours; regulated-set shotcrete should attain this strength by 1 hour. After these early high rates of gain of strength, the rate slows and continues to increase at a decreasing rate. Strengths on the order of 4000 to 6000 psi (27.6 to 41.4 MPa) after one month are not uncommon. It is well known that the addition of accelerators to shotcrete adversely affects the strength of the shotcrete at later ages to a significant degree. The magnitude of this effect depends upon the dosage of accelerator.

Some of the strength data published by others has been assembled in Fig. 9.20 in a strength-versus-logarithm of time plot so the results and comparisons shown in the following sections may be evaluated in terms of other published data.

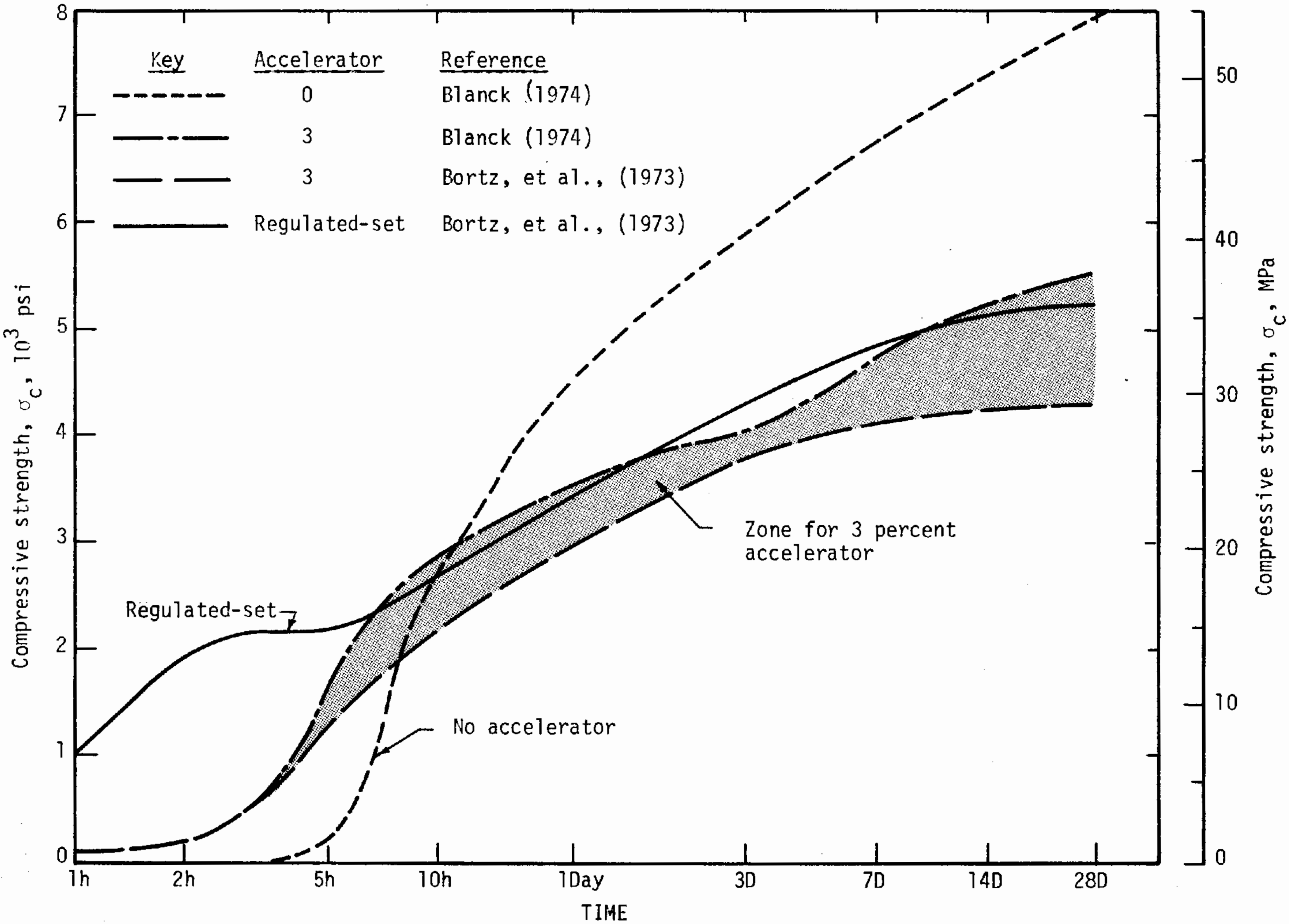


FIG. 9.20 TYPICAL COMPRESSIVE STRENGTH-TIME RELATIONSHIPS THROUGH ONE MONTH REPORTED IN THE LITERATURE

9.7.3 EFFECT OF COLD MATERIAL AND ENVIRONMENTAL TEMPERATURES

All evidence suggests that the primary reason for the very low rate of gain of strength at early ages was the low temperatures. The range of average strength-time curves for conventional non-fibrous shotcrete with about 3 percent accelerator is shown by the curves in Fig. 9.21. For comparison, the composite strength-time curve for 3 percent accelerator from published data at ordinary temperatures shown in Fig. 9.20 has been replotted in Fig. 9.21. Higher accelerator dosages are required when shotcrete is placed using cold materials or in a cold environment. On the other hand, accelerator dosages may be reduced when the materials, water, or environment are hot. Compatibility tests such as the Gillmore Needles test reflect these temperature effects. It is recommended that Gillmore Needles tests be conducted not only at room temperature of 70°F (21.1°C) but also using the material and water temperatures which are anticipated on the job. When environmental or material temperatures change, accelerator dosages should be reevaluated.

In spite of near-freezing temperatures, the quality of shotcrete was very good. Compressive strengths at one month were 4000 psi (27.6 MPa) or greater with only a few exceptions which could be explained by unsatisfactory mix or shooting conditions. Though cold weather shotcreting is not recommended, these results prove that the final product can be good quality shotcrete if proper care and attention are given. However, if accelerator dosages were to be increased to enhance the early strength, the quality and the ultimate strength would suffer.

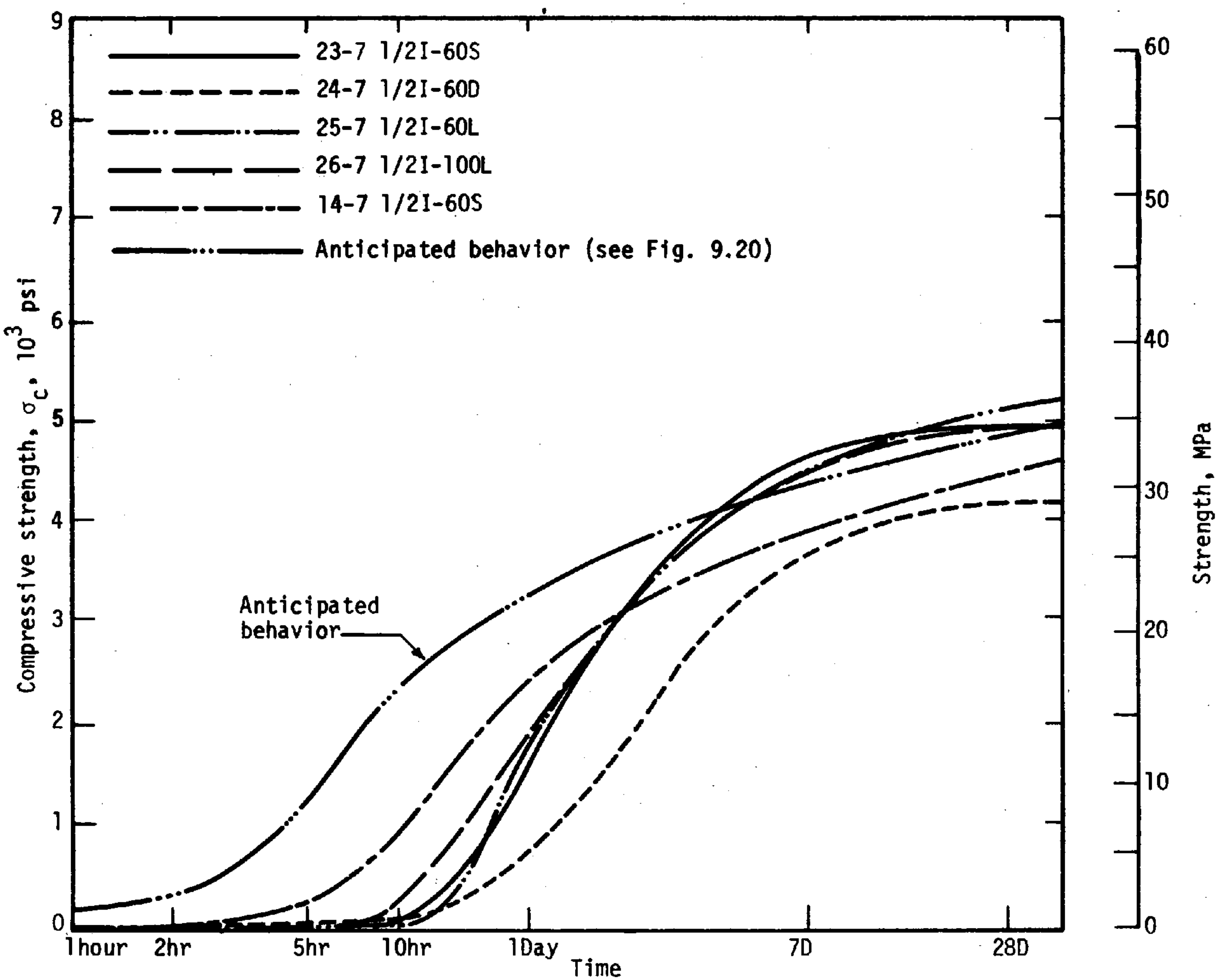


FIG. 9.21 STRENGTH-TIME CURVES FOR CONVENTIONAL MIXES ILLUSTRATING EFFECT OF LOW MATERIAL AND ENVIRONMENTAL TEMPERATURES

9.7.4 EFFECT OF THICKNESS ON CURING TEMPERATURE

Greater thicknesses placed in a relatively short time dissipate less heat of hydration and thus have higher curing temperatures. As discussed in Section 9.4.3 this higher temperature should enhance the rate of gain of strength at early ages. Evidence from concrete technology suggests that somewhat lower ultimate strengths will result if the temperature during early ages is high (Troxell, et al., 1968). The effect of temperature is not as drastic as the effect of accelerator dosage.

9.7.5 CONCEPT OF POTENTIAL "ACTIVITY" OF SHOTCRETE MIX

The interpretation of the test data and a critical assessment of the factors affecting the strength of shotcrete have resulted in the development of the following behavioral model that explains the effect that changes in mix and shooting conditions can have on the behavior of shotcrete. Though the concept was developed for strength considerations, the same concept applies to other aspects such as rebound. The mix and shooting conditions can be described in terms of their "activity". Activity is defined as the potential for hydration, quick-setting, and fast rates of strength gain during early ages. Although changes in just one parameter, such as cement content, can result in an increase or a decrease in strength, it is the combined effect of many parameters during shooting that often governs strength. Some of the more important of these parameters are listed in Table 9.16. Each parameter affects the shotcrete differently depending on whether it is considered to act on the dry mix before shooting or on the shotcrete in place during or immediately after shooting. This difference is reflected in the table by differentiating

TABLE 9.16

FACTORS RELATED TO ACTIVITY OF SHOTCRETE MIXES

I. DRY MIX ACTIVITY

FACTORS THAT TEND TO PROMOTE PREMATURE HYDRATION OF THE MIX BETWEEN TIME OF MIXING AND TIME OF SHOOTING. (Premature hydration tends to cause lower early-and-ultimate strength.)

A. High moisture content of dry mix from excessively wet aggregate.

B. High cement content.

C. High potential of the cement, itself, to set quickly without accelerators

   1. Higher fineness.

   2. Rapid-setting chemistry or characteristics of the cement itself, such as Type III or Regulated-set Cements.

D. High temperature of materials during mixing and temporary storage before shooting.

E. Long storage times between mixing and shooting.

F. Any delay between addition of accelerator and shooting.

II. SHOOTING ACTIVITY

FACTORS THAT TEND TO PROMOTE OR SPEED UP TIME OF SET AND RATE OF GAIN OF STRENGTH AFTER SHOOTING. (Up to some optimum point, these factors individually, or combined, tend to increase early-strength gain, but usually result in lower ultimate strengths.)

Excess of any of these factors or an excess of their combined effect beyond some optimum will reduce both the early rate of gain of strength and the ultimate strength, because of disturbance from subsequent shotcreting.

A. Low water-cement ratio.*

B. High accelerator dosage.

C. High cement content.*

D. High potential of cement, itself, to set quickly without accelerators.

E. High degree of compatibility between cement and accelerator.

F. High nozzle-water temperature.

G. High environmental temperatures.

* A change in these parameters in the indicated direction will increase, not decrease, ultimate strength if the combined activity is below optimum for early strength.

Dry-Mix Activity in Part I from Shooting Activity in Part II. It should be noted that there are aspects of mix design as well as shooting conditions that affect Shooting Activity. Interrelationships between mix design and shooting conditions may be seen in the table.

The factors listed in Part I tend to promote premature hydration of the dry mix. Prehydration of the cement reduces both the early and ultimate strengths of the shotcrete. The moisture in the aggregate will cause the cement to begin to hydrate and, depending on the degree of activity, the effects of such prehydration may become noticeable whenever the dry mix is allowed to sit longer than about 1/2 hour before shooting in contact with the moisture in the aggregates. A delay of only a few minutes between the addition of accelerator and shooting also results in an undesirable prehydration that strongly affects behavior. Subsequent shooting of any mix that prehydrated to any significant degree acts as a disturbance to the setting process.

The effects of the factors in both Part I and Part II of Table 9.16 are interdependent. Each factor can be evaluated separately to determine a trend but the combination of all the factors, not the absolute level of any one parameter, governs the behavior. For instance, if a mix has a high cement content, particular care must be given to minimize the water content of the aggregates, the time of storage before shooting, and the temperatures of the environment and of the materials. An extreme example of this phenomenon of excessive dry-mix activity was the behavior of Mix 42, a 10-1/2 bag (585 kg/m^3) regulated-set cement mix with a very high water content in the aggregate. Despite the low initial materials' temperature and the cold environment, the temperature of the top of the stockpile of the dry mix in the hopper of the shotcrete rig reached 98°F (36.7°C) before shooting. This condition of premature hydration undoubtedly contributed to the lower-than-anticipated strength values for Mix 42 at all ages.

The factors listed in Part II of the table tend to promote or speed up the time of set of shotcrete in the airstream and on the wall. Up to some optimum value, the indicated change in any one parameter (such as a decrease in water-cement ratio or an increase in any of the other parameters) will increase the rate of gain of strength during the first day. In most cementitious mixes, any mix condition that promotes early hydration or fast rates of gain of strength tends to reduce the ultimate strength of the resultant material. Hence, even though some of the factors, up to an optimum value, may increase early strength; they may reduce ultimate strength concurrently. For instance, below the optimum activity, increased accelerator dosage results in an increase in early strength but in reduced ultimate strength. Cement content and water-cement ratio are exceptions to this rule; an increase in cement content tends to yield higher ultimate strength. Another exception is regulated-set cement since it is formulated specifically to provide both high-early and high-ultimate strength without additives.

Above the optimum value, the indicated change will reduce both the early rate of gain of strength and the ultimate strength. It is believed that a particularly active mix (either because of an excess of one parameter or because of the combined effects of several parameters) tends to "set" very quickly, possibly on its way to the wall or within seconds thereafter. Incoming shotcrete subsequent to this "set" disturbs the shotcrete already there at least to a certain depth. This disturbance is detrimental both to the initial rate of gain of strength and to the ultimate strength.

The rate of build up (the material delivery rate) and nozzling techniques may alter the effects of shooting activity. It may be possible to shoot a moderately active mix to the full thickness before the initial set takes place particularly if the mix is shot "wet" at a high material delivery rate. This permits the energy of the incoming shotcrete to be used beneficially in compacting rather than disturbing the material already there. On the other hand, a low material delivery rate or the build up in multiple passes separated by a few minutes for each pass may result in disturbance if the "set" occurs between passes. If the mix is so active that it tends to "set" in the airstream, in the nozzle, or immediately after hitting the wall, the mere act of shooting it provides its own disturbance. Mixes and shooting conditions this active must be avoided. One example of this effect on this project was Mix 34 that had an accelerator dosage of 8.4 percent. The early strength gain and the one-month strength of this mix was substantially lower than that of Mix 33 with only 4.9 percent accelerator. The tendency for high activity can be detected in the compatibility tests. It has been observed often that, above a certain accelerator dosage, there is a reversal in the trend of set times so that the set times begin to increase with higher accelerator dosage. The set times increase because the "set" took place while mixing, and subsequent disturbance, making the patty, affects the set times. Cement-accelerator combinations above this point of reversal are too active and could result in lower early-and-ultimate strengths and higher rebound if shot in the field.

As with the factors in Part I of the table, the effects of the factors listed in Part II are interdependent. Each factor can be analyzed individually to determine a trend but the combination of all the factors governs the overall behavior not the absolute level of any one parameter. Hence, a high cement content and a low accelerator dosage may be just as active as a low cement content and a high accelerator dosage. Certain combinations of the factors will be beneficial to early strength up to some optimum combination beyond which, their effect is detrimental to early strength gain. There is a large number of combinations of these factors that tend to promote higher rates of gain of strength during early ages. Accordingly, there are a large number of optimum combinations of factors beyond which, the mix is "too active" and their combined result is detrimental. The shooting activity of regulated-set Mixes 30 and 42 are believed to have been too active. Mix 30 probably had an acceptable dry-mix activity but unacceptable shooting activity. Both the dry mix and shooting activity of Mix 42 were too active.

Any evaluation of mix designs and shooting conditions on strength, rebound, etc., should consider the entire spectrum of factors and combinations of factors that could affect the activity of the mix.

9.7.6 EFFECT OF ACCELERATOR DOSAGE

Average strength-time curves for steel fiber mixes with various accelerator dosages are plotted in Fig. 9.22. With the one exception of Mix 33A which had 3 percent accelerator, the following trends were observed. The accelerator was essentially ineffective in promoting early strength at dosages below 3.5 percent. An optimum accelerator dosage for early strength appears to have been somewhere between 3.5 and 8.4 percent. The strength-time curve for 4.9 percent accelerator is probably close to the optimum for these particular mix and environmental conditions since it enhanced the early strength

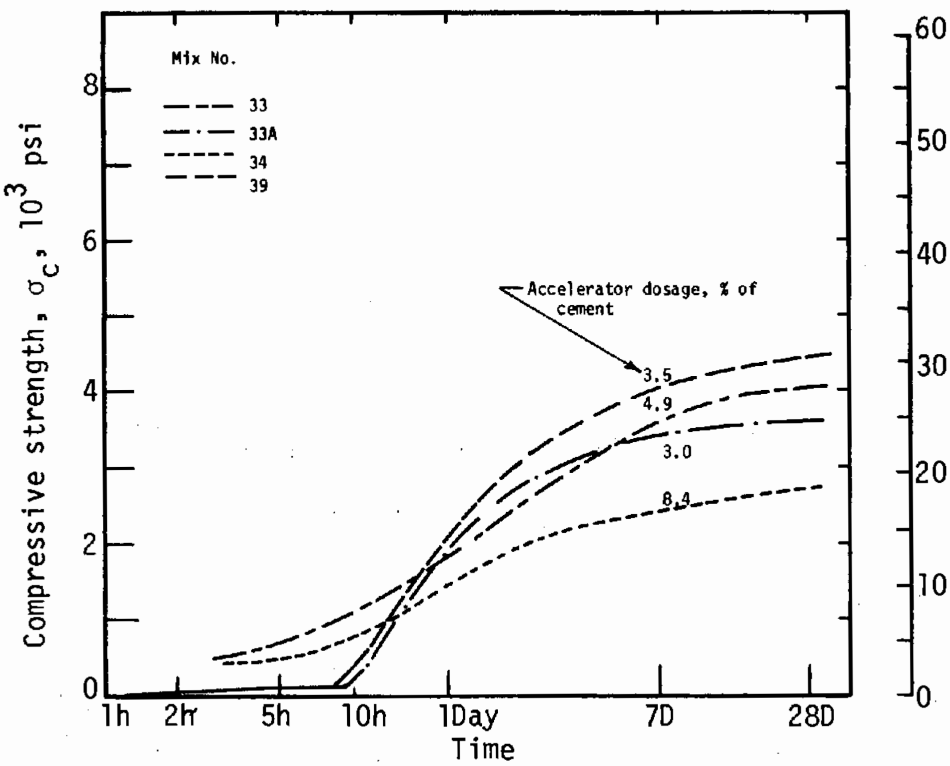


FIG. 9.22 EFFECT OF ACCELERATOR DOSAGE ON COMPRESSIVE STRENGTH-TIME CURVES

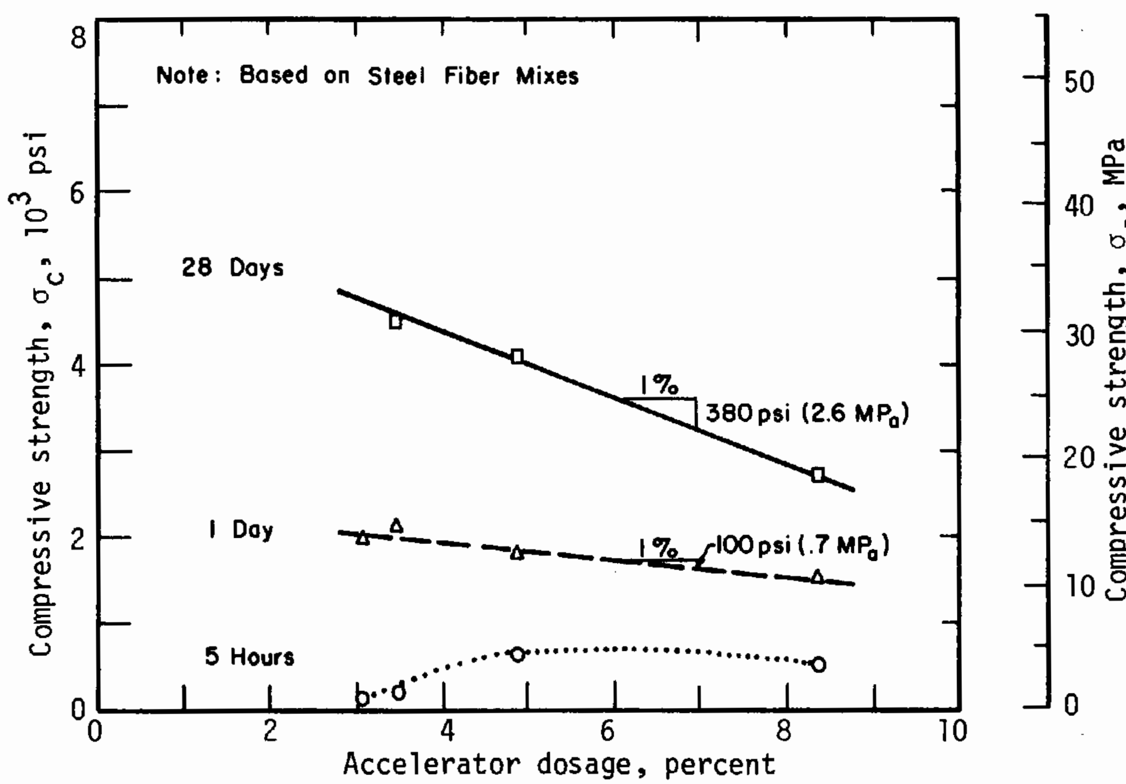


FIG. 9.23 EFFECT OF ACCELERATOR DOSAGE ON 5 HOUR, 1 DAY, AND 28 DAY COMPRESSIVE STRENGTH

substantially yet its one-month strength was only about 400 psi (2.8 MPa) below that of the mix with 3.5 percent accelerator. The strength of the mix with 8.4 percent accelerator was 1650 psi (11.4 MPa) lower than the strength of the mix with 3.5 percent accelerator.

The effects of accelerator dosage are more clearly shown in Fig. 9.23. The optimum for early strength development appears to be between 5 and 7 percent. However, any increase in accelerator dosage resulted in a lower strength at an age of one day or greater.

Figure 9.23 can be used to estimate the effects of increasing accelerator dosage to offset low temperatures such as those under which these test data were obtained. For the test conditions, an increase in accelerator dosage of 1 percent resulted in a one-month strength that was about 380 psi (2.6 MPa) lower. If 5 percent accelerator was necessary to provide adequate support for a rock load in these cold conditions instead of 3 percent, then one must expect the one-month strength to be about 800 psi (5.5 MPa) lower than the strength that can be achieved using 3 percent accelerator; the penalty for going to 8 percent accelerator would be a lower one-month strength by 1900 psi (13.1 MPa). If the relation is assumed to be linear and can be extrapolated back to zero percent accelerator, the one-month strength of unaccelerated shotcrete would be about 6000 psi (41.3 MPa). The strength with the 5 percent dosage would then be about 32 percent less than this estimated strength of unaccelerated shotcrete.

The fact that Mix 34 with 8.4 percent accelerator was probably too active is believed to be a major reason for the lower rate of gain of strength for that mix during early ages.

It appears that there is no optimum accelerator dosage for long term strength; any addition of accelerator caused a reduction of the long term strength as in Fig. 9.23. An increase in accelerator caused lower strengths as early as one day, a one percent increase in accelerator resulted in the one-day strength being lower by about 100 psi (0.7 MPa).

9.7.7 SUPERIOR BEHAVIOR OF REGULATED-SET CEMENT

Although results of the regulated-set data are erratic, these mixes were consistently stronger than their conventional Type I cement counterparts. The superiority of regulated-set shotcrete is most dramatic at early ages. In several instances strengths greater than 1000 psi (6.9 MPa) were measured at 2 hours. The superiority of regulated-set shotcrete is shown graphically in Fig. 9.24. The upper line is a composite upper envelope of all the average strength-time curves for regulated-set mixes. The lower line is a similar composite upper envelope for conventional mixes including those with high accelerator dosages. The dashed-line segment represents the upper envelope for conventional mixes with about 3 percent accelerator. Both envelopes represent the same cement content. The shaded area represents the potential superiority of regulated-set shotcrete over conventional shotcrete.

Under suitable conditions, regulated-set shotcrete is expected to achieve 1000 psi (6.9 MPa) or more in about an hour. This is many times the early strength possible with present-day accelerators though there are new accelerators that are reported to provide similar results. Note that the regulated-set cement shotcrete achieved this high early strength and still achieved a higher ultimate strength than achieved by conventional mixes.

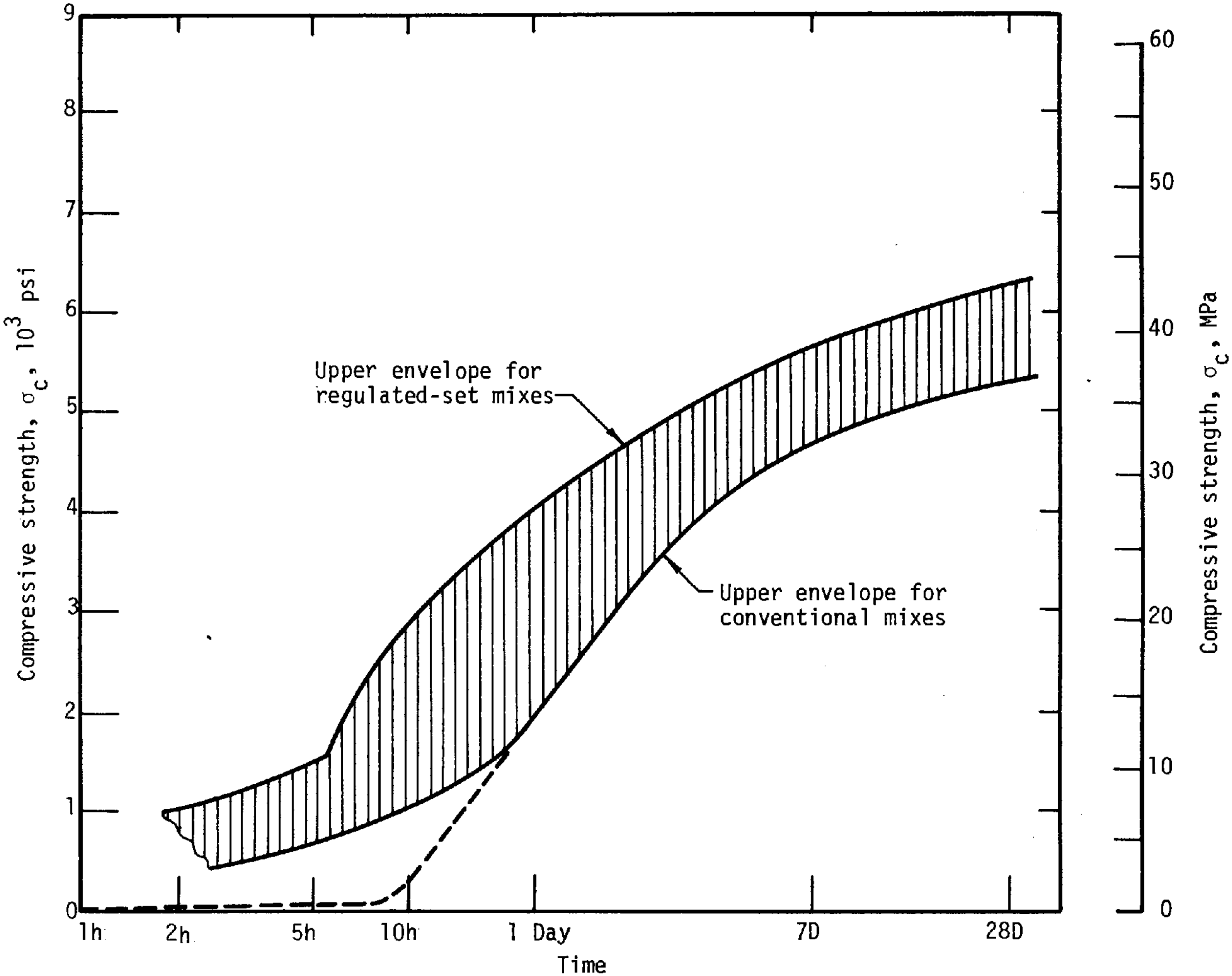


FIG. 9.24 COMPARISON OF UPPER ENVELOPE OF ALL REGULATED-SET MIXES TO UPPER ENVELOPE OF ALL CONVENTIONAL MIXES, DAYS III AND IV

It is believed that regulated-set shotcrete under routine production conditions can consistently achieve high early strengths, but somewhat better quality control than ordinarily provided on shotcrete jobs will be necessary since regulated-set shotcrete is particularly sensitive to changes in shooting conditions. Figure 9.25 contains the strength-time curves for all the regulated-set mixes. The different behavior resulted from variations in cement content and shooting conditions. With proper quality control, strengths close to the upper curves should be possible.

9.7.8 EFFECT OF CEMENT CONTENT

A comparison of the effect of cement content with a minimum of other variables is possible for only three mixes. Batches for regulated-set mixes 29, 28, and 30 contained 6-1/2, 7-1/2, and 8-1/2 bags (360, 420, and 470 kg/m^3) of cement per cu yd respectively. Other conditions for these mixes were as similar as might be expected for field conditions. Figure 9.26 illustrates the effect of cement content on the strength at ages from 10 hours to 6 months; the strength-time curves to one-month are shown in Fig. 9.27.

Data already shown in Table 9.4 indicated that the mix with lowest cement content was the slowest in gaining strength although this could have been partly a result of a slightly higher water-cement ratio. On the other hand, the mix with the highest cement content and the lowest water-cement ratio (Mix 30) did not gain strength as fast as Mix 28 which had an intermediate cement content and intermediate water-cement ratio. Mix 30 is believed to have been "too active" as described in Section 9.7.5. An optimum cement content apparently existed somewhere between 6-1/2 and 8-1/2 bags (360 to 470 kg/m^3) per cu yd. The activity theory explains the results well.

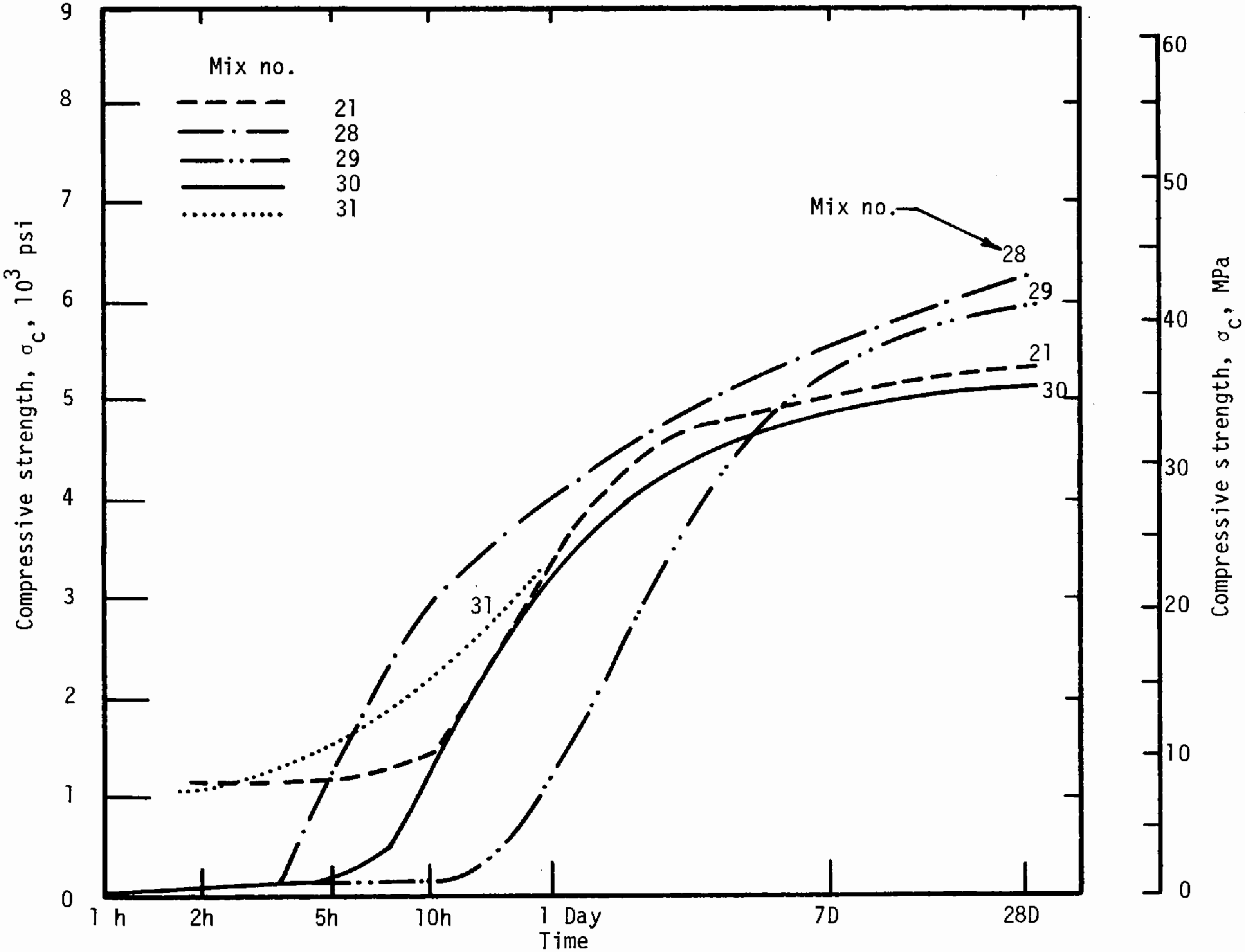


FIG. 9.25 COMPRESSIVE STRENGTH-TIME CURVES FOR THE REGULATED-SET MIXES

Mix no.	29	28	30
Measured water-cement ratio, in situ	0.34	0.30	0.27
Measured cement content in situ, %	22.3	24.0	27.8

*Note: Mix 29 did not begin to gain strength until 12 hours

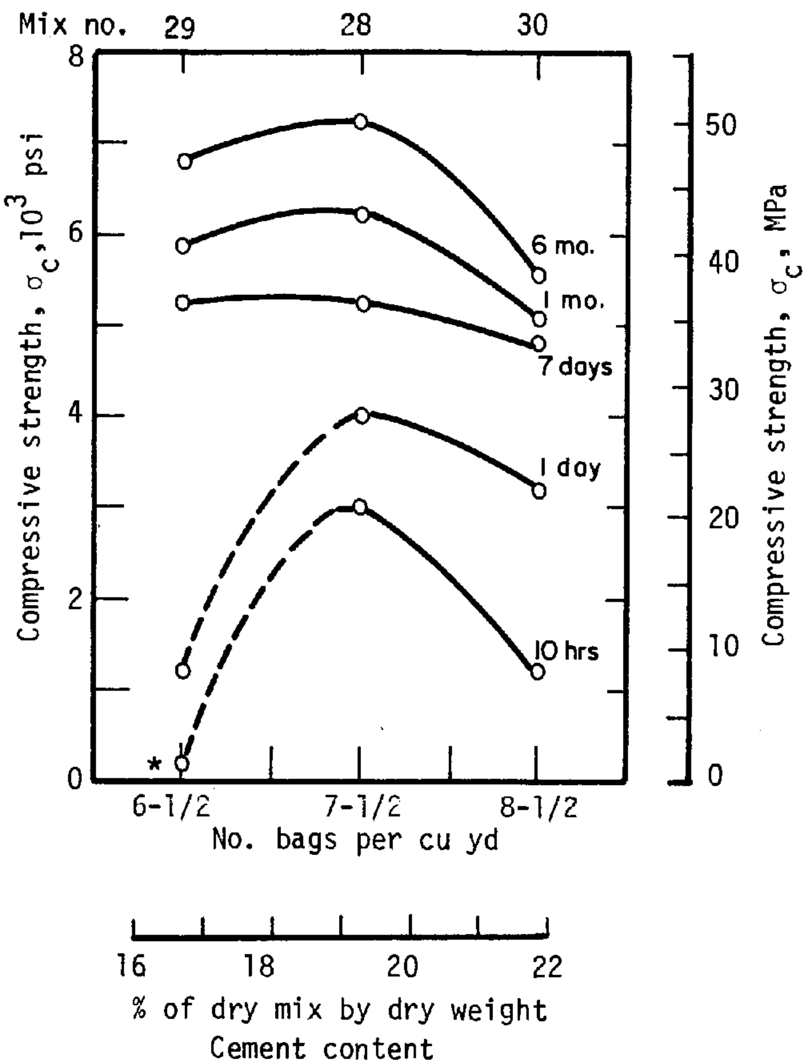


FIG. 9.26 EFFECT OF CEMENT CONTENT ON COMPRESSIVE STRENGTH OF REGULATED-SET MIXES

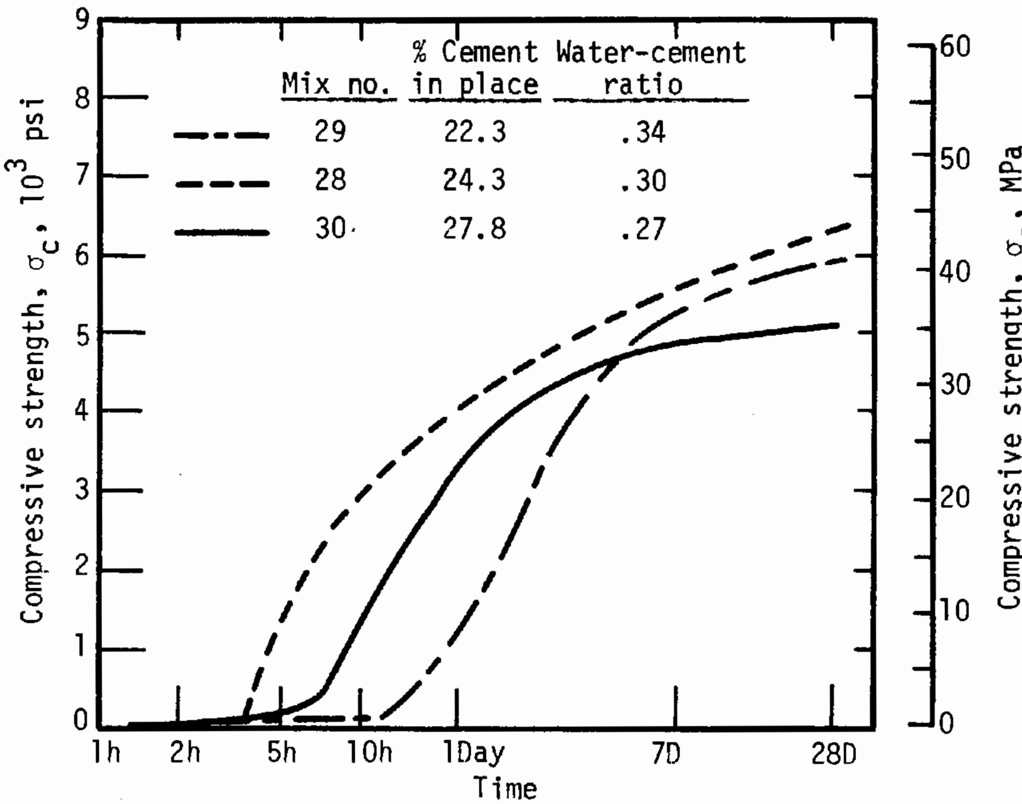


FIG. 9.27 EFFECT OF CEMENT CONTENT ON COMPRESSIVE STRENGTH-TIME CURVES FOR REGULATED-SET MIXES

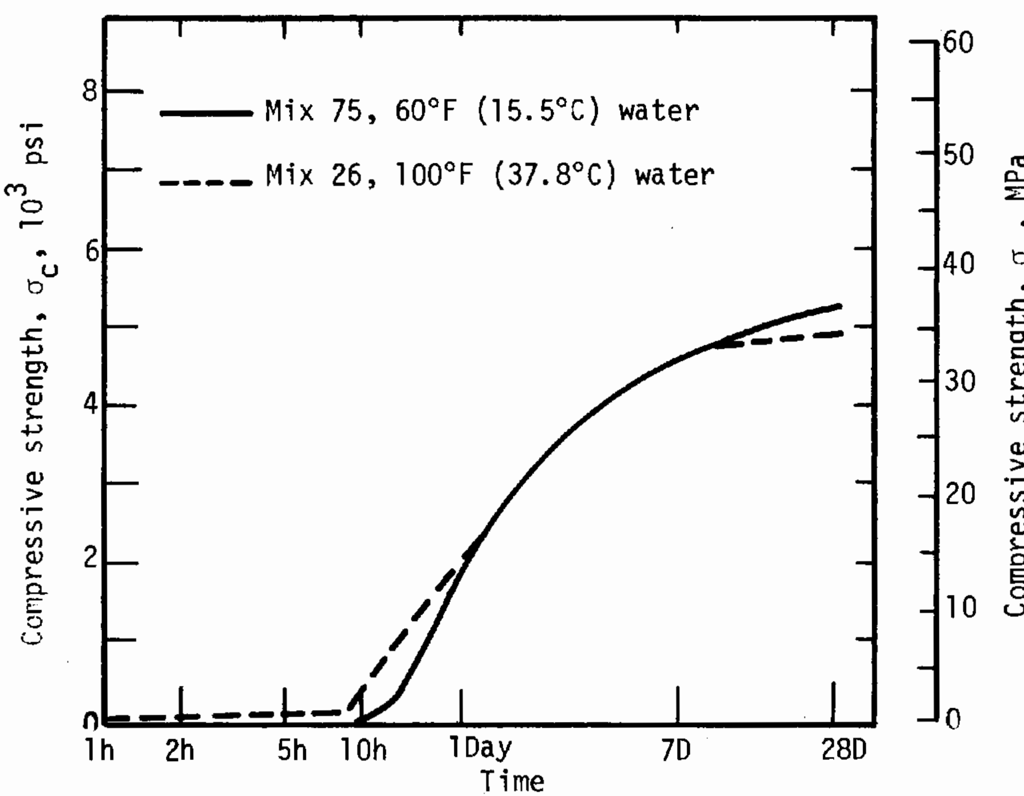


FIG. 9.28 COMPARISON OF COMPRESSIVE STRENGTH-TIME CURVES FOR MIXES WITH DIFFERENT NOZZLE-WATER TEMPERATURES

9.7.9 EFFECT OF NOZZLE-WATER TEMPERATURE

Nozzle-water temperature is one of the important factors that determine the shooting activity of the mix. As with concrete, higher initial temperatures tend to increase early strength and reduce ultimate strength. Figure 9.28 is a plot of the strength-time curves for two conventional mixes; one mix was shot with hot water and the other with cold water. Although Fig. 9.28 shows this tendency for earlier strength gain and lower ultimate strength for the mix with hot water, the two curves nearly lie on top of each other and, for these mixes, other factors are believed to have been more important than water temperature.

Conventional shotcrete requires some accelerator to permit shooting of thick layers in one pass. Some minimum nozzle-water temperature may be required to provide this shooting condition when using regulated-set cement. Regulated-set cement is more sensitive to temperature changes than Type I cement. Regulated-set shotcrete also has an optimum temperature for activity of the mix which, for strength purposes, was probably between 60 and 80°F (15.5 and 26.7°C) for the conditions of these field tests. Data shown in Fig. 9.29 indicates that Mix 31, shot with nozzle-water at 60°F (15.5°C) developed the high early strength expected, while Mix 28 shot with nozzle-water at 100°F (37.8°C) did not begin to develop strength until about 3-1/2 hours. This delay appears to have occurred because the mix was too active when shot with hot water. Unfortunately, Mix 31 had no strength data beyond 21 hours and no comparison of long-term strength can be made.

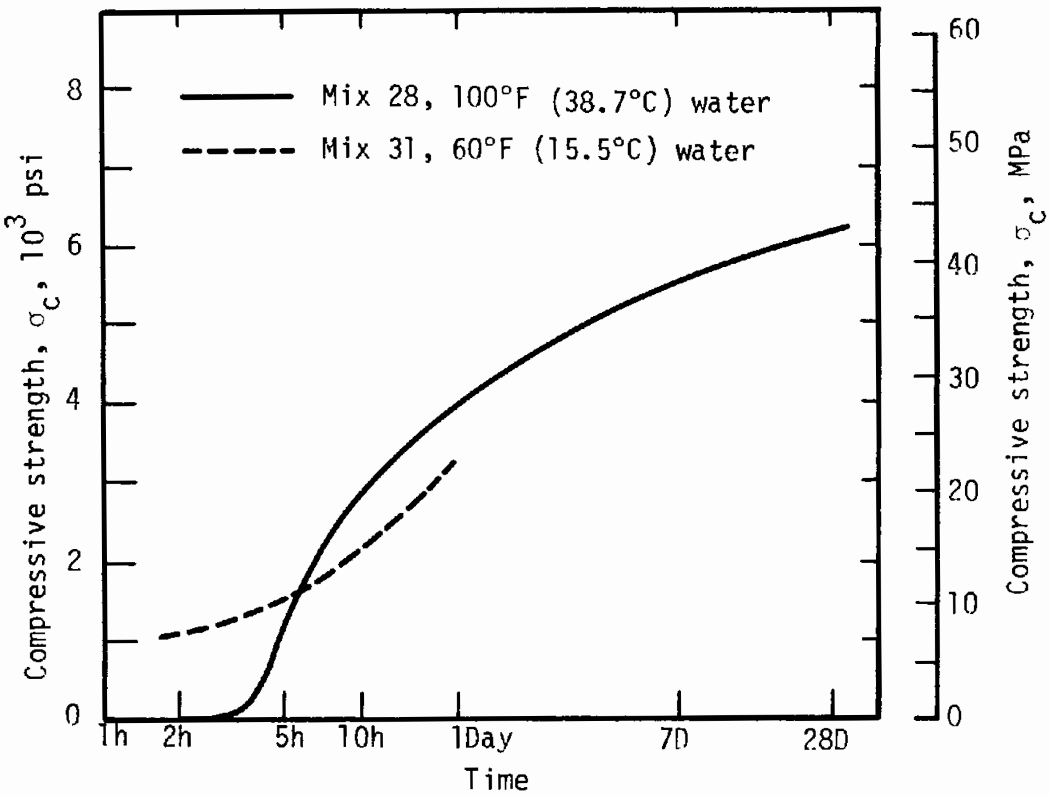


FIG. 9.29 EFFECT OF NOZZLE-WATER TEMPERATURE ON REGULATED-SET MIXES

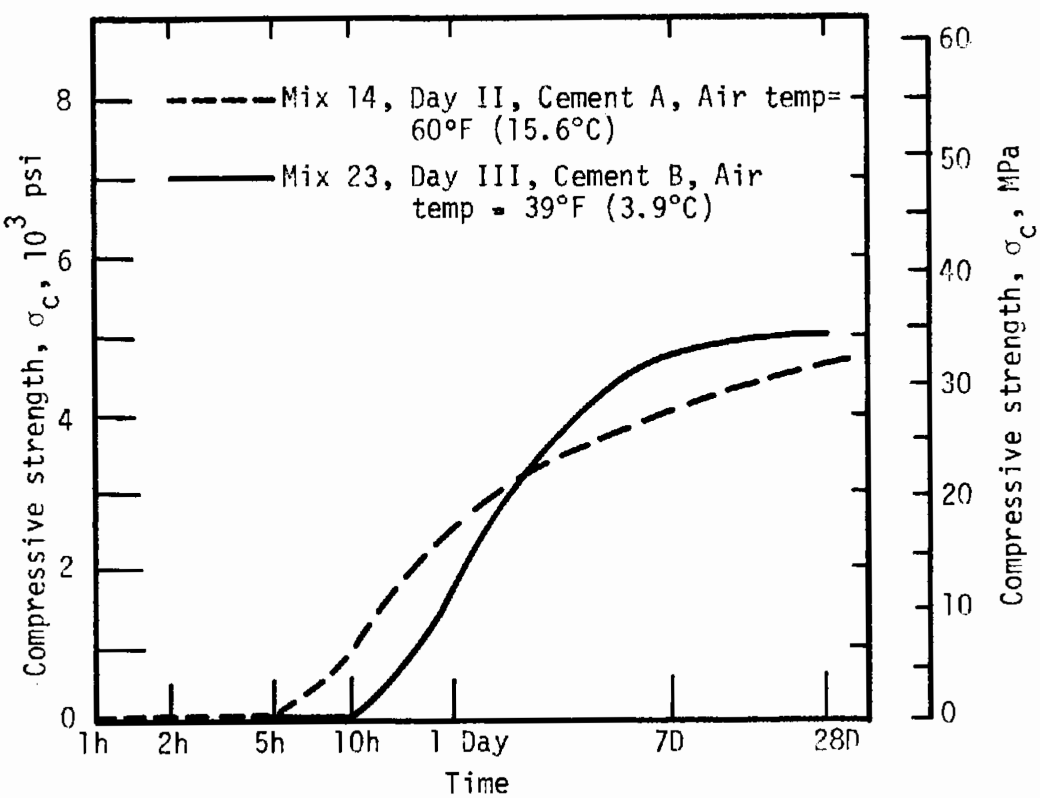


FIG. 9.30 COMPARISON OF COMPRESSIVE STRENGTH-TIME CURVES FOR TWO CONVENTIONAL MIXES WITH DIFFERENT SHOOTING CONDITIONS

In conclusion, warmer nozzle-water temperatures should decrease the time of setting and increase the early strength gain of both Type I and regulated-set cement mixes up to an optimum, beyond which early strength gain is reduced. Above or below the optimum temperature, the long-term strength is probably reduced. For these tests, the temperature of the water added at the nozzle significantly affected the strength of regulated-set mixes but had little effect on the strength of conventional mixes.

9.7.10 EFFECT OF TEMPERATURE OF DRY MIX ON STRENGTH

Prehydration caused by a high activity of the dry mix resulted in a high temperature in the dry mix before shooting and in lower initial and ultimate strengths. One dry mix (Mix 42) became excessively hot before shooting. It was the 10-1/2 bag (585 kg/m^3) regulated-set cement steel fiber mix. Both the prehydration because of excessive dry mix activity and disturbance because of excessive shooting activity are believed to be responsible for lower-than-expected initial and ultimate strengths.

9.7.11 EFFECT OF SHOOTING AND CURING TEMPERATURES

Generally, the warmer the environment, the more favorable the initial strength. If curing temperatures remain high, the ultimate strengths will also be higher. No direct comparison was made to evaluate the effect of temperature of the shooting environment. However, a comparison of Mix 14, shot on Day II with an air temperature of 60°F (15.6°C) with Mix 23 shot on Day III at 40°F (4.4°C) is shown in Fig. 9.30. Mix 14, shot in the warmer environment appears to have had a faster rate of gain of initial strength. However, no further conclusions can be drawn because too many other conditions, including the type of cement, varied in the tests.

The warmer curing conditions after one month clearly resulted in a significantly higher rate of gain of strength as reflected in the 42-day and six-month strengths.

9.7.12 EFFECT OF TYPE OF NOZZLE

Changing to the long nozzle changed several conditions, possibly including the nozzleman's technique. Furthermore, with the exception of Mix 25, all the mixes shot with the long nozzle utilized hot nozzle-water temperatures while most mixes with the short nozzle used normal water temperatures. The long nozzle appeared to provide better mixing action so that the material on the wall appeared more uniform and more plastic (wetter).

Mix and shooting conditions for Mix 23 and Mix 25 were almost identical except that Mix 25 was shot with the long nozzle. The two strength-time curves are compared in Fig. 9.31. Very little difference in strength can be distinguished at early ages and although the mix shot with the long nozzle exhibited slightly more one-month strength, this may be partly attributed to a slightly higher cement content in place as measured in the fresh shotcrete samples. It is, of course, possible that the higher in-place cement content may be caused by the long nozzle.

In conclusion, the long nozzle should improve uniformity of the mix which should minimize the minor variations in strength along the wall. More importantly, the improved uniformity should reduce the tendency for major variations in uniformity that result in laminations. It will be seen that this improved uniformity appears to have increased flexural strength of specimens shot with the long nozzle (Chapter 10). It is plausible that compressive

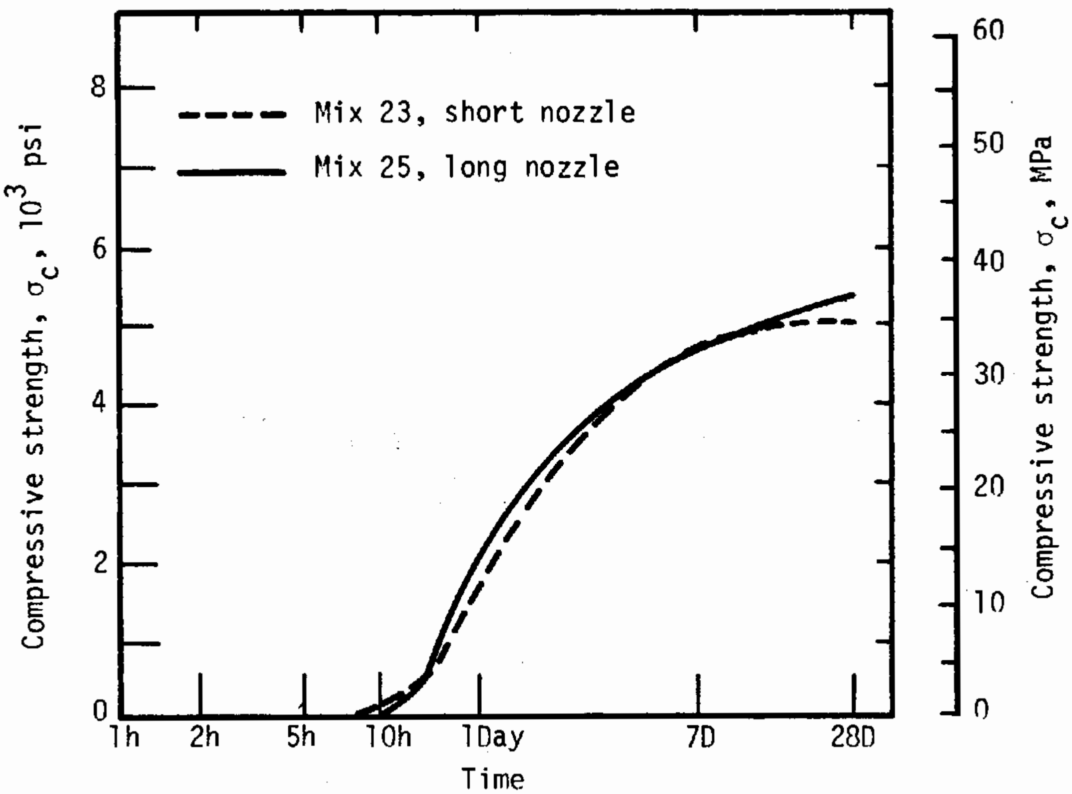


FIG. 9.31 COMPARISON OF TYPE OF NOZZLE IN COMPRESSIVE STRENGTH-TIME CURVES

strength would be increased to some lesser degree. Over a long period of time, the improved uniformity and better mixing should show some slight average strength increases over less efficient nozzles. With the limited comparison available from this data, only a slight tendency for increase in intact strength can be observed, and the amount of this increase that can be attributed to the long nozzle is unknown. The fact that flexural strength appears to have increased also lends credence to the hypothesis that compressive strength was higher because of the improved uniformity of the material.

The water pressure specified by the developer (Valencia, 1974) of the double water ring nozzle could not be achieved and the test on Mix 24 is not considered representative of the shotcrete attainable with this nozzle. The strengths, as a result, are lower than those with the short nozzle.

9.7.13 EFFECT OF FIBER CONTENT

The introduction of fiber to a mix appears to interfere with the placement and compaction process. At ages less than one day, this interference does not appear to affect the strength of steel fiber shotcrete. Hence, fibrous and non-fibrous mixes can be compared up to a strength of about 2500 psi (17.2 MPa). At strengths greater than about 2500 psi (17.2 MPa), steel fiber mixes appear to have a lower compressive strength than their non-fibrous counter-parts. At one month, the average strength of the control mix for steel fiber mixes was about 600 psi (4.1 MPa) less than the non-fibrous control. As a group, steel fiber mixes were about 1080 psi (7.45 MPa) weaker than the non-fibrous group at one month.

The slightly lower strengths (about 10 percent) of steel fiber mixes might be attributed to interference with the compaction process, the presence of small voids around fibers, or to the introduction of significant anisotropy that caused planes of weakness in the shotcrete. The x-ray photographs of specimens reported in Chapter 7 indicate such planes exist. It has been noticed that the effects of ordinary laminations from poor nozzle techniques also do not show up at early ages or low strengths. This lends some credence to the idea that planes of weakness are one of the more important contributing factors in reducing strength.

Mix 40 had only one-half the fiber content of the other fiber mixes; it was batched with 0.5 percent by volume. Despite the fact that it had slightly less cement, the strength of this mix at one month was within four percent of the mix with twice as many fibers and exceeded the strength of one of the non-fibrous control mixes. X-ray photographs of this mix showed fibers oriented in the planes of shooting but the degree of anisotropy was not strong. It is possible that there were fewer planes of weakness that would reduce strength than in other fiber specimens. From these data it appears that the strength reduction is in some way a function of the fiber content, a greater reduction in strength being caused by the introduction of more fiber.

9.7.14 EFFECT OF TYPE OF FIBER

All but two mixes of steel fiber shotcrete contained fiber with a rectangular cross section, 0.010 x 0.022 x 1 in. (0.25 x 0.56 x 25.4 mm) manufactured by U.S. Steel Co. (US fibers). Because of time and material limitations only 2 cu yd (1.5 m^3) of shotcrete with round wire fiber 0.016 x 1 in. (0.41 x 25.4 mm) manufactured by National Standard Steel Co. (NS fibers) were shot. Though one of these mixes, Mix 45, was slated for comprehensive strength testing, difficulties with the dry mix and gun, that were not caused by the fibers, made some of the samples porous and unsound, especially those tested at one month. Accordingly, some of the results at other ages should be considered minimum strengths. In spite of all these problems, shotcrete with NS fiber, Mix 45, obtained a compressive strength nearly as high as the comparable mix with US fibers, Mix 39, at other test ages. The compressive strength data are summarized and compared in Table 9.17. The lower strengths for Mix 45 are attributed to deficiencies, not related to the fiber, that occurred while shooting. At the present time, for compressive strength, there is no particular reason to prefer either type of fiber tested.

TABLE 9.17

COMPARISON OF COMPRESSIVE STRENGTH OF MIXES WITH DIFFERENT FIBERS

Mix	Measured cement content%[1]	Measured fiber content%[2]	Compressive strength, σ_c, psi (MPa) One day	7 days	One month	Six months
39-7 1/2I-100L-1US	24.8	2.6	2100 (14.5)	3890 (26.8)	4450 (30.7)	5880 (40.5)
45-7 1/2I-100L-1NS	19.9	2.1	2000 (13.8)	3120 (21.5)	3900* (26.9)	5410 (37.3)

Note: [1] Average percent by dry weight of total sample measured in fresh shotcrete samples.

[2] Average percent by dry weight of total sample measured in fresh shotcrete samples.

* Obviously poor samples, poorly compacted and porous.

9.7.15 EFFECT OF GRAVEL CONTENT

The unreasonably high accelerator content of Mix 34, the only mix with a lower gravel content, distorted all strength data so that no comparison can be made and the effect of gravel content on strength cannot be evaluated.

9.7.16 SUMMARY OF OBSERVED VARIATIONS IN COMPRESSIVE STRENGTH

VARIATION IN STRENGTH THROUGH THICKNESS

As a result of differences in micro-curing conditions at the exterior and interior surface of a shotcrete layer, the exterior surface will dry more quickly from evaporation unless curing compounds are applied or moist curing is followed. Construction practices seldom include special curing of shotcrete in tunnel construction. Thus, strength variation through the layer can be expected.

During early ages, the shotcrete next to the rock wall stays moist and it stiffens and gains strength slower than the exposed exterior. This effect was dramatically illustrated with the 9-bag (500 kg/m^3) regulated-set shotcrete of Mix 21. The early strength increased so quickly that the field crew found it extremely difficult to separate individual panels on the large frames even though crow bars, sledge hammers and pickaxes were used. Once separated and the plywood backing removed, the interior shotcrete was found to be warm and still moist and, although it had stiffened, it had gained little strength. The strength of the exterior of the approximately 4-in. (10 cm) thick layer was estimated to be on the order of 1000 psi (6.9 MPa) while the strength of the interior side of the layer, on the basis of attempted pull-out tests on the back of the panels, had gained almost no strength. It can be expected for conditions such as these that varying micro-curing conditions through the thickness of the shotcrete cause bond strength between the rock and the shotcrete to develop more slowly than indicated by compressive strength development near the surface. Designers and contractors should appreciate the fact that bond strength may not develop as fast as it appears by inspecting and testing the exterior surface.

At some age, possibly within several hours after shooting, the strength trend probably begins to reverse. The interior of the shotcrete layer received more compactive effort so it should become more dense and stronger than the exterior. More favorable curing conditions and less drying shrinkage also promote greater long-term strength at the interface between the rock and the shotcrete.

EFFECT OF DIRECTION OF TESTING

All specimens were treated in the same manner and in all cases the compressive load was applied subparallel to the potential planes of laminations. It is expected that this resulted in minimum strengths; other orientations should increase compressive strength. Laminations do not appear to reduce the compressive strength of young shotcrete significantly, but they do reduce compressive strength at high stress levels of stronger shotcrete.

EFFECT OF TRIMMING OFF ROUGH EXTERIOR SURFACE

The exterior surface was rough, irregular, exposed to various environmental changes of temperature and humidity, and has not been fully compacted by subsequent incoming shotcrete. Removal or trimming of this outer zone has been shown to result in an average apparent increase in strength of about 300 to 700 psi (2.1 to 4.8 MPa). The shotcrete does not get stronger, since trimmed and untrimmed specimens probably carry about the same load. Trimming the weak outer zone changes the area more than it changes the load carried by the specimen. These effects are discussed in detail in Section 9.6.2.

EFFECT OF SOAKING SPECIMENS

Essentially no difference in strength was observed at six months between dry specimens and specimens soaked for at least 40 hours prior to testing that could be attributed to soaking. This was explained by the fact that specimens broken open to observe the failure surface were found to be soaked no more than 0.25 in. (6 mm) around the perimeter.

EFFECT OF GENERAL CURING CONDITIONS

All tests through an age of one month were conducted on specimens cured in air in a partially completed tunnel at about 55°F (11.1°C). An effort was made to keep all panels up on blocks and clear of wet areas. It is possible that some of the bottom ends of panels became wet for some unknown period during their first month of curing while other panels were standing on a dry surface. Any unknown variation in curing condition would manifest itself as a variation in strength either within the panel or from panel to panel.

Following the transfer of all panels to the Civil Engineering Laboratory in Urbana, Illinois for the one-month tests, all the remaining panels were cured in a much warmer environment of about 70°F (21.1°C). An inspection of the compressive strength-time curves in Appendix E will reveal a significant increase in strength following the one-month-tests which illustrates the effects of curing in a warmer environment.

EFFECT OF SIZE OF SPECIMEN

A few panels tested at six months were thinner than desired, and the compression specimens were weaker than their full-size counterparts. Test data have been reviewed to eliminate individual tests that were particularly small or which had a high length-to-width ratio. Some particularly thin specimens tested at six months were compared with their control in Table 9.15. The average of all panels of Mix 39 with specimens at least 3 in. (7.6 cm) thick was 16 percent stronger than the panel with specimens 2 in. (5 cm) thick.

VARIATIONS WITHIN THE SAME PANEL

Two panels were cut up into 21 specimens each to evaluate the distribution of strength within a panel. The coefficient of variation of all the tests in the conventional shotcrete panel was 11 percent and it was 15 percent for the steel fiber panel. It might be expected that fibrous mixes would have greater variation in strength, and this is the case with these two panels. Both coefficients are considered good for field testing, but occasionally there was as much as 2000 psi (13.8 MPa) difference in strength between adjacent specimens. There was a slight tendency for specimens around the perimeter of the panel to be weaker than interior specimens. The wing walls of the panel create interference in the shooting operation because rebound was bouncing back in an adverse manner which promotes its entrapment. Quality control testing for a tunnel job constructed by drill and blast methods should include panels that have wing walls or other obstacles to shooting that simulate shooting of blasted rock. The results of the study of variations in strength within a panel are obtained in Section 9.6.3.

VARIATION BETWEEN PANELS OF SAME MIX

Each area at a different location on a rock tunnel wall should be expected to have somewhat different shooting conditions and curing conditions. The same is true for the test panels, but to a lesser extent. The maximum variation in the average strength between panels of the same mix was 1330 psi (9.2 MPa) at six months. For all test times the average of the differences between the strength of individual panels from the same mix was only 700 psi (4.8 MPa) or less than 15 percent of the compressive strength. Care has been given to consider all aspects of shooting and curing conditions when assessing and comparing the strength of mixes that the conclusion made is not likely to be affected by the possibility that the results are a fortuitous distribution of panel to panel variations. It is especially difficult to compare mixes with strength varying by about the amount of panel to panel variations.

COMPARISON OF SIMILAR MIX DESIGNS

An assessment of the strength of mixes that had the same or very similar mix designs and whose shooting conditions were similar provide data on expected variations in good shotcrete. Among the conventional mixes, Mixes 14, 23, 24, 25 and 26 had the same batch proportions. Of these, Mix 14 and 24 had different shooting conditions. Though Mixes 23, 25 and 26 differed in type of nozzle and nozzle-water temperature, their strength-time curves fall into the narrow range shown in Fig. 9.32. For comparative purposes, the strength-time curves of Mixes 14 and 24 are also shown in the figure.

The narrow range of the three mixes indicates good quality control, consistent shooting, and a lack of other important variables despite the fact that different nozzles and different nozzle-water temperatures were used. Mix 14, shot with a different brand of cement and under much warmer shooting and curing conditions, shows the expected variation from the range of Mixes 23, 25 and 26. Mix 14 in the figure also illustrates that similar mixes can achieve strengths of about 4500 to 5000 psi (31.0 to 34.5 MPa) at one month yet have significantly different strength-time curves. From a geotechnical standpoint, Mix 14 is far superior for early support of the ground. This vividly illustrates why specifications should require tests to verify minimum early strengths.

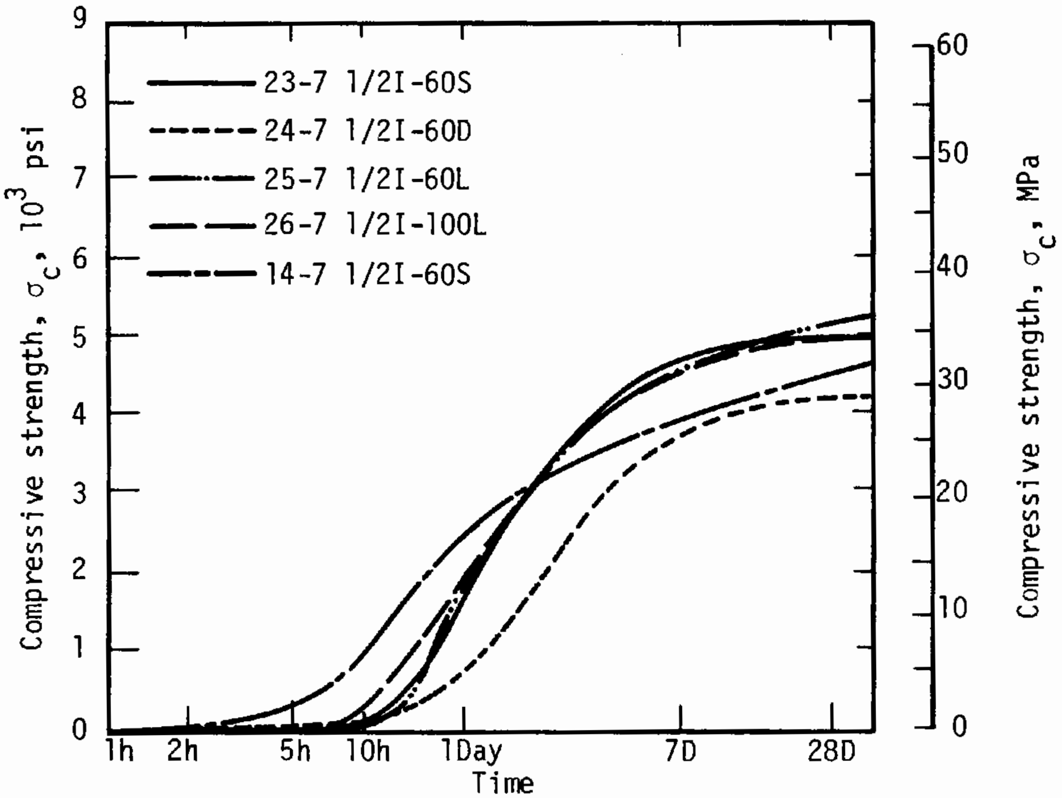


FIG. 9.32 COMPARISON OF STRENGTH-TIME CURVES FOR SIMILAR CONVENTIONAL MIXES

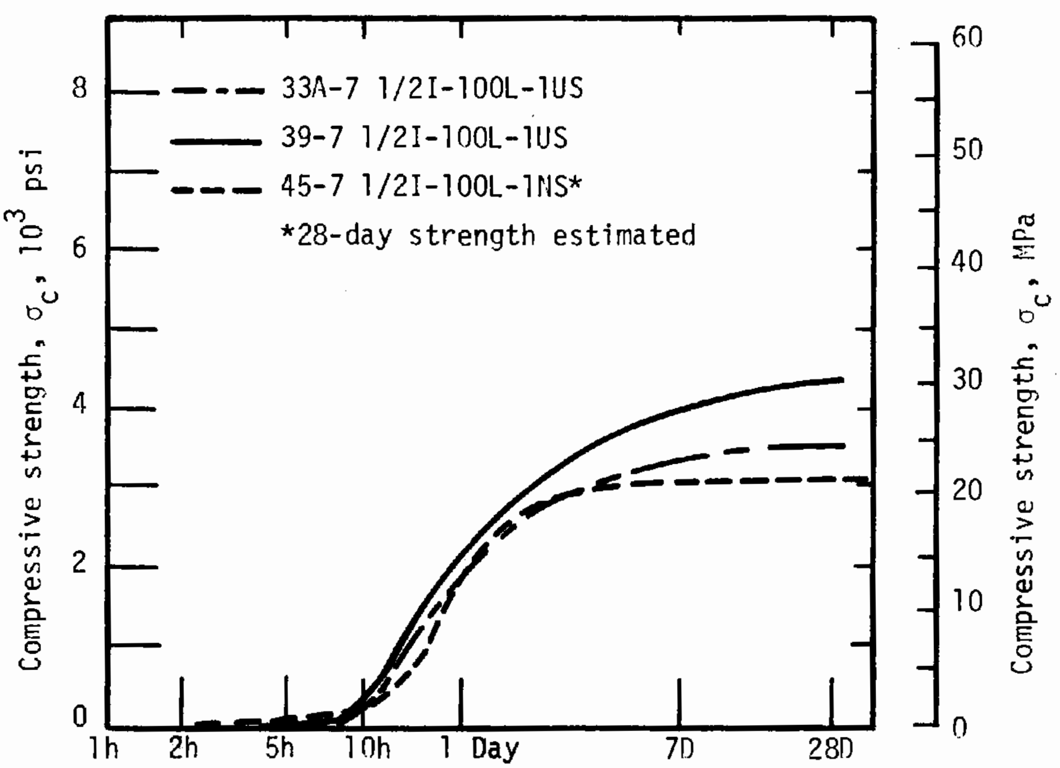


FIG. 9.33 COMPARISON OF COMPRESSIVE STRENGTH-TIME CURVES FOR SIMILAR STEEL FIBER MIXES

Tests at one month do not give any information on the early strength of the shotcrete. Attempts to interpret ultimate strength from one-day tests or for that matter even 3- or, in some cases, 7-day tests can be misleading also. On the other hand, since strength inperfections such as minor laminations do not appear to affect one-day-strengths significantly, tests on young shotcrete will not indicate the presence of these undesirable imperfections.

Apparently Mix 24 suffered from poor shooting conditions throughout its entire age. This probably involved poor water control, poor mixing, and possibly some minor laminations because of lack of the water pressure necessary for the nozzle design.

Three steel fiber mixes, 33A, 39, and to a certain extent, 45, afford a comparison of similar mixes. Their strength-time curves are compared in Fig. 9.33.

9.7.17 EVALUATION OF TIME VARIATION OF STRENGTH

Earlier discussions have indicated that the relative strength between mixes or between major groups change with time. For instance, steel fiber shotcrete was as strong as the non-fibrous conventional shotcrete at young ages but above about 2500 psi (17.2 MPa), steel fiber shotcrete had lower strength than conventional. This section examines the changes of these differences in relative strength that occur with time as well as aspects of the increase in strength of individual mixes with time.

Figure 9.34 shows the development of strength of selected mixes as a percentage of the 28-day strength finally achieved by that mix. The mixes which had regulated-set cement or high accelerator content achieved greater

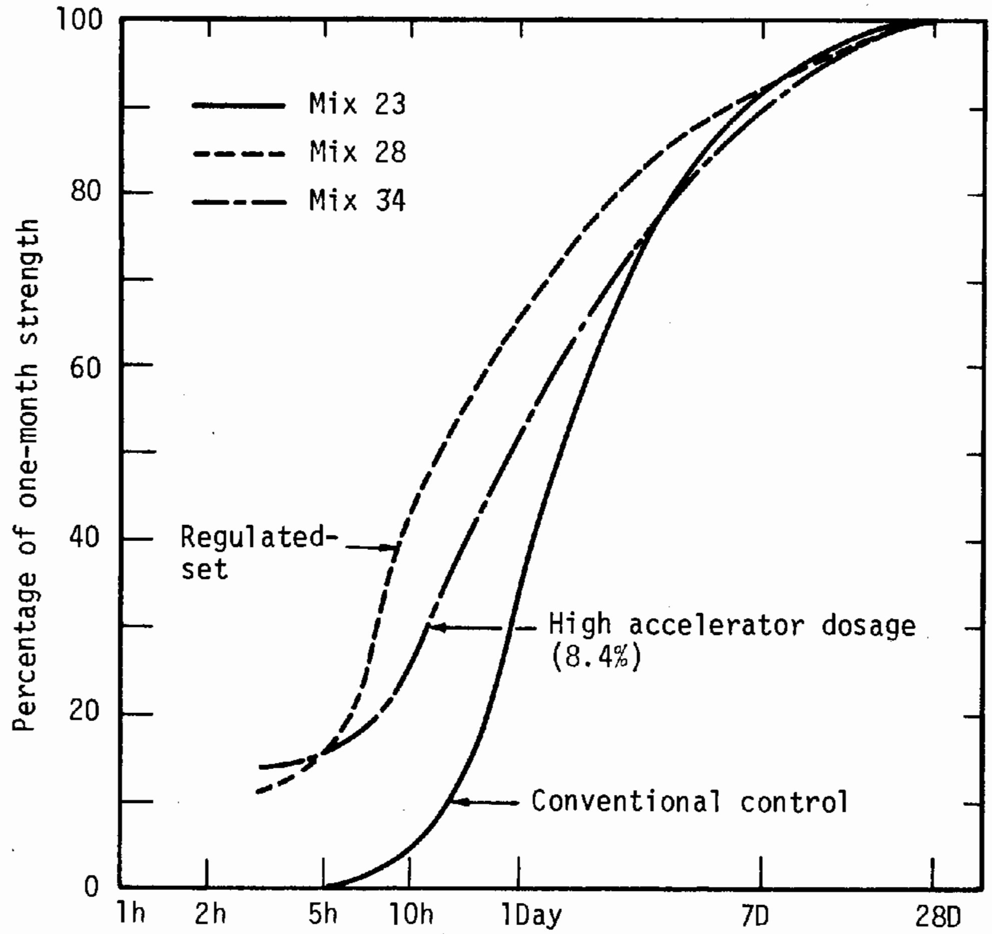


FIG. 9.34 COMPRESSIVE STRENGTH, EXPRESSED AS A PERCENTAGE OF ONE-MONTH STRENGTH-VERSUS-TIME

than 50 percent of the 28-day strength by 1 day. All mixes showed about 90 percent of 28-day strength by 7 days. Table 9.18 presents similar information for most mixes.

By 5 hours, two regulated-set mixes achieved at least 17 percent of their relatively high one-month strength. Strength increases of conventional and steel fiber mixes at this age were minimal except for those with 4.9 percent and 8.4 percent accelerator which had developed to 18 and 15 percent respectively, of their relatively low 28-day strength.

TABLE 9.18

PERCENTAGE INCREASE IN COMPRESSIVE STRENGTH

Conventional shotcrete					Regulated-set shotcrete					Steel fiber shotcrete				
Mix number	Percent 28 day strength at				Mix number	Percent 28 day strength at				Mix number	Percent 28 day strength at			
	5H	1D	7D	180D*		5H	1D	7D	180D*		5H	1D	7D	180D*
MIXES SHOT ON DAY II														
14	5	51	76	--	21	21	65	100	--					
MIXES SHOT ON DAYS III & IV														
23	2	32	95	118	28	17	60	79	110	33	18	45	73	--
24	2	19	--	--	29	2	20	89	115	33A	1	53	93	--
25	1	34	83	--	30	2	63	95	111	34	15	50	81	--
26	1	38	--	138**						38	4	43	89	--
										39	2	47	87	133
										40	--	54	105	147
										42	8	51	91	127
RANGE FOR DAYS III & IV														
MAX	2	38	95	138**		17	63	95	115		18	54	105	147
MIN	1	19	83	118		2	20	79	110		1	43	73	127

* Six-month data reflects more favorable curing conditions than in 28-day tests

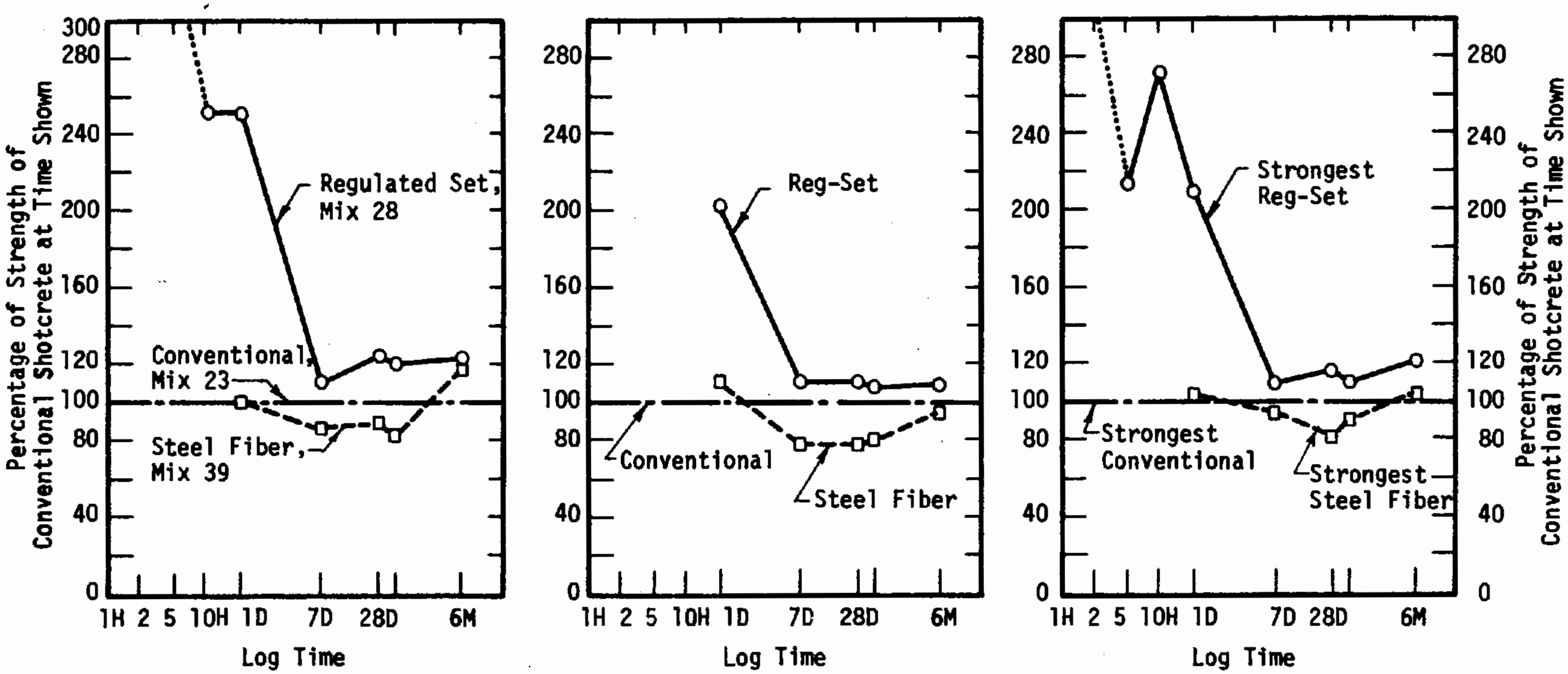
** Believed excessively high

By one day, most regulated-set mixes achieved about 60 percent of their 28-day strength. Steel fiber mixes had achieved about 40 to 50 percent of their 28-day strengths. At 7 days almost all mixes had achieved about 90 percent of their respective 28-day strength. At six months conventional Mix No. 23 had increased about 20 percent while the regulated-set mixes increased 10 to 15 percent over their respective 28-day strengths.

Care must be taken in comparing mixes in this manner since a high relative strength at an early age does not necessarily indicate high long-term strength and, in fact, usually means a lower 28-day strength. For instance, the high accelerator dosage in Mix 34 distorts any interpretation of absolute strength from these data since the one-month strength was so low. Also, all the steel fiber mixes seem to have higher percentage increases than conventional mixes, but the reason for these seemingly high percentages is not that steel fiber is superior but rather the relatively low 28-day strength.

Evaluations of strength as a percentage of the one-month strength should be made in evaluating shotcrete for a project so that strengths at 3 to 7 days can be used to estimate one-month strength. These correlations are useful as a quality control tool. However, it is important to recognize that different types of mixes have different percentage strengths at most ages except perhaps between 7 and 28 days.

The relative strengths of the three major groups of shotcrete are also important. The relative strengths have already been assessed at each age by group in Sections 9.4.3, 9.4.4, and 9.5. The following paragraphs evaluate the change in relative strength with time. Figure 9.35 presents this data for all ages as a percentage of the strength of the conventional shotcrete control mix.



a) Comparison of Control Mixes for Each Group

b) Comparison of Average Strength of All Mixes in Each Group

c) Comparison of Highest Strength in Each Group in Each Time Period

FIG. 9.35 EVALUATION OF STRENGTH OF REGULATED-SET AND STEEL FIBER SHOTCRETE AS PERCENTAGE OF STRENGTH OF CONVENTIONAL CONTROL MIX

Figure 9.35a presents data solely for the control mixes of each group while Fig. 9.35b presents the same comparison based on the average of the mixes in each group. Any differences between Figs. 9.35a and 9.35b reflect differences due to the fact that the changes with time are different for each individual mix. Finally, Fig. 9.35c makes the same comparison, but the highest strength in each group at each time period was used to compute the percentages.

All three figures illustrate the same general trend. Regulated-set shotcrete was many times stronger than conventional shotcrete for the first few hours. Regulated-set shotcrete maintained a substantial strength superiority to some time between 1 and 7 days after which it was consistently over 10 percent stronger than the control mix.

Steel fiber shotcrete was about equal in strength to conventional control until some time between 1 and 7 days, at which time steel fiber shotcrete was about 10 to 20 percent weaker than control. The indication is that this trend reversed, and at six months steel fiber mixes were, by some methods of comparison, even stronger than the conventional control. At least it can be said that steel fiber maintained its strength in terms of percentage of control strength.

MEASURED UNIT WEIGHT VERSUS STRENGTH

Although unit weight was measured carefully at the time of strength testing, no clear correlation appeared between unit weight and strength. The unit weights varied from 144.3 to 149.5 pcf (2313 to 2396 kg/m^3). When unit weight is plotted against strength, considerable imagination is required to discern any valid trends. The range of values of unit weight is just too small to permit a clear relationship.

A concept that explains the reasons why there may be considerable scatter in correlations between unit weight and strength is presented in the next section. Section 9.9 contains a discussion and plotted data of unit weight relationships in terms of the new concept.

9.8 COMPACTION ANALOGY RELATING UNIT WEIGHT TO WATER CONTENT

9.8.1 FACTORS AFFECTING THE WATER CONTENT

The water-cement ratio in dry-mix shotcrete is not a completely independent variable as it is in concrete. Water-cement ratio is dependent upon a large number of factors besides the nozzleman. These factors include the gradation of aggregate; type and amount of cement; compatibility; type and amount of accelerator; combined activity of the mix; and factors involved in compaction such as air pressure, nozzle distance and direction, velocity, uniformity, concentration, and gradation of particles in the airstream; and the consistency of the shotcrete itself.

Nozzlemen often use a slightly glossy appearance of the shotcrete being placed as an indicator of the proper amount of water to be added at the nozzle. It has been established by field observations and experience to be a good water content for quality shotcrete. Zynda (1966) states that it is close to the point of maximum density. The factors enumerated in the paragraph above govern the amount of water necessary to create the glossy appearance. The glossy appearance is an indication of the fact that the shotcrete on the wall is being compacted by impact or vibration and that the compaction energy has reduced the volume of the in situ shotcrete on the surface until it is at saturation or near-saturation. The process of shooting dry-mix shotcrete is one of compaction by impact not too much unlike the process of compaction of soil for earth embankments, since the material can be placed at water contents below saturation. Impact forces from subsequent particles in the shotcrete airstream serve to compact the shotcrete already on the wall.

The fact that the shotcrete looks glossy is believed to be an indication that the material on the wall is acting like a non-plastic material, probably like a very silty sand and gravel for the brief period that it is being shot. The length of this period varies with the length of time it takes for the chemical reactions of the cement and accelerator to begin to dominate the behavior, but it could be as short as a few seconds. The more active the mix, the stiffer it becomes on the wall and the shorter the time it can act non-plastically; highly active mixes possibly never act non-plastically.

9.8.2 CONCEPTUAL COMPACTION ANALOGY FOR SHOTCRETE

These personal field observations lead to the idea that compaction concepts similar to those used in construction control of earth embankments which relate water content, compaction energy, and dry unit weight may be used as a model for the compaction of shotcrete during the brief period when the in-place shotcrete is still susceptible to compaction. The conceptual model for shotcrete will be analogous to the concepts for weight-volume relationships and for compaction of soils as described in Terzaghi and Peck (1967) and other textbooks on soil mechanics. Compaction curves for soil relate the water content of any given soil to the dry density attainable by a certain method of compaction when the soil is compacted by a given energy. Water content is defined as the weight of water in the soil divided by the dry weight of soil particles. The curves show that an increase in water content results in an increase in unit weight up to an optimum point that defines the optimum water content and the maximum dry density. Further increases in water content result in lower density. If the specific gravity of the solids is known, a theoretical curve of zero air voids or 100 percent saturation can be calculated from weight-volume relationships. Each soil has a different compaction curve that can be determined by a standard laboratory test having a specified energy of compaction. Any given soil has a different compaction curve for a different energy of compaction.

9.8.3 EXISTENCE OF SHOTCRETE COMPACTION CURVE

A conceptual model for shotcrete compaction is shown in Fig. 9.36 in which two hypothetical shotcrete compaction curves representing different mix or shooting conditions are shown. The arrow shows the trend for different mix or shooting conditions. The very existence of such curves for shotcrete must be proved; however they serve to illustrate and explain several observations regarding the shooting and strength of shotcrete.

Indeed, the existence of such curves may be impossible to prove because the shotcrete on the wall is neither a reproducible nor uniform material. Instead, shotcrete is the result of a pulsating process of segregation, remixing, and different rates of rebound of each of the constituents, all changing each instant. Accordingly, there may not be any one "mix" for which the density can be measured at several different water contents to obtain an experimental compaction curve. In fact, any change in water content changes the rate of rebound of some of the constituents and, thus, the composition of the mix on the wall. Changes in the mix affect the equivalent specific gravity, and thus,

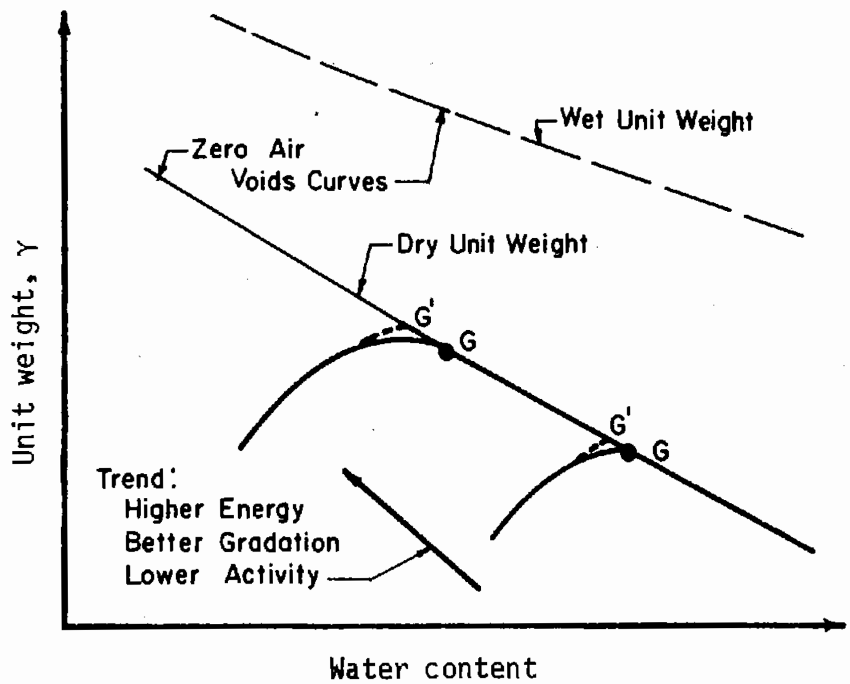


FIG. 9.36 CONCEPT OF COMPACTION CURVE FOR SHOTCRETE

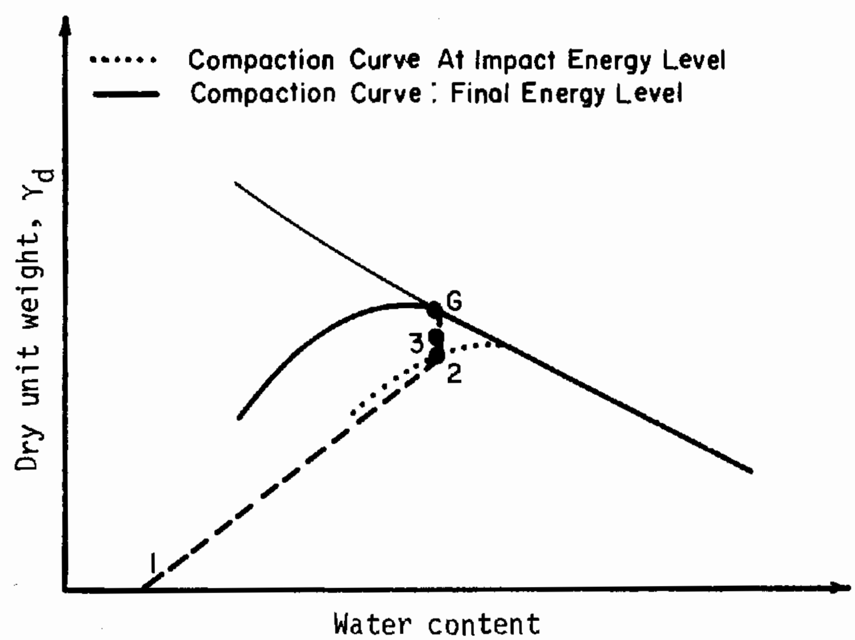


FIG. 9.37 COMPACTION PATHS

the theoretical zero air voids curve. Any sample would have some entrapped air around rebound pockets that would displace the experimental curve to the left of the true theoretical zero air voids curve as in compaction curves for soil. The glossy criterion is not always achieved and a glossy surface does not imply that the entire thickness is saturated. Only the area exhibiting the glossy appearance could be considered saturated. In view of the low permeability, only a thin layer need be saturated to produce a glossy appearance. Even the compaction energy and the water content change every instant as a result of the pulsating nature of the airstream and with every change in nozzle direction and distance. The nature of the compaction energy is such that the compaction curve may, in fact, look like the dashed curve to Point G'. If so, the glossy appearance will occur at the point of maximum density. However, no special significance is being given in this discussion to the shape of the curve in light of the lack of experimental evidence. It is shown flatter and more rounded than it possibly is to illustrate the concept more clearly.

Nevertheless, it can be said that no matter how random or erratic the process may be, there must be some relationship between the compaction energy, the water content, and the dry unit weight for a given material in place. It is important to recognize that the dry unit weight is the unit weight that would be measured as soon as it is shot and before hydration takes place. It is not the unit weight after hardening. The behavior, for purposes of discussion, will be assumed to act in a general sense as if there are equivalent idealized compaction curves for various types of gradations of material and for different levels of energy provided by the airstream. In the following sections in which trends based on the compaction analogy are discussed, the style, adopted for convenience, will assume that the analogy is valid. However, the reader may mentally insert the phrase "if the compaction analogy is valid" wherever he chooses.

If cement content of the shotcrete on the wall is assumed to be represented by a constant average cement content, the abscissa in Fig. 9.36 is both water content and water-cement ratio. The dry unit weight, γ_d, is a measure of void content or particle contact in the shotcrete material. Hence, for a given cement content, the dry unit weight could be approximately proportional to strength. However, other factors such as structural defects and laminations, temperature, and curing conditions, must also be considered in the final evaluation of strength as discussed in Section 9.8.8.

Known relations for compaction curves for soils to changes in gradation, plasticity, and compaction energy will be used in the following sections to estimate the possible trends for different shotcrete conditions.

9.8.4 PATHS OF COMPACTION

The dry mix has some initial water content such as at point 1 on Fig. 9.37. This point is shown on the abcissa because there is no need to associate a unit weight with it nor would it be compatible with the remainder of the figure. The path from 1 to 2 only shows that, while shooting, the dry mix is wetted so that its water content increases and, as it hits the wall, it has a unit weight and water content represented by point 2 that is on the dotted compaction curve, a curve that is characteristic for that material and the level of compaction energy at impact. Subsequent impact or vibration compacts the material more along the vertical constant water-content line to Point G on the final compaction curve. Assume that the water content of points 2 and 3 are at the same water content given by the intersection of the final compaction curve and the zero air voids curve. When the material is at Point G, as long as the material remains non-plastic and has not been buried by subsequent material, it will exhibit a glossy appearance with any additional compaction energy or vibration. Positive pore pressures will be generated and free water will appear on the surface. Because of the relatively low permeability of the mix, additional compaction energy applied to the mix at any point on the zero air voids curve will not result in any densification. The mix will be disturbed and remolded instead. This is true even if the level of incoming energy is increased, perhaps by closer nozzle distance or higher air pressure. Once a material is on the zero air voids curve, additional shooting only acts to disturb it.

9.8.5 COMPACTION OF LAYERS BENEATH SURFACE BEING SHOT

If the first pass of the nozzle only compacts the material to point 3 in Fig. 9.37, additional passes would impart additional energy and could densify the material further, even to Point G, provided the material has not set. Any setting of the cement and accelerator would lower the applicable compaction curve and reduce the amount of additional compaction possible at any given level of energy. The high-speed photographic study described in Chapter 5 led to the conclusion that one of the mechanisms of compaction is the recompaction of buried layers. No doubt some cement bonds already being developed are destroyed or at least distressed by this process of recompaction. If the second pass serves to disturb more than possibly can be gained from increased compaction, it is probably too active.

9.8.6 EFFECT OF VARIOUS FACTORS ON COMPACTION CURVES

The effects of various relative changes in mix and shooting conditions are summarized in Fig. 9.38. The effects of a more active mix (more cement or more accelerator) are expected to be similar to the effects of time after shooting. Both result in the material to be compacted, being stiffer and, thus, less receptive to compaction by a given level of energy. Hence, as shown in Fig. 9.38 increased activity results in a lower shotcrete compaction curve. A low-activity mix shot to the glossy criterion (Point G1) would have a higher unit weight than the same mix with more acceleration (i.e., more active), also shot to the glossy criterion (Point G2), etc. If a mix is so active that it has set before reaching the wall, its initial compaction curve will be low because the mix will act as if it has a different gradation and fewer voids will be filled. Subsequent passes can only disturb the shotcrete already on the wall.

After shooting, the reaction between cement, accelerator and water makes the material already on the wall stiffer. The "free water content" reduces and the material on the wall could become less saturated as some water reacts with cement. The curves shown in Fig. 9.38 are the relative positions of curves for subsequent compaction energy; they shift lower with time as the material in place gets stiffer. The amount of compaction possible during subsequent passes becomes less with time. Fig. 9.38 should not be interpreted to imply the unit weight reduces with time.

Different aggregate gradations also result in different compaction curves that can be estimated from known relationships for soils. If two mixes with different aggregate gradations are shot at the same level of energy to the glossy criterion, the coarser gradation will have a lower water content and a higher unit weight and, in some cases, strength. The relative trends are illustrated in Fig. 9.38. A shotcrete compaction curve for coarse aggregate might be shown by the upper curve; the relative position of a fine-aggregate compaction curve is illustrated by the lower curve. Similar effects should be anticipated

Relative shooting condition

Curve	Gradation	Compaction energy	Activity	Time after shooting	Fiber content
———	Coarse or more well graded	High	Low	Short	Low
- - - -	Finer or poorly graded	Low	High	Long	High

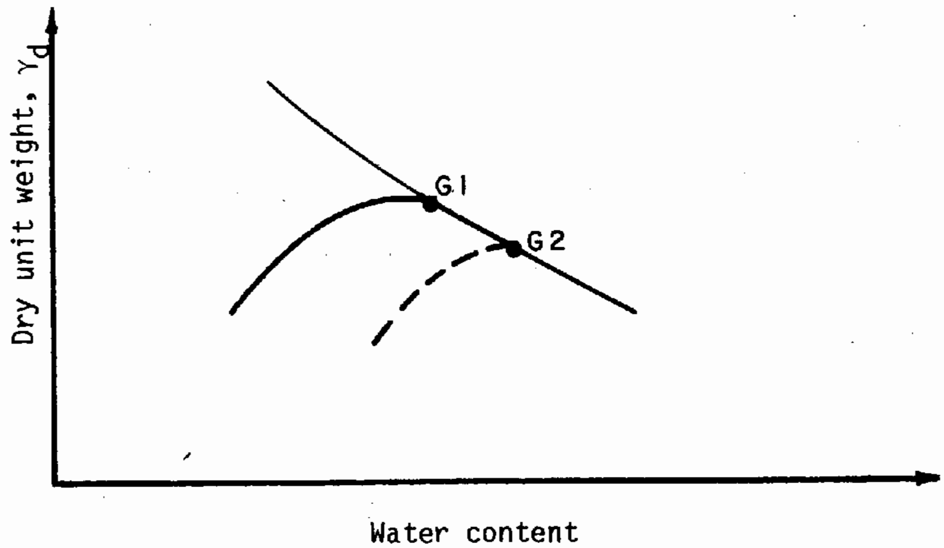


FIG. 9.38 EFFECT OF RELATIVE CHANGES IN MIX AND SHOOTING CONDITIONS ON SHOTCRETE COMPACTION CURVES

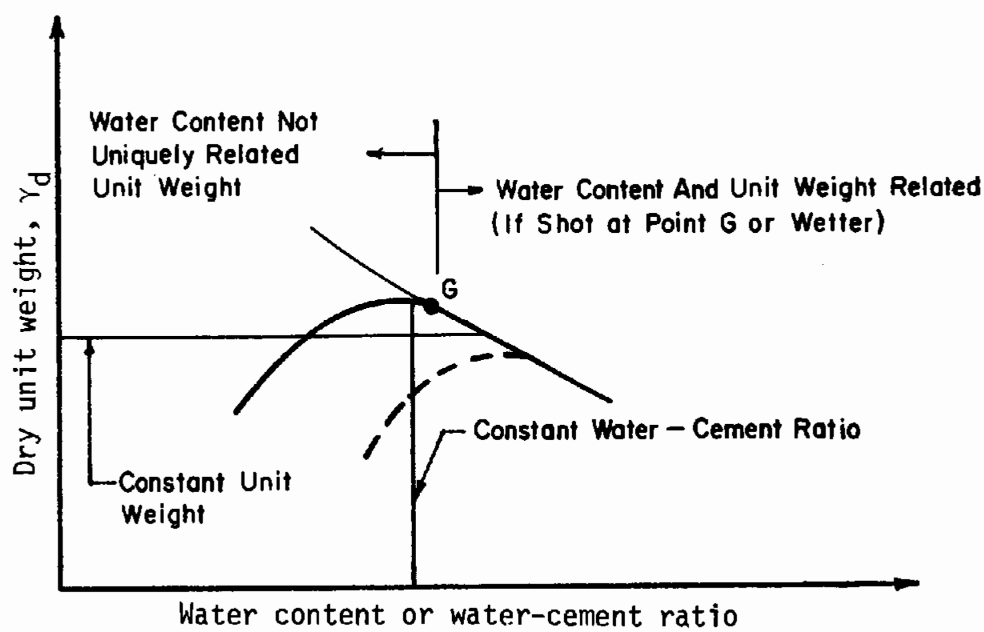


FIG. 9.39 DUAL RELATIONSHIP BETWEEN WATER CONTENT AND UNIT WEIGHT

depending on whether the mix is well graded or not. A poorly-graded or gap-graded material should be expected to have a lower compaction curve. Also, the compaction curve is believed to shift higher with increased cement content when the increase makes the mix more well graded.

It is believed that more energy is required to compact a mix containing fibers, so the addition of fibers or an increase in fiber content is expected to lower the compaction curve for any given level of energy. The strengths of fiber mixes were lower for this study and other investigators have also reported lower strengths with the addition of steel fiber to a mix.

9.8.7 CONTROL EXERCISED BY NOZZLEMAN

From the discussion above, it can be seen that the nozzleman can control the unit weight in many different ways. The most publicized way is his control of the water content of the incoming material. It has been shown that shooting to a glossy criterion probably results in a material that is close to the optimum for the compaction energy level. Shooting slightly drier or wetter than Point G should be acceptable. Shooting much drier or much wetter than Point G will result in lower unit weights and possibly lower strengths. Shooting drier than Point G will increase rebound while shooting wetter reduces rebound. If the nozzle is mixing the ingredients well, (such as in the long nozzle) shooting at Point G will be satisfactory. If the nozzle does not mix ingredients well, the nozzleman could consider shooting on the wet side of Point G to take advantage of remixing on the wall, provided the mix is not too active to preclude this remixing.

The nozzleman can also control the unit weight by altering the incoming energy. He can request air pressure or he can move the nozzle closer to the wall. Moving the nozzle closer to the wall does not increase the velocity at impact but does increase the average pressure or compaction force since the size of the cone of the airstream is reduced (Chapter 5). This increase in energy also results in increased rebound. Finally, the nozzleman can control unit weight by changing the dosage of accelerator, thereby changing the effective compaction curve on the wall. If the mix is too active, lowering the accelerator dosage could result in a higher compaction curve.

9.8.8 WATER CONTENT VERSUS UNIT WEIGHT AND STRENGTH

Water content, unit weight, and strength of shotcrete are not necessarily related. The following discussion relates only to ultimate strength unless otherwise stated. It also assumes that cement contents and curing conditions are similar. Furthermore, the mixes are assumed to have normal activity so that the problem of disturbance does not affect the mix. With these assumptions, the abcissa of all of the compaction curves can be converted directly from water content to water-cement ratio. It should be noted, for the scale the curves are drawn, that the origin of the axes in these diagrams does not represent zero dry unit weight nor zero water content; the origin represents some finite value of dry unit weight and water content.

It can be seen in Fig. 9.39 that, so long as the nozzleman shoots to the glossy appearance (Point G) or wetter, the water-cement ratio for a given mix and shooting condition is closely related to unit weight. The portion of the compaction curve along the zero air voids curve is another way of describing the water-cement ratio concept for concrete. Unit weight should be related to ultimate strength if structural defects and curing are the same, so there could be a relationship between water-cement ratio and ultimate strength.

If, however, the nozzleman shoots on the dry side of Point G, there are several reasons why water-cement ratio and strength may not be related. Horizontal and vertical lines have been drawn in Fig. 9.39; they are lines of constant unit weight and constant water-cement ratio, respectively. The horizontal line intersects the same compaction curve twice, at significantly different water-cement ratios. Both points of intersection could produce the same unit weight and ultimate strength, indicating one condition where water-cement ratio should not relate to strength. In addition, shooting dry tends to increase imperfections such as laminations that reduce strength. The amount of strength reduction depends on the details of the imperfections and not to water content.

The vertical line of constant water-cement ratio intersects different compaction curves at significantly different unit weights. The lower compaction curve could be the same material shot to a lower energy level or a different material gradation shot at the same energy level. Either case will give a different unit weight and a different ultimate strength even though they have the same water-cement ratio.

A different perspective is necessary for an evaluation of early strength. A high water-cement ratio tends to slow the rate of reaction of the cement and accelerator. Hence, for any material with a given compaction curve, shooting wetter will slow the initial set and final set times and reduce the strength at any given early age. However, two mixes shot to the same shooting criterion but with different accelerator dosages will result in a higher early strength, a lower unit weight and a lower ultimate strength for the mix with highest accelerator dosage. The effect accelerator imposes on ultimate strength is both physical and chemical. Physically, additional accelerator dosage gives the material a lower compaction curve; if it is too active, the material is disturbed by subsequent shooting. Both physical effects reduce ultimate strength. However, from the standpoint of chemical reactions, anything that increases early strength, generally reduces ultimate strength. Thus, accelerators reduce ultimate strength for reasons that are both physical and chemical. Accelerator dosage is so important that records should be maintained on the actual dosage used on each shift.

A mix with a higher activity should have a lower compaction curve. Thus, whether placed to the glossy appearance criterion or not, the ultimate strength of the mix should be expected to be lower. If the mix is so active that subsequent incoming material disturbs the bonds of the initial set, the early strength will also be reduced.

Any mix shot so dry that it has laminations or uncemented pockets cannot exhibit any relationship between water-cement ratio and ultimate strength. In this case, strength is not related to unit weight because the strength is governed not by the strength of the matrix but by the details of the imperfections. It has been observed that imperfections do not always affect early strengths, probably because the strength of the matrix and the strength along imperfections are similar at early ages. Imperfections begin to affect strength when the strength of the matrix is high. Thus, because of the influence of these imperfections and of curing conditions, ultimate strengths should not be estimated from one-day or even three-day strengths.

However, temperature and humidity conditions also have a strong effect on ultimate strength in a manner completely unrelated to the water content at time of placement. Warmer and more humid curing conditions result in higher strengths. Hence, the influence of curing conditions alone can overshadow any relationships between water content and strength.

9.8.9 QUALITY CONTROL POSSIBILITIES

The foregoing discussion has some application to quality control. Once the strengths are shown to be adequate, one of the best methods of quality control is observation of the shooting operation. The nozzle should be mixing the ingredients well and the operator using proper nozzling techniques (proper water content, nozzle direction, and distance). The accelerator dosage should be uniform and not excessive. If the nozzleman then shoots to the glossy criterion, one should expect the unit weight and strength to be uniform. Hence, watching the operation and correcting deficiencies should maintain quality control. Routine checks of strength are necessary but in addition, zones that were shot too dry or that are otherwise suspect should be tested.

Because of the possibility that there can be different unit weights at the same water-cement ratio, quality control cannot be made solely on the basis of water content. Only if the nozzleman always shoots at Point G or wetter does water content have a chance of being related to unit weight or strength. If in-place unit weight could be measured accurately, it might be valuable for predicting ultimate strength of properly-cured intact shotcrete since it can relate to ultimate strength. However, curing conditions and the details of imperfections could easily overshadow a relationship between unit weight and strength. Furthermore, the range of unit weights is so small that a well-defined relationship would be difficult.

9.8.10 SUMMARY OF SHOOTING CONDITIONS

Various shooting conditions and their relationships are shown on a shotcrete compaction curve in Fig. 9.40. The curve will be used to evaluate the effect of these shooting conditions on the water-cement ratio, dry unit weight, and strength. Assume that the curve is a compaction curve for an ideal shotcrete mix containing a normal amount of accelerator. Fortunately, the criterion of shooting to a glossy appearance puts the water content close to or at the optimum. The differences in unit weight and in water content between the optimum point and the glossy point are estimated to be small; it is possible that they are the same point. To obtain the maximum strength possible, the nozzleman should adjust the water content so that he is shooting to the glossy criterion or possibly slightly drier.

It is believed that the glossy appearance occurs only at a very narrow range of water contents. It cannot occur unless the material is saturated. On the other hand, remolding begins to occur if the water content is increased above the point of intersection of the compaction curve and the zero air voids curve. This remolding destroys the glossy appearance.

The consistency of the material at water contents higher than Point G gets more and more plastic with increasing water content. The increased plasticity allows remolding to take place on the wall and makes the material more receptive to the embedment rather than rebound of particles. Accordingly, the rate of rebound of particles, after the critical initial thickness is established,

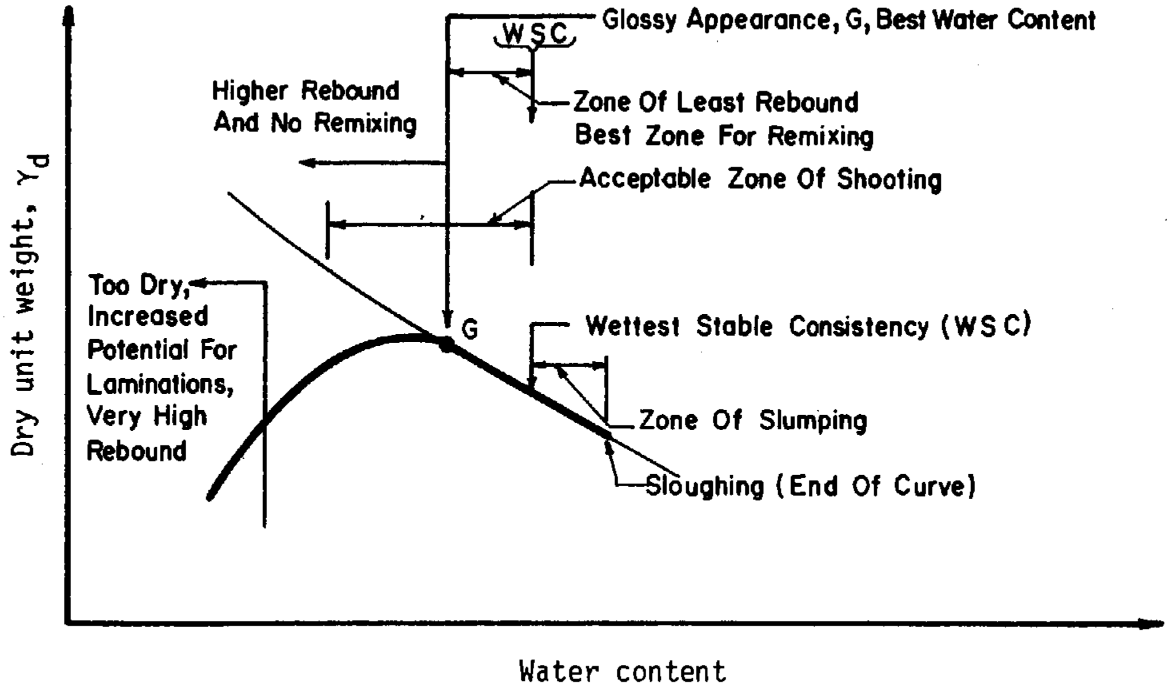


FIG. 9.40 SUMMARY OF SHOOTING CONDITIONS IN TERMS OF COMPACTION CURVE

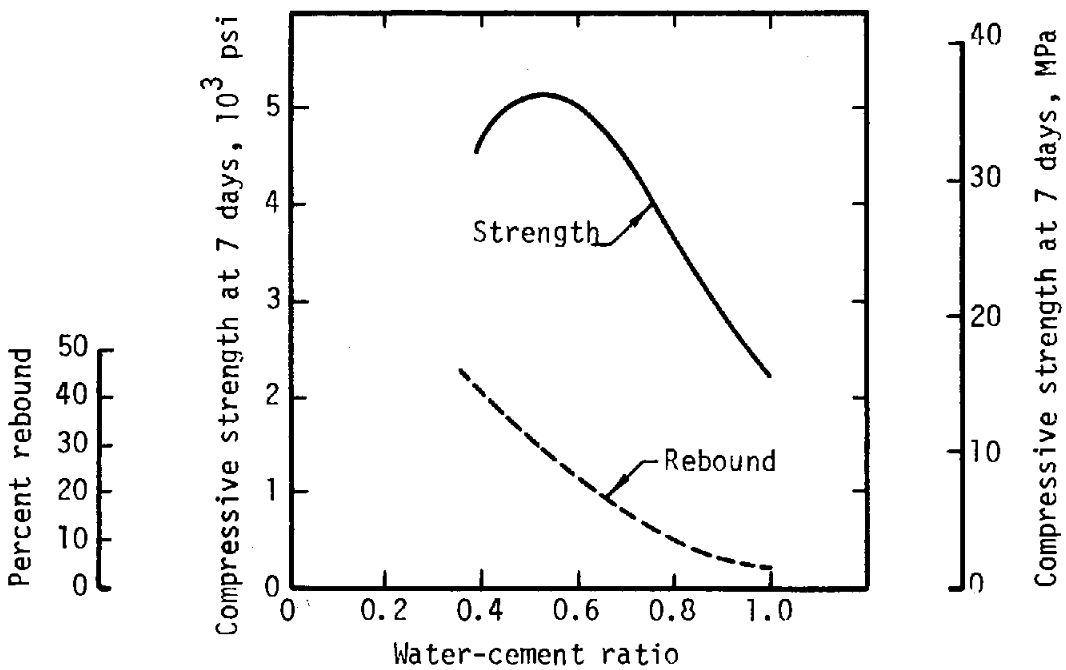


FIG. 9.41 EFFECT OF WATER-CEMENT RATIO ON STRENGTH AND REBOUND OF GUNITE (AFTER STEWART, 1931)

is reduced with increased plasticity of the material on the wall. The increase in plasticity and in water content are accompanied by a slightly reduced unit weight and slightly lower ultimate strength.

Along the zero air voids curve there is a point where the instantaneous strength of the material is so low that it cannot support its own weight; it begins to slump. The point where the shotcrete is at incipient slumping was termed "wettest stable consistency" by Studebaker (1939). Studebaker noted that since the slumping is a result of gravity, the wettest stable consistency, WSC, for overhead shooting will be at a lower water content than the WSC for shooting at a wall. For clarity, only one is shown in the figure. The wettest stable consistency is the highest water content that good quality shotcrete can be expected. According to the shotcrete compaction concept, unit weight, and strength are lower for shotcrete placed at WSC than for shotcrete placed to the glossy criterion.

Shotcrete placed wetter than WSC may still be able to adhere to the wall but it will slump and will not be able to retain its shape. At some water content the shotcrete drops or sloughs off the wall as a result of its own weight. The compaction curve in Fig. 9.40 is stopped at this point.

The optimum point on the compaction curve is at or only slightly drier than Point G. Shooting drier than optimum results in lower density, lower strength, greater rebound, and a greater chance for laminations. There is some threshold value of water content that must be achieved to guarantee the elimination of dry laminations as shown in the figure. Laminations cause a drastic reduction in strength which is not necessarily proportional to unit weight or water content.

9.8.11 PREVIOUS OBSERVATIONS SIMILAR TO COMPACTION CONCEPT

It is common knowledge in the shotcrete industry that it is desirable to shoot at a water content that produces a sheen or a glossy appearance of the shotcrete on the wall; the glossy criterion is used often as an index to the proper water content. Several engineers have attempted to relate strength to water content or water-cement ratio. Stewart (1931), conducted a series of experiments that resulted in the curve shown in Fig. 9.41 relating compressive strength, rebound, and water-cement ratio for a gunite-type mix (maximum size: 0.25 in. (6.25 mm)). The measured water-cement ratio accounted for both the weight of water in the sand and the water added at the nozzle. In a later article (Stewart, 1933), he indicated that during subsequent tests, the rebound of water and atomization losses of water had been measured to be 1 to 2 gallons per sack or an equivalent range in water-cement ratio of about 0.09 to 0.18. The water-cement ratios shown in the figure are therefore high. Stewart (1931) attributed the loss of strength on the dry side of optimum to the fact that "so little water is used that apparently the cement is not properly hydrated". In his second article (Stewart, 1933), a plot of strength versus water content, based on more limited data on another project to to an age of only 3 days, does not have a maximum or node, but he confirms that the relationship in Fig. 9.41 was still satisfactory if water-cement ratio is adjusted for atomization losses. It should be noted that no accelerator was used that would affect strength and that curing conditions for the samples tested by Stewart were probably very similar.

Zynda (1966) discussed the relationship between water-cement ratio and strength of sand-mix shotcrete. His conceptual discussion is similar to the shotcrete compaction concept described in Section 9.8.8 except that his analogy was based on a standard gravity bulking curve for concrete aggregates modified intuitively by the compacting force of the airstream. Zynda's discussion agrees very well with the shotcrete compaction concept described in this chapter which was developed independently from the observations made during this study. The following quote, (Zynda, 1966) illustrates the similarity of the concepts.

> ...."For each mix shown, strengths would increase with decreasing water content, until the W/C ratio corresponding to optimum total water content (as given in Table 12.3) was reached. Beyond that point, further decreases in water content would bring decreases in strength, creating in essence a separate W/C versus strength curve for each mix. There would be two W/C ratios at which there are equal compressive strengths, one on either side of the node. The density would be the same for both points. In one case the voids would contain water, and in the other they would contain air."

Blanck (1975) ran a series of tests in which water content was varied intentionally to determine its effect on strength. The study was done in connection with an underground project using coarse aggregate shotcrete, the results of which are unpublished. He found that shotcrete placed at the glossy criterion achieved the highest strength. Shooting at water contents progressively wetter than the glossy criterion resulted in progressively lower strength. Shooting progressively drier than the glossy criterion also resulted in progressively lower strength, but the rate of reduction in strength on the dry side was much faster than the rate of reduction in strength on the wet side.

9.9 EVALUATION OF TEST RESULTS BY COMPACTION CONCEPT

INTRODUCTION

According to the shotcrete compaction concept, the overall effect of all the mix and shooting conditions govern the water content so that the water content and water-cement ratio are dependent variables. They certainly are not completely independent as is the case for concrete. Yet, there is no such thing as "the water-cement ratio" for dry-mix shotcrete because it constantly varies. The natural variability of shotcrete, especially the pulsating nature of the mix through the nozzle, causes noticeable variations in the water-cement ratio. However, provided the gun and nozzle are operating properly, the compaction curve and, thus, the water-cement ratio could be represented by some average if the nozzleman shoots to a consistent criterion.

The nozzleman, an exceptionally well-qualified nozzleman, was directed to shoot "good shotcrete" and therefore was permitted to vary the water as he desired. He and the field shotcrete expert on the job, also an accomplished nozzleman, carefully watched the shooting and reported all obvious cases of dry and wet shooting. It is important to note that the nozzleman tended to shoot "dry" or to the left of Point G on the compaction curve. Hence, in terms of the conceptual shotcrete compaction curve, the shotcrete was probably never saturated and therefore never would have plotted on the theoretical zero air voids curve, though they could plot along a parallel curve of some percentage saturation.

Accordingly, the strength results from this project need not necessarily be a direct function of either water content or water-cement ratio. The results of an extensive measurement program of the water used during shooting, as well as direct measurements of the water-cement ratio from fresh samples of the in situ shotcrete, are described in Chapter 6. Water contents used in this section are those obtained from the fresh samples on the wall rather than those computed from the water in the aggregate plus the water metered through the nozzle.

UNIT WEIGHT OF HARDENED SHOTCRETE

The unit weight used in the compaction analogy is the dry unit weight of the fresh shotcrete before hardening takes place. Measurement of this parameter must be done immediately after shooting by determining the weight, volume, and water content of a sample removed from the wall before any loss of free water through evaporation or hardening takes place. Field measurements of this unit weight have never been reported, none were made for this study. The direct measurement of the free water in fresh samples was done for this study, however.

The unit weight of air-dry shotcrete specimens was determined at one-month. This unit weight is related to the dry unit weight of fresh shotcrete but to an unknown degree. Values of dry unit weight of the fresh shotcréte were estimated roughly on the basis of the one-month unit weights and the water content of the fresh shotcrete. On this basis it was estimated the dry unit weight of the fresh shotcrete could be approximately 10 to 15 pcf (160 to 240 kg/m^3) lower than the air-dry unit weights at one month. These rough calculations also indicate that the relative magnitudes of unit weights between mixes do not change appreciably. However, the necessary data on degree of hydration and absorption at one month are insufficient to make a refined estimate of the unit weight of the fresh shotcrete. Accordingly, the measured unit weights of hardened air-dry shotcrete at one month will be evaluated instead and the curves in this discussion that relate unit weight with water content or water-cement ratio are not compaction curves.

Figure 9.42 is a plot of the unit weight of hardened shotcrete at one month versus water content. It can be seen that there is a general tendency for a reduction of unit weight with an increase in water content. Two mixes have relatively low unit weights because the samples were of poor quality. It can be shown that the presence of fibers in a sample in the amounts measured increase the unit weight by 2 to 4 pcf (32 to 64 kg/m^3). Thus, those fiber mixes if normalized to a unit weight of non-fibrous shotcrete would plot closer to the approximate line shown. Figure 9.43 is a plot of the same unit weights versus measured water-cement ratio. The mixes shift their relative positions but the same tendency of a reduction of unit weight with increased water content is shown.

However, high unit weight need not be associated with high compressive strength as shown in Fig. 9.44. If the group of fibrous mixes are shifted left the 2 to 4 pcf (32 to 64 kg/m^3) needed to make them compatible with the rest of the data, there is a range of about 4000 psi (27.6 MPa) within a span of only 3 pcf (48 kg/m^3). These data represent the average of all tests made for the mix at one month. Considerably more scatter is seen when the compressive strength of each specimen is plotted against its own unit weight. Accordingly, no relationship between the air-dry hardened unit weight and compressive strength can be established for this study. Other factors, such as accelerator dosage, composition of mix in-place, disturbance during shooting, and curing conditions were more important and were not reflected in the measured unit weight.

WATER-CEMENT RATIO VERSUS STRENGTH

Figure 9.45 is a plot of compressive strength versus water-cement

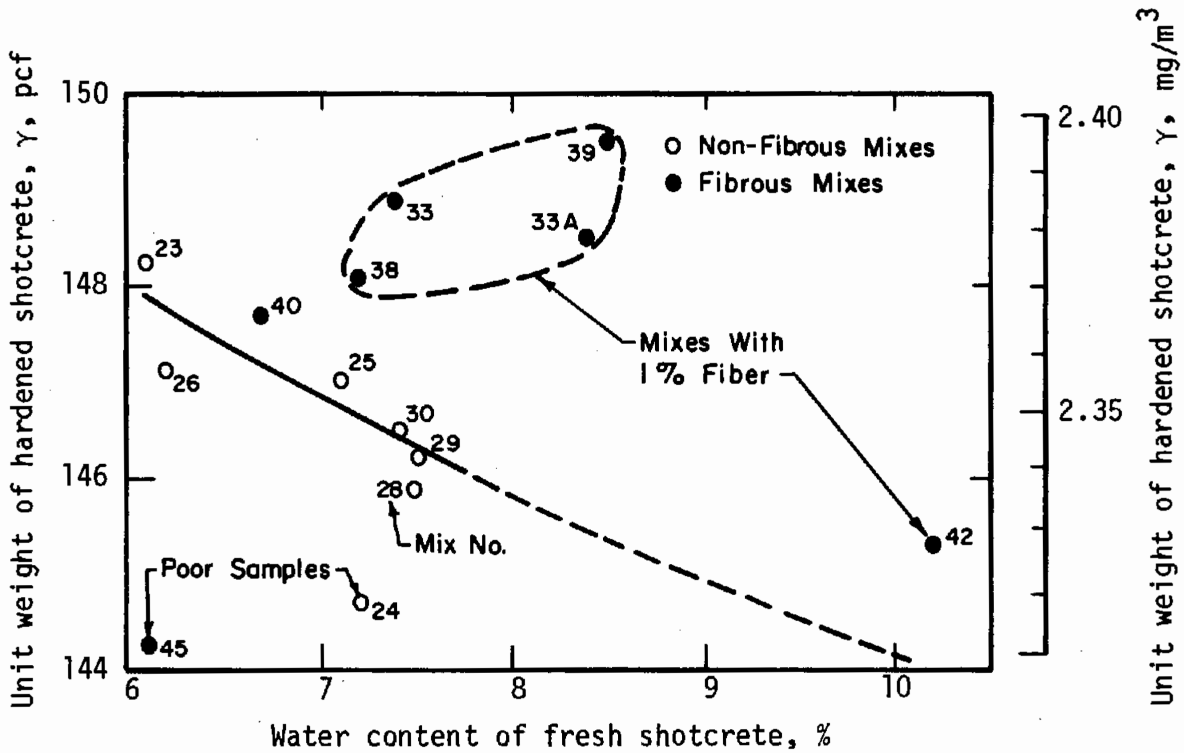


FIG. 9.42 UNIT WEIGHT OF HARDENED SHOTCRETE VERSUS WATER CONTENT OF FRESH SHOTCRETE

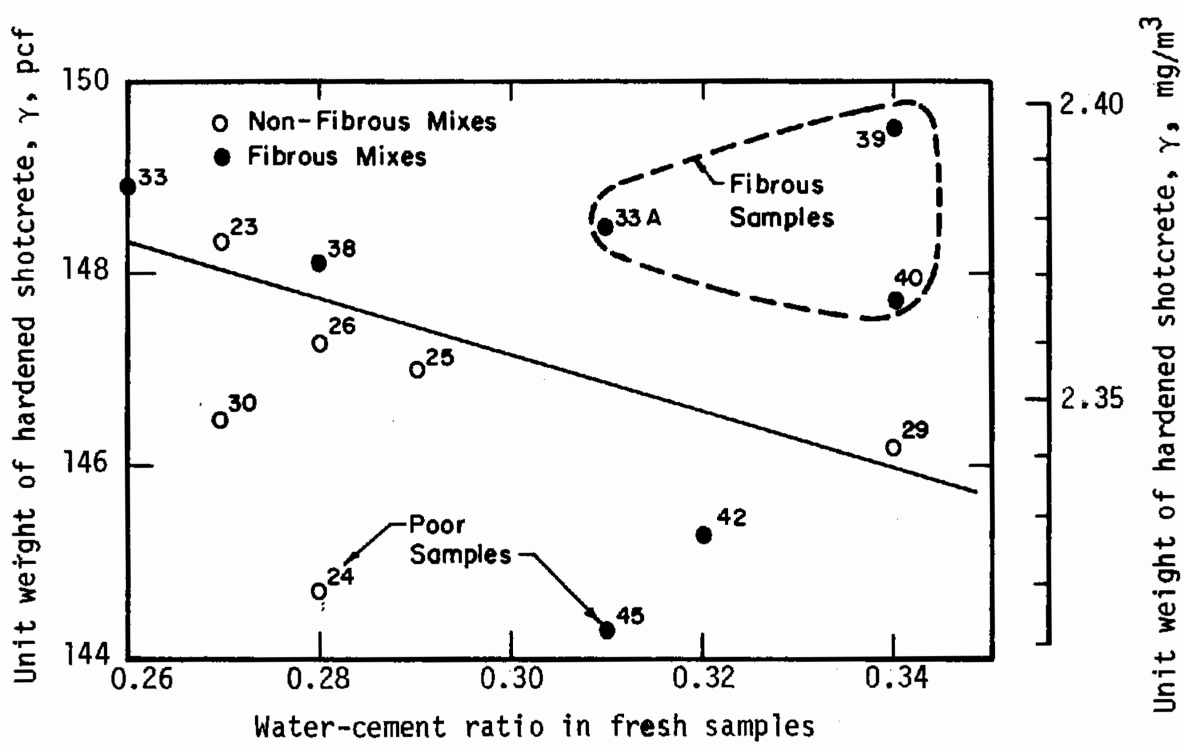


FIG. 9.43 UNIT WEIGHT OF HARDENED SHOTCRETE VERSUS WATER CEMENT RATIO OF FRESH SHOTCRETE

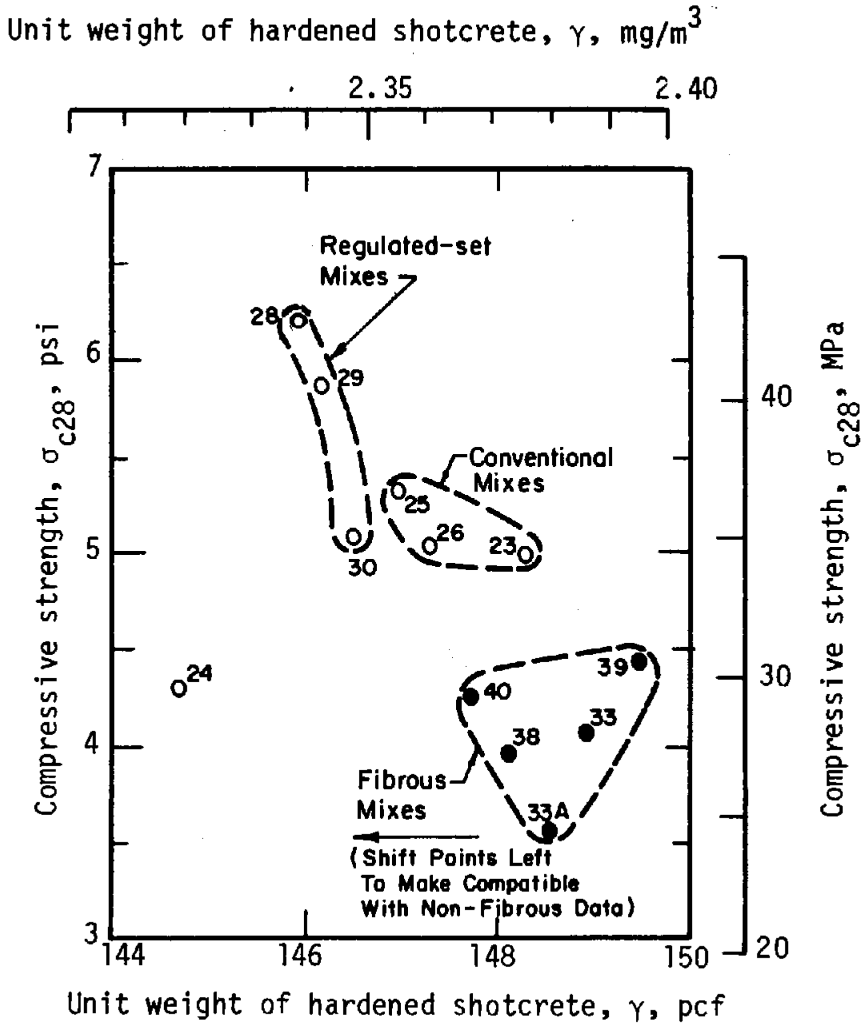


FIG. 9.44 COMPRESSIVE STRENGTH VERSUS HARDENED UNIT WEIGHT

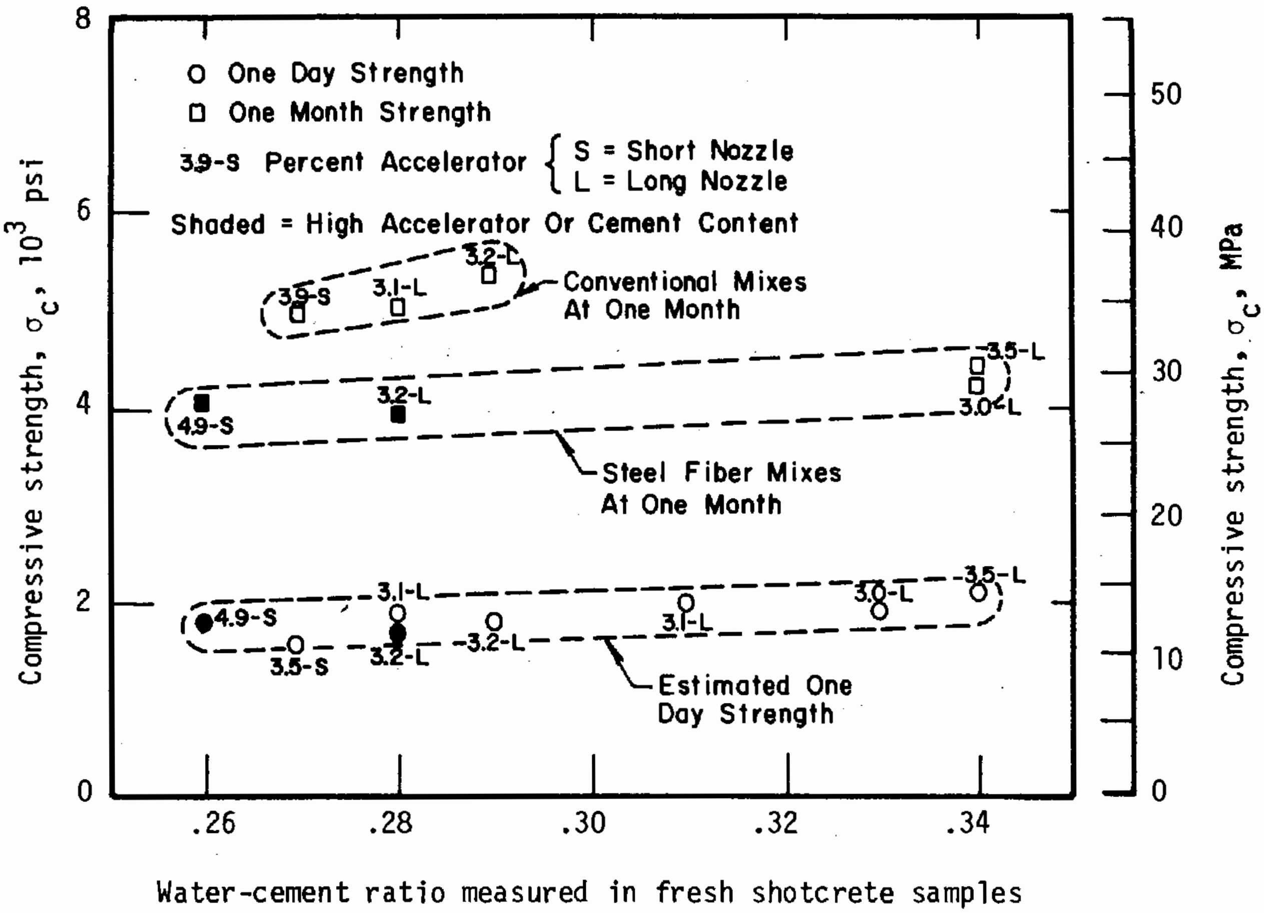


FIG. 9.45 MEASURED RELATIONSHIP BETWEEN WATER-CEMENT RATIO AND COMPRESSIVE STRENGTH

ratio for the tests conducted for this program. It is important to note that the samples for water content were taken from many panels, including the panel cut up for early tests, but not from the same panels cut up for one month compression tests. The water-cement ratio varies from panel to panel, within a panel and even through the thickness of the specimen. Furthermore, curing conditions of each panel are important. Hence, the plot may be expected to have a lot of scatter. The percentage of accelerator and the type of nozzle are noted in the figure. All mixes had about the same cement content and about the same accelerator content except the two mixes denoted by shaded points, one of which had high accelerator content and the other had a high cement content. Earlier, it was pointed out that steel fiber mixes behaved in a similar manner to non-fibrous mixes through the age of one day. This is again shown by the fact that the strength at one day for all mixes plot in the same group.

The steel fiber mixes must be treated as a separate group at ages greater than one day as shown by the lines encircling the groups. The one-month relationships are based upon fewer data points than available for one day and the data points themselves represent somewhat different conditions of activity. For practical purposes, especially when the standard deviation of the scatter associated with each of the average points shown is considered, the trend shown by the groups in Fig. 9.45 is essentially horizontal.

In conclusion, for the results obtained in this program, strength appears to be insensitive to the measured water-cement ratio; other variables discussed in the development of the compaction concept have a strong influence on the strength of shotcrete not reflected in the water-cement ratio. These variables include: average accelerator content, average cement content, gradation, temperature of nozzle-water, type of nozzle, curing conditions and the technique of the nozzleman to shoot "dry", to name a few. The entire history of a mix from the time it is mixed through the time it is tested must be taken into consideration when evaluating strengths of dry-mix shotcrete whether it is for research or whether a contractor or engineer is trying to determine the cause of some low strength shotcrete.

CHAPTER 10

FLEXURAL STRENGTH

10.1 INTRODUCTION

Flexural strength tests were conducted on specimens from most mixes shot during Days III and IV at ages ranging from 4 hours to 6 months. Because of the cold environment, the strength did not develop sufficiently for tests conducted at ages less than 4 hours to be meaningful. The flexural strength program complemented but was not as extensive as that for compressive strength.

10.2 DETAILS OF TESTING

The applicable portions of ASTM C78-64, Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), were followed as closely as possible.

10.2.1 PREPARATION OF SPECIMENS

The specimens usually were 3 x 3 in. (7.6 x 7.6 cm) in cross section ranging from 15 to 17 in. (38 to 43 cm) long. They were sawed from test panels in the manner described in Section 3.2 and illustrated in Fig. 8.3. In all cases, the orientation of the specimen was preserved so that bending was either in or out of the plane of the panel. Through an age of 7 days, most specimens were tested without trimming off the rough outer surface and without soaking in lime water. The outer surface of all specimens older than 7 days was trimmed and the specimens were soaked in lime water for 24 to 48 hours. Capping compounds or special cushions were used to provide full uniform contact between the loading points and rough surfaces. Because the specimens had variable thicknesses, the depth-to-span ratio ranged from about 3 (as specified by ASTM) to about 5. The dimensions of the specimen and its weight were recorded before testing.

10.2.2 TEST PROCEDURE

All specimens were tested for flexural strength using third-point-loading as illustrated schematically in Fig. 10.1. To simulate field conditions, either the front or the back of the beam was on the tension side.

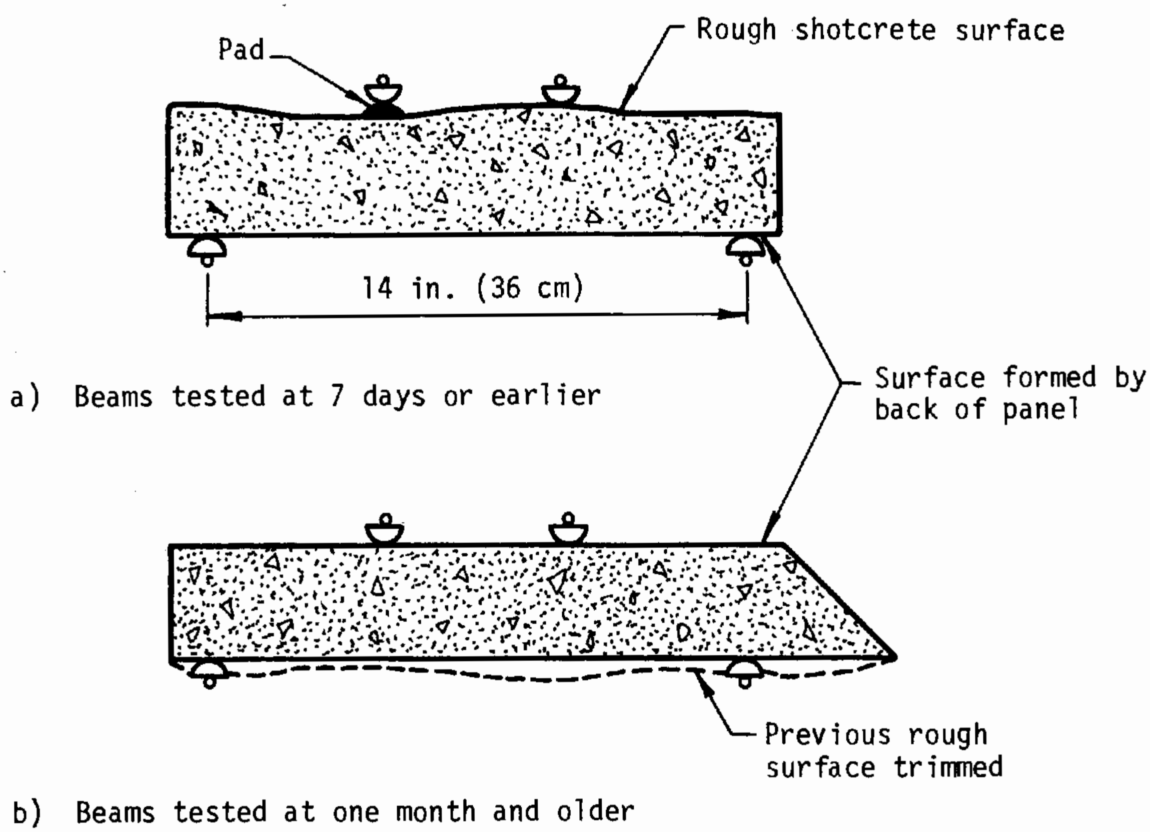


FIG. 10.1 FLEXURAL TESTING ORIENTATIONS

The back surface of the specimen that was in contact with the wood form was on the tension side for all tests through 7 days. At one month, several beams were tested to determine if any differences in flexural strength could be noted between beams tested with the back in tension and those tested with the trimmed front in tension. No significant difference in flexural strength due to orientation was noted. Accordingly, the rough outer surface was trimmed for all subsequent tests and the trimmed surface was on the tension side because it was the smoothest.

The portable hydraulic testing machine used for compression tests (see Section 9.2) was fitted with a third-point beam-test device for flexure tests. Two x-y recorders were used to plot load-versus-head movement of the testing machine and load-versus-strain in the extreme tension fiber. Strain was measured with one of the reusable clip-on electronic strain gages described in Section 9.2.

After failure, the maximum load given by the Bourdon gage of the testing machine was recorded for comparison with that given by the automatic plot. A sketch of the beam was made showing the position of the failure and beam dimensions. The dimensions of the beam cross section at the failure section were measured to the nearest 0.1 in. (2.5 mm). Unusual characteristics noted during testing or observed on the failure surface were also recorded.

10.2.3 CALCULATION OF STRENGTH PARAMETERS

Because all fractures occurred within the middle third of the span, maximum flexural stress, or the modulus of rupture, was calculated with the formula:

$$\sigma_f = \frac{Pl}{bd^2}$$

where:

σ_f = flexural stress (modulus of rupture)

P = maximum applied load

l = span length

b = average width of specimen at the failure section

d = average depth of specimen at the failure section

The failure strain was read directly from the plot of load-versus-strain at the maximum load.

10.3 RESULTS OF FLEXURAL TESTS

10.3.1 GENERAL TRENDS

The result of each flexural strength test has been plotted in the strength-versus-log time plots in Appendix E, and best-fit curves, shown dashed in the plots, drawn through the data on the basis of judgment. The scatter between tests can be visualized in these plots. In addition, summaries of flexural strength at the ages of one day through 6 months are contained in Appendix D. Discussion of the data will be divided into comparisons of absolute values of flexural strength between various groups of mixes and then the relation between flexural and compressive strength for the various groups.

There were few early tests because of the slow strength gain.

The first attempt was at about one hour, but the first meaningful results were from a regulated-set mix at 4 hours; the earliest test on a non-regulated set mix was at 18 hours on Mix 39, a steel fiber mix. The earliest tests of selected mixes are summarized in Table 10.1.

TABLE 10.1

EARLIEST FLEXURAL STRENGTH RESULTS ON SELECTED MIXES

Mix Designation	Age, hr	σ_f psi (MPa)
23-7 1/2I-60S	24	485 (3.3)
28-7 1/2R-100S	14	520 (3.58)
31-7 1/2R-60S	24	620 (4.27)
34-7 1/2I-60S-1US-25CA	24	500 (3.45)
39-7 1/2I-100L-1US	18	170 (1.17)
42-10 1/2R-100L-1US	4	50 (0.34)

There are significant differences between the three major groups of conventional, regulated-set and steel fiber mixes, as can be seen in Table 10.2, which is a comparison of the flexural strengths for the control mixes at ages of one day through one month. Regulated-set shotcrete exhibited the highest flexural strength at all ages. Conventional shotcrete exhibited a flexural strength as high or higher than steel fiber shotcrete. These are the same trends observed for compressive strength. Flexural strength is related to compressive strength so flexural strength follows the same general trends that are discussed in Sections 9.4 and 9.5 for compressive strength.

TABLE 10.2

COMPARISON OF FLEXURAL STRENGTH OF CONTROL MIXES

Mix number	Description	Average flexural strength, psi (MPa) one day σ_{f1}	7 days σ_{f7}	one month σ_{f28}
I. Regulated-set shotcrete				
28	Reg-set control	650 (4.5)	860 (5.9)	1045 (7.2)
23	Conventional control	485 (3.3)	600 (4.1)	855 (5.9)
II. Steel fiber shotcrete				
39	Steel fiber control	460 (3.2)*	925 (6.4)	925 (6.4)
26	Conventional control	---	810 (5.6)	965 (6.7)

*Interpolated from strength-time curve.

The data are grouped by age and examined in more detail in the next section. From a geotechnical or tunnel-support standpoint, the highest flexural strength attainable as early as possible is necessary; so, the absolute level of flexural strength is examined in Sections 10.3.2 - 10.3.5. The relationship between flexural and compressive strength is also of interest, and is examined in Section 10.3.6.

10.3.2 FLEXURAL STRENGTH AT ONE DAY

The specimens were gaining strength rapidly at an age of one day, so comparisons between mixes are difficult; but, sufficient flexural strength tests were made to warrant an evaluation. One-day flexural strengths contained in Appendix D are summarized in Table 10.3. The flexural strengths

TABLE 10.3

SUMMARY OF FLEXURAL STRENGTH AT ONE DAY

Conventional shotcrete			Regulated-set shotcrete			Steel fiber shotcrete		
Mix number	Strength, σ_{fl} psi	(MPa)	Mix number	Strength, σ_{fl} psi	(MPa)	Mix number	Strength, σ_{fl} psi	(MPa)
23	485	(3.3)	28	650	(4.5)	33	480	(3.3)
			29	290	(2.0)	33A	475	(3.3)
			30	660	(4.5)	34	545	(3.8)
						38	510	(3.5)
						39*	460	(3.2)
						42	310	(2.1)
						45	430	(3.0)
AVERAGES, σ_{fl}								
	485	(3.3)		535 (Excluding Mix 29)	(3.7)		460 (Excluding Mix 42)	(3.2)
				655 (35% greater than control)	(4.5)		485	(3.3)

*Estimated from strength-time curve.

show the same trends observed in the compressive strength results given in Section 9.4. One exception to these trends is Mix 42 that had a low flexural strength compared to its compressive strength. However, an insufficient number of tests were conducted and the difficulty with Mix 42 could easily be a result of panel-to-panel variation or test error. However, this mix hydrated in the hopper and was shot very wet. Moment-thrust results discussed in Chapter 12 were also low and erratic for this mix.

The flexural strength of regulated-set shotcrete was about 35 percent greater than the conventional control. The flexural strength of steel fiber mixes was about the same as the conventional control. With the exception of Mixes 29 and 42, the flexural strength at one day was 45 to 60 percent of the flexural strength eventually obtained at 28 days for all types of mixes.

10.3.3 COMPARISON OF FLEXURAL STRENGTH AT SEVEN DAYS

At an age of 7 days, all mixes had attained a minimum strength of at least 600 psi (4.1 MPa) and at least 70 percent of their eventual 28-day flexural strength (Table 10.4). The flexural strength of regulated-set

TABLE 10.4

SUMMARY OF FLEXURAL STRENGTH AT SEVEN DAYS

Conventional shotcrete		Regulated-set shotcrete		Steel fiber shotcrete	
Mix number	Strength, σ_{f7} psi (MPa)	Mix number	Strength, σ_{f7} psi (MPa)	Mix number	Strength, σ_{f7} psi (MPa)
I. Mixes shot with short nozzle					
23	600 (4.1)[1]	28	860 (5.9)	33	880 (6.1)
24	730 (5.0)	29	955 (6.6)	34[2]	615 (4.2)
		30	955 (6.6)		
Averages	665 (4.6)		925 (6.4)		880 (6.1)[3]
II. Mixes shot with long nozzle					
25	875 (6.0)	none		33A	680 (4.7)
26	810 (5.6)			38	680 (4.7)
				39	925 (6.4)
				40	780 (5.4)
				42	770 (5.3)
				45	830 (5.7)
Averages	840 (5.8)				780 (5.4) 7% less than conventional control

Notes: 1. Magnitude believed low.
2. Mix 34 contained an unusually high accelerator dosage.
3. Average excludes Mix 34.

shotcrete mixes was high in keeping with the trends observed for compressive strength. At 7 days and older, mixes shot with the long nozzle consistently exhibited higher flexural strengths. Because of differences attributable to the type of nozzle, it is necessary to group data at 7 days or older according to the nozzle type, as presented in Table 10.4.

There is some indication that the flexural strength of Mix 23 may be unusually low since the ratio of flexural to compressive strength is only 0.13. Since Mix 23 is the control mix for conventional shotcrete, no quantitative comparison can be made between fibrous and non-fibrous mixes shot with the short nozzle or between non-fibrous mixes shot with different nozzles.

A comparison of steel fiber and conventional mixes can be made with the data for mixes shot with the long nozzle. The average for all steel fiber mixes was 780 psi (5.4 MPa) versus 840 psi (5.8 MPa) for the conventional mixes. Fibrous mixes had lower flexural strengths by about 7 percent; the compressive strength of fiber mixes was less than that of non-fibrous mixes also.

10.3.4 COMPARISON OF FLEXURAL STRENGTH AT ONE MONTH

The flexural strength results at one month are summarized in Table 10.5, grouped by major shotcrete type and by nozzle type. The regulated-set mixes continue to show superior strengths; 17 percent higher than their appropriate control mixes. The one steel fiber mix gunned with a short nozzle that can be compared exhibited a flexural strength that was 13 percent less than the corresponding control.

TABLE 10.5

SUMMARY OF FLEXURAL STRENGTH AT ONE MONTH

Conventional shotcrete		Regulated-set shotcrete		Steel fiber shotcrete	
Mix number	Strength, σ_{f28} psi (MPa)	Mix number	Strength, σ_{f28} psi (MPa)	Mix number	Strength, σ_{f28} psi (MPa)
I. Mixes shot on Day II					
none		21	905 (6.2)	none	
II. Mixes shot on Days III and IV with short nozzle					
23	855 (5.9)	28	1045 (7.2)	33	740 (5.1)
24[3]	755 (5.3)	29	1060 (7.3)	34[1]	600 (4.0)
		30	895 (6.2)		
Average	855 (5.9)		1000 (6.9) 17% higher than conventional control		740 (5.1)[2] 13% less than conventional control
III. Mixes shot on Days III and IV with long nozzle					
25	1005 (6.9)	none		33A	690 (4.8)
26	965 (6.7)			38	815 (5.7)
				39	925 (6.4)
				40	805 (5.6)
				42	680 (4.7)
				45[4]	580 (4.0)
Average	985 (6.8) 15% higher than short nozzle				780 (5.4)[4] 21% less than conventional control

Notes: 1. Mix 34 contained an unusually high accelerator dosage.
2. Average does not include Mix 34.
3. Eliminated from average because of poor shooting conditions.
4. Mix 45 produced poor samples; average does not include Mix 45.

The difference between nozzles is quite evident for non-fibrous shotcrete, but not so evident for fibrous shotcrete. The average flexural strength of the conventional mixes shot with the short nozzle was 855 psi (5.9 MPa) while the comparable strength for the conventional mixes shot with the long nozzle was 985 psi (6.8 MPa), an increase of 15 percent. The data were evaluated statistically to ensure that the average values are sufficiently independent to permit a valid comparison (McLaughlin and Hanna, 1966).

A comparison between fibrous and non-fibrous mixes shot with the long nozzle indicates the steel fiber mixes had 21 percent lower flexural strengths (200 psi; 1.4 MPa). This difference is approximately the same as the difference in compressive strengths.

10.3.5 COMPARISON OF FLEXURAL STRENGTH AT SIX MONTHS

Only fourteen pure flexure tests from all the mixes were made at 6 months to determine the pure moment point on the moment-thrust interaction diagrams. The results are contained in Table D.9, and are evaluated with data from earlier ages in the subsequent discussions.

10.3.6 RELATIONSHIP BETWEEN FLEXURAL AND COMPRESSIVE STRENGTH

For some ground conditions, the ability of shotcrete to resist ground loads may be governed principally by its flexural strength. Prediction of this strength is possible from a general knowledge of the compressive strength provided the relation between compressive and flexural strength is known.

Flexural strength at 7 days and one month are plotted against compressive strength in Fig. 10.2 for all mixes to illustrate the general nature of the relationship between these strengths. It can be seen that there is

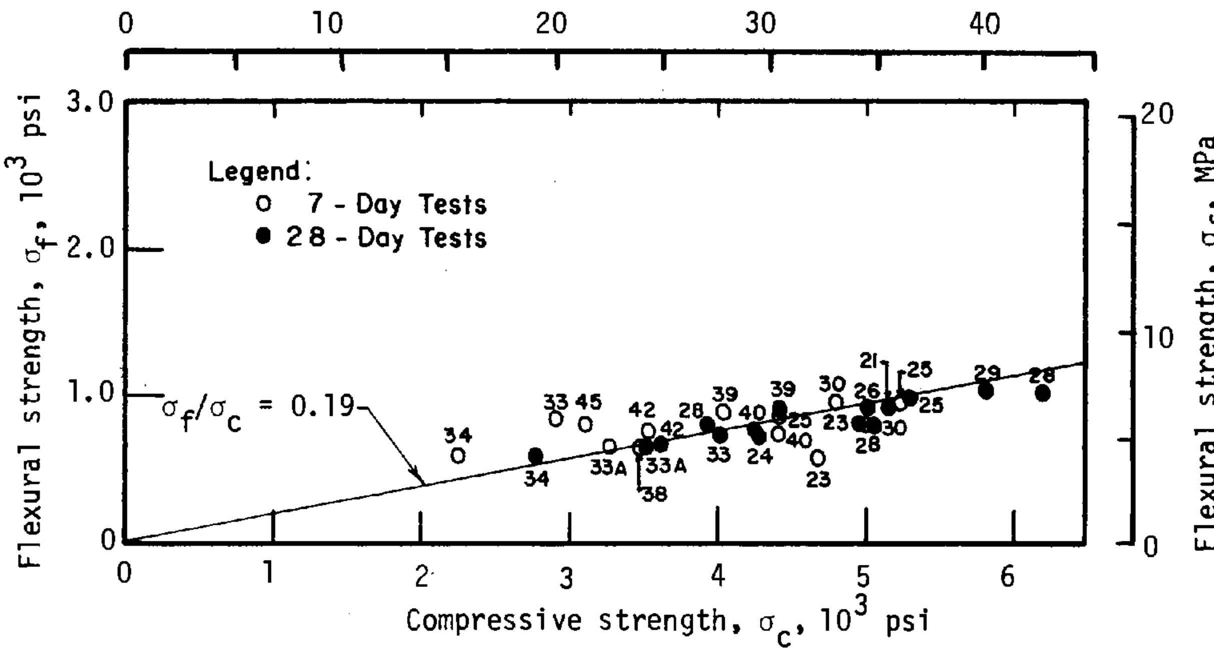


FIG. 10.2 FLEXURAL STRENGTH VERSUS COMPRESSIVE STRENGTH AT SEVEN DAYS AND SIX MONTHS

considerable scatter, but different mix and shooting conditions are represented. The line shown corresponds to a ratio σ_f/σ_c = 0.19; it appears to average the data reasonably well, especially those for compressive strengths between 3000 and 5000 psi (20.7 to 34.5 MPa). For plain concrete, this ratio usually ranges from 0.11 to 0.23 (Troxell, et al., 1968). Mix design, curing conditions and age influence the magnitude of the ratio. Thus, different ratios are expected for the different types of shotcrete under study and accounts for some of the scatter in the figure. The data for one-month tests are plotted to a larger scale in Fig. 10.3; the data for non-fibrous mixes appear to cluster in a group separate from that for fibrous mixes, as shown

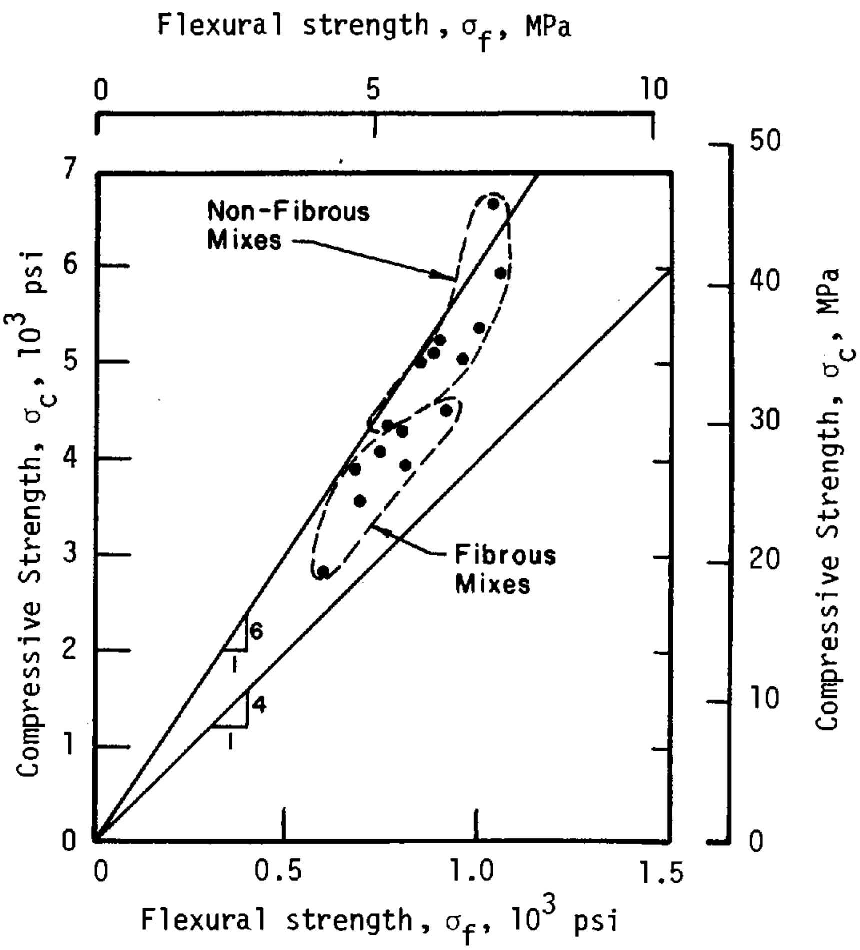


FIG. 10.3 COMPARISON OF COMPRESSIVE AND FLEXURAL STRENGTH AT ONE MONTH

by the dashed lines encircling each group. The line with the 6:1 slope represents σ_f/σ_c = 0.17, while the 4:1 slope represents a ratio of 0.25.

The use of the long nozzle or the addition of steel fiber might be expected to provide a higher flexural strength relative to compressive strength. The long nozzle should improve uniformity and minimize laminations, and thus increase flexural strength more than compressive strength

(Blanck, 1974); fibers in concrete tend to increase flexural strength more than compressive strength (Kesler, 1975). Accordingly, it is important to assess the ratio σ_f/σ_c to determine if there are trends indicating an increase in flexural strength that can be attributed to factors other than compressive strength.

Table 10.6 presents a summary of the ratio σ_f/σ_c for ages of one day, 7 days, one month, and 6 months. Grouping the data according to appropriate categories, as done in the table, permits some conclusions to be made. The averages for each group at each age in the table are plotted against log time in Fig. 10.4. The ratio generally decreases with time. The data ranged from 0.20 to 0.30 at one day to 0.12 to 0.17 at 6 months. One reason why each type of shotcrete plots on separate lines is because the flexural ratio is partly related to the magnitude of compressive strength and each type of shotcrete had a different compressive strength. A plot of the flexural ratio versus compressive strength is given in Fig. 10.5. The line fits the data reasonably well. For each increase of compressive strength of 1000 psi (6.9 MPa), the flexural ratio decreases 0.029; the corresponding decrease in the ratio for an increase in compressive strength of 10 MPa (1449 psi) is 0.042.

At one month, the σ_f/σ_c ratio for most steel fiber mixes ranged from about 0.19 to 0.21, while the non-fibrous mixes generally ranged from 0.17 to 0.19. Ordinary concrete with a compressive strength of about 5000 psi (34.5 MPa) has a ratio ranging between 0.11 and 0.14, so the ratio for these shotcrete mixes appears higher than the usual values for concrete; perhaps, this is because the shotcrete has higher cement contents than those

TABLE 10.6

SUMMARY OF FLEXURE RATIOS (σ_f/σ_c) FOR VARIOUS TIMES

Mix number[1]	One day	Seven days	One month	Six Months
Conventional				
23	0.30	0.13[2]	0.17	0.17
24	--	--	0.18	--
25L	--	0.20	0.19	--
26L	--	--	0.19	--
Average	0.30	0.20	0.18	0.17
Regulated-set				
21	--	--	0.17	--
28	0.16	0.17	0.16	0.12
29	0.25	0.18	0.18	--
30	0.20	0.20	0.18	--
Average	0.20	0.18	0.17	0.12
Steel fiber				
33	0.27	0.30	0.18	--
33AL	0.25	0.21	0.19	--
34	0.39	0.27	0.21	--
38L	0.30	0.19	0.21	--
39L	0.22	0.24	0.21	0.14
40L	--	0.18	0.20	0.15
42L	0.13[2]	0.22	0.17	0.14
45L	0.22	0.27	--	--
Average	0.27	0.23	0.20	0.14

Notes: 1. All mixes shot with long nozzle denoted by "L" after mix number. All other mixes shot with the short nozzle.
2. Believed unreliable.

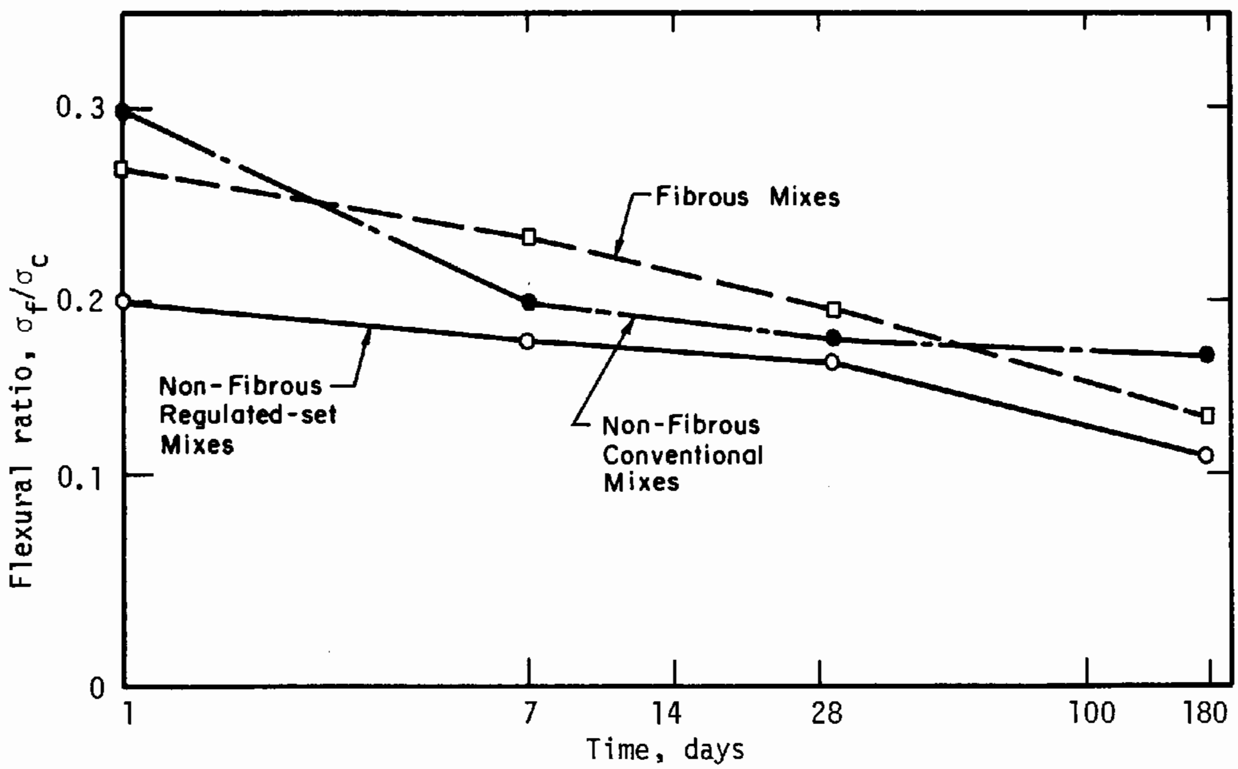


FIG. 10.4 CHANGE OF AVERAGE FLEXURAL RATIO WITH TIME

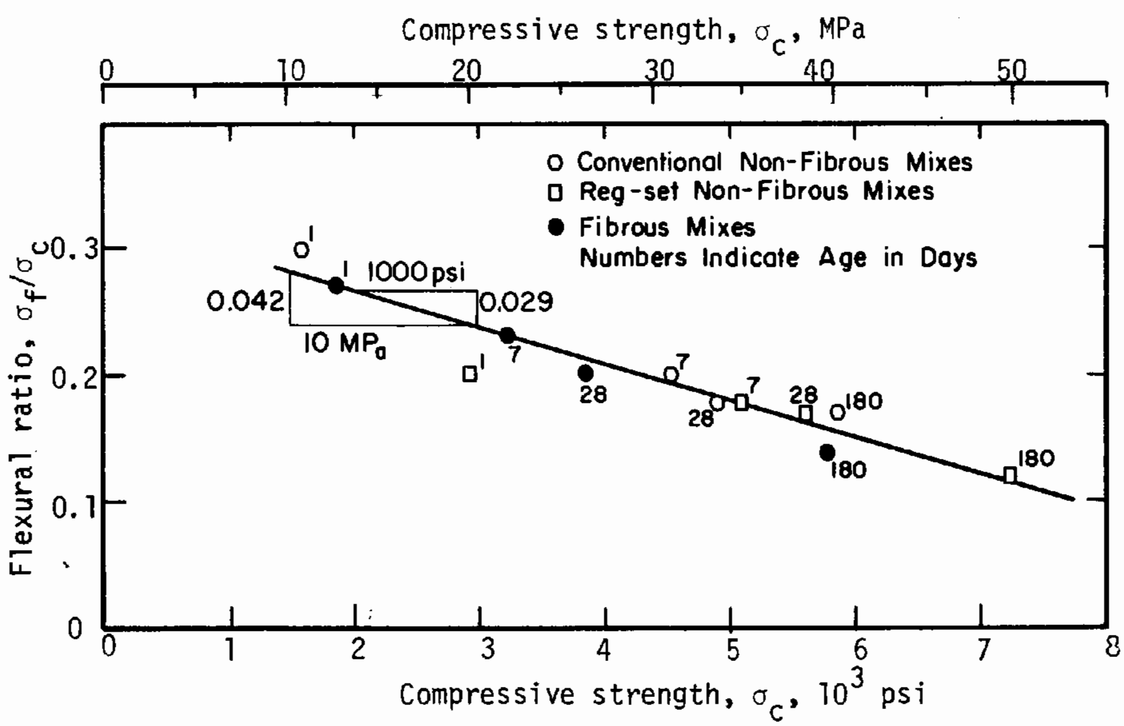


FIG. 10.5 AVERAGE FLEXURAL RATIO VERSUS AVERAGE COMPRESSIVE STRENGTH

used in concrete. The mix with a low gravel content (Mix 34) had the highest ratio at one day, while the mix batched with only one-half percent fiber (Mix 40) had one of the lower ratios. To put these small differences in the ratios into perspective, it should be recognized that, for a compressive strength of 5000 psi (34.5 MPa), a change of 0.02 in the ratio corresponds to a change of 100 psi (0.69 MPa) in the absolute level of flexural strength. This 100 psi (0.69 MPa) change is, however, about 10 percent of the approximately 900 psi (6.2 MPa) flexural strength at a ratio of 0.18. Therefore, a difference of 0.01 or 0.02 in the ratio can be significant.

10.4 EFFECT OF TYPE OF NOZZLE ON FLEXURAL STRENGTH

Mix 25 (σ_f/σ_c = 0.188), shot with the long nozzle, is to be compared to Mix 23 (σ_f/σ_c = 0.172), shot with the short one. Since both mixes were identical except for the type of nozzle, the entire increase in flexural strength can be attributed to the use of the long nozzle. However, it is of interest to evaluate how much of the increase might be independent of the increase in compressive strength. Although the ratio σ_f/σ_c normalizes flexural strength to compressive strength adequately, it is difficult to appreciate the meaning of a small difference in the ratio in terms of the magnitude of flexural strength. Hence, an equivalent magnitude of flexural strength associated with different flexure ratios σ_f/σ_c will be given for an assumed constant compressive strength of 5000 psi (34.5 MPa), i.e., both mixes will be assumed to have a compressive strength of 5000 psi (34.5 MPa).

These normalized equivalent flexural strengths provide meaningful numbers rather than abstract ratios on which to evaluate differences in strength between nozzles and mix designs. If both mixes had the same compressive strength of 5000 psi (34.5 MPa), the equivalent flexural strengths calculated from the ratios would be 940 psi (6.48 MPa) and 860 psi (5.93 MPa) for the long and short nozzles, respectively, a difference of 80 psi (0.55 MPa) on this normalized basis. This 9.3 percent increase for the long nozzle can be attributed to the nozzle design and is independent of compressive strength. Note that the actual difference between the real flexural strengths was 17.5 percent of the actual magnitude of flexural strength for the short nozzle. Accordingly, the component of the increase associated with the increase in compressive strength is about 8.2 percent, and the component of the increase independent of the compressive strength accounts for the remainder of the increase.

Although Mix 33 (short nozzle) had a σ_f/σ_c of 0.18 while Mix 33A (long nozzle) had a σ_f/σ_c of 0.19, the data are insufficient, the differences too small, and conditions, especially accelerator dosage, are sufficiently different to make any comparisons for fibrous mixes inappropriate. It appears that the flexural strength of non-fibrous shotcrete was increased about 17 percent with the long nozzle, partly because of higher compressive strength and partly because of a higher ratio of flexural to compressive strength. The two components were roughly equal, but both were the result of the use of the long nozzle.

10.5 EFFECT OF STEEL FIBER ON FLEXURAL STRENGTH

To evaluate the effect of steel fiber on flexural strength, the non-fibrous Mix 26 (σ_f/σ_c = 0.192) may be compared with fibrous Mix 39 (σ_f/σ_c = 0.207). Normalized to a compressive strength of 5000 psi (34.5 MPa), Mix 26 would have an equivalent flexural strength of 960 psi (6.6 MPa); the comparable value for Mix 39 would be 1035 psi (7.2 MPa). The equivalent apparent increase in flexural strength is 75 psi (0.52 MPa) or 7.8 percent greater than the equivalent flexural strength of the non-fibrous mix. Hence, this increase can be attributed to the steel fiber independent of the compressive strength. In terms of absolute flexural strength, however, the lower compressive strength of the steel fiber mixes offset the effects of the steel fiber to the degree that the actual measured flexural strength of fibrous mixes was lower (965 psi; 6.7 MPa) for the non-fibrous mix versus 925 psi (6.4 MPa) for the fibrous mix. Accordingly, any improvement in flexural strength caused by the presence of fibers can only be inferred. The fact is that for these conditions, both compressive and flexural strength are lower than the comparable strengths for non-fibrous controls.

10.6 EVALUATION OF FIBER CONTENT, DISTRIBUTION AND CONDITION

The effect of the fiber content on the σ_f/σ_c ratio for each mix at one month is compared to the measured in-place fiber content (percent by weight) in Table 10.7. The data in Table 10.7 are arranged in order of increasing fiber content. Figure 10.6 is a plot of the the σ_f/σ_c ratio for the one-month tests of each of the steel fiber mixes with respect to fiber

TABLE 10.7

RELATIONS BETWEEN FIBER CONTENT AND FLEXURAL RATIO AT ONE MONTH

Mix	Fiber content % by weight	σ_f/σ_c
40	1.2	0.189
33A	1.45	0.194
45	2.0	---
34	2.0	0.214
33	2.30	0.183
38	2.35	0.206
39	2.7	0.207
42	2.9	0.174

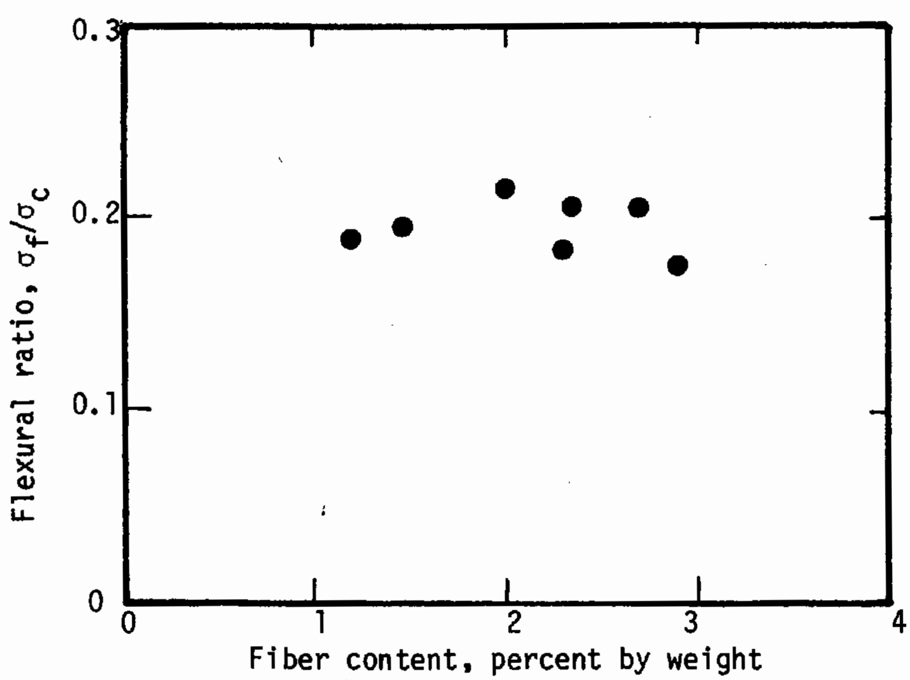


FIG. 10.6 EFFECT OF FIBER CONTENT ON FLEXURAL RATIO

content. It can be seen that there appears to be no definite relationship between fiber content and the flexural ratio. However, it should be recognized that the strength ratio was obtained from different panels than the panel sampled for fiber contents. The normal scatter in the data could preclude any definite relationships, especially since there were wide variations in fiber content from sample to sample.

It appears that there is some minimum fiber content required before an appreciable improvement in flexural strength is realized. Because of the high rate of fiber rebound, the actual fiber content in the specimens was only about 0.5 to 0.7 percent by volume, apparently too low to provide the desired improved flexural strength. Furthermore, the fibers were severely bent (some were "U" shaped) in the mixing process (Figs. 3.5 to 3.11). There is little doubt that these fibers acted as if there were a fewer number of shorter fibers in their effect on flexural strength. Finally, the x-ray photographs of fiber beams that were tested indicated that the distribution of fibers was quite non-uniform and that the flexural crack weaved its way through the zones of the beam that contained the lowest fiber concentration (see Figs. 7.6, 7.7, and 7.9). Hence, the flexural strength of fibrous specimens were minimum strengths that could have been strongly influenced by an erratic fiber distribution.

It is believed that proper mixing and shooting conditions, resulting in a greater amount of straight fibers well-distributed throughout the beam, would provide the improved tensile and flexural strength that was anticipated and that has been reported by other researchers. Because of the low in-place fiber content, the erratic distribution, and the bending of the fibers, the flexural strengths determined in this study were about the same as the non-fibrous controls. The best aspect of the flexure tests of fibrous beams was their large post-crack resistance that is described in the next chapter.

CHAPTER 11

LOAD-DEFORMATION RELATIONSHIPS

11.1 INTRODUCTION

The results and observations of the compression and flexural tests are summarized in this chapter. Load-deformation was measured and characteristics of failure were observed on each compression, flexure, pullout and moment-thrust interaction test. Observations on moment-thrust data and pullout tests are contained in Chapters 12 and 13 respectively. The data permit general observations and conclusions about the variations of modulus of elasticity between mixes and with age, load-deformation (stress-strain) relations, and the modes of failure.

11.2 METHODS OF EVALUATION

11.2.1 COMPRESSION TESTS

The compression specimens were right rectangular prisms with a length-to-width ratio of about 2.3. The prisms were always oriented during testing in the same way as during shooting as described in Chapter 8, so the load was applied parallel to the potential laminations. Since these specimen proportions were not the standard of the concrete industry (6 x 12 in., (15.2 by 30.5 cm) cylinders), strict conformity to the established relations for concrete cannot be expected, but, the general trends should be the same.

As described in Section 9.2, the load-deformation behavior in each test was automatically and continuously recorded by two x-y recorders. A plot of load-versus-head movement was recorded for all tests and, in addition, for most of the tests, strain over a 1-in. (2.5-cm) gage length was measured with a clip-on gage. There are many reasons why the deformation of the head of the testing machine should be much greater than the value obtained by multiplying a measured strain in the specimen times the length. These include seating of the head, adjustments in the capping compound, deformation of the structural frame of the testing device, and the variations in strain throughout the specimen. This load-versus-head movement plot was recorded primarily as a gross back-up in case of failure or inability to obtain the more accurate and useful strain-gage data. There were several occasions when this load-versus-head movement record was the only practical way to obtain load-deformation data.

The reusable clip-on-type strain gage was attached to each of the two sawed sides of the specimen at mid-height. A photograph of this device, was given in Fig. 9.3. The gage length of this device was 1-in. (2.5 cm) and it measured deformation in inches so it recorded strain directly. Placing the clip-on strain gage required less than one minute but its adjustment was time consuming. Its use was abandoned for many of the tests at ages less than one day in order to increase the rate of testing to meet the required test schedule. Since then, new techniques have been devised which, in the future, will permit installation and adjustment of the clip-on strain gage more quickly.

Each stress-strain curve was evaluated individually to ensure that the stress-strain data was compatible with the mode-of-failure. A chord Modulus (E) was computed in accordance with ASTM C-469 and illustrated in Fig. 11.1. Strain at maximum load will be called failure strain.

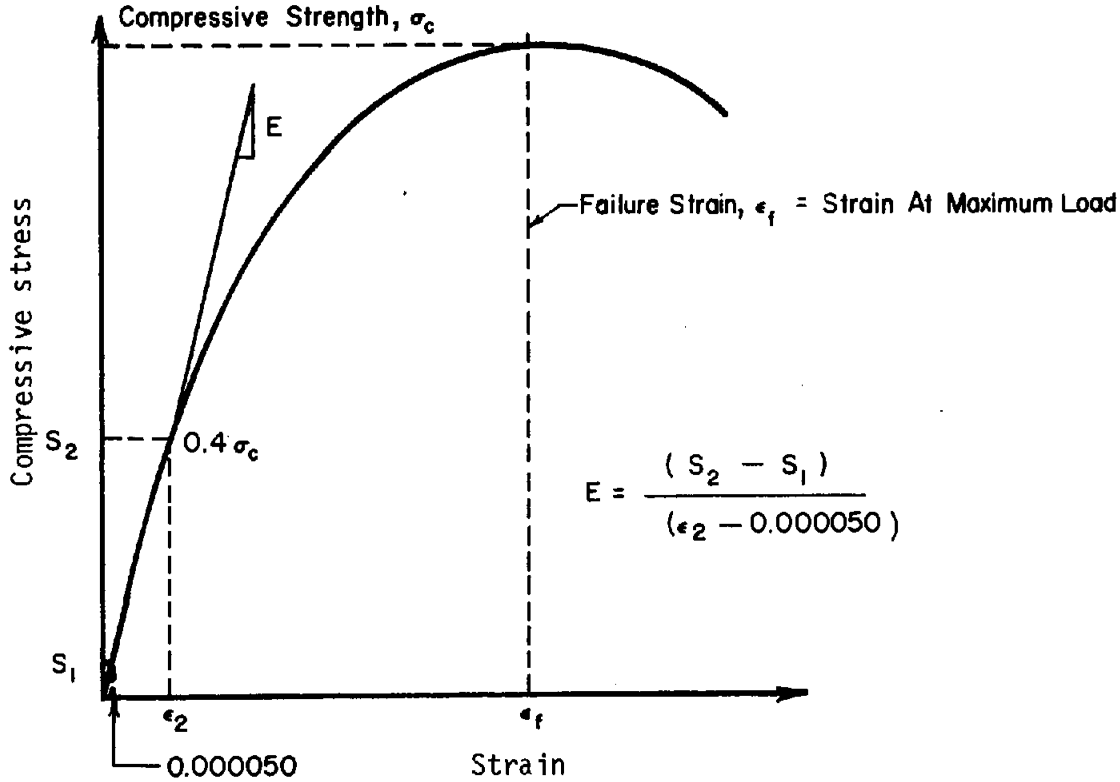


FIG. 11.1 ILLUSTRATION OF METHOD FOR CALCULATION OF MODULUS OF ELASTICITY

The portable testing machine cannot be considered a "stiff" machine so the post-failure portion of the curve cannot be considered accurate for the stronger specimens. However, the general post-crack behavior is clearly demonstrated by the load-strain and/or load-deformation curves.

Immediately after each test the failure surface was inspected and a sketch of the specimen in its failed condition was made. Observations such as irregularities in the failure surface, whether the failure was explosive or not, post-crack behavior, etc., were also recorded.

11.2.2 FLEXURAL TESTS

The load-deformation behavior of flexural tests was also recorded automatically and continuously by both x-y recorders as described for compression. One x-y recorder plotted load-versus-head movement; the other plotted load versus strain. One reusable strain gage was placed on the bottom of the beam at mid-span to measure outer-fiber tensile strain.

Immediately after testing, a sketch was made of the beam showing the nature of the failure surface, distance of the failure surface from the loading points, and dimensions of the cross section of the beam at the point of failure. Observations on the condition of the failure surface (wet or dry, many or few fibers, etc.), the post-crack behavior, etc., were also recorded.

11.3 OBSERVED LOAD-DEFORMATION BEHAVIOR IN COMPRESSION

11.3.1 STRESS-STRAIN CURVES

Plots of typical stress-strain curves of samples from tests at various ages are given in Figs. 11.2 and 11.3. Figure 11.2 presents the results from conventional shotcrete while the curves in Fig. 11.3 represent regulated-set shotcrete. Changes in the stress-strain curve with age are similar to those for concrete. The initial portions of each successively older test curve are steeper indicating a higher modulus with age and higher strength.

A similar plot of typical stress-strain curves of steel fiber, Mix 39, at selected ages is given in Fig. 11.4. Figures 11.2 through 11.4 are drawn to the same scales so that direct visual comparisons can be made. Generally, the slopes of the initial portion of the curves for steel fiber are flatter than those for conventional shotcrete, indicating a lower modulus. The salient feature of the stress-strain curves for steel fiber is the substantial post-crack resistance.

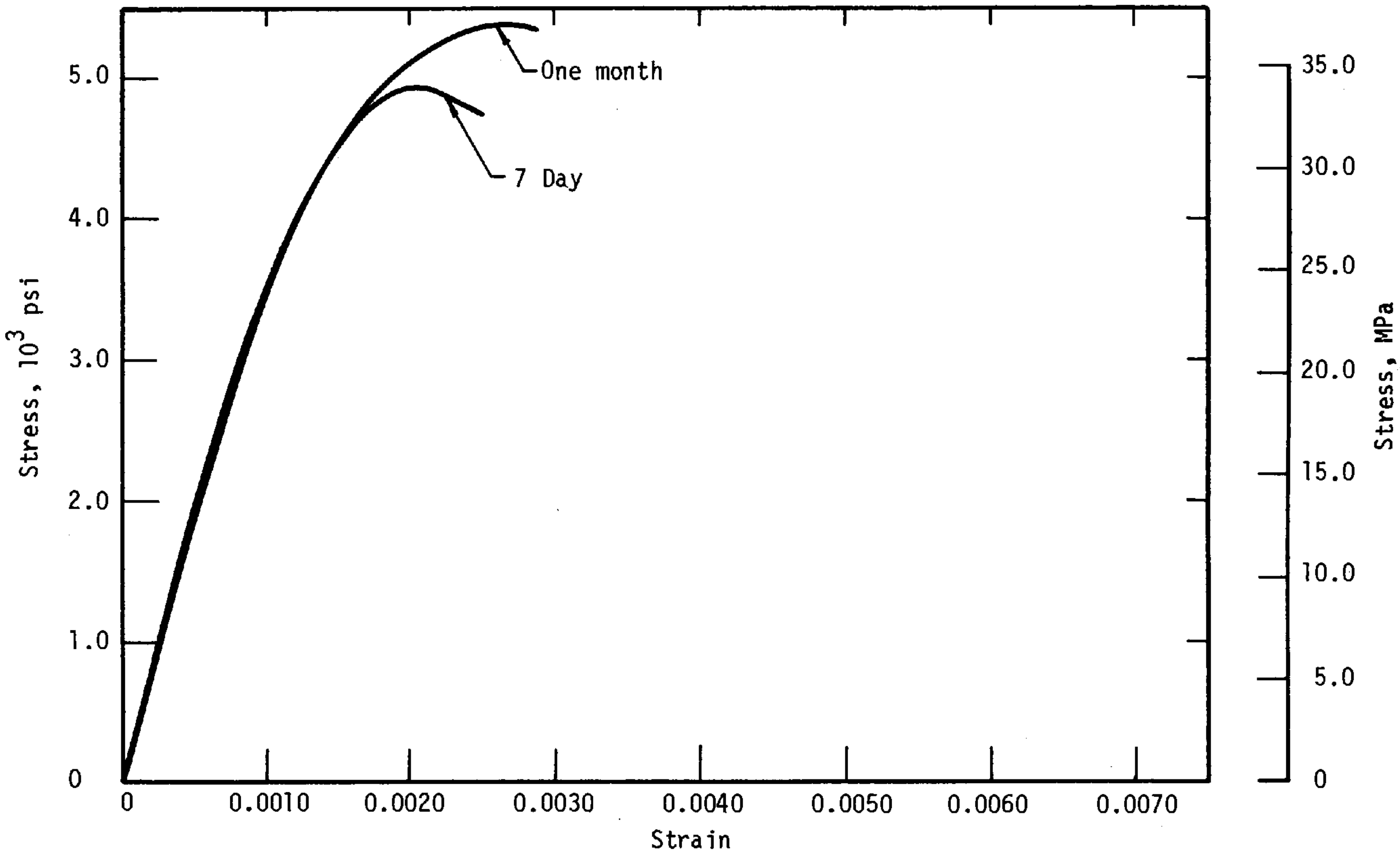


FIG. 11.2 TYPICAL STRESS-STRAIN CURVES: CONVENTIONAL SHOTCRETE COMPRESSION TESTS

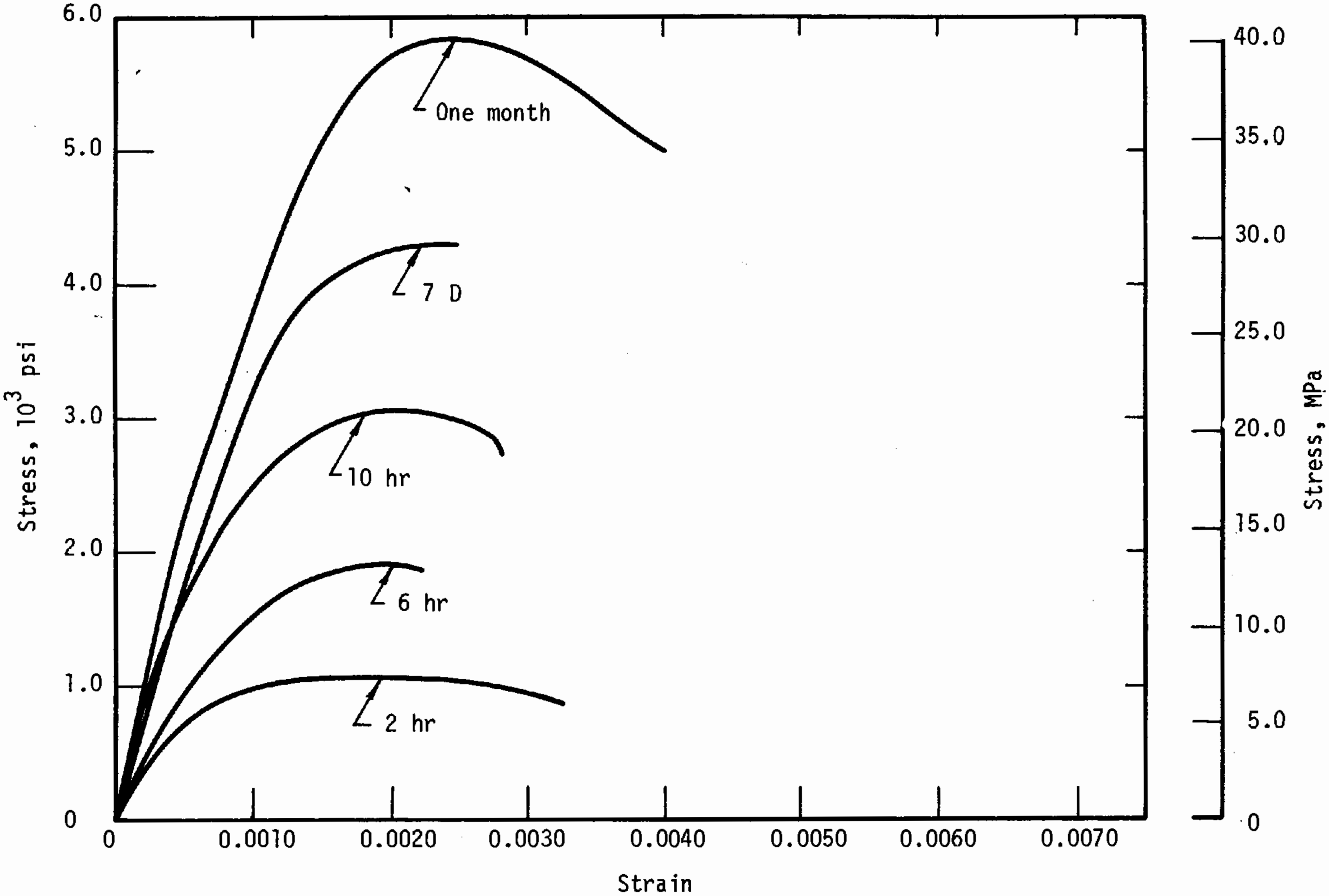


FIG. 11.3 TYPICAL STRESS-STRAIN CURVES: REGULATED-SET COMPRESSION TESTS

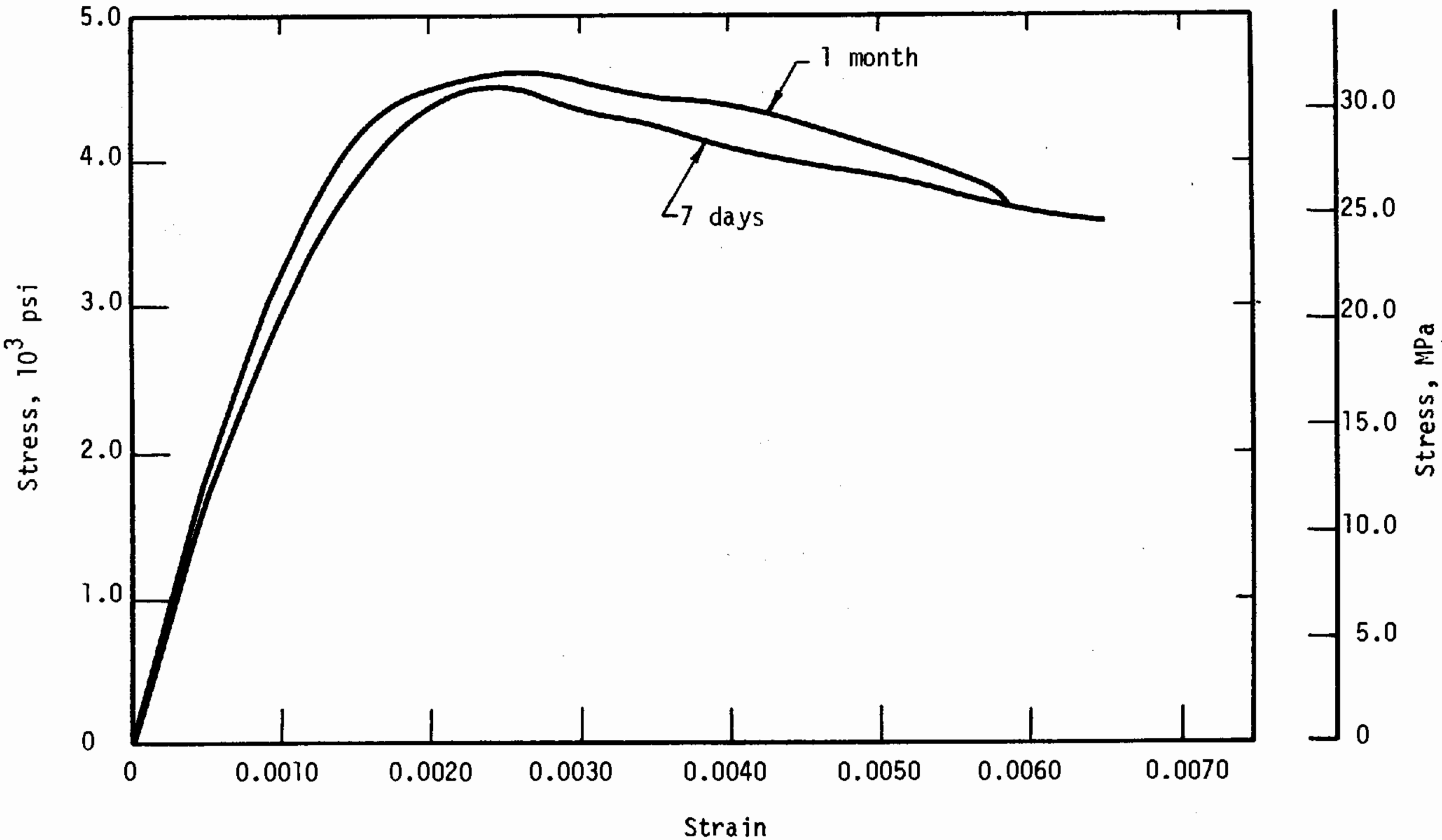


FIG. 11.4 TYPICAL STRESS-STRAIN CURVES; STEEL FIBER COMPRESSION TESTS

A typical stress-strain curve for very-low-strength non-fibrous specimens is given in Fig. 11.5. Only a few of these low-strength curves were measured, none were of steel fiber specimens.

11.3.2 FAILURE STRAIN

Strain to failure for most of the shotcrete compression specimens followed trends similar to those of ordinary concrete which usually fails in compression at a strain of about 0.002. Table 11.1 is a summary of failure strains at selected ages for the three types of shotcrete tested.

TABLE 11.1

SUMMARY OF FAILURE STRAINS

Type of Shotcrete	Normal Range	Average		
		7 days	28 days	42 days
Conventional (Non-Fibrous)	.0018 to .0022	.0018	.0020	.0020
Regulated-set	.0019 to .0023	.0020	.0024	.0021
Steel fiber	.0018 to .0024	.0019	.0020	.0020

Failure strains measured by using the reusable strain gages were very consistent and exhibited very little scatter.

The load-deformation curves of the very-early-strength-tests (compressive strength less than about 1200 psi; 8.3 MPa) were generally poorly defined and flat at the peak so that it was difficult to locate the strain at maximum load with accuracy. In addition, there was considerable scatter in these results. The failure strain of samples with compressive strength having less than 100 psi (0.69 MPa) often was as high as 0.008.

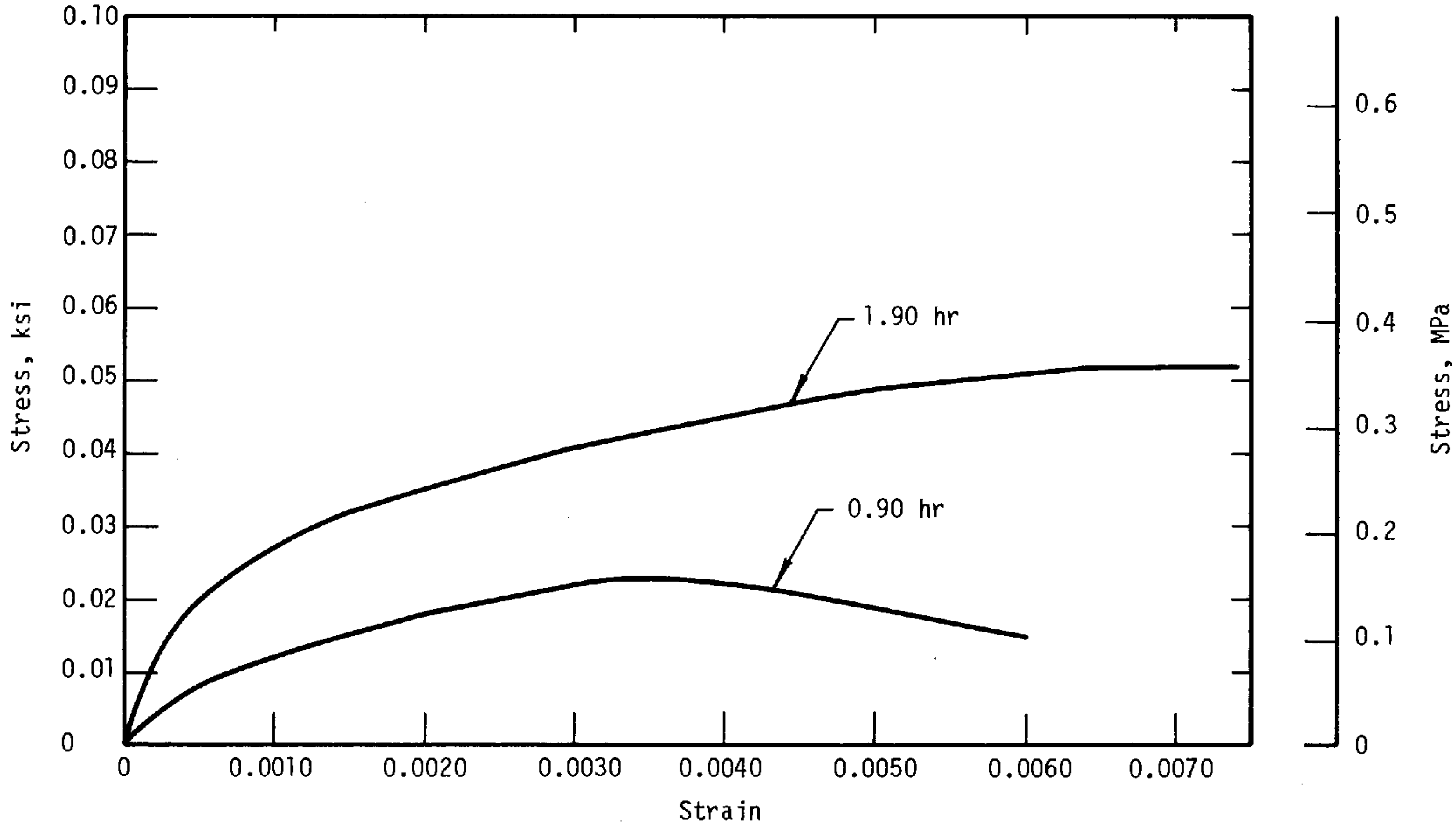


FIG. 11.5 TYPICAL STRESS-STRAIN CURVES FOR VERY-LOW-STRENGTH NON-FIBROUS SHOTCRETE

11.3.3 MODULUS OF ELASTICITY

INTERMEDIATE AND LONG-TERM STRENGTHS

The average moduli are summarized by panel and by mix for ages of 7 days through 6 months in Appendix D; they also follow the typical trends for concrete. The average moduli of the control mixes for each major group are summarized in Table 11.2

TABLE 11.2

COMPARISON OF MODULI FOR CONTROL MIXES

Mix	Description	Average Modulus of Elasticity, ksi, (GPa)			
		7 day	28 day	42 day	6 month
23	Conventional	3950 (27.2)	4120 (28.4)	4430 (30.6)	3890 (26.8)
28	Regulated-set	3520 (24.3)	3800 (26.2)	4220 (29.1)	4460 (30.8)
39	Steel fiber	3450 (23.8)	3590 (24.8)	4330 (29.9)	4050 (27.9)

It can be seen in Appendix D and Table 11.2 that the values of the moduli range from about 3000 to 8000 ksi (20.7 to 34.6 GPa). The modulus for steel fiber mixes is usually less than the modulus for conventional mixes as expected since the compressive strength of steel fiber shotcrete was lower. The modulus of concrete is often related to the square root of the compressive strength by a factor of about 57,000 (ACI, 1971). This relationship is of course for 6 by 12 in. (15.2 by 30.5 cm) cylinders rather than the prisms used on this project. The average calculated ratios of $E/\sqrt{\sigma_c}$ are summarized for the control mixes in Table 11.3. The results are also presented graphically in Fig. 11.6.

TABLE 11.3

RATIO OF MODULUS TO SQUARE ROOT OF COMPRESSIVE STRENGTH: CONTROL MIXES

		$E/\sqrt{\sigma_c}$			
Mix	Description	7 day	28 day	42 day	6 month
23	Conventional	57,000	58,000	59,000	52,000
28	Regulated-set	50,000	48,000	51,000	52,000
39	Steel fiber	54,000	54,000	58,000	53,000

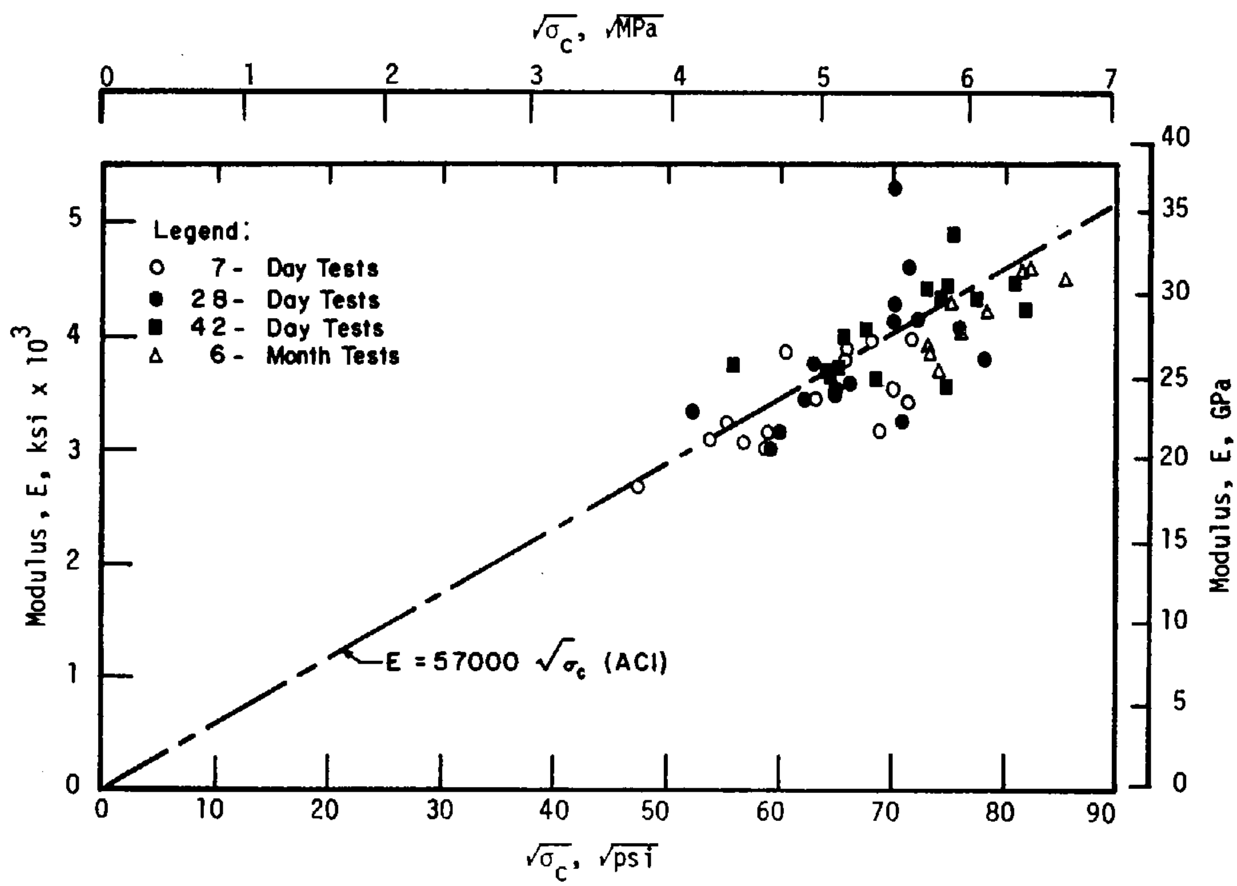


FIG. 11.6 RELATIONSHIP BETWEEN MODULUS OF ELASTICITY AND SQUARE ROOT OF COMPRESSIVE STRENGTH

The data indicate fair agreement with the ACI factor even though the size and shape of the specimen is different from the standard cyclinder. The data indicates that the modulus for steel fiber shotcrete is generally lower than the ACI factor for concrete. The lower factor for regulated-set shotcrete is attributed to a higher than normal compressive strength. At an age of 6-months the factor was only about 52,000 for all control mixes.

YOUNG SHOTCRETE

Modulus-versus-time curves for the three control mixes at strengths below 2000 psi (13.8 MPa) are presented in Fig. 11.7. It can be seen that the modulus for the various mixes increases with age in a manner similar to compressive strength as expected. Figure 11.8 presents the correlation between the modulus and the square root of the compressive strength, $E/\sqrt{\sigma}$ for these same tests.

11.4 MODE OF FAILURE

11.4.1 ORIENTATION OF FAILURE SURFACE

There was a very strong preferred orientation of the failure surface. The right rectangular compression prisms were placed in the testing machine in the same orientation that they were shot. In virtually all cases, the failure surface was a diagonal plane from the back of the sample (the panel side) to the front of the sample (the exposed surface), as illustrated in the sketch in Fig. 11.9. The failure plane often appeared to be a coalescense of many failure planes following and then crossing potential laminations. On particularly strong samples (6,000 psi; 41.4 MPa or more), the failure surface occasionally also crossed from one side to the other in addition to the primary back-to-front surface.

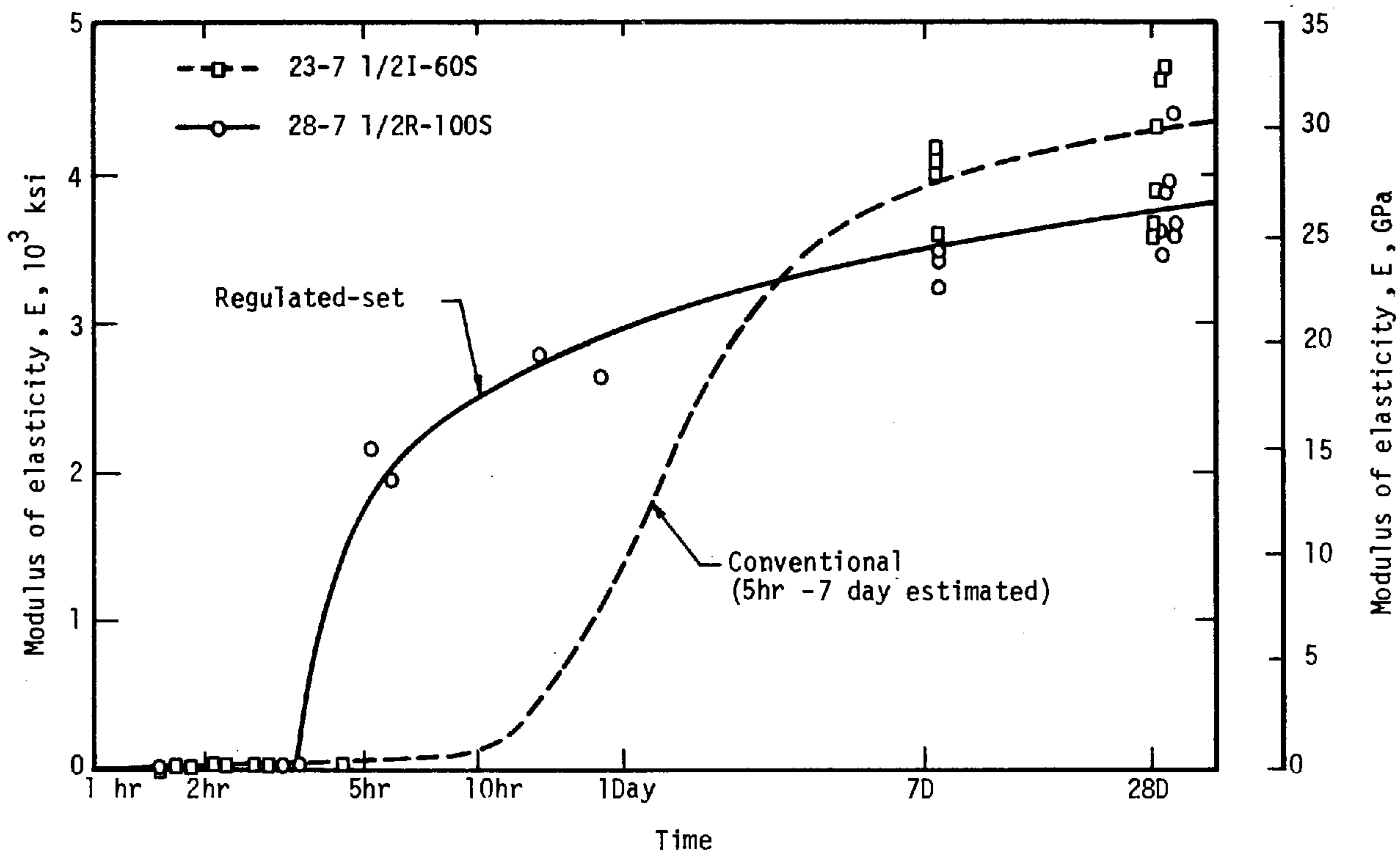


FIG. 11.7 MODULUS OF ELASTICITY VERSUS LOGARITHM OF TIME FOR NON-FIBROUS CONTROL MIXES

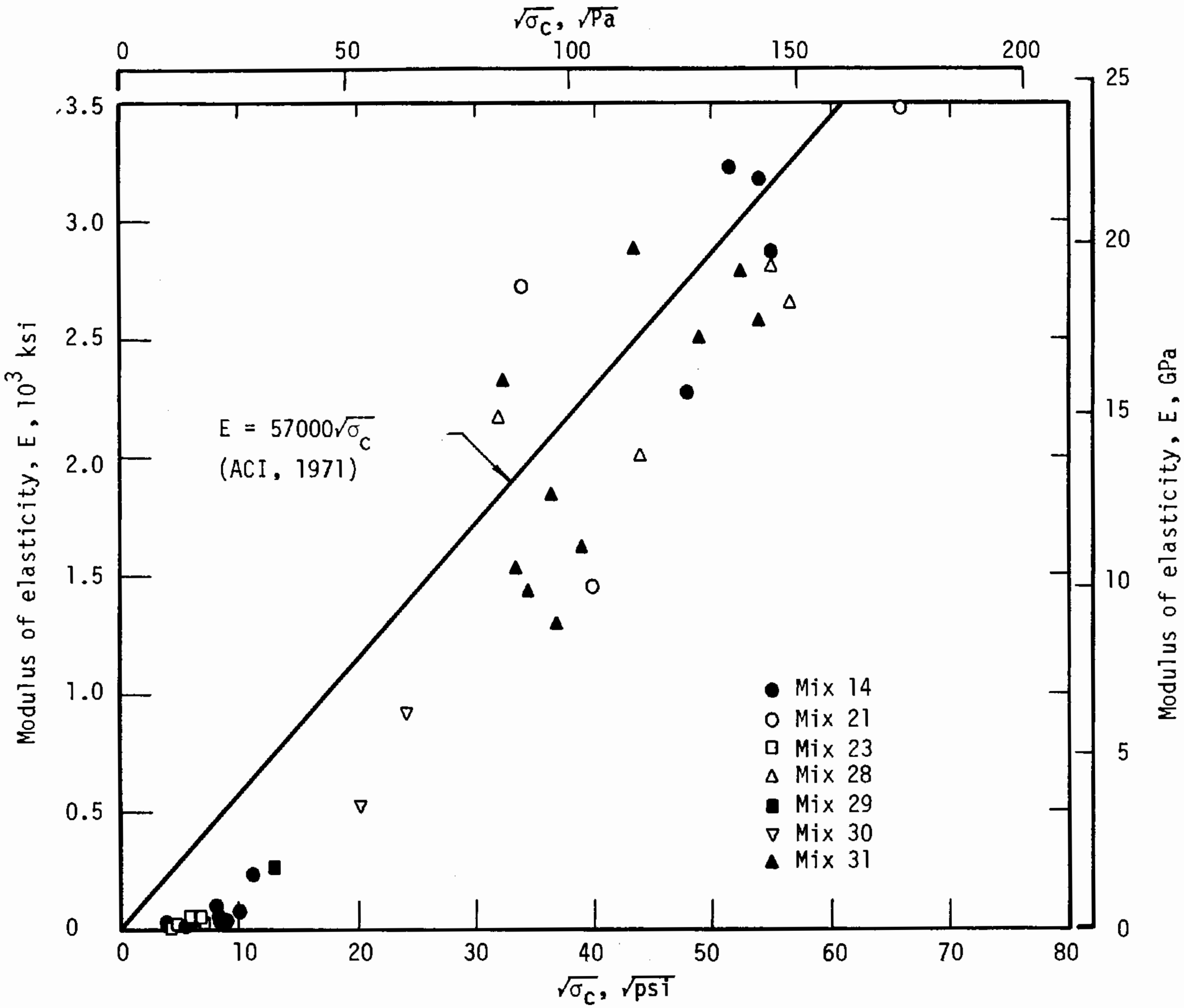


FIG. 11.8 CORRELATION BETWEEN MODULUS AND SQUARE ROOT OF COMPRESSIVE STRENGTH FOR YOUNG SHOTCRETE

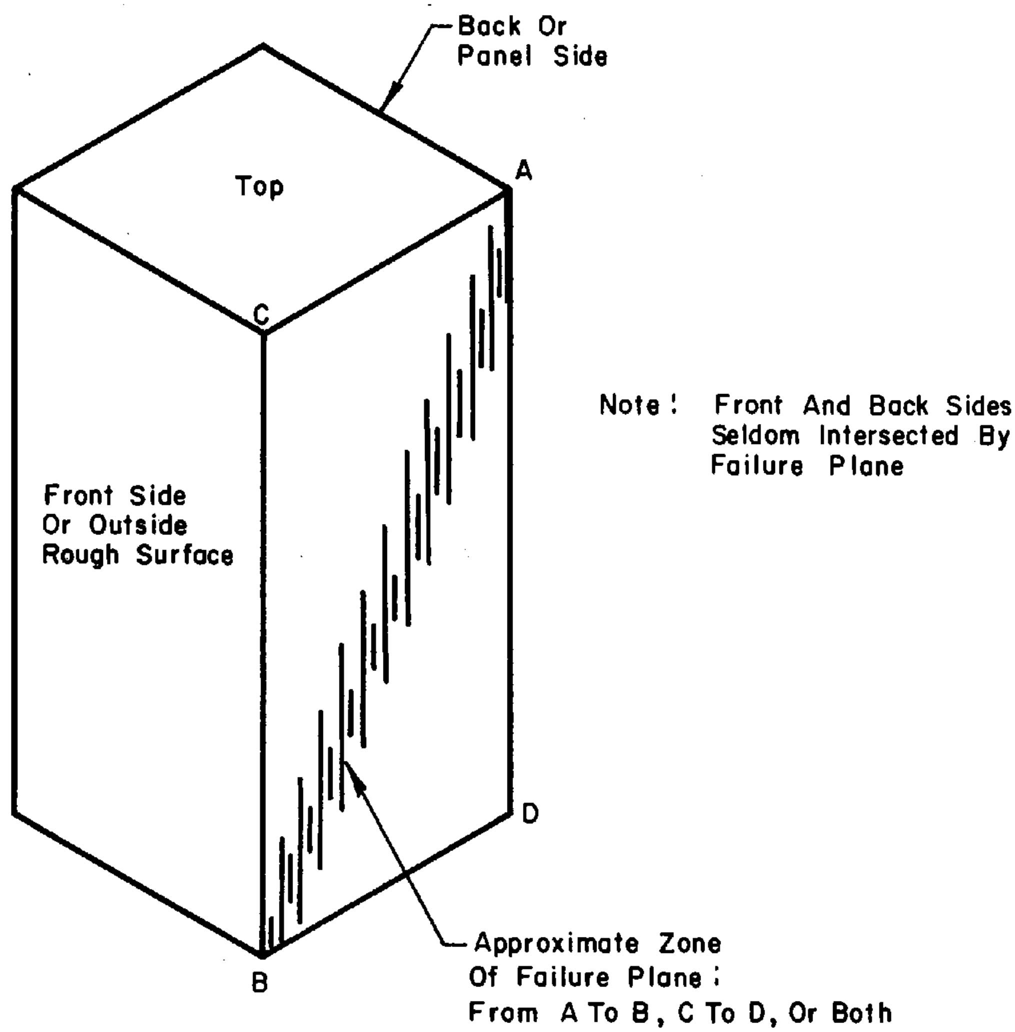


FIG. 11.9 ILLUSTRATION OF TYPICAL FAILURE PLANE
FOR COMPRESSION SPECIMEN

To ensure that testing methods and procedures were not causing this preferred orientation, samples were put into the machine upside down, and rotated 90 and 180° around its longitudinal axis. The same orientation persisted. The ability to observe the direction of the failure plane easily because of the rectangular shape of the sample was another advantage of using this type of sample on this project. This phenomenon cannot be observed with cored samples unless the cores are taken parallel to the wall and unless they are oriented prior to coring. Naturally, cubes and cores taken perpendicular to the surface cannot show this preferred orientation.

11.4.2 BEHAVIOR AT AND BEYOND MAXIMUM LOAD

The load-deflection curves and the post-failure behavior of most young shotcrete specimens were similar. The load-deflection curves of shotcrete having a compressive strength less than about 100 psi (0.7 MPa) were generally curved with a distinct flat-top at the peak (Fig. 11.5). This was true for both fibrous and non-fibrous shotcrete although fibrous shotcrete specimens could hold together for substantially larger strains.

Older specimens with compressive strength greater than about 1000 psi (6.9 MPa) began to show significant differences between fibrous and non-fibrous specimens in the mode of failure. Non-fibrous specimens usually failed suddenly; the very strong specimens failed violently. As soon as the maximum load was achieved, or shortly thereafter, the specimen was no longer capable of carrying load. The violent failures resulted from the release of energy stored in the machine and the sudden total inability of the specimen to resist that much load. The failure surface was generally an irregular diagonal plane or planes running from the back to the front of the specimen. Usually pieces spalled off and portions of the specimen crumbled.

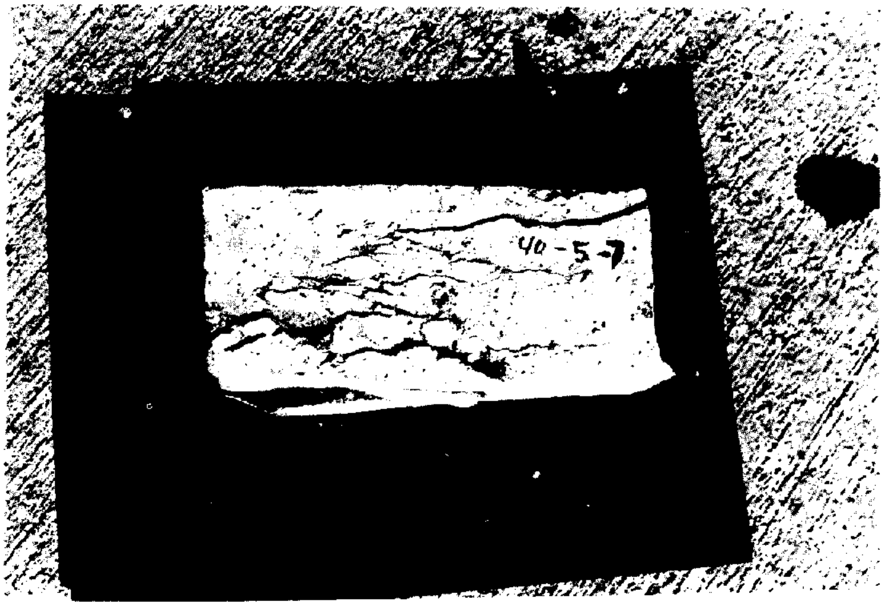
The mode of failure of older fibrous specimens was substantially different in two ways. First, steel fiber specimens never failed suddenly on reaching maximum load. Second, the steel fiber specimens always held together even though the sample was deformed to over 10 percent strain and had broken up into many pieces. Photographs of typical failed specimens of fibrous and non-fibrous shotcrete are presented for comparison of failure surfaces in Fig. 11.10.

11.5 OBSERVED LOAD-DEFLECTION BEHAVIOR IN FLEXURE

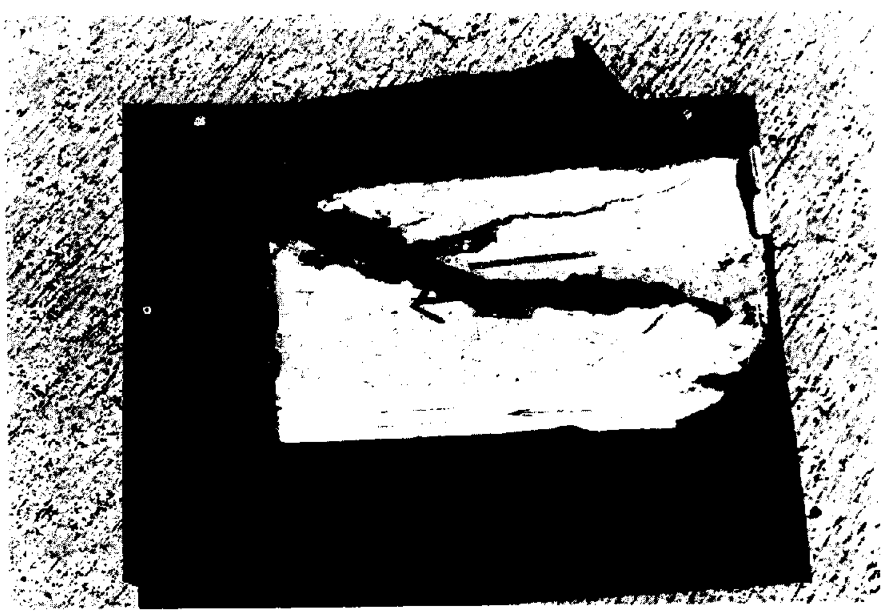
11.5.1 LOAD-DEFLECTION CURVES

The load-deflection curves of flexural tests were obtained primarily to illustrate the differences between steel fiber and conventional shotcrete. They also aided the interpretation of test results since an unusual load-deflection curve usually was an indication of problems with the tests. The load-strain data was not converted to an equivalent modulus because of the difficulties in interpreting such data. Strain curves in this section are continued beyond the cracking load only to illustrate post-crack behavior of steel fiber beams. A different interpretation of both strain and moment beyond the cracking load is necessary.

Figure 11.11 shows the load-deflection curve of a flexural test made on Mix 42 (steel fiber regulated-set) at an age of 4.2 hours at which time the flexural strength was 50 psi (0.35 MPa). This was the earliest successful



a) Fibrous specimen



b) Non-fibrous specimen

FIG. 11.10 COMPARISON OF MODE OF FAILURE IN COMPRESSION: FIBROUS VERSUS NON-FIBROUS SPECIMENS

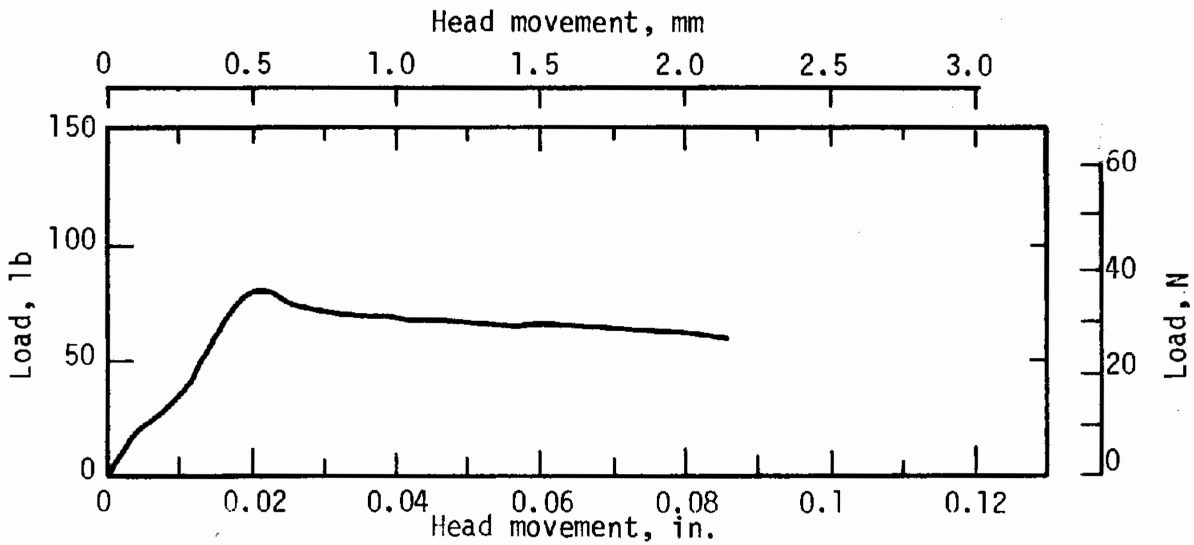
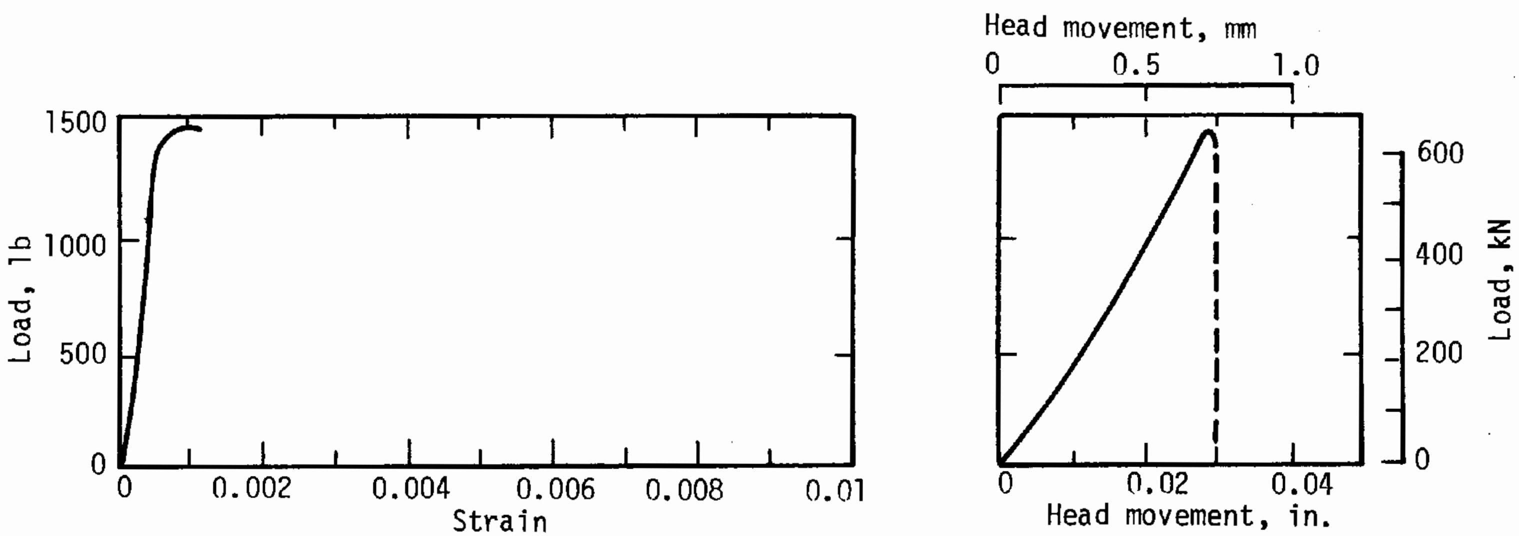


FIG. 11.11 LOAD-DEFLECTION CURVE OF STEEL FIBER REGULATED-SET BEAM AT 4.2 HOURS



a) Load-strain curve

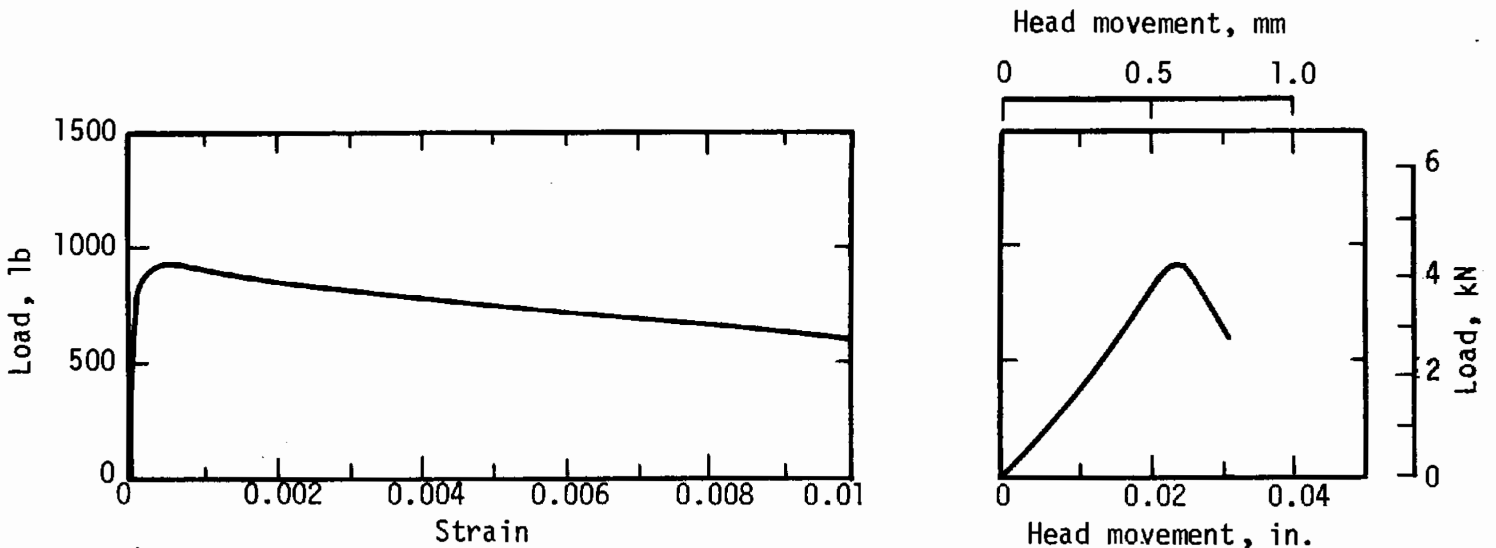
b) Load-deflection curve

FIG. 11.12 TYPICAL LOAD-DEFORMATION BEHAVIOR OF NON-FIBROUS BEAMS TESTED AT ONE MONTH flexural test conducted on any mix. The curve clearly illustrates the substantial post-crack resistance of fiber mixes. Conventional shotcrete beams cracked and lost load immediately.

Fibrous specimens showed an increasingly peaked load-deflection curve with increasing strength. The load carried by the specimen beyond the peak dropped gradually to about 15 to 30 percent of the maximum for substantial deformations before the test was stopped with the sample still carrying load.

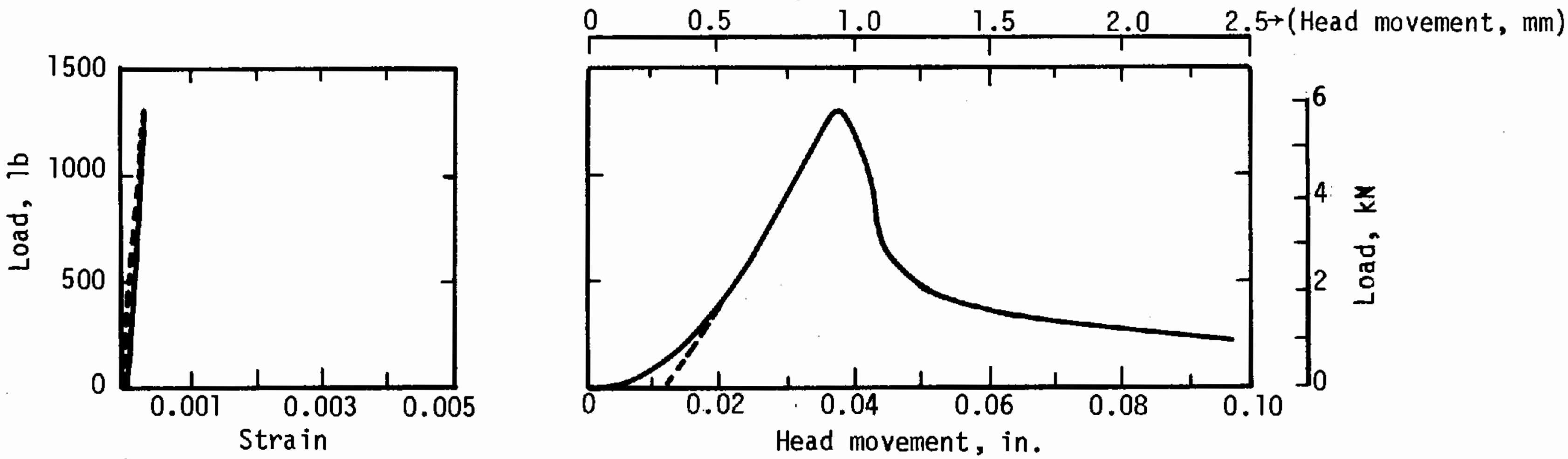
Figure 11.12 shows a load-deflection and a load-strain curve for a non-fibrous beam from Mix 24 tested at one-month. The one-inch-long strain gage was located on the tensile side of the beam and straddled the location of the eventual crack. Figure 11.12a is the curve generated by the x-y plotter for the strain gage while the curve of load-versus-head movement is presented in Fig. 11.12b. It is likely that the non-fibrous beams failed so suddenly that the downward portion of the curve was not captured by the slow response of the x-y plotter. All non-fibrous specimens exhibited similar brittle behavior.

Figure 11.13 is a similar set of curves for a steel-fiber beam from Mix 39 also at an age of one-month. The strain gage also straddled the crack on this beam. The substantial post-crack resistance is shown clearly in these diagrams. The test was stopped only because the limit of the x-axis of the plotter was exceeded. Figure 11.14 is a set of curves for another steel-fiber beam from Mix 39 that was tested at one month. The strain gage was not across the crack on this test. Figure 11.14a is a plot of load against outer-fiber strain, but it was not the maximum outer fiber strain, so, the plot shows the



a) Load-strain curve
b) Load-deflection curve

FIG. 11.13 TYPICAL LOAD-DEFORMATION BEHAVIOR OF STEEL-FIBER BEAMS TESTED AT ONE MONTH (STRAIN GAGE STRADDLED CRACK)



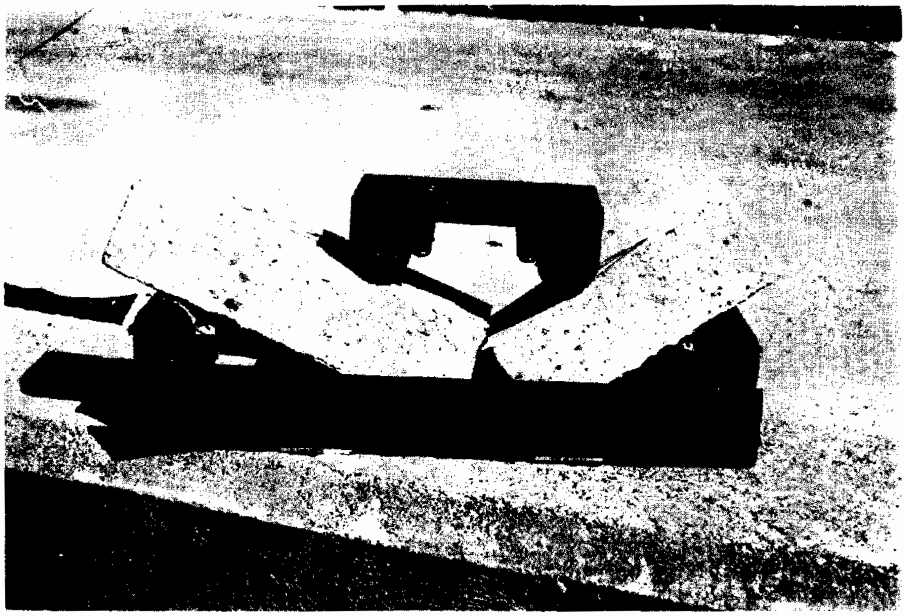
a) Load-strain curve
b) Load-deflection curve

FIG. 11.14 TYPICAL LOAD-DEFORMATION BEHAVIOR OF STEEL-FIBER BEAMS TESTED AT ONE MONTH (STRAIN GAGE NOT ON CRACK) increase in strain (solid line) up to a maximum and then a decrease back down approximately the same path (dashed line). This nearly elastic behavior was observed in every load-strain curve for steel fiber beams in which the strain gage did not straddle the crack. The comparable load-deflection curve is shown in Fig. 11.14b where a fairly sharp deflection is shown after the maximum load was reached, caused by the release of energy stored in the test machine. After the initial drop in load occurred at a deflection of about 0.038 in.(0.95mm); substantial load (about 200 lb; 91 kg) was still carried by the beam when the test was stopped after deflecting about 0.1 in. (2.5 mm).

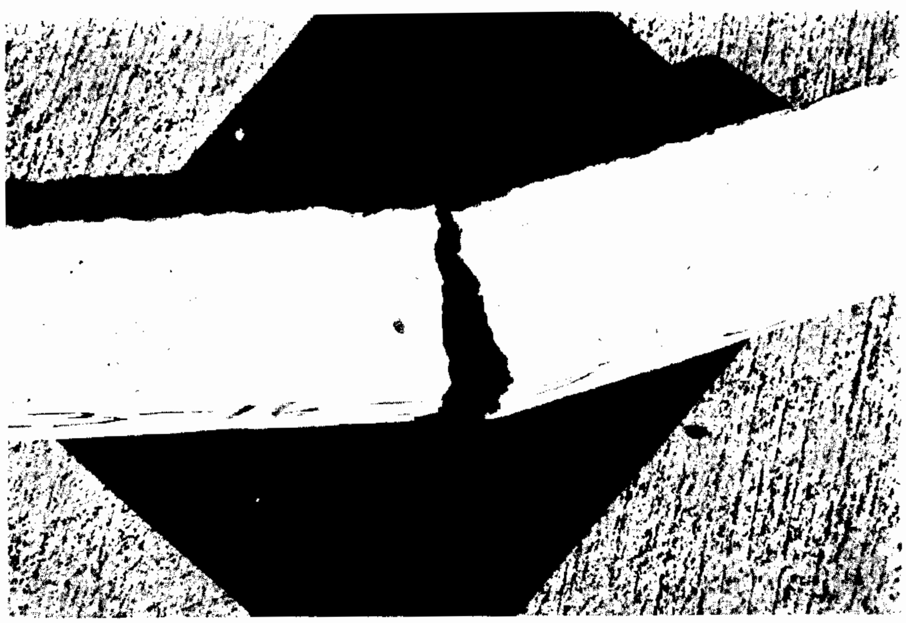
Since a few beam tests did have the strain gage located across the crack, a general idea of the average strain in the 1-in. (2.5-cm) gage length can be obtained. Generally the measured strain at the top of the rounded load-strain curve (at maximum load) ranged from .0005 to .0015 for both types of specimens; for non-fibrous specimens it ranged from 0.0005 to 0.0008 while for fibrous beams the range was 0.0006 to 0.0016. The maximum tensile strains recorded in all the beams in which the strain gage did not cross the eventual crack ranged from about 0.0003 to 0.0005.

11.5.2 MODES OF FAILURE

The modes of failure of the fibrous and non-fibrous beams are evident from the preceeding sections. The non-fibrous beams fail suddenly in a brittle fashion. Figure 11.15 illustrates a typical failure of non-fibrous beams. The flexural crack propagated a more or less regular failure surface that was approximately perpendicular to the axis of the beam.



a) Non-fibrous specimen after failure



b) Close-up of failure crack

FIG. 11.15 MODE OF FAILURE IN FLEXURE:
NON-FIBROUS BEAMS

All fibrous beams, including those with low fiber content, failed slowly and exhibited significant toughness or post-crack resistance. Though the literature often refers to the mode-of-failure as ductile, the terms toughness or post-crack resistance are considered to be more appropriate. Figure 11.16a illustrates a 200 lb (91 kg) engineer standing on a cracked fibrous beam which had already been deflected far past cracking load in the testing machine. The close-up photograph in Fig. 11.16b illustrates the irregular open crack of the loaded beam in detail. Figure 11.17 is another illustration of the sinuous failure surface and of the sizable width of crack in a beam that was still carrying considerable load. The failure surface in fibrous beams tended to be more irregular and sinuous. The flexural crack propagated slowly up the path where it intersected the least number of fibers. Since the distribution of fiber is not uniform through the thickness, the flexural crack follows a sinuous path. The x-ray photographs of fibrous beams in Chapter 7 illustrate the effect of the distribution of fibers on the eventual location of the flexural crack.

(a) Load on a fibrous beam after testing

(b) Irregular open crack of a beam after testing

FIG. 11.16 POST-CRACK STRENGTH OF FIBROUS BEAMS

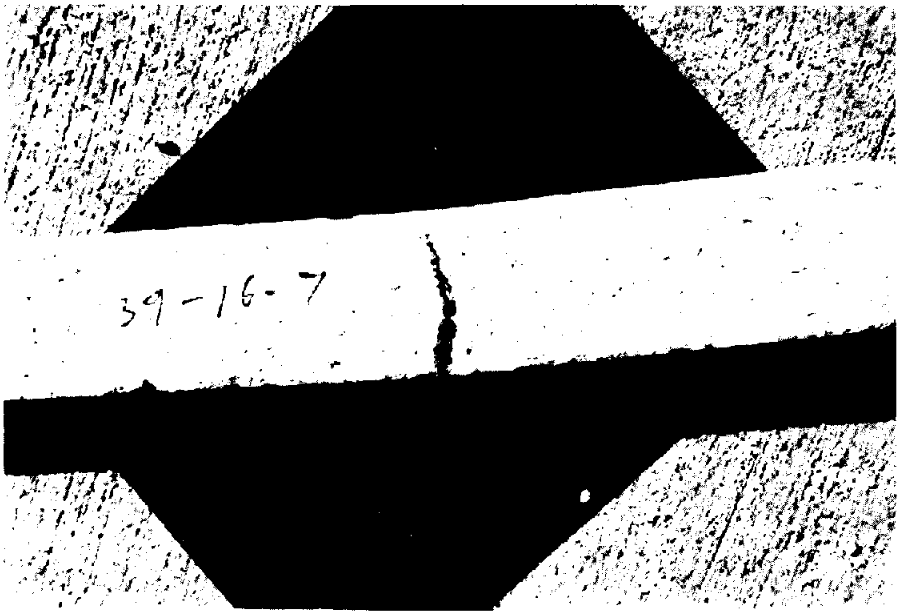


FIG. 11.17 FAILURE MODE OF FIBROUS BEAMS

CHAPTER 12

MOMENT-THRUST INTERACTION TESTS

12.1 INTRODUCTION

The purpose of these tests was to investigate the behavior of shotcrete members subjected to combined bending and axial load. Both conventional non-fibrous and fibrous shotcrete were tested to compare their behavior. Results are presented in the graphical form of a moment-thrust failure envelope. Diagrams of this type are used to predict failure of members in a structure subjected to combined bending and axial load. The relevance of the moment-thrust test to tunnel conditions is illustrated in Fig. 12.1. Although moment-thrust envelopes have been utilized for design of reinforced concrete structures, tests such as these have not been performed to construct the envelopes for shotcrete.

Beam-column specimens were tested from Mixes 23, 28, 39, 40 and 42 at an age of six months. Twelve specimens were tested from Mix 39 to obtain information regarding the effect of different specimen orientations relative to the shooting direction. Six specimens were tested from all other mixes. Most specimens were tested in positive moment, where positive moment is defined as the specimen orientation that puts the compressive stress on the back or formed surface of the shotcrete. Specimens from Mix 39-10 were tested with negative moment, and those from Mix 39-4 with positive moment. For each mix, beam-column specimens were tested at eccentricity ratios (e/t) of about 0.1, 0.15, 0.2, 0.3, 0.4 and 0.5, where e is the

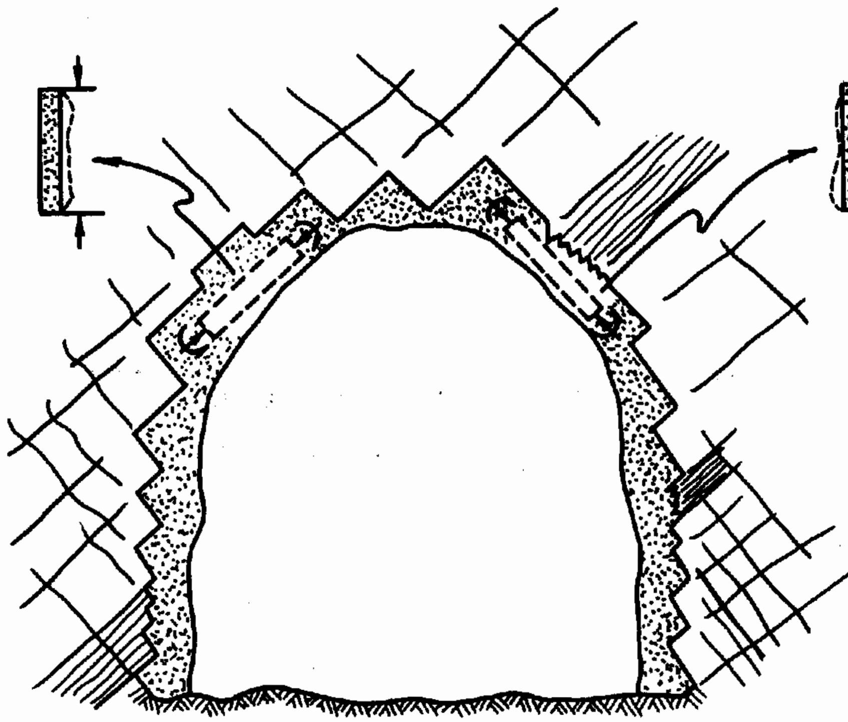


FIG. 12.1 SIMULATION OF MOMENT-THRUST CONDITIONS BY BEAM-COLUMN TEST

distance from the load point to the centroid of the cross section and t is the thickness in the direction of bending.

The beam-columns were all 3 in. (76 mm) wide, thickness (t) varied from 2.4 to 2.6 in. (61-66 mm) and total length was 24 in. (610 mm). The prismatic section between load caps was 18 in. (450 mm) long. Deflection in the plane of eccentricity and head movement were each plotted continuously against load by an X-Y recorder.

Conclusions about the influence of steel fibers on the moment-thrust behavior of shotcrete should account for the in-place fiber content, as the retention of fibers in the wall was only one-half to two-thirds of those batched in the mix. These low fiber contents plus the bending of most of the fibers in the mixer makes comparison with studies on fiber reinforced concrete or on other steel fiber shotcretes difficult.

12.2 PREPARATION OF SPECIMENS

Beam-columns were sawed from 24 in. (610 mm) square panels. The shooting log was consulted before making panel selections to avoid those with inconsistencies in shooting. Seven beam-columns were sawed from selected panels so as to maintain their vertical orientation. The top of each test specimen corresponded to the top of the panel as it was shot. Each specimen was sawed to a 3 in. (76 mm) width, ends were trimmed to make them perpendicular to the sides, and the front was trimmed to eliminate irregularities and to facilitate placement of the LVDT's used for measuring deflections. About 1/8 to 1 in. (3 to 25 mm) of the thickness was trimmed from the front side of the specimens.

A device was attached to the ends of the specimens to transmit eccentric load to the prismatic beam-column specimen. Fig. 12.2 is a photograph of a specimen with the end-clamps. A C-clamp held temporary metal sides on the end-clamp device while it was filled with hot sulphur-capping compound to a depth of about 1/2 in. (13 mm). The beam-column was inserted and aligned immediately, and after the initial capping compound had hardened the remainder of the space between the specimen and the loading device was filled. The side plates were removed once the capping compound hardened.

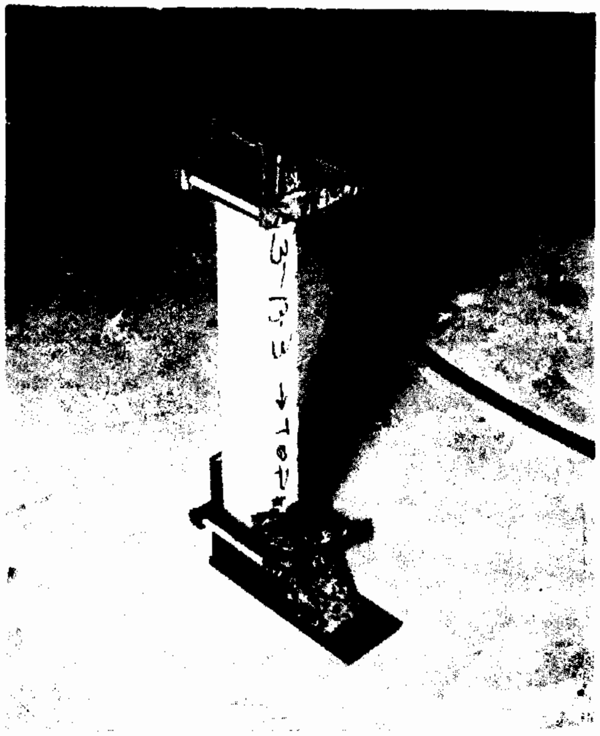


FIG. 12.2 BEAM-COLUMN SPECIMEN WITH END-CLAMP DEVICES

Bolts on either side of the device were tightened to compensate for shrinkage of the capping material during cooling. A special frame was used to hold the specimen in place while the end-clamp was attached, and to insure that the specimen was perpendicular to the end-caps.

One column from each panel was cut into a 7-in. (180-mm) prismatic compression specimen and one 17-in. (430-mm) flexure specimen. Additional compression and flexure specimens were cut from undamaged portions of tested beam-column specimens. All compression and flexure specimens were prepared as described in Chapters 8, 9 and 10. All specimens were soaked in lime water 40 hours immediately prior to testing.

12.3 TESTING PROCEDURE

All specimens were loaded through cylindrical bearings at a constant rate of head movement of 0.03 in./min (0.008 mm/min). A deflection bridge supported 3 LVDT's that furnished deflection readings in the plane of eccentricity at the midpoint and 5.5 in. (140 mm) above and below the midpoint. They were connected to automatic plotters that provided a continuous load-deflection record. A test set-up is shown in Fig. 12.3 and Fig. 12.4 shows a test on non-fibrous shotcrete after failure.

The centers of the cylindrical bearings were considered the center of loading for measuring eccentricity in the testing machine. Actual initial eccentricities are estimated to be within ±0.06 in. (15 mm) of the desired value. The specimens were loaded to failure; fibrous specimen tests were continued beyond maximum load to determine the post-crack behavior.

12.4 INTERACTION DIAGRAMS

There was insufficient data to allow plotting an accurate interaction diagram for each mix, so all the non-fibrous specimen results are combined in Fig. 12.5a and all the fiber specimen results are combined in Fig. 12.5b. The test results and specimen dimensions are summarized in Appendix D. Moments used in the figures were calculated as the maximum load times the total eccentricity at maximum load; total eccentricity (e) was taken as the initial eccentricity plus the lateral deflection of the specimen at midheight. Failure was defined by a reduction in load. The ordinate at zero moment is the average of all axial compression tests, and the

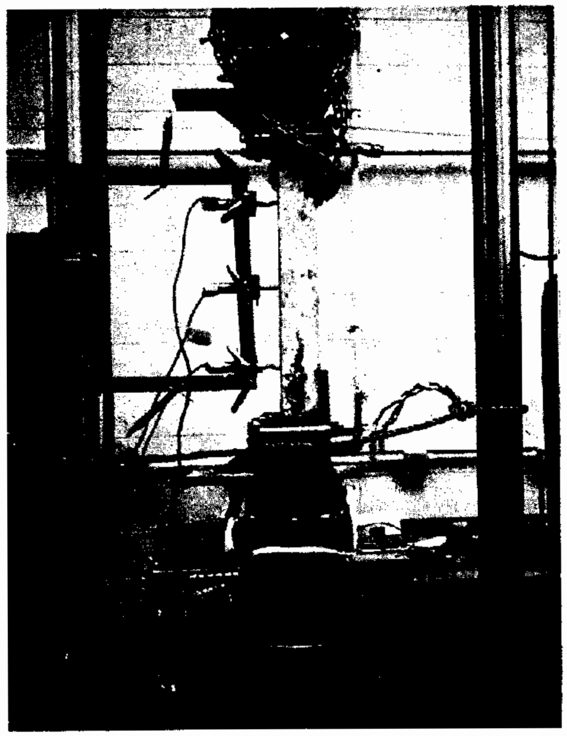


FIG. 12.3 BEAM-COLUMN SPECIMEN IN TESTING MACHINE

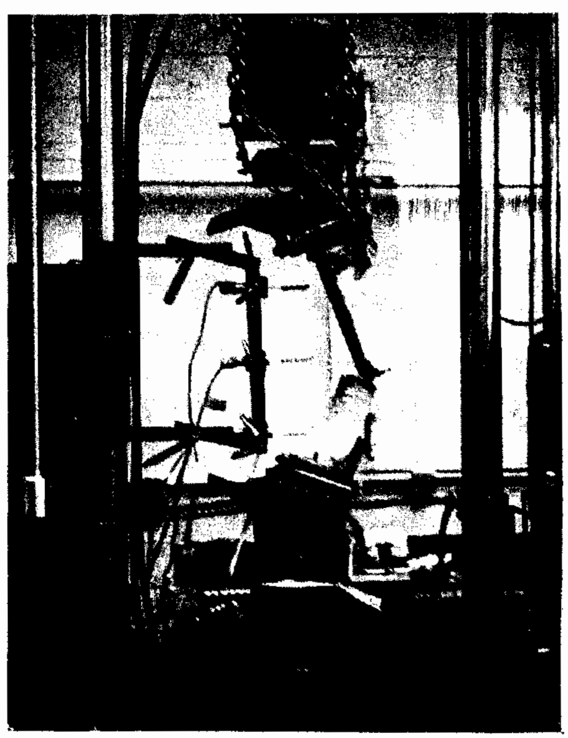
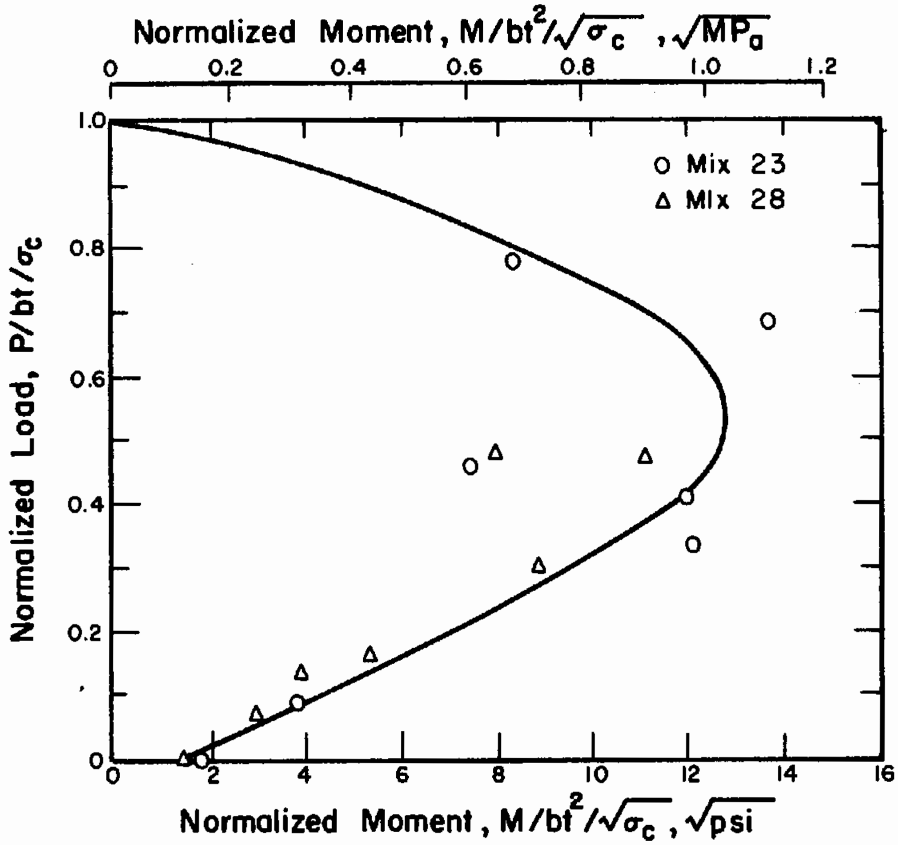
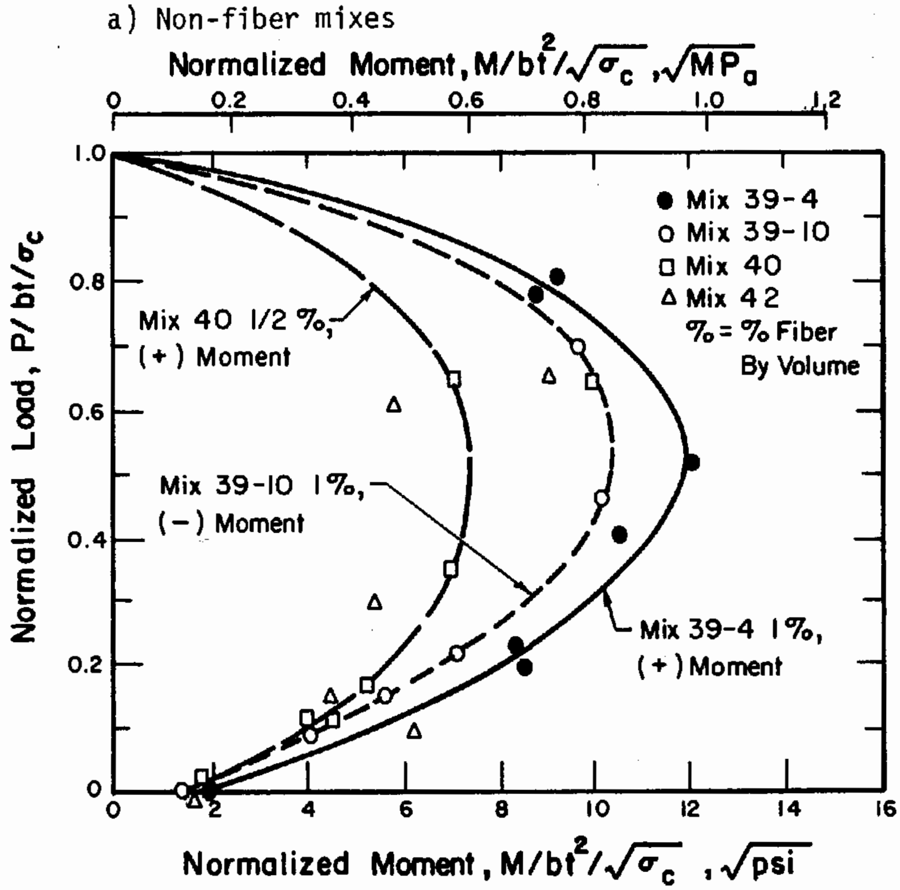


FIG. 12.4 FAILURE OF NON-FIBROUS BEAM-COLUMN SPECIMEN



a) Non-fiber mixes



b) Fiber mixes

FIG. 12.5 THRUST-MOMENT FAILURE ENVELOPES abscissa at zero thrust is the average of all flexural test results for the same group of specimens. The specimens were of varying sizes and there were several shotcrete strengths, so a special method of normalization was necessary to combine the results as shown in the figures.

The data shown represent failure conditions. Specimens with high thrust and low moment fail when a stress is reached that is related to the compressive strength of the shotcrete. Therefore, it is reasonable to normalize the failure loads in this region of the interaction curve with the factor $bt\sigma_c$; this corresponds to dividing the failure load of the beam-column by the failure load that would have occurred if the specimen had been loaded axially, since the stress σ_c is obtained from the axial compression tests.

Specimens with low thrust and high moment fail when a stress is reached that is related to the flexural strength of the shotcrete (σ_f). Therefore, it is reasonable to normalize the moments in this region of the interaction curve with the factor $bt^2\sigma_f$, as this factor is related by a constant to the failure moment with no axial load (pure flexure). The flexural stress σ_f is generally considered to be proportional to $\sqrt{\sigma_c}$, so if this substitution is made in the normalizing factor, it becomes $bt^2\sqrt{\sigma_c}$, and remains proportional to the failure moment in pure flexure. The latter factor was used because there was more data for σ_c than for σ_f available and it appeared more reliable. The use of $\sqrt{\sigma_c}$ in the normalizing factor for moments is more appropriate in this case than the more common use of σ_c because failure below the balance point actually depends on a material property that is related to $\sqrt{\sigma_c}$. This factor should, therefore, be more effective in reducing the data scatter when mixes with different strengths are combined.

The data shown in Fig. 12.5 have been normalized in this way using the compressive strengths obtained from the 180-day tests because they were close to the age of the beam-column test specimens.

12.5 GENERAL DESCRIPTION OF MODES OF FAILURE

Those specimens loaded at small eccentricity ratios (less than 0.15) failed by crushing of the shotcrete in compression. Failures of specimens containing fibers were somewhat less brittle than those without fibers. A typical example of a brittle type of failure is shown by specimen 23-13-6 in Fig. 12.6. Specimens loaded at eccentricity ratios greater than 0.3 failed due to lack of internal tensile resistance without crushing in compression. Examples of this type of failure are shown by specimen 40-5-6 in Fig. 12.7 and specimen 23-13-1 in Fig. 12.6.

Specimens tested with an eccentricity ratio of about 0.2 fall near the knee of the failure envelope and appear to fail simultaneously by crushing and by lack of tension capacity. In conventional terms, these specimens may be said to exhibit a balanced mode of failure. A typical example is shown by specimen 40-5-2 in Fig. 12.7.

The midpoint deflection of the specimen was used to obtain the eccentricity for maximum moment calculations even when failure did not occur at midheight. This is justified because the midheight section was resisting this slightly larger moment at failure.

FIG. 12.6 PHOTOGRAPH OF NON-FIBROUS SPECIMENS 23-13-6 AND 23-13-1

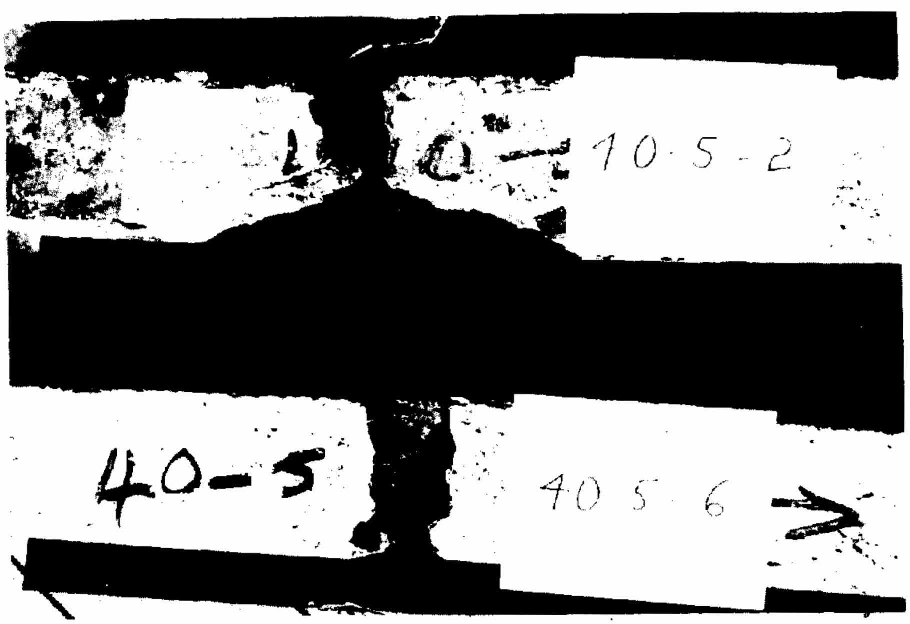


FIG. 12.7 PHOTOGRAPH OF FIBROUS SPECIMENS 40-5-2 AND 40-5-6

12.5.1 COMPRESSION FAILURE

The compression mode of failure of eccentrically loaded beam-columns was similar to the failure of the shorter compression specimens. In almost all tests with an eccentricity ratio less than 0.15, the compression side of the specimen developed cracks parallel to the direction of compressive force, and slabs 1/2 in. (13 mm) thick spalled off the compression side. Specimens without fiber usually failed suddenly and explosively.

Specimens containing fiber tended to have pieces spall away from the compression face also, but the fragments were held to the specimen by the steel fiber. In addition, fiber specimens had a residual strength on the order of 15 percent of maximum, while those without fiber did not exhibit any residual strength.

12.5.2 TENSION FAILURE

Specimens in this category, tested at eccentricity ratios of 0.3 or greater, showed the most notable difference between fibrous and nonfibrous mixes. Specimens without fiber exhibited no residual strength after maximum load, and failure occurred when the tension crack propagated rapidly through the specimen to the compression face. In one case, failure was observed at two locations in the same specimen.

Specimens with fiber continued to support substantial loads although the tension crack ran completely through the depth and had opened as much as 1/8 in. (6 mm) or more. Although the load was only a few hundred pounds, the moment (because of the large additional eccentricity) was relatively large. Cracking began on the tension surface, in most cases, where the untrimmed specimen was thinnest.

12.5.3 NEAR-BALANCED FAILURE

At an eccentricity ratio near 0.2, failures of fibrous and nonfibrous shotcrete were similar. In addition to the spalling observed in compression failures, these specimens showed a tension crack that ran to the neutral axis near the compression face. The spalling cracks ran subparallel to the compression face from the tension crack at the neutral axis.

12.6 POST-CRACK RESISTANCE

Investigations of the influence of steel fibers in a concrete matrix have shown a moderate increase in compressive strength with a corresponding moderate increase in the deformability of compression specimens. The influence of steel fiber on flexure specimens has been more dramatic with a sizable increase in loads and a several fold increase in deformability. These observations have been shown to apply to shotcrete as well when the fibers are well distributed through the matrix. Therefore, the post-crack resistance of shotcrete or its capacity to deform substantially under load depends on the relative amount of moment and thrust applied to the specimen. Consistent with this reasoning it was observed that the beam-columns with fibers showed more post-crack resistance than those without and that the difference increased with increasing eccentricity.

When failure occurred because of lack of tensile capacity, the influence of fibers was most noticeable. In Fig. 12.8 the midheight lateral

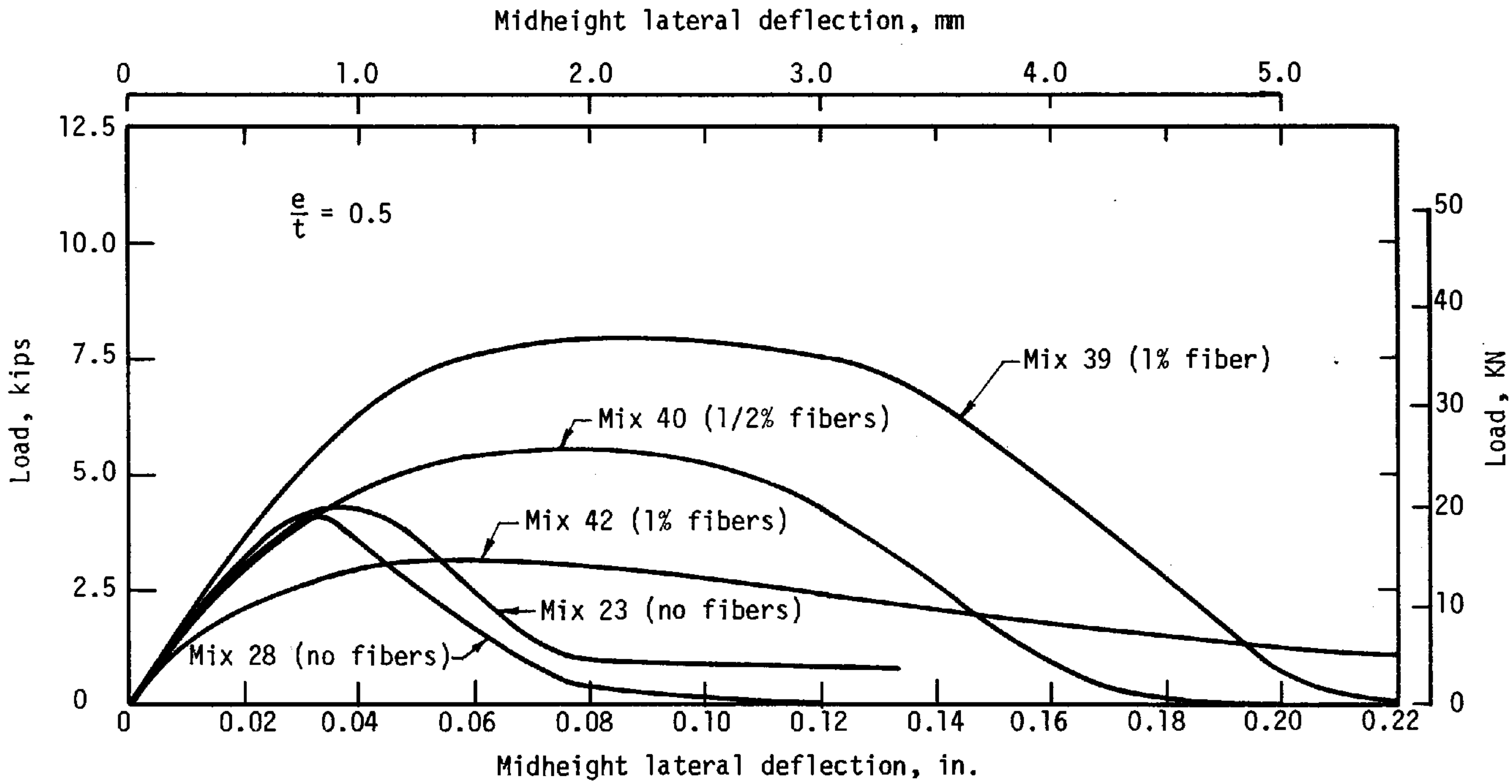


FIG. 12.8 COMPARISON OF DUCTILITY OF BEAM-COLUMNS WITH AND WITHOUT FIBERS

deflection of beam-column specimens is shown during loading with an eccentricity of one-half the dimension in the direction of applied moment. These curves have not been normalized so the differences in height (strength) depend on other factors as well as the presence of fibers; however, the curve shapes are of particular interest. With fibers in the mix, the peak specimen loads occurred at much larger deformations and fell off much less rapidly. Even the mix with only one-half percent fibers had a post-crack resistance comparable to the mixes with one percent fibers.

12.7 DISCUSSION

The data for both fibrous and non-fibrous mixes have considerable scatter. X-ray examination of the failed fibrous specimens showed that when a tension crack formed it followed a path of low fiber content (Chapter 7). Therefore, the strength of these specimens depended on the fiber distribution, or the occurrence of zones of very low fiber content. When fibers are not present in cast concrete specimens, failure in the tension region is known to be related to flaws or stress raisers such as small voids, and voids are probably more likely to occur in shotcrete than in cast concrete. Therefore, the data scatter may not be larger than would be expected theoretically.

Overall consideration of the curves in Fig. 12.5 shows shapes that are similar to those obtained for reinforced concrete members. The balance point or knee of the curves occur at a thrust near one-half the ultimate axial thrust. There was not an improvement in moment-thrust capacity with the addition of fibers. The fibers are believed to interfere with the shotcrete compaction and a lower compressive strength resulted. In addition, the fibers were bent in the mixer for these specimens and, therefore, were not fully effective in improving tensile strength. Hence, the moment-thrust envelopes for fibrous and non-fibrous mixes are not significantly different.

When the data for fibrous mixes are grouped in Fig. 12.5b for comparison, some general observations can be made. The specimens with one-half percent fibers by volume were weaker than those with one percent and weaker than those with no fibers, because it appeared that the fibers interfered with the compaction process yet did not increase tensile strength. There is a difference between panels 4 and 10 for Mix 39 that were tested with positive and negative moments, respectively. This difference is attributed to variation in fiber distribution through the thickness of the beam.

Mix 42 should compare with Mix 39, panel 4 as it had one percent fiber and was subjected to positive moment, but there is too much scatter to make observations from it. This mix contained regulated-set cement and hydrated in the hopper before shooting. It also contained a large amount of cement and more than usual amounts of water were added at the nozzle. This may explain the scatter in the results.

12.8 CONCLUSIONS

The moment-thrust resistance of plain shotcrete is similar to plain concrete. Test results used to define the failure envelopes show somewhat more scatter than occurs in cast concrete, indicating greater variability in the in-place materials. This greater variability should influence any design philosophy based on calculation of resistance that in turn depends on material properties. Many more series of tests are required to determine the normal variability and to determine experimentally the properties and trends necessary for design. The test results to date are insufficient for design. Furthermore, rational design procedures utilizing moment-thrust results are not in common use underground.

The steel-fiber-reinforced specimens did not show a significant increase in strength either in thrust or flexure over their unreinforced counterparts, but they did display a considerably larger ductility and post-crack resistance.

In general, ductility of resisting members is considered to be very valuable in the design of conventional structures; its importance to thin shotcrete liners must still be demonstrated. The failure envelopes are similar in appearance on the normalized plots for specimens with and without steel fiber reinforcement. The knee of the curve occurs near $P/bt\sigma_c = 0.5$. The normalized pure moment occurs between $M/bt^2\sqrt{\sigma_c} = 10$ and $12\ \sqrt{psi}$ for non-fibrous shotcrete and that with one percent fiber. Because of the small amount of data, the low fiber content in situ, bending of the fibers by the mixer, and the limited number of mixes and shooting conditions, these data are believed to underestimate the influence of steel fibers on the mechanical properties of shotcrete. Additional moment-thrust tests are required on more representative samples of steel fiber shotcrete to evaluate the full potential of the steel fibers.

CHAPTER 13

PULL-OUT STRENGTH

13.1 INTRODUCTION

The pull-out test is a way of assessing the strength or quality of shotcrete either in situ or in test panels. The test is performed by pulling a previously embedded anchor out of the hardened shotcrete with a special jacking device that controls the surface of rupture to that of a truncated cone (frustrum) of given dimensions. The force required to extract the anchor is a measure of the strength of the shotcrete that has been related empirically to compressive strength. This test method has been used successfully on shotcrete by several other investigators in the United States (Richards, 1974; Bawa, 1974; and Rutenbeck, 1974). Malhotra (1975) presents test data on the use of the method to determine the strength of in situ concrete. Patents have been registered in various countries (Malhotra, 1975). Test equipment for use in shotcrete is available commercially in Europe.

The University subcontracted with Mr. Owen Richards to conduct a pull-out test program on panels shot during the field testing phase of this study. The pull-out test results were to augment the conventional strength testing program. In particular, it was hoped that early strength might be assessed by the pull-out method and that the pull-out tests could be conducted faster than conventional strength tests. This additional data was to be used to supplement and more clearly define the strength-versus-time curves. Finally, it was desired to evaluate the applicability and usefulness of the pull-out test method in general. Difficulties with differences in strength between panels of the same mix and with a variable σ_c/σ_p ratio changing with time prevented an accurate correlation with compressive strength at early ages.

13.2 ADVANTAGES AND LIMITATIONS OF PULL-OUT TESTING

The pull-out anchor can be attached to the wall and embedded in the shotcrete as the wall is gunned. This method is relatively fast and inexpensive because of the low cost of the pull-out anchors and test equipment because the equipment is portable enough to minimize testing-labor costs. One distinct advantage that results from the low cost is that numerous anchors can be embedded; anchors to be tested can be selected at random. Hence, the nozzleman does not know which anchor will be tested and cannot improve his quality of work for the test specimen as he may or may not be inclined to do when shooting a test panel.

In its present form, the pull-out test method has several limitations, modifications and new concepts are being developed to overcome some of these (Rutenbeck, 1974). The strength results are highly dependent on the actual depth of embedment, which is sometimes variable. Methods to install the testing devices after the shotcrete has hardened are being developed to avoid this problem. The roughness and irregularity of the shotcrete surface cause additional problems in testing, since it is difficult to align the jack so that it will pull in a perfectly axial direction, as required to prevent moment being applied to the anchor. Even if the direction of pulling can be made axial by special pads or adjustments made to the jack, a rough shotcrete surface across the pull-out frustrum complicates the evaluation of the area of the failure surface. The surface could be ground smooth, plane and perpendicular to the shaft around the anchor and to the proper depth of anchor embedment. Such pregrinding of the shotcrete surface has been attempted by some researchers to minimize these problems.

A very important limitation of the pull-out test in its present form is the fact that the results are not strongly affected by the presence of laminations. Though the direction of pulling is correct, the restraint provided by the outer ring forces a shear surface that is not affected by weak inter-laminar bonding. Other limitations stem from the fact that the pull-out test evaluates the strength of only a small portion of the thickness of the shotcrete.

The correlation between pull-out strength and other strength parameters such as compressive strength is empirical. One of the problems is that the state of stress on the failure surface is complicated; it is neither pure compression nor pure tension. In the past, pull-out strength had been related to compressive strength probably because compressive strength is the most widely used quality control parameter.

Finally, the correlation factor between pull-out and compressive strength appears to change somewhat with time or age of curing and possibly with many other factors such as cement type, mix design, gradation, etc.

Despite these limitations, the prospect for improvements is good and even in its present form, the pull-out test is useful for determination of a relative value of strength at a given age. It appears possible that, for a given project, correlations between absolute compressive strength and pull-out strength with time can be made to permit an assessment of absolute strength.

Unless a correlation is developed for each project, the correlation factor must be estimated and the resulting estimated compressive strength will only be approximate. The advantages warrant further investigation and improvement for its use for testing the in situ strength of shotcrete.

13.3 EQUIPMENT

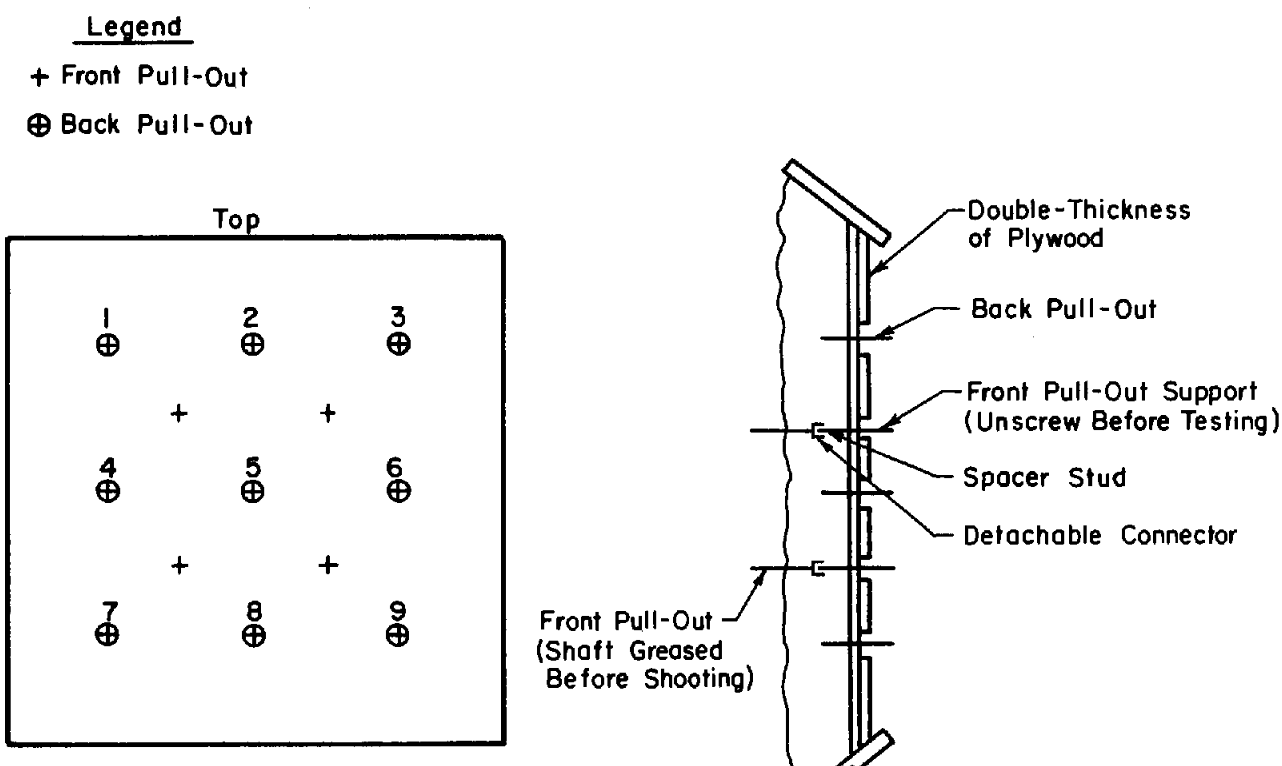
13.3.1 GENERAL

Because of the irregularity of the surface of the shotcrete, most of the pull-out anchors for this project were placed so they could be pulled from the back of the panels where the formed surface (back of the test panel) of shotcrete was smooth. Several advantages were realized by this procedure. The anchor could be installed so it was always perpendicular to the back surface, the depth of embedment could be the same for all tests, and, as noted previously, the surface of shotcrete was always smooth. Naturally, this technique is inapplicable to in situ testing on the rock wall, as the anchor must be pulled from the front, but it would be appropriate for any test panel.

PANEL CONFIGURATION

Some of the standard 2 by 2 ft (0.61 by 0.61 m) wood panels used for other strength tests were drilled so that 12 pull-out anchors could be attached prior to shooting in a manner that the desired depth of embedment could be approximated. Panels were drilled so that 9 pull-out devices could be extended through the back of the panel to a precise depth of embedment in rows of three as shown in Fig. 13.1. Also shown are four anchors placed at the estimated depth of embedment so they could be pulled from the rough front surface of the panel.

Details of the back pull-out devices are shown in Fig. 13.2. The shaft of the device was a 1/2-in. (12 mm) high-strength threaded rod while the anchor was made up of a washer between 2 nuts at the extreme end of the embedded portion of the shaft. The anchor was installed perpendicular to the back of the panel at a predetermined depth of embedment by bolting the shaft to the back of the panel with nuts and washers as shown in Fig. 13.2.



a) Plan view

b) Profile of pull-out panel

FIG. 13.1 CONFIGURATION OF PULL-OUT PANELS AND LOCATION OF ANCHORS

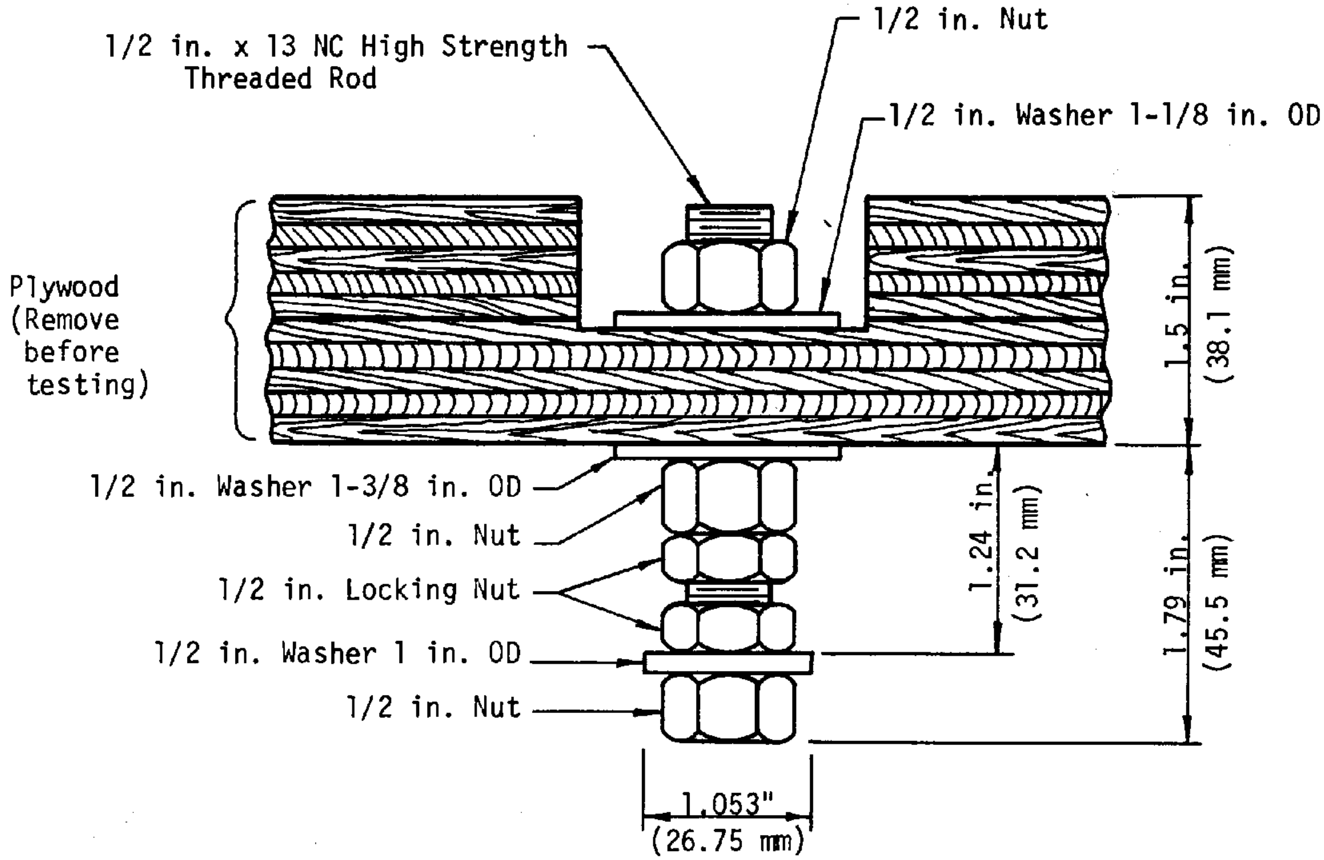


FIGURE 13.2 DETAIL OF PULL-OUT ANCHOR

Since the back of the panel consisted of two 3/4-in. (19 mm) plywood boards, the outer board was countersunk so that the end of the pull-out device did not protrude beyond the back of the panel. This proved extremely convenient since panels could be carried and stacked on top of each other without interference from protruding studs.

The four front pull-out devices were attached to a spacer stud which, in turn, was bolted to the back of the panel in a manner so that the anchor would have the proper depth of embedment if the thickness of the shotcrete in the panel was actually 3-in. (76 mm). The anchor was attached to the spacer stud by screwing a few threads of the spacer stud into the bottom nut of the anchor itself. This necessitated greasing the shaft of the bolt before shooting and unscrewing the shaft a few turns to disengage the spacer stud before making the test.

TESTING EQUIPMENT

A sketch of the center-hole hydraulic ram attached to a pull-out anchor is shown in Fig. 13.3. The rim of the ram gained reaction from the back of the slab through a bearing ring 1/2-in. (12-mm) thick with a center hole 2-11/16 in. (68 mm) in diameter. The bearing ring forced a particular failure surface. As shown in the figure, the madrel screwed to the shaft of the pull-out anchor and secured to the jack with the locking nut.

Hydraulic pressure was provided through a hose from a separate hand pump having a calibrated 5-in. (13-cm) diameter dial gage. A photograph of the test equipment and set-up is shown in Fig. 13.4.

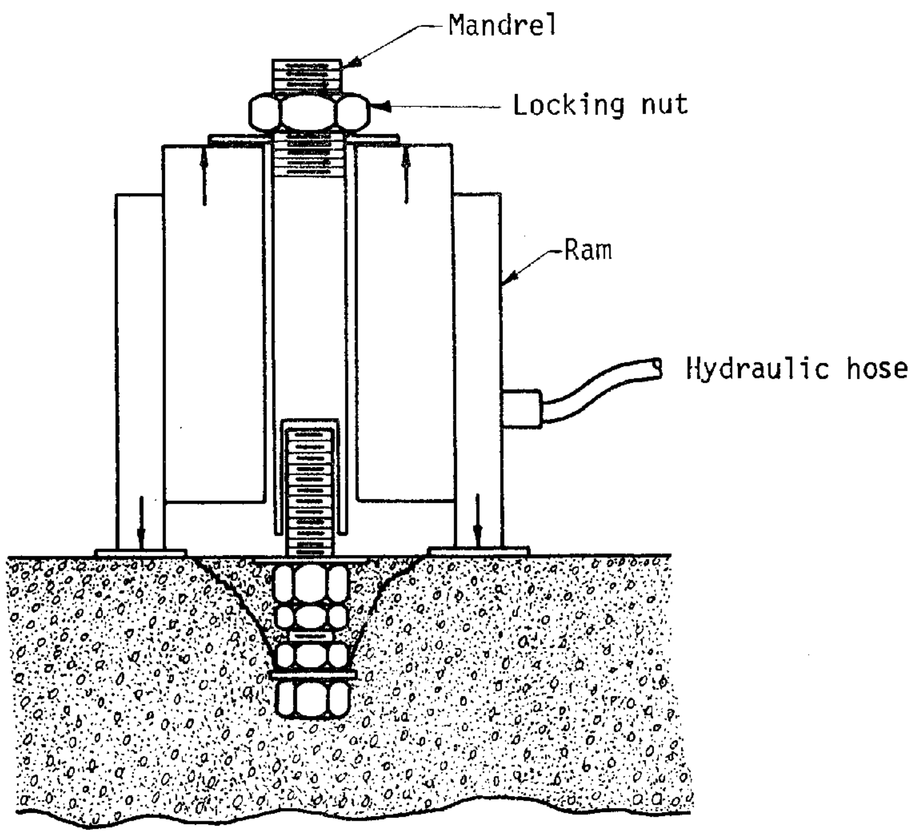


FIG. 13.3 SKETCH OF CENTER-HOLE JACK ATTACHED TO ANCHOR

13.4 TEST PROCEDURE AND SCHEDULE

In order to gain access to the back pull-out anchors, the front pull-out anchors had to be pulled. The panel could then be turned over on a bed of sand that provided good support for the irregular front surface. Once the nuts holding the plywood panel were removed, the wood form could be removed with the aid of a crow bar, or hammer, if necessary. The ram was attached, as described in the previous paragraph, and the anchor extracted with several strokes of the hydraulic pump. A test could be completed in about 3 minutes.

The time, panel and test number, as well as the maximum load, the

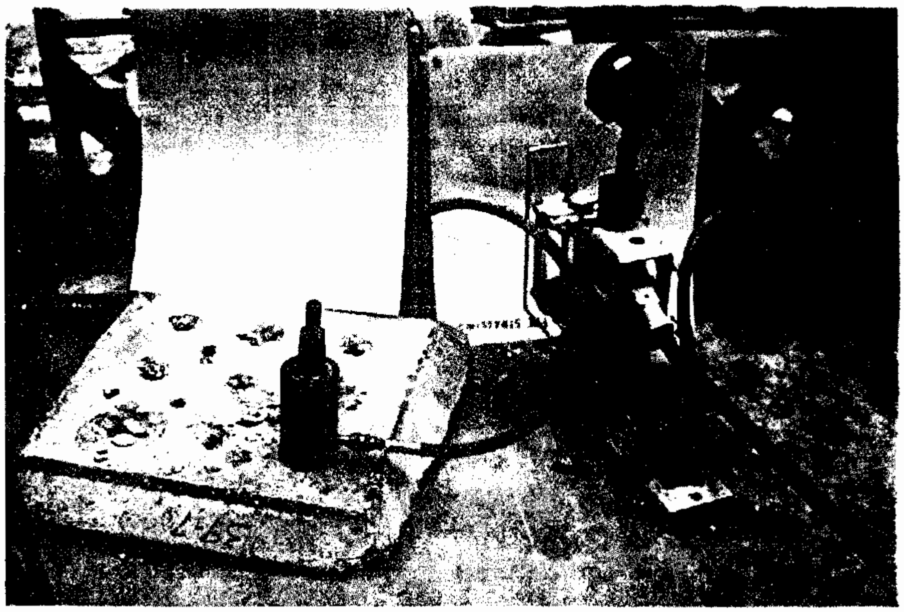


FIG. 13.4 PULL-OUT TEST EQUIPMENT

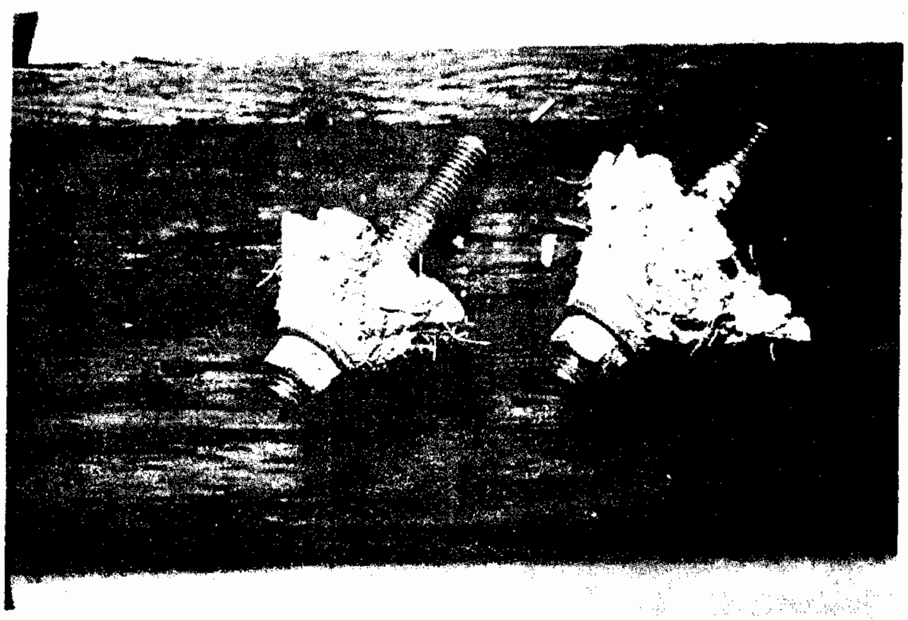


FIG. 13.5 PULL-OUT FRUSTRUMS EXTRACTED FROM STEEL FIBER SHOTCRETE

condition, length, and geometry of the frustrum extracted and comments about the speed and mode of failure were all recorded. The pull-out force was usually low whenever the frustrum disintegrated upon extraction. Whenever a pull-out frustrum of non-fibrous shotcrete disintegrated, the test results were considered invalid. A large number of the tests on steel fiber shotcrete resulted in broken frustrums because the fibers would not pull out of the shotcrete cleanly. Since it was usually impossible to tell if a frustrum disintegrated because of a bad break or because of fiber interference, there was no rational criterion available for rejecting test results. Consequently, the test results for steel fiber shotcrete are more variable. Figure 13.5 shows two intact cones extracted from steel fiber shotcrete.

Sufficient pull-out panels were gunned to permit numerous tests during the first few hours after shooting. Though these tests were made, reliable results were not obtained before about 3 hours, even on regulated-set panels. Tests were performed at intervals through one day, and then at three days, 28 days and 6 months. However, it was not until the six-month tests that pull-out test data could be correlated with compressive strength data from the same panel. Prior to the six-month tests, these correlations were made on the basis of pull-out tests from one panel and compressive tests on other panels.

13.5 RESULTS OF PULL-OUT TESTS

13.5.1 GENERAL

The pull-out strength is defined as the maximum force required to extract the anchor divided by the area of the conic failure surface.

The gage reading obtained from the pull-out test was converted to a force by the constant obtained during calibration tests for the particular device used. The area of the failure surface is obtained from the following formula:

$$\text{AREA} = \pi\ (D/2 + W/2) \sqrt{H^2 + (D/2 - W/2)^2}$$

where

W = anchor washer diameter 1.053 in. (26.75 mm)

D = ring diameter 2.687 in. (68.25 mm)

H - frustrum height 1.24 in. (31.2 mm)

The surface area for the design H was 8.72 in.^{2} (56 cm^2). Whenever H varied, the failure surface area was computed with the proper H since the results are sensitive to H. Results of pull-out tests are contained in the 28-day strength-time plots in Appendix E and in the tabulated results through six months in Appendix D.

To be useful, the relationship between pull-out strength and other strength parameters must be known. The following sections address that problem in terms of the ratio σ_c/σ_p. Pull-out tests and compressive strength tests were conducted on the same panel only at six months. These results will be evaluated first and then the evaluation of the same relations at one-month and earlier will be evaluated. Once the proper pull-out factor σ_c/σ_p is known, the compressive strength can be estimated.

13.5.2 RESULTS OF SIX-MONTH TESTS

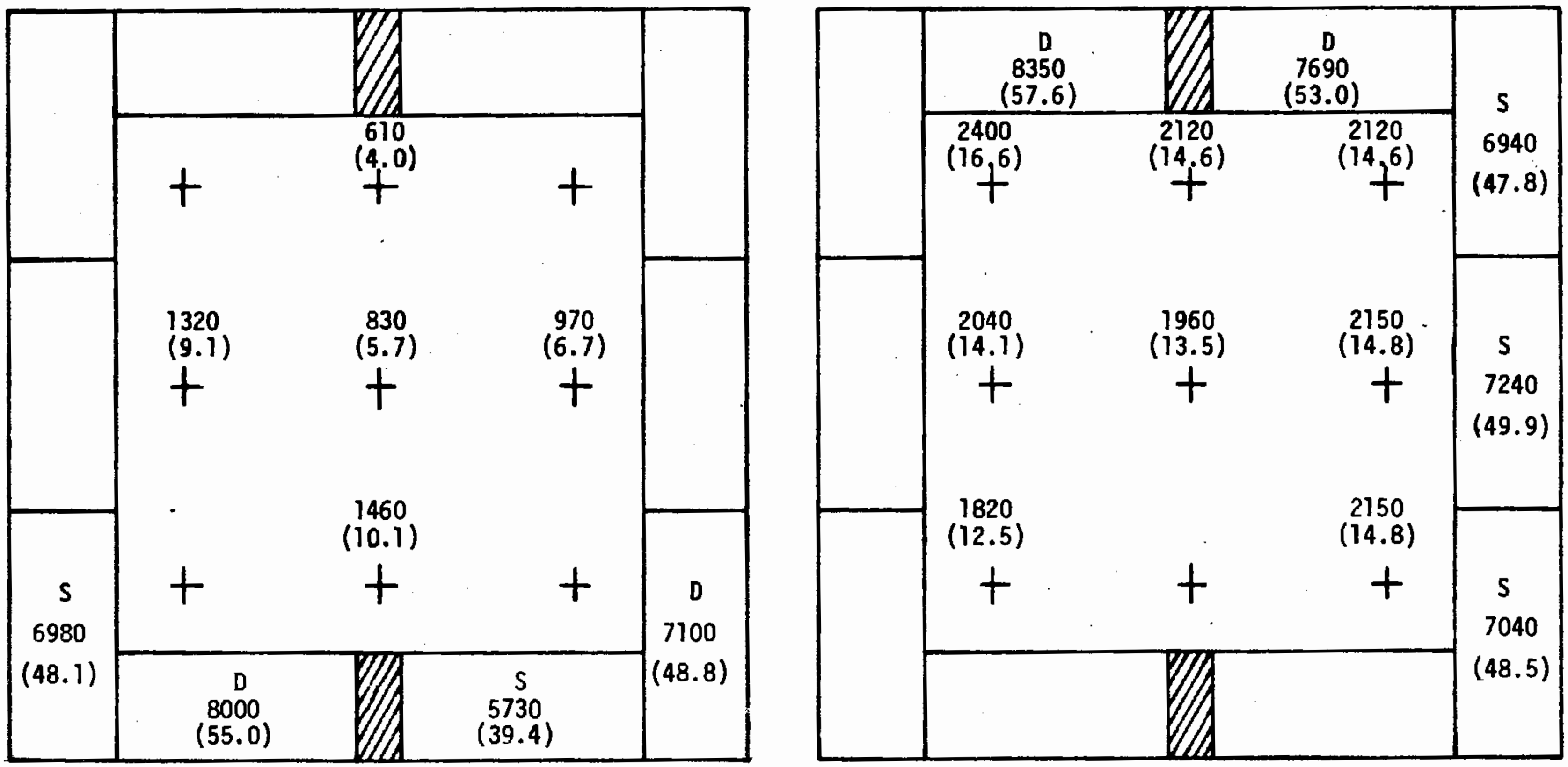
Pull-out panels for seven mixes remained to be tested at six months.

In order to more properly evaluate the relationship between pull-out and compressive strength, compression tests were performed on the remnants of the panels after pull-out testing was complete. The results are presented graphically in Fig. 13.6. Generally, the only space available that would provide prisms of sufficient size and length-to-width ratio was the perimeter of the panels. The locations of the tests and the results are contained in the figures so the strengths can be compared with their location in the panel visually.

One of the major differences between the pull-out tests and compressive tests conducted at 7 days or later was the fact that compression specimens were soaked prior to testing, while pull-out tests were conducted on air-dry panels. To assess this factor, about one-half of the compression specimens tested at six months were soaked in lime water for about 40 hours, while the other half were tested air dry. The condition of each specimen is shown on the figures by D (Dry) or S (Soaked).

The various average strengths for each panel are given in the figure for each panel. These are summarized in Table 13.1. The absolute value of the pull-out strength of steel fiber mixes is less than that of regulated-set mixes. However, the compressive strength of steel fiber mixes was lower and the evaluation must be made on the basis of the ratio of σ_c to σ_p. The ratio shown in the last column is the average strength of all prisms (soaked and dry) tested from one panel, divided by the average of all pull-out tests for the same panel. The ratio of the strength of each prism to the strength of the nearest pull-out test was evaluated but was not useful because of the large individual test variations. The average pull-out strength of all panels will be compared to

Number at cross mark is pull-out strength, σ_p, in psi (MPa).
Key for compressive strength data: D = Dry, S = Soaked; number in box is σ_c in psi (MPa)



Dry σ_c = 7550 (52.0) Soaked σ_c = 6360 (43.9)
Average σ_c = 6950 (47.9) Average σ_p = 1040 (7.17)

Note: σ_c and σ_p results subject to question

a) Panel 26-6

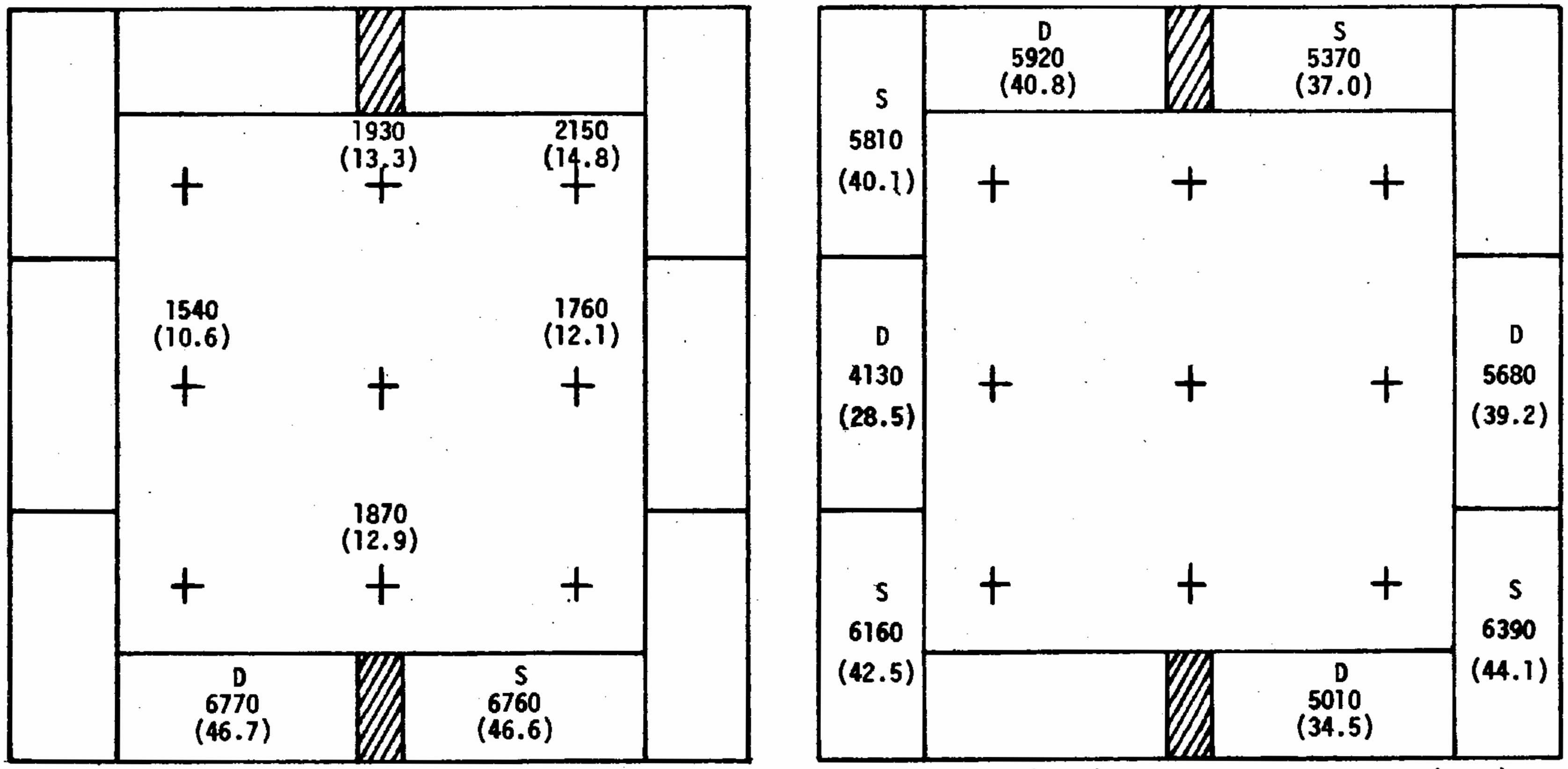
Dry σ_c = 8020 (55.3) Soaked σ_c = 7070 (48.7)
Average σ_c = 7450 (51.4) Average σ_p = 2090 (14.4)

b) Panel 28-8

FIG. 13.6 PULL-OUT AND COMPRESSIVE STRENGTH RESULTS FROM PULL-OUT PANELS AT SIX MONTHS

Number at cross mark is pull-out strength, σ_p, in psi (MPa)

Key for compressive strength data: D = Dry, S = Soaked number in box is σ_c in psi (MPa)



Dry σ_c = 6770 (46.7) Soaked σ_c = 6760 (46.6)

Average σ_c = 6760 (46.6) Average σ_p = 1850 (12.8)

c) Panel 29-10

Dry σ_c = 5190 (35.8) Soaked σ_c = 5930 (40.9)

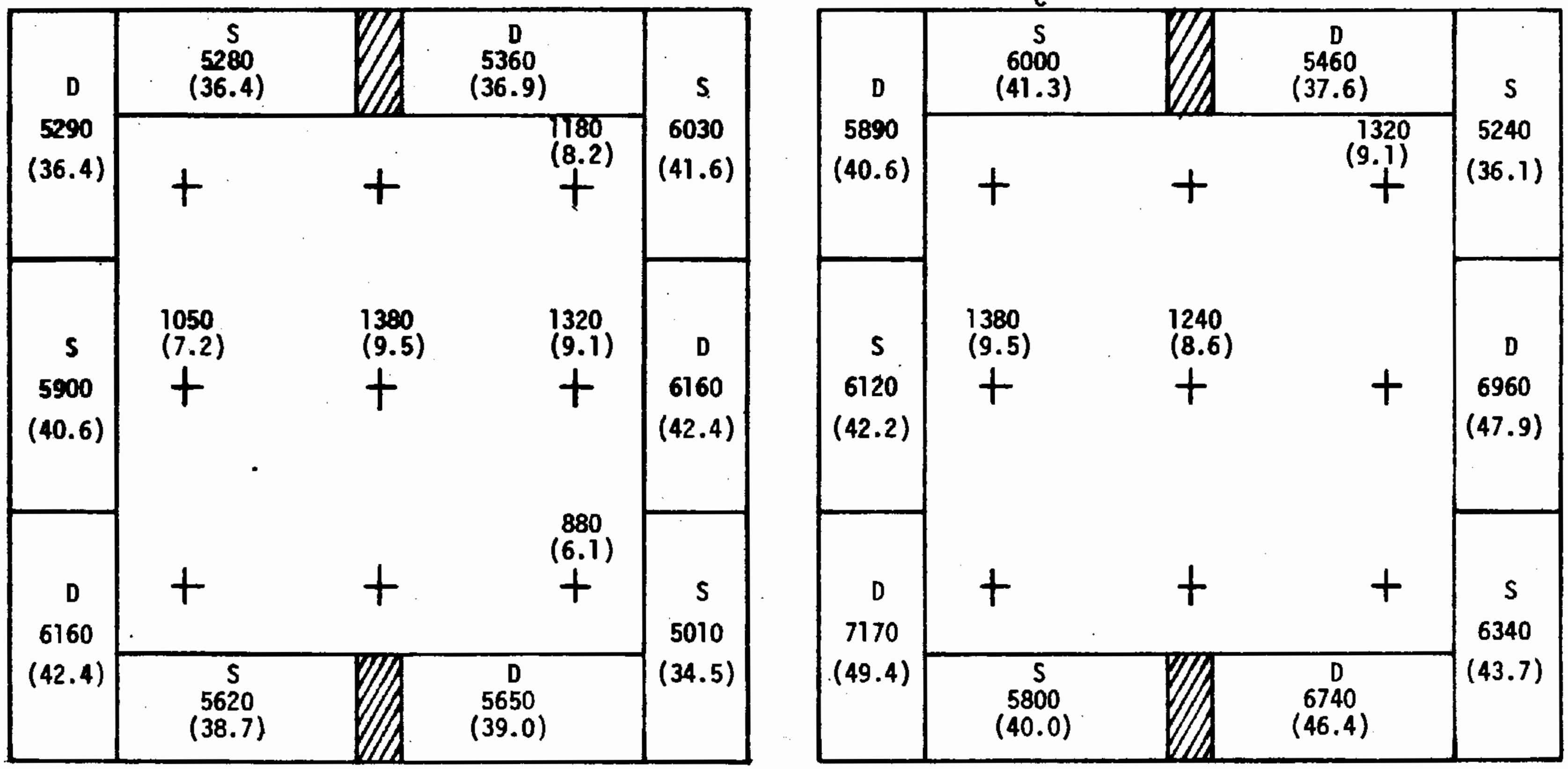
Average σ_c = 5560 (38.3) No pull-out tests

d) Panel 30-7

FIG. 13.6 (CONTINUED)

Number at cross mark is pull-out strength, σ_p, in psi (MPa)

Key for compressive strength data: D = Dry, S = Soaked, number in box is σ_c in psi (MPa)



Dry σ_c = 5720 (39.4) Soaked σ_c = 5570 (38.5)
Average σ_c = 5650 (39.0) Average σ_p = 1160 (8.0)

e) Panel 39-6

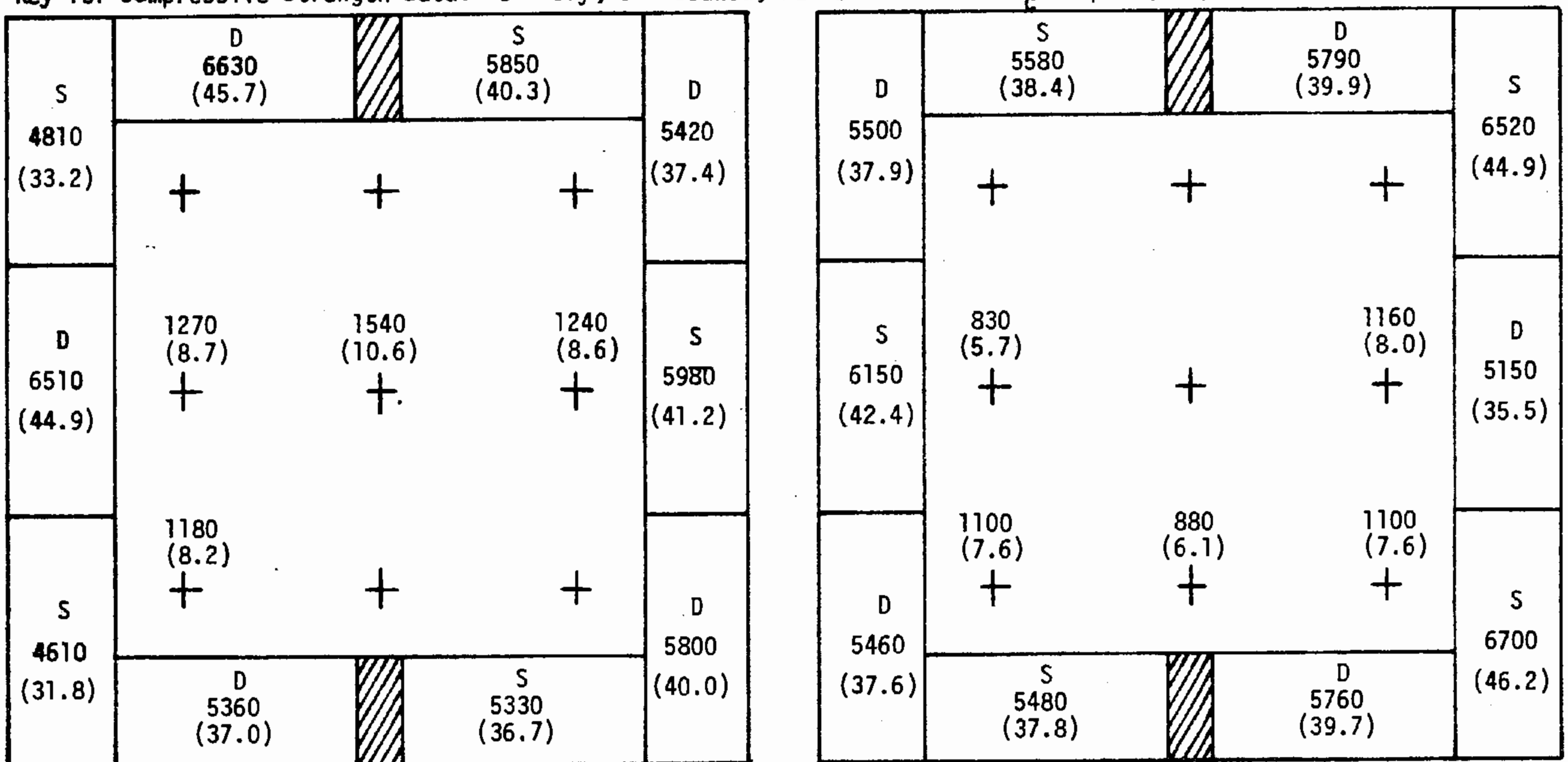
Dry σ_c = 6440 (44.4) Soaked σ_c = 5900 (40.7)
Average σ_c = 6170 (42.5) Average σ_p = 1310 (9.0)

f) Panel 39-7

FIG. 13.6 (CONTINUED)

Number at cross mark is pull-out strength, σ_p, in psi (MPa).

Key for compressive strength data: D = Dry, S = Soaked, number in box is σ_c in psi (MPa)



Dry σ_c = 5940 (41.0) Soaked σ_c = 5320 (36.7)

Average σ_c = 5630 (38.8) Average σ_p = 1310 (9.0)

g) Panel 39-8

Dry σ_c = 5530 (38.1) Soaked σ_c = 6090 (42.0)

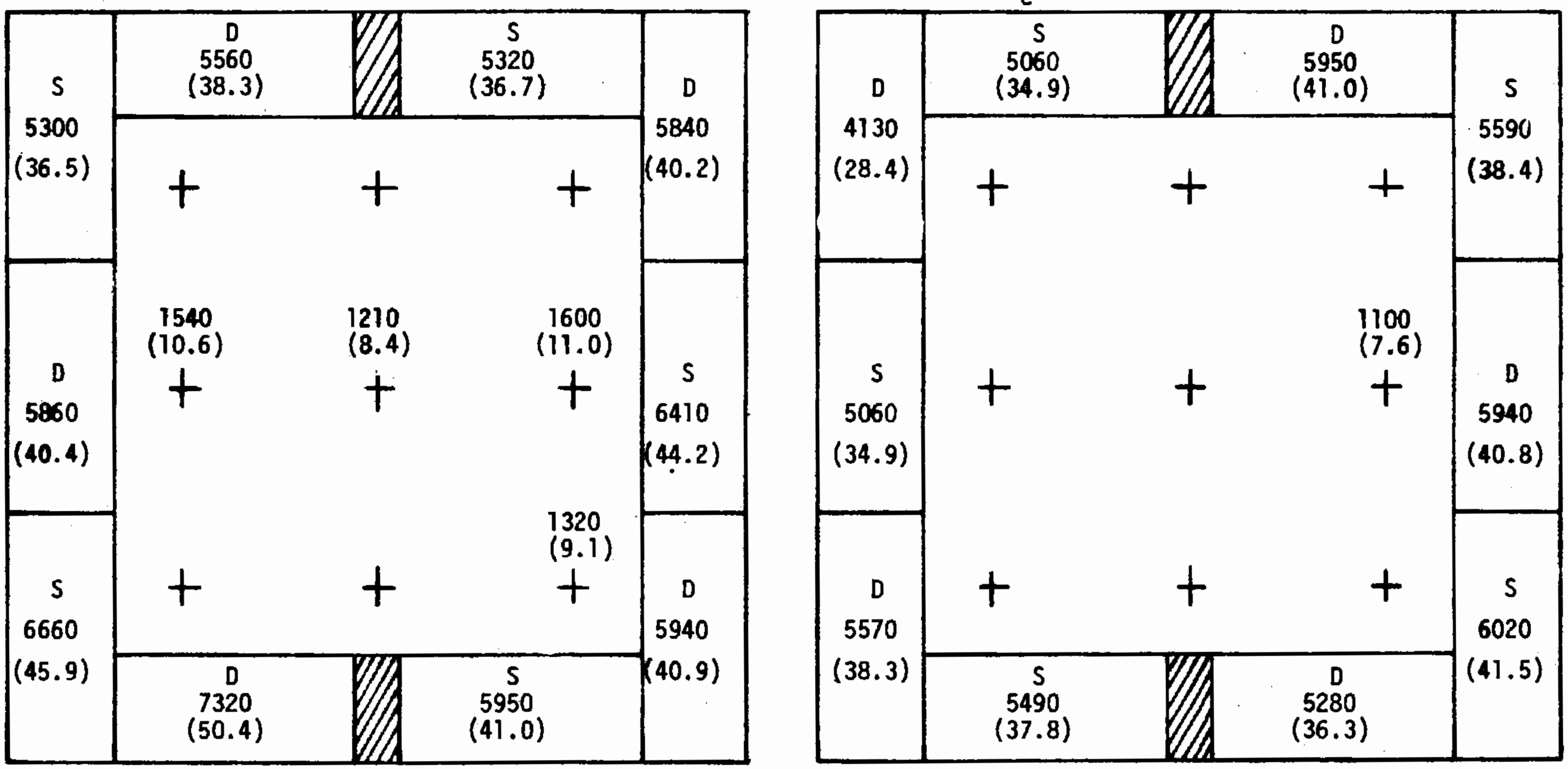
Average σ_c = 5810 (40.1) Average σ_p = 1010 (7.0)

h) Panel 40-4

FIG. 13.6 (CONTINUED)

Number at cross mark is pull-out strength, σ_p, in psi (MPa)

Key for compressive strength data: D = Dry, S = Soaked, number in box is σ_c in psi (MPa)



Dry σ_c = 6110 (42.1) Soaked σ_c = 5930 (40.9)

Average σ_c = 6020 (41.5) Average σ_p = 1420 (9.8)

i) Panel 40-9

Dry σ_c = 5370 (37.0) Soaked σ_c = 5440 (37.5)

Average σ_c = 5400 (37.2) Average σ_p = 1100 (7.6)

j) Panel 45-3

FIG. 13.6 (CONTINUED)

TABLE 13.1

COMPARISON OF AVERAGE PULL-OUT STRENGTH TO AVERAGE COMPRESSIVE STRENGTH AT SIX MONTHS

Mix and Panel Number	Number of Pull-out Tests	Average Pull-out Strength, σ_{p180}, psi (MPa)	Number of Compressive Specimens		Compressive Strength, σ_{c180}, psi (MPa)			Ratio of Average Compressive Strength to Pull-out Strength, for Panel
			Dry	Soaked	Dry	Soaked	Average	
Type I Cement Mixes								
26-6*	5	1040 (7.17)	2	2	7550 (52.0)	6360 (43.9)	6950 (47.9)	6.68
Regulated-Set Cement Mixes								
28-8	8	2090 (14.41)	2	3	8020 (55.3)	7070 (48.7)	7450 (51.4)	3.56
29-10	4	1850 (12.8)	1	1	6770 (46.7)	6760 (46.6)	6760 (46.6)	3.65
30-7	0	--	4	4	5190 (35.8)	5930 (40.9)	5560 (38.3)	--
Steel Fiber Mixes								
39-6	5	1160 (8.00)	5	5	5720 (39.4)	5570 (38.5)	5650 (39.0)	4.87
39-7	4	1310 (9.03)	5	5	6440 (44.4)	5900 (40.7)	6170 (42.5)	4.71
39-8	4	1310 (9.03)	5	5	5940 (41.0)	5320 (36.7)	5630 (38.8)	4.30
40-4	5	1010 (6.97)	5	5	5530 (38.1)	6090 (42.0)	5810 (40.1)	5.75
40-9	4	1420 (9.79)	5	5	6110 (42.1)	5930 (40.9)	6020 (41.5)	4.24
45-3	1	1100 (7.59)	5	5	5370 (37.0)	5440 (37.5)	5400 (37.2)	4.91
			Average Excluding Mix 26		6120 (42.2)	6000 (41.4)		

* Results of both pull-out and compressive strength are considered unreliable and are not included in averages.

the average compressive strength of all panel tests. For a variety of reasons, mostly associated with the poor quality of the panel and specimens, neither the pull-out strength nor the compressive strength of Panel 26-6 is considered reliable and these have not been included in the averages. This means there is no reliable information regarding conventional shotcrete.

Regulated-set shotcrete has a σ_c/σ_p ratio ranging between 3.56 and 3.69 at six months. Steel fiber shotcrete has a much higher ratio that ranges from about 4.24 to 5.75.

For comparison, Rutenbeck (1974) reports a relationship between pull-out tests and compression tests on 2 by 4 in. (5 by 10 cm) cores of about 4. Richards uses a similar ratio for concrete. Thus, the order of magnitude of the ratio obtained on these six-month tests appears reasonable. However, the ratio appears to be different for different types of shotcrete mixes. The stress path along the failure surface varies with the nature of the material. Perhaps the presence of fibers in steel fiber mixes interferes with the compaction process in the vicinity of the obstruction created by the pull-out device. Such a phenomenon would reduce the pull-out strength and result in a higher σ_c/σ_p ratio. This explanation is more likely than an unusual increase of the compressive strength because the compressive strength of pull-out panels is comparable to the strength of non-pull-out panels. Another reason for the higher strength ratio may be a greater strength gradient through the thickness of steel fiber shotcrete, the outer portions of a layer being significantly stronger than that close to the rock wall. The pull-out tests on this project represent the strength of the back of the layer and the strength ratio would be higher if the strength of the back of the panel, as measured by σ_p, were much lower than the average strength of the layer as measured by testing a prism.

There are many factors involved in the correlation between compressive and pull-out strength. One of these is the fact that after one day, all compressive specimens were soaked for 24 to 48 hours prior to testing while pull-out tests were never conducted on soaked shotcrete. To evaluate this effect, one-half of the six-month compression tests were soaked about 40 hr prior to testing while the other half were tested dry. The results, given in Table 13.1, indicate that soaking the specimens for the six-month test does not appear to be a controlling factor in the strength. Some of the panels exhibited a higher-than-average strength for soaked specimens, but a greater number of panels had a higher average dry strength. Observations of the failure surfaces of soaked specimens indicated that only the outer 0.25 in. (6 mm) appeared to have absorbed water during the 40 hr soaking period. Accordingly, it is unlikely that soaking could have been a significant factor in the six-month strengths. The variations in strength are, therefore, a result of the normal testing variations as discussed in Section 9.6. The overall averages of dry and soaked strengths of all panels, except Mix 26, indicated that the average dry strength was only about 120 psi (0.83 MPa) higher.

13.5.3 CHANGES IN PULL-OUT STRENGTH WITH TIME AND MIX

GENERAL

As a result of hydration, compressive strength of any cementitious material increases with time at a rate governed by many factors including the mix, placement, and curing conditions. This process also causes an increase in the elastic properties and in the other strength parameters such as flexural and pull-out strength. However, the rates of change of these elastic properties and of the common strength parameters, such as flexural strength, are not the same as the rate of change in compressive strength. These parameters generally are related non-linearly to compressive strength, usually approximated by assuming the parameters are related to the square root of compressive strength.

There are no rational, physical reasons why the relationship between pull-out strength and compressive strength should be significantly different than the relations established for other strength parameters, although there is a tendency in some of the literature to make the tacit assumption that σ_p is related to σ_c linearly, or at least that there is only one σ_c/σ_p ratio.

Malhotra (1975) reports the results of a comparative program that evaluates the ratio for concrete mixes at different ages and different compressive strength at each of the ages. He concludes from the study that "The pull-out strength: compressive ratio varies directly with the compressive strength of concrete.". . . ."However, for any strength level the ratio does not significantly change with age." He also speculates that it is probable that pull-out tests on concrete made with aggregate having different hardness and surface textures will correlate differently with compressive strength.

Malhotra's findings agree with the data collected for this project, which indicates that the ratio σ_c/σ_p decreases with time or, more properly, with increasing compressive strength. Furthermore, different types of shotcrete appear to have different ratios. These findings are discussed in the following sections.

EARLY STRENGTH RESULTS

The plots in Appendix E illustrate the pull-out strength-time relationship for individual mixes. It can be seen that measured pull-out strength at very early ages is a substantial percentage of the measured compressive strength. In fact, in Mixes 24, 28, 30 and 42, the pull-out strength appears to be as great or greater than the compressive strength. These were regulated-set cement mixes and the high pull-out strengths confirm the ability of this cement to achieve high early strength. The reason for unusually high pull-out strength, in some cases, is believed to be a result of considerable panel-to-panel variation in the early strength behavior of some of the regulated-set mixes.

Some panels seemed to have achieved the expected high-early-strength, while others from the same mix did not. Single pull-out tests, usually on front pull-out devices, were performed on selected panels of each mix from about 5 to 10 minutes after shooting until a reliable strength could be measured. At least 2 or 3 of the back pull-out devices of that panel were then tested to obtain an average pull-out strength for that age. This method resulted in testing of the pull-out panel with the fastest strength gain. This may explain why pull-out strength appears to be greater than compressive strength in selected regulated-set mixes because compression specimens were not selected to give the highest strength.

RESULTS AT AGES GREATER THAN ONE DAY

The fact that the measured pull-out strength was nearly as high as the measured compressive strength results in a low σ_c/σ_p for very-early strength.

Compressive strength for regulated-set Mix 28 is plotted against pull-out strength in Fig. 13.7. The curve shown is based on the average strength-time curves for Mix 28 (Appendix E) rather than the tabulated data for each test in Appendix D. Because of the greater uncertainty in such a correlation between two types of tests on two different panels at a time of rapid gain of strength, the curve is shown dashed for ages less than one day or less than about 4000 psi (27.6 MPa). Subsequent to one day, the ratio σ_c/σ_p continues to change. Similar plots for other mixes also indicate a variable σ_c/σ_p ratio.

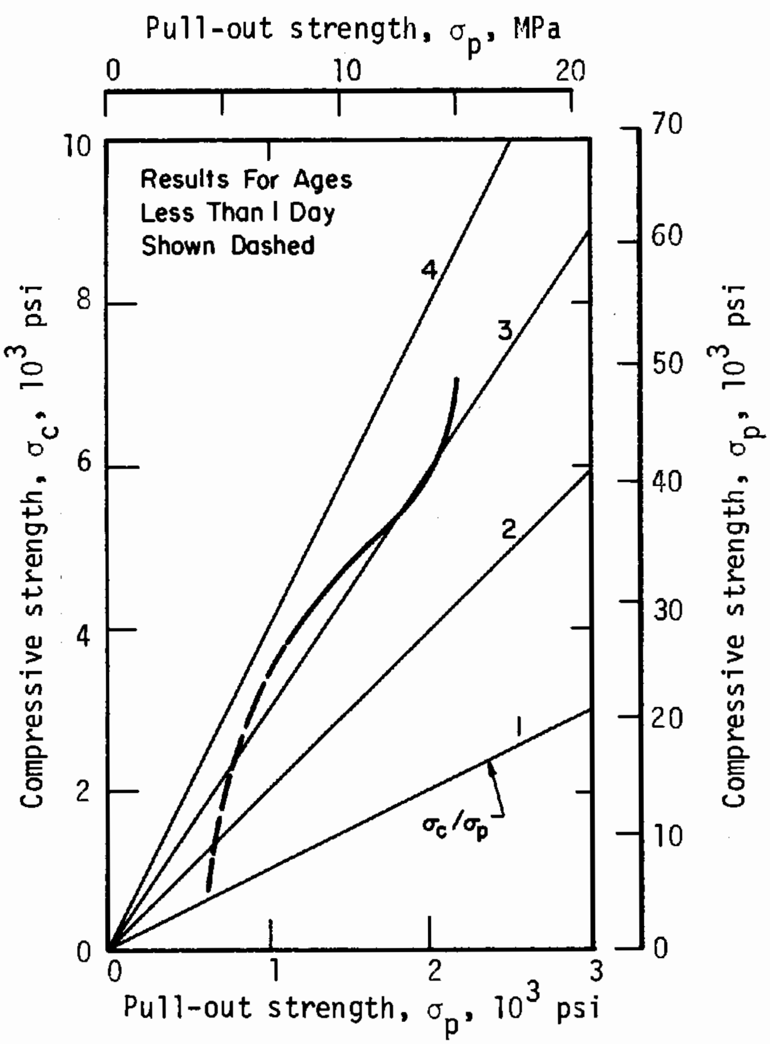
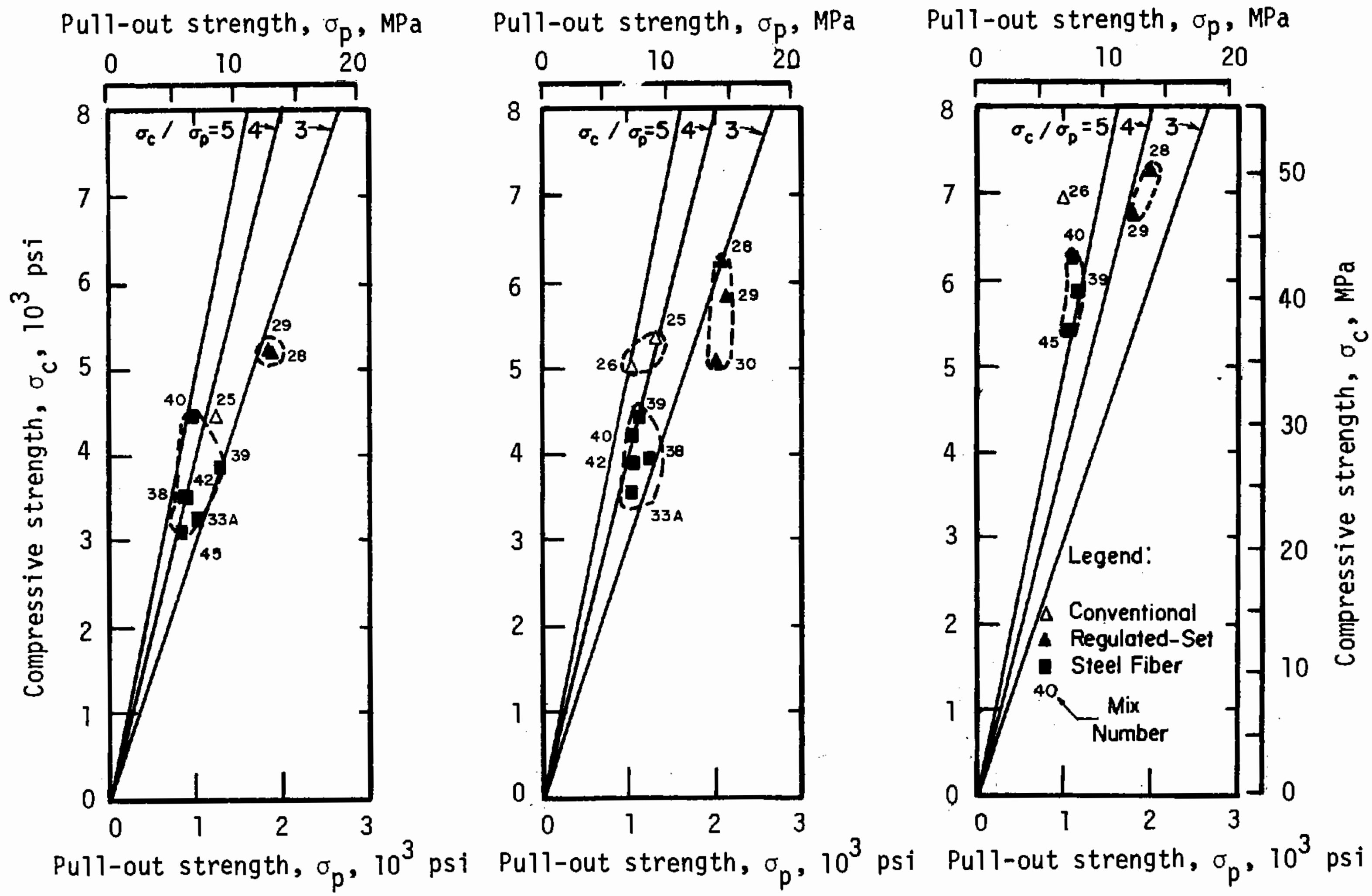


FIG. 13.7 RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND PULL-OUT STRENGTH: REGULATED-SET MIX 28

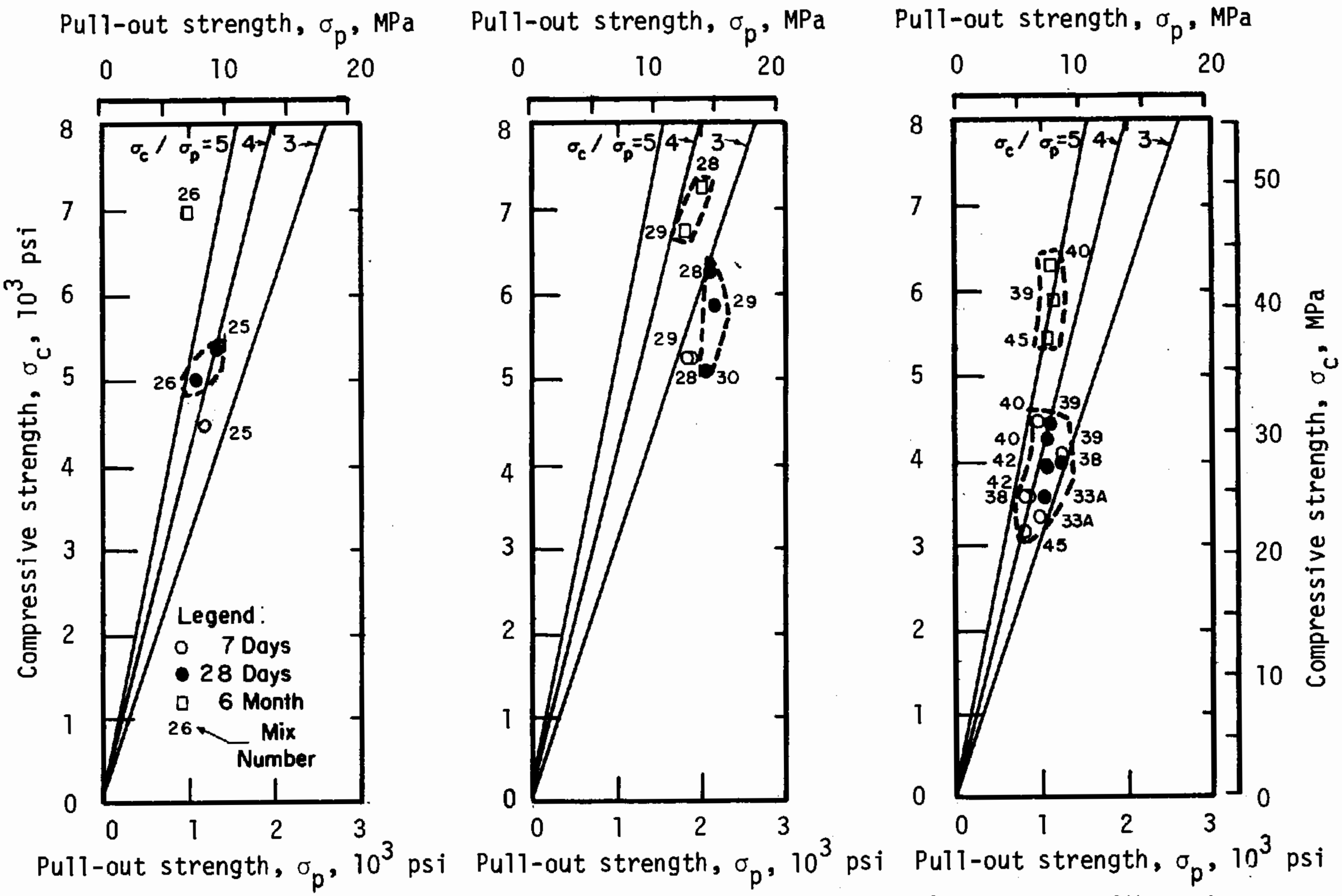
As can be seen in the plotted strength data in Appendix E, the pull-out strength-time curves are more similar to the flexural than to the compressive strength-time curves. Plots between pull-out and flexural strengths are almost linear. As far as the mode of failure is concerned, the flexural and pull-out strengths are more nearly tensile modes of failure and their similar magnitudes of strength and strength-time curves are not surprising. Accordingly, the pull-out tests are a better index of intact flexural strength--an important property, geotechnically, for tunnel support. Unfortunately, pull-out tests do not test the mass physical properties that include defects such as laminations. The compression tests, tested parallel to laminations as they were done for this project, are sensitive to these defects; this, coupled with the fact that pull-out tests are not as sensitive to laminations, accounts for some of the scatter and some of the variations in the σ_c/σ_p ratio. Also, the influence of laminations on compressive strength varies with age of the specimen.

Additional data regarding the correlation of pull-out strength to compressive strength are summarized in Figs. 13.8 and 13.9. Figure 13.8 contains three plots of average compressive strength versus average pull-out strength for tests at seven days, one month and six months. Dashed lines encircle all the mixes in the same major group, i.e., conventional non-fibrous, non-fibrous regulated-set, and fibrous mixes. Lines of constant σ_c/σ_p ratio are included in the plots; the line for $\sigma_c/\sigma_p = 4$ very closely approximates the regression line given by Rutenbeck (1974) for the correlation between pull-out strength and the strength of cores taken from the same shotcrete panel. It can be seen that mixes in the same group tend to cluster in each figure for each age. Likewise, the data tend to cluster by age when it is replotted separately



a) Tests at 7 days
b) Tests at one month
c) Tests at six months

FIG. 13.8 RELATIONSHIP OF COMPRESSIVE STRENGTH TO PULL-OUT STRENGTH, ACCORDING TO AGE



a) All conventional mixes b) All regulated-set mixes c) All steel fiber mixes

FIG. 13.9 RELATIONSHIP OF COMPRESSIVE STRENGTH TO PULL-OUT STRENGTH ACCORDING TO MAJOR GROUP OF MIXES into major groups, as done in Fig. 13.9. In both figures, each small cluster tends to have a lot of scatter that is probably associated with panel-to-panel strength differences and to different mix designs and shooting conditions within each group. Figures 13.8 and 13.9 are merely the same data plotted differently; however, the plots highlight the conclusion that the ratio σ_c/σ_p varies with different types of shotcrete, with the absolute levels of strength (function of age), and probably with mix design and shooting conditions within each major group. The tendency is for the ratio σ_c/σ_p to decrease with increasing strength. There does appear to be a centroid for each group that might be used for that group which indicates that, with sufficient calibration testing, a good average value of σ_c/σ_p could be determined for any particular type of shotcrete at a particular age. Also, it appears that a minimum ratio could be determined statistically. Correlations based on this minimum ratio would give results on the conservative side.

13.5.4 MODE OF FAILURE

Mixes that did not contain fiber failed like a brittle material, giving little or no warning. The extracted frustrums had very regular cross sections. The failure surface was somewhat curved rather than straight, which adds slightly to the failure surface area. The failure surface sheared through about one-half the pieces of aggregate in its path. Most frustrums of nonfibrous shotcrete were intact on extraction. It was clear that breakage of a frustrum was an indication of improper testing conditions. Rejection of data from broken frustrums should be part of the test procedure.

Mixes that contained fiber never failed suddenly, but acted as a ductile-like material. After the maximum load had been reached, additional pumping was necessary to fully extract the frustrum. The failure surfaces were seldom regular and, in a few cases, it even extended outside the inner edge of the steel reaction ring. Shotcrete material was observed to cling to the steel fiber in most cases. Many frustrums were broken on extraction, not only because of improper test conditions, but also because of the interference with steel fibers. Steel fibers did not yield; instead, they were pulled from the adjacent shotcrete matrix, usually disrupting the matrix in the process.

13.5.5 RELIABILITY OF RESULTS

Considering the conditions, the coefficients of variation for non-fibrous mixes were good; for tests at seven days and one month, the coefficient of variation generally ranged from one to six percent. These good results are partly attributable to the fact that the depth of embedment was controlled carefully. For the poorer panels tested at six months, the coefficient of variation ranged up to 12 percent with the exception of the data from Mix 26 which were not considered reliable for a variety of other reasons.

The coefficient of variation for steel fiber mixes ranged from one to 35 percent; most of the values were from 10 to 20 percent. There was greater scatter with the steel fiber mixes because frustrums that were broken on extraction were included in the results. There was no simple foolproof method to determine if the breakage was the result of poor test conditions or if it was caused by interference of fibers after a clean break.

More field testing is required to evaluate the repeatability of results and the sensitivity of the method to changes in the strength of the matrix and to structural defects such as laminations. Fortunately, the method is inexpensive and promising, and further research is warranted.

CHAPTER 14

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

14.1 INTRODUCTION

The application of shotcrete by the dry-mix process and the engineering properties of coarse aggregate shotcrete have been investigated in detail. Processes and quality-control aspects of shotcrete, previously taken for granted, have been identified, described, evaluated, and, where possible, quantified.

The findings and conclusions are summarized in this chapter with a brief discussion of their significance. Where appropriate, applications of the results to practice are emphasized in terms of improvements to specifications, inspection, quality control, or design techniques. Geotechnical implications of the results are discussed and the needs for future research given.

14.2 IMPORTANCE OF FIELD TESTING AND CONTRACTUAL ARRANGEMENTS

Shooting conditions have a dominant influence on the engineering behavior of coarse-aggregate shotcrete with fast-set accelerators and these shooting conditions cannot be duplicated by small-scale laboratory tests and small trial batches. There is a need for full-scale research under controlled conditions, but, ultimately, shotcrete must be tested in the field using typical crews and equipment. Factors that can be controlled in the laboratory often cannot be controlled in the field to a degree that the results are affected. The environment and procedures underground are sufficiently different that field testing underground is warranted to proof-test new materials, equipment, or methods.

One way of accomplishing the field testing within a reasonable time schedule is to engage a contractor already using shotcrete on an active job. Cooperative field research projects on on-going construction projects are difficult to arrange contractually. They require a special interest in the study on the part of all the involved parties. Arrangements for the research for this study resulted from cooperation between a university, contractor, owner, resident engineer, and the Federal Government. One of the accomplishments of this program was the successful negotiation of the necessary arrangements and contracts among parties to conduct a major field research program on an active construction job. It was made possible because the Owner, WMATA, elected to administrate the research by means of a change order to an existing construction contract. These arrangements were entirely satisfactory and similar arrangements might be a means for permitting future major research projects on active construction projects.

14.3 IMPORTANCE OF DOCUMENTATION OF FIELD CONDITIONS

The shooting conditions are so important to the engineering behavior of shotcrete that the environmental and shooting conditions must be documented in detail in order to be able to assess the test results properly. This is true not only for research studies but also for everyday problems faced by a contractor or engineer trying to determine the cause of low-strength or otherwise unsatisfactory shotcrete. This has great practical significance during preconstruction testing when the relative merits of several mix and shooting conditions must be determined to select the most economical mix design.

It was found that many of the parameters describing the shooting conditions were interdependent. A change in one parameter may cause an uncontrolled change in other parameters or may require an adjustment in other parameters to maintain satisfactory operation. Thus, it is quite difficult to change only one parameter. Documentation of field conditions would show which parameters remained constant and which changed.

Consistent accurate dispensing of accelerator is very difficult; it has been neglected in the past. Difficulties with variable accelerator dosages complicated this study. The accelerator dosage has been shown to have such great importance to the early and ultimate strength of shotcrete that specifications should require frequent calibration of dispensers and should require that field records be maintained on the actual accelerator dosage used on each shift as well as the location of shotcrete placed during the shift. Zones with high dosages must be tested.

One of the most useful parameters measured was the material delivery rate (MDR). Measurement of the material delivery rate permits a quantitative evaluation of the shooting operation; MDR reflects many shooting conditions including, at least in the case of air operated guns, air pressure and accelerator dosage. There is an optimum MDR for shotcreting that should be determined for each job. Subsequently, the equipment should be operated at the optimum MDR.

14.4 REGULATED-SET CEMENT SHOTCRETE

Regulated-set cement was successfully field tested in dry-mix shotcrete using typical crews and equipment found in underground construction.

Rebound may have been slightly higher but was not excessive and it was shown that regulated-set shotcrete can be placed under flowing-water conditions.

Regulated-set shotcrete has properties that give it superior rock supporting capabilities especially in loosening ground conditions that require substantial early support. Regulated-set shotcrete requires no accelerators, but its set can be accelerated by heating the water added at the nozzle. Even with the low temperatures that prevailed in this study, one mix achieved a compressive strength of 1350 psi (9.3 MPa) in 2 hours; 27 times the strength of shotcrete with 3 percent accelerator and 2 to 3 times the strength of a mix with about 5 percent accelerator. The strength of regulated-set shotcrete consistently exceeded the strength of all conventional mixes at all ages, but its strength advantage reduced with time. Its compressive strength of about 6220 psi (42.9 MPa) at one month was about 25 percent greater than the strength of conventional shotcrete. Its six-month compressive strength was 7250 psi (50.0 MPa).

Regulated-set cement is very temperature-and-moisture sensitive. Many mixes shot for this program were batched with very wet aggregate and were shot with nozzle water that was too hot. Because of these erratic shooting conditions, the early strengths were erratic and many mixes did not achieve the expected very high early strength, yet they were still consistently higher than conventional shotcrete. Trial mixes will be necessary for each project using regulated-set cement to determine the optimum shooting conditions. Although weight batching of regulated-set shotcrete was successful, continuous-type mixers are believed to be essential for any non-experimental application.

Regulated-set cement is not suitable for presently-available (1975) wet-mix equipment because it will set in the lines in a few minutes in the event of equipment breakdown or routine work stoppages.

Since regulated-set cement requires no accelerator, the exposure of the crew to caustic additives is minimized, an important safety aspect. It is expected to be more expensive. Presently, regulated-set cement is available in limited quantities at only one location in the United States.

Future research on reg-set shotcrete should include studies of the temperature and moisture sensitivity of the material to determine a range of optimum conditions. Its cost, sulfate resistance, and safety aspects should be investigated. Although presently (1975) impractical, special techniques to utilize regulated-set cement in the wet-mix process might be investigated. Such a process might include artificial cooling of the wet-mix followed by reheating during shooting, but must include appropriate emergency clean-out precautions.

14.5 STEEL FIBER SHOTCRETE

Several mixes of steel-fiber, coarse aggregate shotcrete were also successfully shot using typical crews and equipment. The use of coarse aggregate steel fiber shotcrete has not been reported before. Compressive strengths of fibrous mixes were about the same as non-fibrous conventional mixes up to about one day. The one-month strength of fibrous mixes was about 10 to 20 percent lower than conventional non-fibrous shotcrete. The presence of fibers in a mix are believed to interfere with the compaction process which, in turn, produces a lower compressive strength. Average rebound of the steel fiber mixes shot was comparable to other mixes.

The full potential of the fibers in flexure was not achieved in this program because of the low fiber contents in-place and because the fibers had been severely bent by the pug-mill mixer. The bent shapes of the fibers reduced their effective length and caused some problems with balling of the fibers during mixing. It is recommended that mixing equipment proposed for fiber shotcrete be tested before final selection. The rebound rate of the fibers was extremely high, a fact that increases the cost of an already expensive material. The fiber content in-place was only 1/2 to 2/3 of the fiber content batched. These factors resulted in essentially the same flexural strength for both conventional and fibrous mixes. However, the fibrous specimens exhibited substantial post-crack resistance, a very important factor for rock support. Substantial loads were carried by test beams even after a large crack had opened.

It is believed that future work in steel fiber shotcrete can, with proper quality control, attain higher fiber retention so that the expected higher flexural strengths can be obtained. These higher strengths, together with the substantial post-crack resistance, will make steel fiber shotcrete a more effective support for tunnels in loosening ground conditions in jointed rock. It is not a substitute for mesh but may suffice where mesh is not absolutely required or where it is impractical to place mesh. Steel-fiber, regulated-set shotcrete, also successfully tested, would be well-suited for loosening ground conditions in jointed rock requiring substantial early support.

The retention of fiber was studied by counting fibers exposed on the cut surfaces of specimens, by weighing fibers in fresh samples, and by weighing fibers obtained from pulverized samples of hardened shotcrete. Numerous conditions were changed when shooting the fibrous samples to evaluate their effect on fiber retention, but none except possibly a substantial increase in cement content, appeared to affect the retention of fibers. A high-speed photographic study of the airstream did not indicate any particular interference between coarse aggregate and fibers. Hence, the presence of coarse aggregate was not necessarily responsible for the high fiber losses. Fibers appeared to be located mostly in the peripheral zone of the airstream where conditions for rebound or for being carried away by the remnant air currents were most favorable. High cement or high accelerator contents and the details of nozzling are believed to be important to fiber retention. Nozzlemen will have to be trained to look for and correct conditions conducive to high fiber losses. Routine inspection procedures should include an evaluation of fiber content, distribution, and orientation.

The distribution and orientation of fibers in hardened samples was studied by x-ray methods. The fibers were oriented primarily in the plane of the wall. They appeared to be concentrated in sub-parallel bands that are believed to be surfaces that were exposed for a fraction of a minute between successive passes of the nozzle. X-rays of beams that had been tested in flexure indicated that the flexural cracks followed the sinuous paths of least fiber concentration (least resistance) through the thickness of the specimen.

No special problems were encountered with the fibers. The fibers posed no more a missile hazard than coarse aggregate. The normal protective clothing that must be worn by the nozzleman and others near the nozzle was found to be adequate. Wearing of goggles by everyone in the shooting area is essential; the nozzleman should have a full face mask. There is a greater potential safety hazard to personnel before and after shooting fiber which can be minimized by an adequate training program.

Future research on steel fiber shotcrete must focus on improved fiber retention. The effectiveness of lower air pressure, higher cement or cement-fly ash contents, pre-treatment of fibers, or finer or more well-graded aggregate gradation to enhance fiber retention should be investigated. Shooting conditions that affect the orientation of fibers and the effect of various orientations on flexural strength should be determined so optimum conditions may be specified. The effect of various fiber contents on compressive and flexural strength must be studied to determine the optimum fiber content for maximum compressive or flexural strength, maximum post-crack resistance, or maximum economy consistent with some desired level of engineering properties. Other factors that deserve attention are the corrosion resistance of steel fibers, before and after cracking; the shrinkage behavior of fibrous shotcrete; and its long term durability. The relative costs and benefits between mesh and fibrous shotcrete should be determined. Finally, the geotechnical aspects of increased flexural strength and post-crack resistance should be evaluated and rational design procedures for fibrous shotcrete developed.

14.6 REBOUND

The process of rebound was studied in detail by means of field rebound tests; close visual observation; high-speed photographic studies; and by evaluation of the fresh samples taken from the dry mix, wall, and rebound; and by theoretical means.

Though it is common knowledge in the shotcrete industry that more rebound occurs when first shooting against a bare, hard surface than during subsequent stages, the importance of this phenomenon has never been fully recognized. The most important finding of this study was the fact that, because of this phenomenon of high initial losses, rebound tests, as customarily conducted, are so strongly affected by the thickness shot that they may not even be representative of the project on which the rebound test was made unless the test thickness equaled the project thickness. Comparisons with other projects are impractical unless the thickness was reported.

The process of rebound of dry-mix shotcrete was idealized by separating it into two phases in which the behavior is quite different. Phase 1 consists of the build-up of the initial critical thickness and has very high rebound losses. Phase 2, characterized by a relatively low rate of rebound, begins after an initial critical thickness of fresh shotcrete has been established on the wall.

Several parameters were introduced to quantitatively describe the process of rebound and the changes in rebound behavior with the build-up of thickness on the wall. The Rebound Rate Ratio, RRR, was defined as the instantaneous ratio of the weight of material that rebounds to the weight of material shot. The magnitude of RRR is close to 1.0 at the beginning of shooting against a hard surface. The value of RRR reduces rapidly with the build up of the critical thickness and becomes approximately constant during Phase 2 at a level of about 0.05 to 0.30. Rebound Rate Ratio, properly determined, will accurately reflect the physical behavior throughout the duration of the test. It is quite sensitive to changes in mix or shooting conditions and nozzling techniques and, thus, is good for comparisons. RRR is not suitable for economic comparisons, however, unless converted to other parameters. Rebound Rate Ratio was determined experimentally in this study by conducting several multiple-tarp rebound tests that isolated the material rebounded during several separate intervals of a continuous rebound test. Experimental values of RRR ranged from 0.5 to 0.9 during Phase 1 and from 0.05 to 0.15 during Phase 2; RRR was nearly constant after the critical thickness (about 0.2 in. (5mm)). Hence, in Phase 1, about 50 to 90 percent of the material shot rebounds.

The parameter Average Rebound, RAVE, was defined as the cumulative weight that has rebounded during the entire duration of a test divided by the cumulative weight that was shot during the same interval. RAVE is the value that is most often reported by the industry and is often called the rebound percentage. RAVE accurately reflects the total amount of rebound lost when shooting to a given thickness and, thus, has economic importance. Accordingly, thin linings should have high values of average rebound, RAVE, while a thick lining should be expected to have a moderate to low RAVE. Thin linings should be more expensive than thick linings on a unit cost basis. However, the magnitude of RAVE is dominated by the very high losses during Phase 1 such that the magnitude of RAVE decreases slowly as more material is shot to a greater thickness. Accordingly, the magnitude of RAVE is high and is decreasing slowly at a time when the true rate of rebound (a function of RRR) has been constant at a low level. The effect is caused by the fact that RAVE is defined as an average of two vastly different rates of rebound.

This delayed reflection of the physical rebound behavior means two identical rebound tests will give different values of average rebound, RAVE, if they are conducted in the customary manner but to different thicknesses; the test shot to the least thickness will have the highest measured value of average rebound. Thus, rebound results previously reported in the literature have limited value unless they were properly documented by the actual thickness shot. That does not mean that the data were incorrect. In fact, if the thickness in a rebound test was the same thickness as used on the project, and if a certain surface area was shot to a uniform thickness during the rebound test, the measured RAVE accurately reflected the actual losses on the project. On the other hand, if the thicknesses were different, the test value was not representative of actual losses. In fact, previously-reported high rebound values may not have been the result of poor workmanship but only the result of the fact that the test thickness was relatively thin. In addition, many previously reported values of rebound have some unknown bias caused by the thickness effect, many to the extent that they cannot be used for correlation with other projects.

This influence of the thickness effect on the magnitude of RAVE was verified in this study by a multiple-tarp rebound test. The test was shot continuously to 4.2 in. (10.7 cm) except for a few seconds necessary to place each tarp. If this test had been stopped arbitrarily at 1, 2, 3, or 4 in. (2.5, 5.0, 7.6, or 10 cm), the measured RAVE would have been 39, 25, 20 or 19 percent, respectively. This thickness effect overshadowed all other parameters in the 27 experimental values of RAVE obtained. A well-defined curve was obtained by plotting the measured RAVE versus total thickness. This curve was also derived theoretically using reasonable assumptions for RRR. A similar trend from documented field results was also established.

Several changes in mix design and shooting conditions were made during the experimental program; no parameter was as important as the thickness shot which overshadowed and complicated all other comparisons. The low temperatures also complicated the study and are believed to have resulted in higher rebound values. Moderate changes in cement content, accelerator content, and type of surface shot did not appear to have a strong effect on the measured values of average rebound, RAVE. Increasing the temperature of nozzle-water reduced rebound in one series of tests and a high accelerator dosage resulted in high rebound. Other comparisons had mixed results. Shooting too dry resulted in substantially higher rebound even though the air pressure had been reduced; this shows the importance of water content to rebound. In another series of tests, reducing air pressure and shooting at the same consistency, reduced rebound. A direct comparison between regulated-set and Type I cement with accelerators indicated that regulated-set shotcrete in general had higher rebound; yet the lowest value of RAVE measured was a thick lift of a very rich mix of regulated-set shotcrete, shot with very hot water. In all the tests, about 95 percent of all material that rebounded landed within 4 ft (1.2 m) of the base of the wall.

Equations that can be used to determine the weight of material that must be shot to obtain a given weight or yield on the wall were derived and used to illustrate several important considerations regarding the economics of rebound. The desired weight in-place must be multiplied by the Overshoot Factor, OSF, a function of RAVE, to determine the weight that must be shot. It was shown that economic comparisons should be made on the basis of OSF. When RAVE is above 50 percent, the rebound losses become extremely important and costly. Specifications should include a maximum allowable value for rebound. Because of the high Phase 1 losses each time a new lift is shot, it was found to be more expensive to shoot a lining in multiple-lifts than in one single continuous lift. Further, it was concluded that the reduction of the high losses of Phase 1 is a very important goal, but that this improvement cannot be made at the expense of higher losses during Phase 2.

Because of the thickness effect, a standard rebound test, incorporating a standard thickness, was proposed. The test is simple and it results in the determination of RRR for Phase 1 and for Phase 2, as well as RAVE at the standard thickness of 10 cm (4 in.). Factors that should be reported for all rebound tests are also given. Nozzlemen should be required to demonstrate their ability to minimize rebound by shooting a standard rebound test frequently.

Finally, the process of rebound was described qualitatively on a micro as well as a macroscopic scale. On a microscopic scale, the rebound behavior of each individual constituent in the airstream was described and the rebound rate of each constituent was estimated quantitatively. On a macroscopic scale, mix and shooting conditions that reduce the rebound losses of Phase 1 are not necessarily good for reduction of rebound losses during Phase 2. However, shooting at the wettest stable consistency should reduce rebound losses during Phase 2.

Clearly, research on rebound of shotcrete should focus on its reduction. For dry-mix shotcrete, the reduction of rebound during Phase 1 is particularly important. This will require new equipment, new techniques, and a more comprehensive and detailed knowledge of the true causes of rebound under various conditions other than those studied herein. The effect of consistency of material on the wall, size and gradation of aggregate, cement content, accelerator dosage, and velocity of particles on rebound during both Phases, should be quantified. Differences in rebound between wet-and-dry mix processes and large and fine aggregate mixes, wall and overhead, should be carefully evaluated.

A backlog of rebound data, both in terms of RRR and RAVE, should be collected at various thicknesses for various conditions so that several curves can be established that define an acceptable range of rebound for each condition. Mix designs and shooting conditions that are optimum for the reduction of rebound should be established.

14.7 IMPROVED STRENGTH TESTING METHODS

Improved methods of obtaining samples were developed and proven. The method of sawing prisms from small panels with a table-type masonry saw worked extremely well and is recommended for consideration by the industry as a standard method of collecting and preparing samples for testing. The method was fast, simple, inexpensive and it provided an oriented sample with an appropriate length-to-width ratio.

Some specimens for this study were cut from panels that were less than 15 minutes old, and at a time when the compressive strength was only about 20 psi (0.14 MPa). No other sample preparation method permits an accurate, direct measurement of strength of weak shotcrete. Furthermore, the orientation of the sample was known at all times and the sample was placed in the compression testing machine so that the force was applied parallel to the potential laminations and parallel to the direction of anticipated principal compressive stress in situ. The same advantages apply to flexural specimens. Accordingly, these oriented samples provide the information needed for quality control; the test strength is governed either by the strength of the matrix or the strength of the structural defects, whichever is least.

Several different load cells with different ranges were used to supplement the dial gage on the portable testing machine. The equipment was satisfactory for strengths ranging from 20 to 7500 psi (0.14 to 51.7 MPa). One load cell, sensitive to a force of about 5 lb (22 N) permitted accurate testing of samples with compressive strengths as low as 20 psi (0.14 MPa). A reusable clip-on electrical strain gage was used in conjunction with the load cells to automatically and continuously plot load-versus-strain for almost every test. This equipment was assembled and protected specifically for field use and operated satisfactorily in the field for a period of several months. The sophistication of the equipment was ideal for research purposes but is not required for routine testing. It should be noted, however, that the primary element was a commercially-available portable compression tester found in most laboratories. However, the successful testing of low strength specimens does require testing equipment conforming to ASTM C 39 with a large dial gage strictly for the low-load range which is calibrated frequently.

Strength results from these methods of sample preparation and testing were quite good with relatively little scatter. The average of the coefficients of variation for all mixes and ages was only 9 percent. The rough outer surface of samples for this study was not trimmed. For routine testing, all four sides should be square to reduce scatter. Studies should be undertaken to determine the optimum dimensions for the prisms.

The small test panels were stored in the tunnel lined up against the wall so that their curing conditions would be similar to that of the in situ shotcrete. Duplication of curing conditions is essential to satisfactory quality control testing as evidenced by the significant effects of curing conditions observed during this study. It is concluded that if groundwater conditions are such that the shotcrete would always be saturated, the panels should be kept moist. Otherwise air drying in a relatively humid tunnel should result in a reasonable, conservative estimate of strength.

14.8 POTENTIAL ACTIVITY OF SHOTCRETE MIX AND SHOOTING CONDITIONS

A qualitative concept of "potential activity" of mix and shooting conditions was developed to explain and predict the relative strength of shotcrete placed under various conditions. The concept can also be applied to relative evaluations of rebound.

Two types of activity are defined: dry mix activity and shooting activity. Dry-mix activity is the tendency of the dry-mix to prematurely begin significant hydration before shooting. Various mix conditions were identified that tend to increase dry-mix activity. Prehydration before shooting tends to reduce both early and ultimate strength and more active mixes should result in lower strengths. Greater dry-mix activity increases rebound because of increased prehydration of the cement and the resultant stiffer consistency.

The second type of activity applies during and after shooting; shooting activity is defined as the tendency for a mix to set quickly and begin to gain strength rapidly. The factors that tend to promote or speedup the time of set of shotcrete in the airstream and on the wall were identified. They include mix conditions, such as cement content, and shooting conditions, such as accelerator dosage or temperature of materials. A particularly active mix tends to set very quickly; possibly on the way to the wall or immediately thereafter. It is the combined effect of the factors involved in activity that must be considered. A high cement content and low accelerator dosage may be just as active as a low cement content and a high accelerator dosage. Up to some optimum activity, determined by the combined effects, an increase in shooting activity will reduce rebound and increase the rate of gain of strength during the first day, but will result in lower ultimate strengths. Above the optimum, increased activity results in an increase in rebound, and lower early and final strengths. Above the optimum, the mix has set too fast, the surface is too stiff to be conducive to embedding material and subsequent shooting disturbs the set. Accordingly, specifications should include a criterion for a maximum accelerator dosage as well as a required initial set time.

14.9 COMPACTION ANALOGY

Despite the similarities in appearance, ingredients, and the final product, shotcrete made with fast-set accelerators is not concrete. Shotcrete is not placed in a saturated flowable state as is the case for concrete. Accordingly, rules of thumb and accepted concepts for concrete technology need not be applicable to shotcrete. Shotcrete is placed and compacted by impact of the particles in the airstream, often at water contents below saturation. The similarity of compaction of shotcrete to that of soil for the construction of earth embankments was described and an analogy made between soil compaction curves and conceptual shotcrete compaction curves. Known relations between water content and dry unit weight for soils were used to estimate relative shotcrete compaction curves for changes in water content at time of placement, changes in shooting conditions such as nozzle distance and air pressure, changes in mix conditions, and for changes in activity or accelerator dosage. As in the compaction of soil, an increase in water content causes an increase in unit weight up to a maximum. For physical reasons, the water content at this point of maximum unit weight is shown to be very close to the water content required for the material on the wall to exhibit a glossy appearance or a sheen. The glossy appearance is an indication that the material under compaction is saturated; higher energy generally gives denser materials, but as long as it remains saturated, additional energy cannot densify it. Hence, the commonly-used field criterion of shooting at a water content that achieves a glossy appearance of the material on the wall has a rational basis. Only if shotcrete of the same mix is placed wet-of-optimum can there possibly be a unique relation between water content, or water-cement ratio and unit weight. If shotcrete is placed dry-of-optimum, there can be different water contents with the same unit weight or there can be different unit weights for the same water content. The effects of curing conditions and accelerators make a correlation between water content and strength even more difficult as will be described later.

The compaction analogy is conceptual, shotcrete compaction curves have not and may not be able to be determined experimentally. However, as a conceptual model, the analogy serves to provide a basis for rational interpretation of shooting and mix conditions. The concept was used to explain the relationships for well-known field shooting conditions regarding strength and rebound. Previous concepts and test data that confirm the rationale of the compaction analogy are given; the concept is consistent with known behavioral patterns of shotcrete.

With this rational basis for interpretation of shooting conditions, it is concluded that one of the best quality control measures is through critical observation of the shooting process. Shotcrete placed for optimum strength should be placed at the glossy criterion because it is near the optimum unit weight for the compaction force available and because it is one of the few visual indications of material behavior available to the nozzleman. For minimum rebound, shotcrete should be placed at the wettest stable consistency.

The compaction concept accounts for most shooting conditions including the concept of dry-mix activity. However, other shooting conditions such as disturbance after set has taken place because of a high shooting activity, defects such as rebound pockets and laminations, environmental conditions such as curing, humidity, and temperature, and chemical considerations such as the effect of high dosages of accelerators also govern strength, and the effects of these considerations on the early and ultimate strength have been identified as departures from the compaction concept. When attempting to evaluate mixes within the framework of the compaction analogy, these potential overshadowing effects must be considered. It was shown by the compaction analogy that unit weight need not correlate uniquely with water content and that, because of differences in curing conditions and in accelerator dosage, unit weight need not correlate with strength. In this study, there was essentially no relationship between water-cement ratio and strength, and between unit weight of hardened shotcrete and strength. In fact, water content appears to be more of a dependent variable which is controlled by shooting conditions.

Because of these features, the entire history of a mix from the time of batching through the time of testing may be required in order to understand why a mix gives a certain strength.

14.10 COLD WEATHER SHOTCRETING

The strength test results were affected significantly by near-freezing shooting temperatures and by relatively cool curing temperatures during the first month of curing. Yet the quality of shotcrete was excellent; this shows that shotcreting in low temperatures can be acceptable if good quality control is maintained. Compressive strengths of most non-fibrous mixes at one-month were about 5000 psi (34.5 MPa) or greater.

The low temperatures essentially made the accelerator ineffective. It was shown that cement-accelerator combinations that are compatible at room temperature may not be compatible at lower temperatures. Accordingly, it is recommended that an entire series of compatibility tests be conducted using material temperatures that represent the range anticipated throughout the project. This series of compatibility tests should be conducted before final selection and purchase of the cement and accelerator since some cements and accelerators, that are compatible at an acceptable economical dosage at room temperature, may be compatible at low temperatures only at an excessive dosage of accelerator, or may not be compatible at all. The family of curves that can be generated from this series of tests can be used on the job so that the most economical compatible percentage can be selected for any temperature encountered. The reactions between the cement and accelerator are very important to both the early and the ultimate strength. Compatibility between cement and accelerator is governed by their precise physical and chemical properties, some of which change from batch to batch and with age. The compatibility results should be checked occasionally since small variations in the composition of the cement and accelerator can alter the proper accelerator dosage.

14.11 GENERAL STRENGTH OBSERVATIONS

COMPRESSIVE STRENGTH

Except for regulated-set mixes and mixes with high accelerator dosages, the compressive strength of shotcrete placed for this study did not begin any significant increase before 8 or 10 hours because of the low temperatures. The optimum accelerator dosage for early strength was at about 5 percent; lower dosages were essentially ineffective, while higher dosages resulted in lower early strength gain than for the optimum. For later test times, any increase in accelerator dosage resulted in a lower strength as early as one day; each increase of one percent resulted in a lower one-month strength of about 380 psi (2.6 MPa). Accordingly, it is concluded that accelerators should not be used unless necessary, and when accelerator is used, no more accelerator should be used than necessary. Nevertheless, strict adherence to compatibility criteria between cement and accelerator must be maintained for optimum results when accelerator is needed.

For regulated-set mixes, the optimum cement content was found to be at about 7-1/2 bags per cu yd (418 kg/m^3). Because of the influence of shooting activity, most shotcrete mixes are expected to have an optimum cement content.

A substantial change in the strength trend occurred after curing conditions changed after one month, indicating the importance of curing conditions on strength. Significant variations in strength were found to exist within any given panel and especially between panels. Accordingly, for quality-control testing or for testing of trial mixes during pre-construction testing, several samples from each of several test panels should be tested at any given age to obtain an appropriate average strength for the mix.

There was only a slight tendency for the compressive strength to be higher for mixes shot with the long nozzle; the increase was not conclusive nor significant. It is believed that the long nozzle results in greater uniformity that is reflected in a tendency for a slightly greater average strength because of fewer low strength values caused by structural defects.

FLEXURAL STRENGTH

The flexural strength, determined through six months, generally followed the trends shown by compressive strength. However, beams shot with the long nozzle had substantially higher flexural strength with less scatter in the results. This is believed the result of greater uniformity of mixing and fewer laminations when using the long nozzle.

Steel fiber specimens had no more flexural strength than non-fibrous specimens but they exhibited considerable post-crack resistance. The ratio of flexural to compressive strength was slightly higher for fibrous specimens. The lack of improved flexural strength for fibrous specimens can be related to the fact that there were few fibers retained in the wall and those that were retained were bent. Future studies on flexural strength should determine the flexural behavior within the first few hours after shooting.

LOAD-DEFORMATION BEHAVIOR

Load-deformation behavior and modes of failure were observed on all strength tests. The fact that the compression samples were oriented and were prisms, permitted the observation that almost all compression failures consisted of failure surfaces that were diagonal planes from the back to the front of the sample which appeared to be a coalescence of many little failure planes along, and then crossing, potential laminations.

A clip-on-type reusable strain gage was used with great success both on compression and flexural samples. Moduli and failure strains were in the range of what would be expected for 6 x 12 in. (15 x 30 cm) concrete specimens despite the difference in size and shape.

Steel fiber specimens never failed suddenly and always held together to large deformations both in compression and in flexure.

MOMENT-THRUST INTERACTION TESTS

Moment-thrust interaction envelopes were determined on both fibrous and non-fibrous shotcrete specimens. The failure envelopes were similar to those for plain concrete; test results such as these might be utilized for structural analysis and compare the structural effectiveness of various types of shotcrete. The tests conducted for this project were just an initial series to determine the feasibility and applicability of the method. More tests are recommended to develop a backlog of experimental information that can be used in structural analysis of shotcrete linings.

Steel fiber shotcrete did not show significant improvement in its failure envelope, primarily because of the low fiber contents, irregular distribution, and the bent fiber shapes.

PULL-OUT STRENGTH

Pull-out tests were conducted from 3 hours to 6 months. The ratio of pull-out to compressive strength decreased with increasing compressive strength. Further, the ratio was different for the different types of shotcrete. Plots of pull-out strength-versus-time were shown to be similar to curves of flexural strength-versus-time.

At any given small range in compressive strength and for any specific type of shotcrete, a simple average correlation factor can probably be determined experimentally for use in subsequent testing. The advantages and limitations of the pull-out test were discussed. The method should be investigated further.

BOND STRENGTH

Bond strength was not tested, however, it was noted in several cases that the compressive strength of shotcrete panels within the first few hours varied through the thickness of the shotcrete. In one case a rich regulated-set mix appeared to have gained over 1000 psi (6.9 MPa) from observing the exposed surface in about one hour but when the back of the panel was removed, the shotcrete had gained little strength on the interior side. Bond strength, and the increase of bond strength with time during the first few hours, when it has such geotechnical importance to ground support, should be investigated.

14.12 FRESH SAMPLE ANALYSES

Determinations of water content, cement content, and aggregate gradation were made on samples of the dry mix, in-place shotcrete, and rebound. These data from fresh samples compared favorably with calculated results from measured batch weights and measured rates of nozzle water. The average water-cement ratio was 0.30. The average cement content increased from 19 percent in the dry mix to 24 percent on the wall, an increase equivalent to about 2 bags per cu yd (110 kg/m^3). Only 12 percent of rebound was cement. Gravel content decreased from an average of 44 percent in the dry mix to 32 percent in place; rebound consisted of 66 percent gravel-sized particles. Only about 1/2 to 2/3 of the fibers were retained in the wall.

The results of the fresh shotcrete tests were used in a continuity analysis that assumed that all materials mixed and shot either end up in the wall or as rebound. A hypothetical example using typical results obtained from the fresh sample was used to illustrate the concept. It was shown that the different constituents in the airstream must rebound at different rates, as shown by the fact that in-place shotcrete is richer than the dry-mix. The example was used to calculate numerical values of rebound for each constituent. If the overall rate of rebound was 25 percent; the rebound of cement is 11 percent, sand 14 percent, gravel 40 percent, and water 22 percent. A practical implication of this analysis is that the water-cement ratio in place should be less than the water-cement ratio in the airstream simply because water rebounds at a greater rate. Past measurements of water-cement ratio on the basis of metered water readings may therefore be high.

14.13 HIGH-SPEED PHOTOGRAPHIC STUDIES

High-speed photographic studies were very effective in evaluating nozzle design, mechanisms of rebound, etc. Pulsations of the amount of material in the airstream appeared to be directly related to the pulsating nature of the discharge into the material delivery hose. Within a fraction of a second, the nature of particles in the airstream changed from mostly coarse, to mostly fine, to well-mixed. The long nozzle produced a more concentrated and better mixed airstream and was judged to be superior to the short nozzle in every respect observed in the photographs.

Most coarse particles traveled at a rate of about 65 to 75 ft per sec (20 to 23 m/sec). Many coarse aggregate particles, especially elongated ones, tended to spin about their axes at a high rate.

In certain cases, compaction is believed to occur behind the zone of remolding. Compaction is a function of the nature of the impacting shotcrete and of the consistency of the shotcrete being compacted. The compaction depends on the energy of impact and the efficiency of the impact. Shotcrete that has not "set" can be compacted; after initial set, it can only be disturbed. An increase in water content up to an optimum may enhance compaction, above which, shotcrete is only pushed around. Active mixes with high cement and accelerator contents are disturbed rather than compacted.

The photographic study resulted in the identification of several factors as being important in the mechanism of rebound. Their effect on rebound was evaluated and summarized individually. Though the interaction and relative degree of importance of each of the factors was unknown, they, together with the results of the fresh sample study, and the rebound studies, provide a consistent model for the process of rebound.

14.14 PRINCIPAL CONCLUSIONS

The following are the principal conclusions drawn from this study:

1. Despite the similarities in the ingredients and in their appearance, shotcrete, made with fast-set accelerators, is not concrete and its behavior must be evaluated from a different perspective than used in concrete technology. The shooting conditions and the chemical and physical effects of the fast-set accelerators have such great importance that they often invalidate, or at least, reduce the applicability of many of the empirical rules established for concrete. Accordingly, several concepts that can be used to evaluate the effects of various parameters on the engineering behavior and properties were developed or clarified in this study specifically for shotcrete.

2. Shotcrete cannot be duplicated by small-scale laboratory methods. There is a need for full-scale research under controlled laboratory conditions, but, ultimately, improvements to shotcrete must be tested underground using typical crews and equipment under well-documented conditions.
3. Accordingly, the environmental and shooting conditions must be documented carefully and in detail in order to properly assess the reasons for any given engineering behavior. This is true not only for research but also for everyday problems faced by a contractor or engineer who must determine the cause of unsatisfactory shotcrete or who desires to determine the most economical mix design.
4. Rebound has great economic importance and it deserves much more attention by owners, engineers, and contractors. Technical and economic aspects of rebound can be viewed from an entirely new perspective made possible by this study. The effects of the high rebound losses that occur when first shooting against a hard surface are far more pronounced and more far-reaching than previously believed. Thin linings have a high average rebound; average rebound reduced with thickness shot. These effects can even make a rebound test inapplicable to the very project for which it was intended unless the test thickness is the same as that being routinely shot for the project. Also, previously reported values of rebound have limited value for correlation with other tests unless documented by the thickness

shot. The single parameter that had the greatest and most significant effect on the test value of rebound in this study was the total thickness shot. A proposed standard rebound test, incorporating a standard thickness, should be conducted if comparisons are to be made.

5. Good quality shotcrete can be placed in a very cold environment with proper precautions and quality control. However, the cement and accelerator may no longer be compatible at the low temperatures, making the use of higher accelerator dosages necessary for early-strength development. Significant reduction in ultimate strength must, however, be expected. During pre-construction testing, cement-accelerator compatibility must be tested for the entire range of temperatures anticipated on the project. For control of difficult ground, compatibility must always be maintained. However, because of the detrimental effects of fast-set accelerators, the accelerator dosage should be adjusted frequently, as conditions change, so that no more than the minimum necessary dosage is ever used.

6. Regulated-set cement shotcrete and steel fiber shotcrete have been tested successfully under typical field conditions and may be considered for use on projects requiring their special advantages. Regulated-set shotcrete is well-suited for support of loosening ground conditions requiring early support. Its use is expected to be restricted primarily because of limited and inconvenient supply and its resultant high cost.

Steel fiber shotcrete is well-suited for temporary support of loosening ground conditions in jointed rock. Its use is expected to be restricted primarily by the added cost of the steel. It is not a substitute for mesh but may suffice for conditions where mesh is not absolutely required or where it is impractical to place.

The acceptability of regulated-set or steel fiber shotcrete for any given project must be tested by trial shooting during pre-construction testing.

7. The method of sawing prisms from small panels is recommended for consideration by the industry as a standard method for collecting and preparing samples for testing. The method was fast, simple, inexpensive and it provided an oriented sample with an appropriate length-to-width ratio. No other sample preparation method permits an accurate measurement of strength immediately after shooting.

8. The simple, homemade, long nozzle consisting of an extra-long hose tip on a single-water-ring nozzle body, was found to be superior to the short-tip nozzle. Other improvements in equipment and techniques are believed within easy reach of present technology and the potential savings far outweigh the costs of the research necessary.

9. The process of shotcreting, though not yet well understood, is no longer as uncertain as it once was. Many portions of the process still require further investigation, but in every case

in this study there were rational reasons to explain the behavior observed. The great controversies in shotcreting, i.e., large vs fine aggregate, wet vs dry process, optimum accelerator compatibility, etc., can be solved by practical research programs using techniques developed in this study. Other programs that address these problems and that evaluate the applicability of the results of this study to different mix and shooting conditions should be undertaken by those familiar with field problems in shotcreting. There is an urgent need for field studies to develop proven rational mix design procedures that can be used to reduce the time required during preconstruction testing to determine the most economical acceptable mix for the purpose intended.

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APPENDIX A

DESCRIPTION OF EXPERIMENTAL SHOTCRETES

A.1 REGULATED-SET SHOTCRETE

Regulated-set cement (Reg-set) (Cement R) is a new portland cement containing a new ingredient, calcium fluoroaluminate; the cement has been patented by the Portland Cement Association and now has a limited availability commercially. Reg-set is an entirely new cement, not a mixture of different types of cement or accelerators; all ingredients are blended in the kiln. The calcium fluoroaluminate significantly alters the setting time and the strength during the first several hours after mixing. At room temperature, regulated-set cement begins to set in about 10 minutes even without additives; set occurs almost immediately if it is mixed with hot water at about 100°F (38°C). The initial rate of gain of strength is very rapid for the first few hours. Then the rate of gain of strength reduces as the effect of the calcium fluoroaluminate subsides. The compressive strength that can be achieved during these first few hours ranges from 1000 to 3000 psi (6.9 to 20.7 MPa) depending upon the cement content of the mix and the percentage of calcium fluoroaluminate in the cement itself. After about one day the rate of gain of strength and the physical properties of regulated-set shotcrete are similar to those of Type I cement shotcrete.

Regulated-set shotcrete exhibits the greatest superiority over conventional shotcrete at early ages when it can be most beneficial in controlling loosening ground. The strength of regulated-set shotcrete is higher than the strength of conventional shotcrete with fast-set accelerators at all ages; however, the difference becomes less significant with increasing age.

Some of the advantages and disadvantages of regulated-set shotcrete are listed in Table A.1. Regulated-set cement begins to hydrate as soon as it is mixed with moist aggregate so the shotcrete mix should be used as soon as possible. Regulated-set shotcrete has been mixed successfully in batch-type operations; all of the mixes for this field program were batched. However, a volumetric continuous auger-type mixing operation is recommended for regulated-set shotcrete so that mixing can be performed at the heading immediately before shooting. This procedure would minimize premature hydration

TABLE A.1

EVALUATION OF REGULATED-SET SHOTCRETE

Advantages	Disadvantages
1. No accelerator required. a) Eliminates costs associated with accelerators (material and labor costs). b) No metering problems. c) Exposure to caustic materials reduced.	1. Cement costs more than regular portland cement. 2. High shipping costs from source. 3. Limited availability.
2. Strength of reg-set shotcrete during first few hours is many times that of similar conventional shotcrete mixes with fast-set accelerators.	4. Special handling may be required to reduce time between mixing and shooting. 5. Source of hot water may be required.
3. Does not exhibit reduction in 28-day strength experienced with high dosages of accelerators.	6. With the present technology, it should not be used in the wet-mix process. 7. Has potentially low sulfate resistance.

of this very active cement. Reg-set sets too fast to be used in present-day (1975) routine wet-mix operations. It is conceivable that new technology might result in specialized equipment and techniques that might permit the use of reg-set in a wet-mix process sometime in the future. Reg-set has been proposed for use in a slipformed tunnel lining (Parker et al., 1971; Halvorsen, Kesler, and Paul, 1975). Equipment or techniques developed for the slipform system might lead to successful wet-mix shotcrete applications. Reg-set is potentially susceptible to soluble sulfates. Regulated-set shotcrete may be less hazardous to personnel than conventional shotcrete with accelerators since personnel exposure to caustic products is reduced by not having to handle the accelerator.

Present availability of regulated-set cement is limited even in the United States where the only known commercial source is the Huron Cement Co.,[1] Alpena, Michigan. There are also a few sources outside the United States. A list of sources can be obtained from the Portland Cement Association. Early supplies of the cement required soda ash as an accelerator, but all the mixes used in the current field program were from Huron's Burn 4 which contains all the ingredients and which will set immediately without additives. Soda ash can still be added to reduce set time further. At the present time, quality control standards for the cement do not exist so the chemistry and the behavior of the cement vary significantly between the different sources and between different burns from the same source.

The material cost of reg-set cement is expected to be at least double the cost of ordinary portland cement. The cost of shipping from a

[1] Names of products and equipment are given for identification only. Identification does not imply endorsement.

distant source will increase the cost at the job further. This offsets the savings resulting from the elimination of accelerators. However, the use of any new material should not be evaluated just on a material-cost basis, especially if it is a small fraction of the cost in-place. The evaluation must be made on the basis of the total cost of the support in-place considering material costs in the real market delivered to the site, rebound losses, design thickness, safety, etc. Labor costs which are a major consideration should be reduced with the use of regulated-set cement. It is too early to discuss these cost considerations other than to say that under certain conditions it may be competitive with conventional Type I cement for use in shotcrete underground.

There are no known tunnels that have been supported by regulated-set shotcrete. An early assessment of regulated-set shotcrete for underground support was made by Parker, et al. (1971). A laboratory study on regulated-set shotcrete has been completed recently by the IIT Research Institute (Bortz, et al., 1973; Singh and Bortz, 1974; and Anderson and Poad, 1974).

A.2 STEEL FIBER SHOTCRETE

Steel fiber shotcrete is essentially conventional shotcrete to which thousands of steel fibers have been added. Steel fibers in shotcrete provide considerable tensile strength and impressive post-crack resistance since the fibers act as crack arrestors. The need for increased tensile strength in certain situations such as blocky rock has been demonstrated often (Cording, 1974; Jones and Mahar, 1974; Deere, et al., 1969).

The steel fibers most widely used in shotcrete are usually rectangular or circular in cross section and about 1 in. (25 mm) long; their thickness is about one-fourth that of the wire in a conventional paper clip (see Fig. 3.4). The fibers always fail in bond so they would be more effective if longer, but long thin fibers do not mix well. Hence, the 1-in. (25-mm) long fiber is a compromise between strength and workability. Other sizes and shapes of fibers are commercially available; lengths range from about 0.5 to 1.5 in. (13 to 40 mm).

The fibers are furnished in boxes weighing 40 to 50 lb (18 to 23 kg) and the fibers are literally sprinkled into the mixer, usually while mixing the aggregate. Sather (1974) gives information on field batching of fibrous concrete. The amount of steel fiber added is usually between one percent and two percent by volume (3 to 6 percent by weight). One percent by volume is 132 lb per cu yd (78 kg/m^3). If the fibers are not dispersed in the mix correctly, or if the aggregates are too wet, they will collect into "fiber balls" that must be removed from the mix prior to shooting. Fiber contents greater than 2 percent by volume are difficult to mix and shoot.

Most experimental work and field applications of steel fiber shotcrete have high-cement-content gunite-type mixes that do not contain coarse aggregate. Most mixes shot for this study contained only about 700 lb of cement per cu yd (415 kg/m^3) and 50 percent of the aggregate was a gravel, 0.5 in. (13 mm) maximum size. Similar coarse aggregate mix designs have been shot by Fernandez, Mahar, and Cording (1975). Accelerators are added to the mix in the usual manner.

No published data are available in mix designs for wet-mix steel fiber shotcrete, although steel fiber shotcrete has been placed by the wet-mix process. The main consideration for wet-mix steel fiber shotcrete is pumpability since steel fibers reduce pumpability. Pumpability consideration for steel fiber concrete are given by Ounanian, Halvorsen, and Kesler (1975).

The presence of steel fiber in shotcrete has been reported to increase its tensile and flexural strength, but not compressive strength, above that of conventional shotcrete (Poad and Serbousek, 1975). The most significant difference in behavior between fibrous and non-fibrous shotcrete is in the substantial post-crack resistance of fibrous shotcrete. This increased post-crack resistance provides a ductile-like behavior that improves the overall effectiveness of shotcrete for tunnel support; fiber shotcrete shows promise for supporting blocky and mildly squeezing ground. Since most of the long axes of the fibers are parallel to the rock surface, the fibers are oriented favorably for resisting tensile and flexural stresses. In addition, the presence of fibers reduces the effect of shrinkage and thermally-induced strains that tend to cause cracking of the lining. An important safety aspect of the post-crack resistance is that if the shotcrete lining does crack, the steel fibers tend to continue to carry load to permit redistribution of load, thus minimizing the risk of sudden failure. The shotcrete tends to hold together, instead of breaking into pieces, giving a safer visual indication of distress before complete failure.

Some investigators report lower average rebound for fibrous shotcrete, whereas others contend that the presence of fibers does not significantly affect rebound losses. The rebound losses of the fibers themselves are quite high. Ryan (1975) reports that the fiber content in-place for overhead shooting was only 40 percent of the batched fiber content; on the wall, only 65 percent of the batched fiber content was embedded in the wall to perform useful service. With the present cost of steel, such losses are unacceptable; however, several steel fiber shotcrete projects have been completed successfully and, apparently, economically. It is believed that rebound of the fibers themselves would not be as high for wet-mix steel fiber shotcrete.

The use of steel fiber shotcrete is comparable, from a cost standpoint, to shooting a reinforced shotcrete lining. Thus, the cost of materials will be greater than the materials cost for conventional shotcrete by at least the cost of the fiber added. Compared to some alternatives, such as the awkward and time-consuming placement of mesh, steel fiber shotcrete may still be economically feasible. However, the use of fiber in present proportions does not provide as great a resistance or ductility as shotcrete containing wire mesh. The same comments made in a previous paragraph about the cost of regulated-set shotcrete also apply to steel fiber shotcrete. It is too early to discuss cost in detail, except to say that it may be economically feasible under certain conditions; there are several projects that have already used steel fiber shotcretes, apparently successfully and economically when compared to the alternatives available.

Steel fiber shotcrete has been gunned using both the wet- and dry-mix processes. It is being used routinely in operational coal mines in England and in several coal mines in the United States. Ryan (1975) summarizes studies and applications in England. Henager (1975) describes its properties and some of its uses in the United States. Chrionis (1974) describes its use in coal mines in the United States. Major steel fiber shotcrete projects have been completed in the last few years for support of an adit in a dam abutment and for rock slope stabilization of a railroad cut for the U.S. Corps of Engineers, Walla Walla District (Kaden, 1974a, 1974b). Research has been conducted on steel fiber shotcrete by the U.S. Bureau of Mines in Spokane, Washington, together with Battelle Pacific Northwest Laboratories (Poad and Serbousek, 1972; Poad, et al., 1975). Steel fiber shotcrete has recently been tested and compared to conventional shotcrete in a large-scale tunnel model of jointed rock at the University of Illinois (Fernandez, Mahar, and Cording, 1975).

APPENDIX B

MATERIALS AND EQUIPMENT

This appendix contains details of the more important materials and equipment used during this study. The details of the equipment in both the field studies and the subsequent testing are contained in Table B.1; the materials used are described in Table B.2. Typical physical and chemical properties of the cements are contained in Table B.3 while the results of Gillmore Needles Tests conducted at various temperatures on samples of materials actually used on Days III and IV are contained in Table B.4. Table B.5 is a tabulation of the grain size analysis of both the fine and the coarse aggregate; these data are presented graphically in Fig. B.1. Photographs of the coarse aggregate and of the dry mix are given in Figs. B.2 and B.3, respectively.

TABLE B.1

LIST OF EQUIPMENT

FIELD EQUIPMENT	
Pug-mill mixer	2 cu yd (1.5 cu m) with 2 counter rotating blades (see Figure 2.3)
Shotcrete machine	Meynadier Dry Mix Gun, Meyco Model No. GM-57
Shotcrete nozzle	Conventional straight-through type single water ring body (Fig. 2.5c); difference between long and short nozzle is the length of the rubber hose tip: short nozzle 15 in. (38 cm) - Fig. 2.5a long nozzle 13.5 ft (4.1 m) - Fig. 2.5b Double water ring nozzle (Fig. 2.5d), special experimental design (see Valencia, 1974)
Water heater	80 gal. (305 liter) 240 volt A.C., upper element 4500 watts, lower element 4500 watts, 9000 watts maximum, A.O. Smith, Kankakee, Illinois, Model No. Ken 80-780.
Water mixing valve	Thermostatically blends hot and cold water, Powers Regulator Company, Model 433 Hydroguard
Water meter	Trident Meter, Neptune Meter Co., New York, Graduated in 0.10 gal (0.38 liters)
Air hose pressure meter	Hand held needle-type air pressure meter, (34-1105 KPa) Range 5-160 psi, Model 1050, Ingersoll Rand Co.
High speed camera	Fastax Model WF17, with goose. Accepts 100 ft (30.5 m) rolls of 16 mm film.
Film for high speed camera	Kodak high speed film (16 mm) Black and white: 4X (ASA 400) Color: Ektachrome EF Tungsten (ASA 25)
Flashbulb for high speed camera	Sylvania FF-33, rated at 140,000 lumen-seconds. Burns about 1.5 seconds
Thermal probes	Battery-operated concrete temperature meter, Soil test, Model CT 615; Thermistor temperature sensing cells, Soil test, Model CT-618

TABLE B.1 (continued)

SAMPLE PREPARATION AND TESTING EQUIPMENT	
Saw	Clipper Masonry Table Saw, model BL-52C, 5 HP, 3600 rpm, 230 volt A.C., single phase motor, Norton Construction Products Division, Worchester, Massachusetts
Saw blade	Diamond blade C-30B, 14 in. x 0.125 in. (35.6 cm x 3.2 mm), Cushion Cut, Harbor City, California
Portable testing machine (All compression and flexure tests)	Dual range, electrically-operated with variable loading rate, model FT-40-DR, Forney's Inc., New Castle, Pennsylvania
Load cell for low-strength compression and all flexural tests	Model 3112, 3000 pound (13.3 KN) capacity, LeBow Assoc. Inc.
Load cell for high-strength compression tests	Airplane load cells from airplane weighing kit, Model CS-7, Cox and Stevens Electronic Scales, Wallingford, Connecticut
Strain gage	Clip-on strain gage, 1.0 in. (2.54 cm) gage length, model no. 632.11, MTS Systems Corp., Minneapolis, Minnesota
Linear variable differential transducer (LVDT)	Model 7DCDT-250, Sandborn Co., Waltham, Massachusetts, Range ±0.25 in., linearity: 0.1% of full scale
XY plotter	Esterline Angus, Model XY530, will accept 11 x 16.5 in. (28 x 42 cm) graph paper
Testing machine for moment-thrust interaction tests	600,000 lb (2.67 MN) capacity, hydraulic testing machine, load frame model no. 311.52, hydraulic control no. 509.01, MTS Systems Corp., Minneapolis, Minnesota

TABLE B.2

LIST OF MATERIALS

Material	Product
Accelerator	Sigunite - Sika Chemical Co., Lindhurst, New Jersey
Aggregate	From Silver Hills, Maryland See also Table B.5 and Figure B.1 for gradation.
Cement "A"	Type I, Lone Star Cement Co.
Cement "B"	Type I, Medusa Cement Co.
Cement "R"	Regulated-set Huron Cement Co. Alpena, Michigan
Steel Fiber "NS"	Round fibers, 0.016 in. (0.41 mm) diameter, 1 in. (2.5 cm) long, brass coated, National Standard Co.
Steel Fiber "US"	Rectangular fibers, 0.010 in. x 0.022 in. x 1.0 in. (0.25 mm x 0.56 mm x 25.4 mm), United States Steel Corp., Pittsburgh, Pennsylvania

TABLE B.3

PROPERTIES OF CEMENTS

	Type I cement		Regulated-set cement
Chemical Analysis	Lone Star (Cement A) (Days I and II)	Medusa (Cement B) (Days III and IV)	Huron (Cement R) Burn #4
SiO_2	20.19	20.7	13.48
Al_2O_3	6.35	5.9	12.37
Fe_2O_3	2.46	2.6	2.31
CaO	63.02	63.0	57.86
MgO	2.97	3.3	1.47
SO_3	2.91	2.54	6.80
Loss on ignition	1.11	.51	3.91
Insolubles	0.12		0.84
C_3S	48.6	48.8	
C_2S	21.2	22.7	
C_3A	12.7	11.3	
C_4AF	7.5	7.9	
$CaSO_4$	4.9		
Physical Properties			
Specific surface			
Wagner	1869	2076	
Blaine	3430	--	
Gillmore needle results			
Initial set	150 min	300 min	
Final set	285 min	600 min	
Vicat needle results	2 hr 10 min	2 hr 15 min	
Air content	7.7%	8.5%	
Compressive strength			
3 day	1586 psi	3100 psi	
7 day	4119 psi	4000 psi	
28 day	5211 psi	5400 psi	

Note: Chemical and physical analyses for specific batches could not be obtained. Data shown were provided by manufacturers as being typical for these cements in this area during this time period.

TABLE B.4

GILLMORE NEEDLE TEST RESULTS ON SAMPLES OF MATERIALS USED ON DAYS III and IV

Accelerator[1] percent	Initial set min-sec	Final set min-sec	Temperature °F (°C) Cement	Water
I. TYPE I CEMENT AND ACCELERATOR AT ROOM TEMPERATURE				
2	5-00	15-30	68 (20)	64 (17.7)
3	3-40	13-00	68 (20)	64 (17.7)
4	3-00	10-30	68 (20)	66 (18.8)
6	2-40	7-30	68 (20)	66 (18.8)
II. TYPE I CEMENT AND ACCELERATOR AT ROOM TEMPERATURE, WATER HEATED				
3	0-35	30-00[2]±	68 (20)	110 (43.3)
III. TYPE I CEMENT, ACCELERATOR AND WATER REFRIGERATED				
2	6-00	42-00	42 (5.5)	42 (5.5)
4	4-30	33-00	42 (5.5)	42 (5.5)
IV. REGULATED-SET CEMENT WITHOUT ACCELERATOR AT VARIOUS TEMPERATURES				
0	1-30	7-00	70 (21.1)	65 (18.3)
0	0-30	3-50	70 (21.1)	100 (37.7)
0	34-00	160-00	42 (5.5)	42 (5.5)

[1] Cement sample 50 grams; water-cement ratio 0.40.

[2] Sample set rapidly to approximately 80 percent of final set. A false set restricted further development of early strength. Possibly a shorter mixing time would have prevented this problem.

TABLE B.5

GRAIN SIZE ANALYSIS OF SHOTCRETE AGGREGATES

Sieve	Fine aggregate: Wt retained (cumulative) (g)	Fine aggregate: % Passing	Sieve	Coarse aggregate: Wt retained	Coarse aggregate: % Passing
# 4	11.2	98	1/2"	0	100
# 8	104.9	79	3/8"	82.8	85
# 16	179.2	64.5	# 4	465.3	15.5
# 30	266.8	47	# 8	532.7	3.0
# 50	403.6	20	# 16	539.8	2.0
# 100	481.9	4.0	# 30	542.7	1.3
# 200	495.6	1.5	# 50	545.6	--
Pan	503.0		# 100	547.8	--
			# 200	548.4	.3
			Pan	550.1	

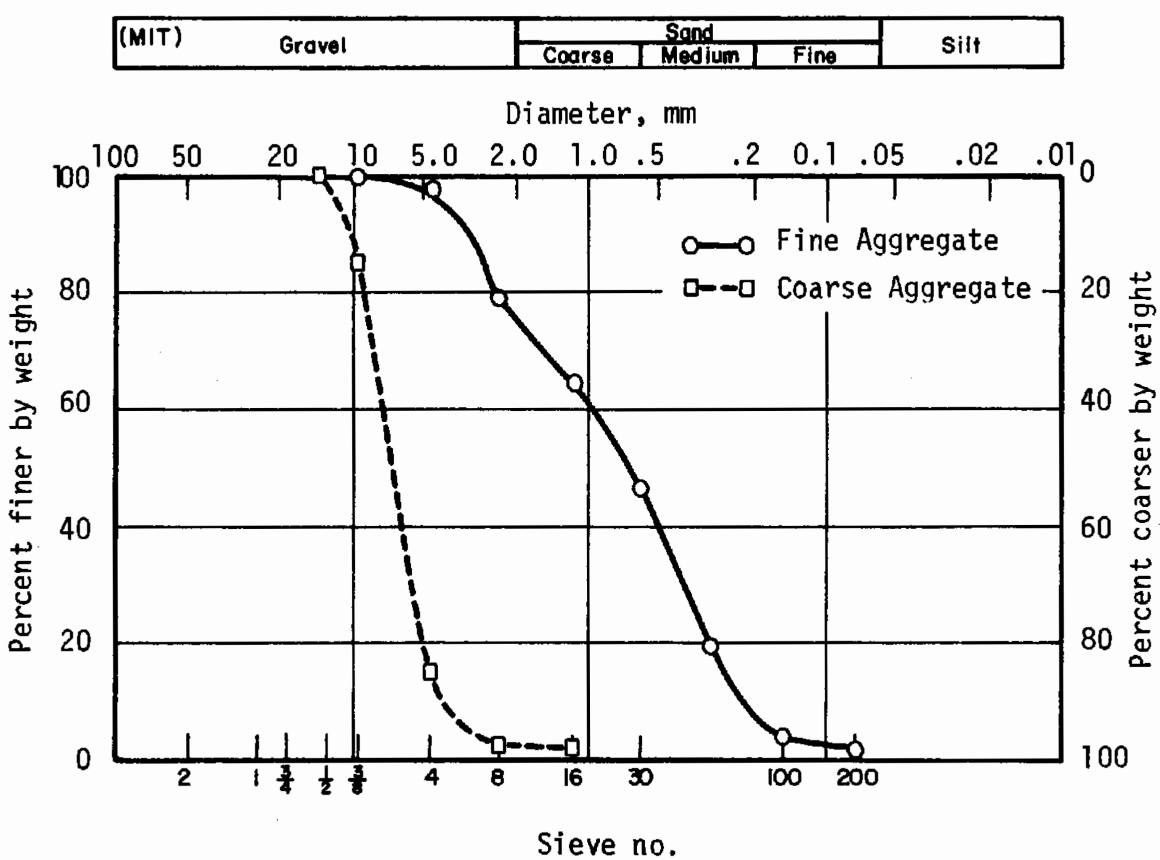

FIG. B.1 AGGREGATE GRADATION CURVES

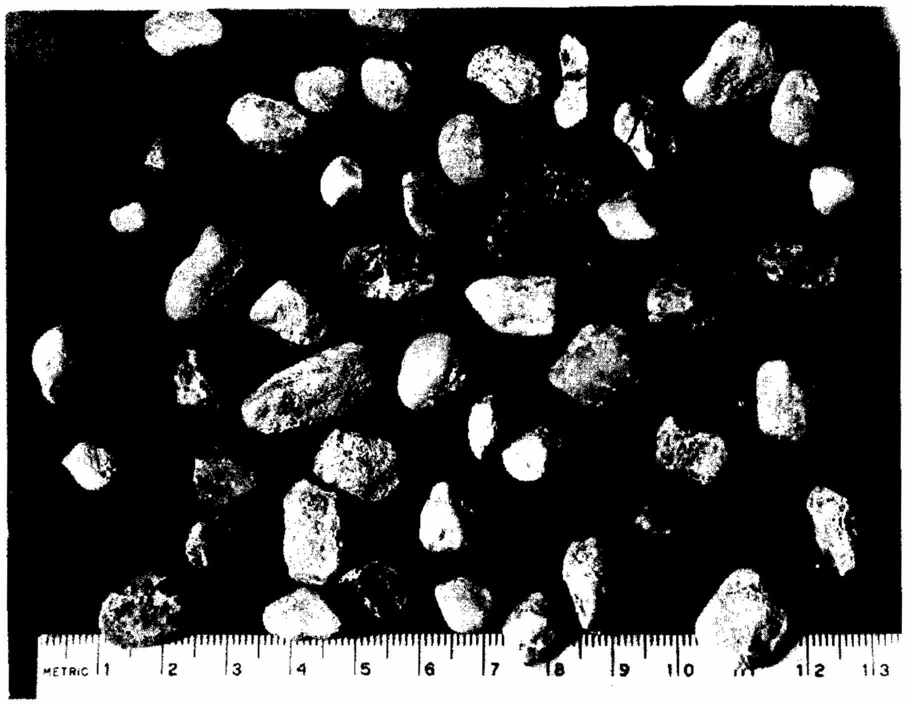

FIG. B.2 PHOTOGRAPH OF COARSE AGGREGATE

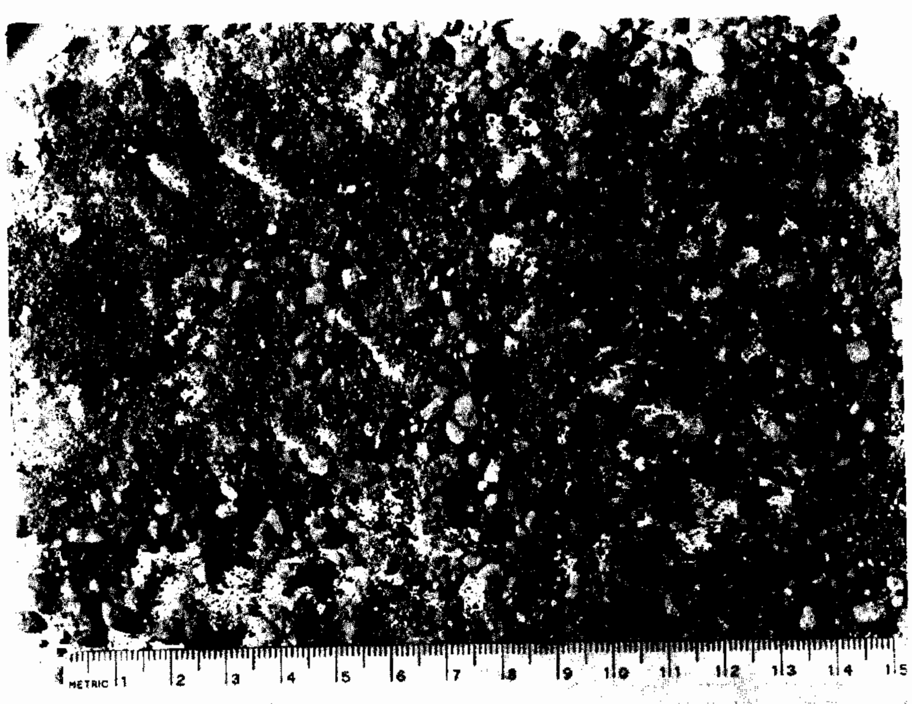

FIG. B.3 PHOTOGRAPH OF DRY-MIX

APPENDIX C

RESULTS OF FIELD DOCUMENTATION PROGRAM AND REBOUND TESTS

The field documentation program for Days III and IV were substantially more comprehensive than for previous Days after the need for such documentation was recognized during Days I and II. The field documentation data presented in this appendix represent the results of the more comprehensive efforts of Days III and IV. Batch proportions for Mixes 23 through 45 are contained in Table C.1; the standard mix design is given in Chapter 2. Table C.2 is a tabulation of the calculated material delivery rates (MDR) for each constituent in the airstream and of the water-cement ratios calculated on the basis of the known batch weights, the water contained in the aggregates, the material delivery rates, and the rate of water added at the nozzle when shooting a strength panel or when shooting a rebound test. Samples of dry mix, fresh shotcrete, and rebound material were taken immediately after shooting for subsequent analysis; these results are presented in Table C.3. The methods of sampling and a discussion of these results are contained in Chapter 6. Tables C.4 and C.5 contain the details of each of the rebound tests conducted on Days I and II and Days III and IV, respectively. The methods for conducting the rebound tests and an evaluation of the results of the rebound tests are contained in Chapter 4.

TABLE C.1

ACTUAL BATCH PROPORTIONS: DAY III AND DAY IV

Mix no.	Equivalent batch size		Total batch weight (including fibers and water in aggregates)		Cement			Fine aggregate			Coarse aggregate			Steel fiber			Total weight of dry constituents		Water in both fine and coarse aggregates		
	cu yd	(cu m)	lb	(kg)	lb	(kg)	%[3]	lb	(kg)	%[3]	lb	(kg)	%[3]	lb	(kg)	%[3]	lb	(kg)	lb	(kg)	%[3]
22	0.5	(0.38)	2850	(1294)	530	(240)	19.4	1069	(485)	39.2	1137	(512)	41.6	0	0	-	2736	(1242)	114	(51.7)	4.2
23	2.5	(0.76)	9505	(4315)	1765	(801)	19.3	3567	(1619)	39.1	3794	(1722)	41.6	0	0	-	9126	(4143)	379	(171.9)	4.1
24	1.0	(0.76)	3805	(1727)	705	(320)	19.3	1429	(649)	39.1	1520	(690)	41.6	0	0	-	3654	(1659)	151	(68.5)	4.1
25	1.0	(0.76)	3805	(1727)	705	(320)	19.3	1429	(649)	39.1	1520	(690)	41.6	0	0	-	3654	(1659)	151	(68.5)	4.1
26	1.0	(0.76)	3805	(1727)	705	(320)	19.3	1429	(649)	39.1	1520	(690)	41.6	0	0	-	3654	(1659)	151	(68.5)	4.1
27	1.0	(0.76)	3805	(1727)	705	(320)	19.3	1429	(649)	39.1	1520	(690)	41.6	0	0	-	3654	(1659)	151	(68.5)	4.1
28	1.0	(0.76)	3805	(1727)	705	(320)	19.3	1429	(649)	39.1	1520	(690)	41.6	0	0	-	3654	(1659)	151	(68.5)	4.1
29	1.0	(0.76)	3810	(1729)	610	(277)	16.7	1475	(670)	40.4	1569	(712)	42.9	0	0	-	3654	(1659)	156	(70.8)	4.3
30	1.0	(0.76)	3800	(1725)	800	(363)	21.9	1382	(627)	38.0	1470	(667)	40.4	0	0	-	3652	(1658)	148	(67.1)	4.0
31	1.0	(0.76)	3805	(1727)	705	(320)	19.3	1429	(649)	39.1	1520	(690)	41.6	0	0	-	3654	(1659)	151	(68.5)	4.1
33	1.0	(0.76)	3760	(1707)	705	(320)	19.5	1369	(621)	37.8	1412	(641)	39.0	130	(59)	3.6	3616	(1642)	144	(65.4)	4.0
33A	1.0	(0.76)	3760	(1707)	705	(320)	19.5	1369	(621)	37.8	1412	(641)	39.0	130	(59)	3.6	3616	(1642)	144	(65.4)	4.0
34	1.0	(0.76)	3810	(1729)	705	(320)	19.5	2028	(921)	60.0	760	(345)	21.0	130	(59)	3.6	3623	(1645)	187	(84.8)	5.2
35	0.5	(0.38)	1905	(865)	355	(161)	19.4	714	(324)	39.0	760	(345)	41.6	0	0	-	1829	(830)	76	(34.5)	4.2
38	1.0	(0.76)	3855	(1750)	800	(363)	21.5	1369	(621)	36.9	1412	(641)	38.0	130	(59)	3.5	3711	(1685)	144	(65.4)	3.9
39	1.0	(0.76)	3760	(1707)	705	(320)	19.5	1369	(621)	38.0	1412	(641)	39.2	130	(59)	3.6	3616	(1642)	144	(65.4)	3.9
40	1.0	(0.76)	3700	(1678)	650	(295)	18.3	1369	(621)	37.6	1469	(666)	40.7	65	(29.5)	1.8	3553	(1613)	147	(66.7)	4.1
42	1.0	(0.76)	4040	(1834)	985[4]	(447)	25.3	1369	(621)	33.9	1412	(641)	36.2	130	(59)	3.3	3896	(1787)	144	(65.4)	3.7
43	0.5	(0.38)	2000	(908)	0	0	-	922	(419)	46.1	980	(445)	51.5	0	0	-	1902	(863)	98	(44.5)	5.1
45	1.0	(0.76)	3760	(1707)	705	(320)	19.5	1369	(621)	36.4	1412	(641)	39.0	130	(59)	3.6	3616	(1642)	144	(65.4)	4.0

Notes: [1] See Table 2.1 for nominal weights as batched including water in aggregates. Data here is calculated from actual recorded batch weights and the known water content in aggregates. Calculations are carried out to the nearest pound (0.5 kg) to facilitate checking of percentage calculations. Accuracy greater than ± 5 to 10 lb (2.3 to 4.5 kg) is not implied.

[2] One Equivalent Cubic Yard defined as 3805 lb. On this basis, one cu m would be 2254 kg.

[3] Percentage is the percentage of weight of all dry constituents (cement, fiber and net weight of aggregates less water in aggregates)

[4] Estimated; see Section 6.4.3.

TABLE C.2

SUMMARY OF FIELD MEASUREMENTS OF SHOOTING CONDITIONS MADE ON DAY III AND DAY IV

Mix no.	Average Material Delivery Rate, MDR lb/min (kg/min): Total MDR (includes nozzle water)	Cement MDRc	Total water MDRw[1]	Accelerator dosage %[2]	Percentage of total water which was added at nozzle[3]	Calculated water-cement ratio: While shooting strength panels	While shooting rebound	Overall average of entire mix
22	378 (172)	69 (31.5)	21 (9.5)	3.5	30.7			
23A	388 (176)	71 (32.5)	19 (8.5)	3.4	20.7	0.27	0.37	0.29
23B	369 (167)	67 (30.5)	21 (9.5)	3.6	20.7	0.27	0.37	0.29
24	369 (167)	67 (30.5)	21 (9.5)	3.6	31.0	0.34	0.37	0.31
25	412 (187)	75 (34.0)	25 (11.5)	3.2	32.1	0.36	0.30	0.34
26	449 (204)	77 (35.0)	-- ----	3.1	47.0	0.41	0.40	0.41
27	520 (236)	95 (43.0)	29 (13.0)	0[2]	28.9	0.31	0.28	0.30
28	511 (232)	92 (42.0)	33 (15.0)	0[2]	39.7	0.36	----	0.36
29	412 (187)	64 (29.0)	27 (12.5)	0[2]	39.8	0.38	----	0.38
30	511 (232)	99 (45.0)	39 (18.0)	0[2]	53.2	0.39	----	0.39
31	600 (272)	-- ----	-- ----	0[2]	----	----	----	----
33	305 (138)	56 (25.5)	19 (8.5)	4.9	39.1	0.33	0.32	0.33
33A	396 (180)	73 (33.0)	24 (11.0)	3.0	30.0	0.32	0.31	0.32
34	181 (82)	33 (15.0)	13 (5.5)	8.4	31.0	0.38	0.38	0.38
35	337 (107)	62 (28.0)	19 (8.5)	3.6	31.4	0.31	----	0.31
38	335 (152)	68 (31.0)	19 (8.5)	3.2	31.1	0.26	0.26	0.26
39	342 (155)	63 (28.5)	19 (8.5)	3.5	30.8	0.30	----	0.30
40	426 (194)	73 (33.5)	25 (11.5)	3.0	35.1	0.31	0.38	0.35
42	366 (166)	85 (38.5)	30 (13.5)	0[2]	58.0	0.35	0.34	0.35
45	388 (176)	72 (32.5)	21 (9.5)	3.1	30.3	0.29	0.29	0.29

Notes:

[1] MDRw is the total of the water rates contributed by aggregates and the measured water added at the nozzle.

[2] Accelerator not required for regulated-set shotcrete.

[3] Percent water added at nozzle is $\frac{MDRnw}{MDRaw + MDRnw}$

TABLE C.3

AVERAGE PHYSICAL PROPERTIES OF FRESH SHOTCRETE SAMPLES: DAY III AND DAY IV

	Water Content %[1]	Cement Content %[1]	Water-Cement Ratio	Fiber Content %[1]	Gravel Content %[2]
Mix 23					
Dry mix	4.3				54
In place					
Strength panels	6.1	22.8	.27		35
Rebound wall	7.8	20.6	.37		44
Weighted average[3]	6.2	22.4	.29		36
Rebound material	4.6	12.7	.38		64
Mix 24					
Dry mix	5.4	18.2	.30		46
In place					
Strength panels	7.2	26.1	.28		35
Rebound wall	7.4	25.6	.30		27
Weighted average[3]	7.3	25.7	.29		29
Rebound material	4.8	13.8	.39		59
Mix 25					
Dry mix	3.7				45
In place					
Strength panels	7.1	24.8	.29		39
Rebound wall	7.3	24.0	.28		33
Weighted average[3]	7.2	24.0	.29		38
Rebound material	3.8	9.7	.40		76
Mix 26					
Dry mix	4.8	19.5	.24		49
In place					
Strength panels	6.2	22.2	.28		36
Rebound wall	7.0	22.5	.31		37
Weighted average	6.7	22.4	.30		36
Rebound material	3.6	11.0	.33		71
Mixes 27 & 28					
Dry mix	3.4	19.2	.18		52
In place					
Strength panels	-	24.0	-		25
Rebound wall	7.5	24.6	.30		27
Weighted average	7.5	24.3	.30		26
Rebound material	4.8	13.4	.34		64

TABLE C.3 (Continued)

	Water Content %[1]	Cement Content %[1]	Water-Cement Ratio	Fiber Content %[1]	Gravel Content %[2]
Mix 29					
Dry mix	3.4	18.2	.19		44
In place					
Strength panels	7.5	22.3	.34		36
Rebound wall	-	-	-		-
Weighted average	7.5	22.3	.34		36
Rebound material	-	(No rebound test)			-
Mix 30					
Dry mix	4.2	24.2	.18		43
In place					
Strength panels	7.4	27.8	.27		39
Rebound wall					
Weighted average	7.4	27.8	.27		39
Rebound material	-	(No rebound test)			-
Mix 31					
Dry mix	3.6	20.7	.18		33
In place					
Strength panels	8.1	25.1	.32		23
Rebound wall	7.6	26.6	.29		30
Weighted average	7.7	26.1	.30		27
Rebound material	5.6	15.0	.37		51
Mix 33					
Dry mix	-	(No data)			-
In place					
Strength panels	7.4	29.0	.26	2.4	19
Rebound wall		(No data)			
Weighted average	7.4	29.0	.26	2.4	19
Rebound material	4.1	10.6	.39	2.5	67
Mix 33A					
Dry mix	4.3	18.6	.23	2.4	39
In place					
Strength panels	8.4	24.3	.33	1.6	29
Rebound wall	8.5	26.4	.32	1.1	27
Weighted average	8.5	25.7	.32	1.2	28
Rebound material	4.4	10.1	.43	3.9	69
Mix 34					
Dry mix	-	(No data)			25
In place					
Strength panels	-	-	-	1.9	21
Rebound wall		(No data)			
Weighted average	-	-	-	1.9	21
Rebound material	4.2	10.4	.43	3.8	58

TABLE C.3 (Continued)

	Water Content %[1]	Cement Content %[1]	Water-Cement Ratio	Fiber Content %[1]	Gravel Content %[2]
Mix 38					
Dry mix	4.2	22.0	.19	3.6	44
In place					
Strength panels	7.2	25.4	.28	2.2	35
Rebound wall	-	25.3	-	3.1	33
Weighted average	7.2	25.4	.28	2.5	34
Rebound material	4.1	11.4	.36	2.6	70
Mix 39					
Dry mix	3.8	19.1	.20	2.2	43
In place					
Strength panels	8.5	24.8	.34	2.6	29
Rebound wall		(No rebound test)			
Weighted average	8.5	24.8	.34	2.6	29
Rebound material	-	(No rebound test)			-
Mix 40					
Dry mix	3.2	18.6	.18	2.3	44
In place					
Strength panels	6.7	19.7	.34	1.4	38
Rebound wall	7.6	19.2	.37	0.8	43
Weighted average	7.4	19.4	.36	1.1	41
Rebound material	6.2	9.2	.70	1.6	75
Mix 42					
Dry mix	3.0	26.3	.11	3.0	41
In place					
Strength panels	10.2	31.5	.32	3.2	29
Rebound wall	10.3	30.8	.34	3.1	27
Weighted average	10.3	31.0	.33	3.1	27
Rebound material	5.0	14.2	.36	2.0	70
Mix 45					
Dry mix	-	(No data)			-
In place					
Strength panels	6.1	19.9	.31	2.1	39
Rebound wall	7.3	22.2	.33	1.6	30
Weighted average	6.3	20.2	.31	2.0	38
Rebound material	3.8	9.4	.41	5.0	62

Notes: [1] Percentages based upon dry weight of all constituents in mix.
[2] Grand content is defined as percentage of total dry weight of sample, including cement and fibers, that was retained on No. 4 sieve. It should not be confused with % coarse aggregate.

TABLE C.4

SUMMARY OF REBOUND MEASUREMENTS MADE ON DAY I AND DAY II

Mix and tarp no.[1]	Shooting time[2] min.	Weight on tarp, lb (kg)	Rebound rate, RR, lb/min (kg/min)	Total material delivery rate, lb/min (kg/min)	Weight shot during interval, lb (kg)	Rebound rate ratio, RRR	Calculated thickness on wall at end of interval, in. (cm)	Total weight collected, lb (kg)	Total weight shot, lb (kg)	Average rebound, RAVE, %	Calculated thickness at end of test, in. (cm)
2-1	0.53	121 (54.9)	228 (103.4)	412 (186.9)	218 (98.9)	.555	0.3 (0.8)	121 (54.9)	218 (98.9)	55.5	
2-2	1.67	72 (32.7)	43 (19.5)	412 (186.9)	687 (311.6)	.105	2.5 (6.4)	193 (87.5)	905 (410.5)	21.3	
2-3	1.45	82 (37.2)	56 (25.4)	412 (186.9)	598 (271.2)	.136	4.2 (10.7)	275 (124.7)	1503 (681.7)	18.3	
2	3.65							275 (124.7)	1503 (681.7)	18.3	4.2 (10.7)
3	3.66	384 (174.2)	105 (47.6)	418 (189.6)	1530 (694.0)	--	4.0 (10.2)	384 (174.2)	1530 (694.0)	25.1	4.0 (10.0)
4	3.63	257 (116.6)	71 (32.2)	397 (180.0)	1440 (653.2)	--	4.1 (10.4)	257 (116.6)	1440 (653.2)	17.8	4.1 (10.4)
5-1	0.65	191 (86.6)	294 (133.4)	326 (147.9)	212 (96.2)	.901	0.1 (0.3)	191 (86.6)	212 (96.2)	90.1	
5-2	3.80	66 (29.9)	17 (7.7)	326 (147.9)	1238 (561.5)	.053	4.1 (10.4)	257 (116.6)	1450 (657.7)	17.7	
5	4.45							257 (116.6)	1450 (657.7)	17.7	4.1 (10.4)
6-1	0.72	227 (103.0)	315 (142.9)	389 (176.4)	279 (126.6)	.812	0.2 (0.5)	227 (103.0)	279 (126.6)	81.4	
6-2	1.75	34 (15.4)	19 (8.6)	389 (176.4)	681 (308.9)	.050	2.4 (6.1)	261 (118.4)	960 (435.4)	27.2	
6	2.47							261 (118.4)	960 (435.4)	27.2	2.4 (6.1)
7	1.63	135 (61.2)	83 (37.6)	400 (181.4)	652 (295.7)	--	3.0 (7.6)	135 (61.2)	652 (295.7)	20.7	3.0 (7.6)
9	7.25	740 (335.7)	102 (46.3)	547 (248.1)	3963 (1797.6)	--	4.0 (10.2)	740 (335.7)	3963 (1797.6)	18.7	4.0 (10.2)
11	10.83	1183 (536.6)	109 (49.4)	438 (198.7)	4745 (2152.3)	--	3.2 (8.1)	1183 (536.6)	4745 (2152.3)	24.9	3.2 (8.1)
12	12.66	699 (317.1)	55 (24.9)	300 (136.1)	2028 (919.9)	--	2.9 (7.4)	699 (317.1)	3800 (1723.6)	18.4	2.9 (7.4)
17	3.75	383 (173.7)	102 (46.3)	526 (238.6)	1973 (894.9)	--	5.0 (12.7)	383 (173.7)	1973 (894.9)	19.4	5.0 (12.7)
18	6.16	297 (134.7)	48 (21.8)	329 (149.2)	2028 (919.9)	--	5.5 (14.0)	297 (134.7)	2028 (919.9)	14.6	5.5 (14.0)
19	6.00	310 (140.6)	52 (23.6)	337 (152.9)	2022 (917.2)	--	5.4 (13.7)	310 (140.6)	2022 (917.2)	15.3	5.4 (13.7)
20	5.75	246 (111.6)	43 (19.5)	352 (159.7)	2024 (918.1)	--	5.6 (14.2)	246 (111.6)	2024 (918.1)	12.2	5.6 (14.2)

Notes: [1] Chronological order of tarp given after Mix No. When no tarp designation given, line is data for entire rebound test.

[2] Net time material was shot at wall and collected on the tarp after subtracting all delays.

TABLE C.5

SUMMARY OF REBOUND MEASUREMENTS MADE ON DAY III AND DAY IV

Mix and tarp no.[1]	Shooting time[2] min.	Weight on tarp, lb (kg)	Rebound rate, RR, lb/min (kg/min)	Total material delivery rate, lb/min (kg/min)	Weight shot during interval, lb (kg)	Rebound rate ratio, RRR	Calculated thickness on wall at end of interval, in. (cm)	Total weight collected, lb (kg)	Total weight shot, lb (kg)	Average rebound, RAVE, %	Calculated thickness at end of test, in. (cm)
23-1	0.7	135 (61.8)	194 (61.5)	369 (167.0)	258 (117.0)	.527	0.4 (1.1)	136 (618.0)	258 (117.0)	52.7	
23-2	2.95	78 (35.5)	26 (12.0)	369 (167.0)	1089 (494.0)	.072	3.9 (9.9)	214 (97.1)	1347 (611.0)	15.9	
23								214 (97.1)	1347 (611.0)	15.9	3.9 (9.9)
24-1	0.83	186 (84.5)	223 (101.0)	369 (167.0)	307 (139.5)	.605	0.4 (1.0)	186 (84.5)	307 (139.5)	60.5	
24-2	4.46	253 (115.0)	57 (25.5)	369 (167.0)	1646 (746.5)	.153	5.2 (13.2)	439 (199.1)	1953 (885.9)	22.5	
24	5.29							439 (199.1)	1953 (885.9)	22.5	5.2 (13.2)
25	2.03	272 (123.6)	134 (61.0)	412 (187.0)	837 (379.5)	--	1.9 (4.8)	272 (123.6)	837 (379.5)	32.5	1.9 (4.8)
26	3.0	271 (123.2)	90 (41.0)	449 (204.0)	1348 (611.5)	--	3.7 (9.4)	271 (123.2)	1348 (611.5)	20.1	3.7 (9.4)
27	2.75	340 (154.5)	124 (56.0)	520 (236.0)	1431 (649.0)	--	3.8 (9.6)	340 (154.5)	1431 (649.0)	23.7	3.8 (9.6)
31	1.83	307 (139.5)	168 (76.0)	600 (272.0)	1098 (498.0)	--	2.7 (6.7)	307 (139.5)	1098 (498.0)	28.0	2.7 (6.7)
33-1	0.85	164 (74.5)	193 (87.5)	305 (138.5)	259 (117.5)	.633	0.3 (0.8)	164 (74.5)	259 (117.5)	63.3	
33-2	3.10	52 (23.6)	18 (7.5)	305 (138.5)	956 (433.5)	.054	3.4 (8.6)	216 (98.0)	1215 (552.3)		
33				305 (138.5)				216 (98.0)	1215 (552.3)	17.8	3.4 (8.6)
33A	2.83	279 (126.8)	99 (44.5)	396 (179.5)	1121 (508.5)	--	2.9 (7.4)	279 (126.8)	1121 (508.5)	24.9	2.9 (7.4)
34	6.85	307 (139.5)	46 (21.0)	181 (82.0)	1203 (546.0)	--	3.1 (7.9)	307 (139.5)	1203 (546.0)	25.5	3.1 (7.9)
38	3.13	249 (113.2)	80 (36.0)	335 (152.0)	1048 (475.5)	--	2.8 (7.1)	249 (113.2)	1048 (475.5)	23.8	2.8 (7.1)
40	1.03	200 (90.9)	194 (88.0)	426 (193.5)	439 (199.1)	--	0.8 (2.0)	200 (90.9)	439 (199.1)	45.6	0.8 (2.0)
42	2.50	283 (128.6)	113 (51.5)	366 (166.0)	916 (415.5)	--	2.2 (5.6)	283 (128.6)	916 (415.5)	30.9	2.2 (5.6)
45	2.42	318 (144.5)	131 (59.5)	388 (176.0)	939 (426.0)	--	2.1 (5.3)	318 (144.5)	939 (426.0)	33.9	2.1 (5.3

Notes: [1] Chronological order of tarp given after Mix No. When no tarp designation given, line is data for entire rebound test.

[2] Net time material was shot at wall and collected on the tarp after subtracting all delays.

APPENDIX D

TABULATED RESULTS OF STRENGTH TESTS

Results of the strength tests for each mix are tabulated in this appendix. The modulus of elasticity obtained from the compression tests and the air dry unit weights at one month are also included. The results of tests for each mix at a given age are averaged; only the average is reported rather than the result of each test. However, the reliability of the average can be evaluated from the standard deviation, the coefficient of variation and number of tests shown for each average value. Each individual test has been plotted on the graphs in Appendix E in which a visual impression of the scatter can be observed. The methods used in performing the tests are described in Chapter 9 through 13; additional details on the preparation of the specimens are given in Chapter 8. Composition of the mixes and shooting conditions are described in Chapter 2 and Appendix C.

TABLE D.1

ESTIMATED* ONE DAY COMPRESSIVE STRENGTHS

Mix	Estimated Compressive Strength, psi	(MPa)
14	2500	(17.3)
21	3400	(23.5)
23	1600	(11.0)
24	800	(5.5)
25	1800	(12.4)
26	1900	(13.1)
28	4000	(27.6)
29	1200	(8.3)
30	3200	(22.1)
31	3500	(24.1)
33	1800	(12.4)
33A	1900	(13.1)
34	1400	(9.7)
38	1700	(11.7)
39	2100	(14.5)
42	2300	(15.9)
45	2000	(13.8)

*Values estimated from strength-time curves for each mix.

TABLE D.2

COMPRESSIVE STRENGTH RESULTS AT 7 DAYS

Mix	Panel	Mean Psi	Mean MPa	Std. dev. Psi	Std. dev. MPa	Coef. of Variation,%	No. of Samples
14	2	3560	24.5	580	4.0	16	3
	4	3890	26.8	490	3.3	12	3
Ave. Mix 10		3720	25.7	510	3.5	13	6
21	1	5190	35.8	670	4.6	13	5
23	1	4950	34.2	-	-	--	1
	2	4590	31.6	-	-	--	2
Ave. Mix 23		4710	32.4	410	2.8	8	3
25	5	4450	30.7	-	-	--	1
28	4	4570	31.5	-	-	--	2
	5	6070	41.9	480	3.3	8	4
	14	4700	32.4	480	3.3	10	4
Ave. Mix 28		5220	36.0	840	5.8	16	10
29	1	5240	36.1	610	4.2	12	4
30	11	4820	33.2	710	4.9	15	3
33	1	2940	20.2	140	0.9	5	4
33A	2	3300	22.7	320	2.2	10	4
34	7	2280	15.7	120	0.8	5	4
38	3	3530	24.3	230	1.6	6	3
39	3	4380	30.2	-	-	--	1
	5	3610	24.9	-	-	--	1
	11	4090	28.2	390	2.7	10	4
Ave. Mix 39		3890	26.8	480	3.3	12	6
40	11	4460	30.7	480	3.3	11	7
42	4	3540	24.4	650	4.5	18	3
45	2	3110	21.4	230	1.6	7	5
	5	3150	21.7	290	2.0	9	3
Ave. Mix 45		3120	21.5	230	1.6	7	8

TABLE D.3

COMPRESSIVE STRENGTH RESULTS AT ONE MONTH

Mix	Panel	Mean Psi	Mean MPa	Std. Dev. Psi	Std. Dev. MPa	Coef. of Variation,%	No. of Samples
14	2	4910	33.9	650	4.5	13	3
21	1	5200	35.8	820	5.6	16	3
23	15	4980	34.3	290	2.0	6	6
24	4	4300	29.7	400	2.8	9	3
25	6	5330	36.7	180	1.2	3	3
26	5	5020	34.6	45	0.3	1	3
28	1	5920	40.2	80	0.5	1	3
	7	6450	44.5	280	1.9	4	4
Ave. Mix 28		6220	42.9	350	2.4	6	7
29	3	5870	40.4	260	1.8	4	4
30	1	5080	35.0	75	0.5	1	3
33	3	4040	27.9	90	0.6	2	3
33A	4	3560	24.5	230	1.6	6	3
34	3	2800	19.3	120	0.8	4	3
38	1	3950	27.2	280	1.9	7	3
39	2	4450	30.7	480	3.3	11	5
40	1	4260	29.3	210	1.5	5	3
42	3	3900	26.9	260	1.8	7	3

TABLE D.4

COMPRESSIVE STRENGTH RESULTS AT 42 DAYS

Mix	Panel	Mean Psi	Mean MPa	Std. dev. Psi	Std. dev. MPa	Coef. of Variation,%	No. of Samples
23	15	5700	39.3	430	3.0	8	7
24	4	4630	31.9	530	3.7	1	3
25	6	6120	42.2	810	5.6	13	4
26	5	5780	39.9	360	2.5	6	5
28	1	6740	46.5	-	-	-	2
	7	6890	47.5	-	-	-	2
Ave. Mix 28		6820	47.1	300	2.1	4	4
29	3	6630	45.7	740	5.1	11	4
30	10	5700	39.3	-	-	-	2
33	3	4380	30.2	750	5.2	17	4
33A	4	4400	30.3	550	3.8	13	4
34	3	4210	29.0	670	4.7	16	4
38	1	4790	33.0	320	2.2	7	4
39	2	5700	39.3	610	4.2	10	4
	3	4620	31.8	-	-	-	1
	5	6470	44.6	-	-	-	1
Ave. Mix 39		5650	38.9	750	5.2	13	6
40	1	5430	37.4	470	3.2	9	4
42	3	4090	28.2	940	6.5	23	4
	9	4470	30.8	100	0.7	2	4
Ave. Mix 42		4280	29.5	650	4.5	15	8
45	6	3160	21.8	680	4.7	21	4

TABLE D.5

COMPRESSIVE STRENGTH RESULTS AT SIX MONTHS

Mix	Panel	Mean Psi	MPa	Std. Dev. Psi	MPa	Coef. of Variation,%	No. of Samples
23	6T*	5850	40.3	670	4.6	12	11
	6R	5580	38.5	620	4.3	11	10
	13	6070	41.9	910	6.3	15	8
	16	6240	43.0	160	1.1	3	4
Ave. Mix 23		5880	40.5	730	5.0	12	22
26	6	6950	47.9	940	6.5	13	4
28	2	7110	49.0	640	4.4	9	7
	8	7450	51.4	580	4.0	8	5
Ave. Mix 28		7250	50.0	610	4.2	8	12
29	10	6770	46.7	-	---	-	2
30	7	5560	38.3	720	5.0	13	8
39	1T*	6210	42.8	870	6.0	14	11
	1R	5550	38.3	790	5.4	14	10
	4	6610	45.5	250	1.7	4	5
	6	5650	39.0	410	2.8	7	10
	7	6170	42.5	630	4.3	10	10
	8	5630	38.8	660	4.6	12	10
	10	6770	46.7	460	3.2	7	2
	16**	4920	33.9	570	3.9	11	4
Ave. Mix 39		5880	40.5	700	4.8	12	47
40	4	5810	40.1	500	3.5	9	10
	5	6750	46.5	430	2.9	6	8
	9	6020	41.5	630	4.3	10	10
Ave. Mix 40		6260	43.1	870	6.7	14	28
42	9	4910	33.8	640	4.4	13	9
45	3	5410	37.3	510	3.9	11	10

* Trimmed samples, not included in average.
** Samples too thin, not included in average.

TABLE D.6

FLEXURAL STRENGTH RESULTS AT ONE DAY

Mix	Panel	Mean Psi	Mean MPa	Std. Dev. Psi	Std. Dev. MPa	Coef. of Variation,%	No. of Specimens
23	1	510	3.5	40	0.3	8	3
	2	410	2.8	-	-	--	1
Ave. Mix 23		485	3.3	60	0.4	12	4
28	4	650	4.5	120	0.8	18	5
29	12	290	2.0	40	0.3	14	4
30	12	660	4.5	-	-	--	2
33	2	480	3.3	60	0.4	12	3
33A	2	500	3.5	-	-	--	1
	1	450	3.1	-	-	--	1
Ave. Mix 33A		475	3.3	-	-	--	2
34	2	545	3.8	-	-	--	2
38	3	510	3.5	-	-	--	1
39	3	460*	3.2*	-	-	--	2
42	1	310	2.1	-	-	--	1
45	2	330	2.3	-	-	--	1
	5	485	3.3	-	-	--	2
Ave. Mix 45		430	3.0	100	0.7	23	3

*Interpolated from strength-time curve

TABLE D.7

FLEXURAL STRENGTH RESULTS AT 7 DAYS

Mix	Panel	Mean Psi	Mean MPa	Std. Dev. Psi	Std. Dev. MPa	Coef. of Variation,%	No. of Samples
23	2	595	4.1	85	0.6	14	6
	14	630	4.3	-	-	--	1
Ave. Mix 23		600	4.1	80	0.6	13	7
24	3	730	5.0	-	-	--	2
25	5	875	6.0	95	0.7	11	3
26	3	810	5.6	-	-	--	2
28	4	1035	7.1	-	-	--	1
	5	820	5.7	280	1.9	34	5
Ave. Mix 28		860	5.9	265	1.8	31	6
29	1	1175	8.1	-	-	--	2
	12	730	5.0	-	-	--	2
Ave. Mix 29		955	6.6	270	1.9	28	4
30	11	1065	7.3	-	-	--	2
	12	735	5.1	-	-	--	1
Ave. Mix 29		955	6.6	190	1.3	20	3
33	1	920	6.3	-	-	--	2
	2	835	5.8	-	-	--	2
Ave. Mix 33		880	6.1	95	0.7	11	4
33A	1	630	4.3	-	-	--	1
	2	700	4.8	-	-	--	2
Ave. Mix 33A		680	4.7	40	0.3	6	3
34	2	615	4.2	125	0.9	20	4
38	2	730	5.0	-	-	--	1
	3	660	4.6	75	0.5	11	3
Ave. Mix 38		680	4.7	70	0.5	10	4
39	3	925	6.4	-	-	--	2
40	1	875	6.0	90	0.6	10	3
	11	755	5.2	175	1.2	23	5
Ave. Mix 40		780	5.4	145	1.0	19	8
42	1	770	5.3	60	0.4	8	3
45	1	875	6.0	265	1.8	30	3
	2	850	5.9	25	0.2	3	3
	5	625	4.3	-	-	--	1
Ave. Mix 45		830	5.7	180	1.2	22	7

TABLE D.8

FLEXURAL STRENGTH RESULTS AT ONE MONTH

		Mean		Std. Dev.		Coef. of	No. of
Mix	Panel	Psi	MPa	Psi	MPa	Variation,%	Samples
21	BC	905	6.2	105	0.7	12	3
23	15	855	5.9	150	1.0	18	7
24	4	775	5.3	60	0.4	8	3
25	6	1005	6.9	40	0.3	4	4
26	5	965	6.7	85	0.6	9	4
28	1	1070	7.4	95	0.7	9	4
	7	1020	7.0	140	1.0	14	4
Ave. Mix 28		1045	7.2	115	0.8	11	8
29	3	1060	7.3	75	0.5	7	4
30	10	895	6.2	-	-	--	2
33	3	680	4.7	110	0.8	16	3
	4	915	6.3	-	-	--	1
Ave. Mix 33		740	5.1	150	1.0	20	4
33A	4	690	4.8	35	0.2	5	3
34	3	600	4.0	40	0.3	7	3
38	1	815	5.6	160	1.1	20	4
39	2	925	6.4	70	0.5	8	7
40	1	805	5.6	60	0.4	7	4
42	3	685	4.7	40	0.3	6	4
	9	670	4.6	70	0.5	10	4
Ave. Mix 42		680	4.7	50	0.4	7	8
45	6	580	4.0	65	0.4	11	4

TABLE D.9

FLEXURAL STRENGTH RESULTS AT SIX MONTHS

Mix	Panel	Mean Psi	Mean MPa	Std.dev. Psi	Std.dev. MPa	Coef. of Variation, %	No. of Samples
23	13	805	5.5				1
	16	985	6.8	90	0.6	9	4
Ave.	Mix 23	950	6.5	115	0.8	12	5
28	2	710	4.9				1
	16	890	6.1	75	9.5	8	4
Ave.	Mix 28	850	5.9	105	0.7	12	5
39	4	960	66				1
	10	690	4.8				1
Ave.	Mix 39	875	6.0	-	-	--	2
40	5	920	6.3				1
42	9	710	4.9				1

TABLE D.10

PULL-OUT STRENGTH RESULTS AT 7 DAYS

Mix	Panel	Mean Psi	Mean MPa	Std. Dev.* Psi	Std. Dev.* MPa	Coef. of* Variation,%	No. of Pullouts
25	2	1220	8.4	150	1.0	12	3
26	4	1090	7.5	-	-	--	2
28	8	1930	13.3	0	0	0	3
	13	1910	13.2	30	0.2	2	3
Ave. Mix 28		1920	13.2	20	0.1	1	6
29	5	1880	13.0	0	0	0	3
33A	5	1010	7.0	15	0.1	1	3
38	6	840	5.8	255	1.8	30	4
39	5	1240	8.6	120	0.8	10	3
40	3	990	6.8	150	1.0	15	4
42	7	860	5.9	180	1.2	21	5
45	2	840	5.8	40	0.3	5	3

* Sample population too small in some cases to give meaningful results.

TABLE D.11

PULL-OUT STRENGTH RESULTS AT ONE MONTH

Mix	Panel	Mean Psi	Mean MPa	Std. Dev.* Psi	Std. Dev.* MPa	Coef. of* Variation,%	No. of Pullouts
25	2	1340	9.2	-	-	--	2
	3	1430	10.0	60	0.4	4	3
Ave. Mix 25		1400	9.6	80	0.6	6	5
26	6	1100	7.5	-	-	--	2
28	10	2110	14.6	70	0.5	3	4
29	5	2180	15.0	140	1.0	6	3
30	7	2070	14.3	60	0.4	3	3
33A	5	1090	7.5	100	0.7	9	7
	6	1100	7.6	35	0.2	3	3
Ave. Mix 33A		1080	7.5	85	0.6	8	10
38	4	1380	9.5	30	0.2	2	4
	6	1200	8.3	190	1.3	16	4
Ave. Mix 38		1290	8.9	160	1.1	12	8
39	5	1120	7.7	-	-	--	2
	8	1320	9.1	60	0.4	5	3
	6	1190	8.2	190	1.3	16	4
	7	1050	7.2	100	0.7	10	3
Ave. Mix 39		1180	8.1	160	1.1	14	12
40	3	950	6.6	135	0.9	14	5
	4	1030	7.1	65	0.4	6	4
	9	1300	9.0	40	0.3	3	5
Ave. Mix 40		1100	7.6	180	1.2	16	14
42	7	710	4.9	-	-	--	1
	8	1040	7.2	310	2.2	30	8
	10	1430	9.9	125	0.8	9	5
Ave. Mix 42		1140	7.9	320	2.2	28	14
45	2	1100	7.6	385	2.7	35	5

* Sample populations too small in some cases to give meaningful results.

TABLE D.12

PULL-OUT STRENGTH RESULTS AT SIX MONTHS

Mix	Panel	Mean Psi	Mean MPa	Std. Dev.* Psi	Std. Dev.* MPa	Coef. of* Variation,%	No. of Pullouts
26	6**	1040	7.2	350	2.4	34	5
28	8	2090	14.4	170	1.2	8	8
29	10	1850	12.8	220	1.5	12	5
39	6	1160	8.0	200	1.4	17	5
	7	1310	9.1	70	0.5	5	3
	8	1310	9.0	160	1.1	12	4
Ave. Mix 39		1250	8.6	170	1.2	14	12
40	4	1010	7.0	150	1.0	15	5
	9	1420	9.8	180	1.2	13	4
Ave. Mix 40		1190	8.2	260	1.8	22	9
45	3	1100	7.6	-	-	--	1

Notes: * Sample populations too small in some cases to give meaningful results.

** Results considered unreliable.

TABLE D.13

MODULUS OF ELASTICITY RESULTS AT 7 DAYS

Mix	Panel	Mean 10^3 Psi	Mean GPa	Std. Dev. 10^3 Psi	Std. Dev. GPa	Coef. of Variation,%	No. of Specimens
14	10C	3670	25.3	1040	7.2	28	3
	N	4030	27.8	800	5.5	20	3
Ave. Mix 10		3850	26.5	850	5.9	22	6
21	RS	3410	23.5	640	4.4	19	4
23	1	3630	25.0	-	-	-	1
	2	4105	28.3	-	-	-	2
Ave. Mix 23		3950	27.2	290	2.0	7	3
25	5	3800	26.2	-	-	-	1
28	5	3660	25.2	-	-	-	2
	14	3250	22.4	-	-	-	1
Ave. Mix 28		3520	24.3	300	2.1	8	3
29	1	3970	27.4	380	2.6	10	4
30	11	3160	21.8	115	0.8	4	3
33	1	3080	21.2	340	2.3	11	4
33A	2	3070	21.2	130	0.9	4	4
34	7	2655	18.3	340	2.3	13	4
38	2	3660	25.2	-	-	-	1
39	3	4380	30.2	-	-	-	1
40	11	3890	26.8	370	2.5	10	5
42	4	3030	20.9	-	-	-	2
45	2	3370	23.2	750	5.2	22	3
	5	2810	19.4	-	-	-	1
Ave. Mix 45		3230	22.3	680	4.7	21	4

TABLE D.14

MODULUS OF ELASTICITY RESULTS AT ONE MONTH

Mix	Panel	Mean 10^3 Psi	Mean GPa	Std. Dev. 10^3 Psi	Std. Dev. GPa	Coef. of Variation,%	No. of Specimens
14	28C	5300	36.5	1080	7.4	20	3
21	28RS	4610	31.8	570	3.9	12	3
23	15	4125	28.4	490	3.4	12	6
24	4	3560	24.5	360	2.5	10	3
25	6	4130	28.5	330	2.3	8	3
26	5	4270	29.4	470	3.2	11	5
28	1	3880	26.7	450	3.1	12	3
	7	3720	25.6	210	1.4	6	4
Ave. Mix 28		3790	26.1	310	2.1	8	7
29	3	4050	27.9	260	1.8	6	4
30	10	3260	22.5	240	1.7	7	3
33	3	3750	25.8	390	7.7	10	3
33A	4	3010	20.7	490	3.4	16	3
34	3	3320	22.9	630	4.3	19	3
38	1	3420	23.6	300	2.1	9	4
39	2	3580	24.7	270	1.9	8	5
40	1	3520	24.3	350	2.4	10	3
42	3	3110	21.4	80	0.6	3	3
	9	3160	21.8	450	3.1	14	3
Ave. Mix 42		3135	21.6	290	2.0	9	6

TABLE D.15

MODULUS OF ELASTICITY RESULTS AT 42 DAYS

Mix	Panel	Mean 10^3 Psi	Mean GPa	Std. Dev. 10^3 Psi	Std. Dev. GPa	Coef. of Variation,%	No. of Specimens
23	15	4430	30.5	350	2.4	8	7
24	4	4050	27.9	280	1.9	7	3
25	6	4305	29.7	230	1.6	5	4
26	5	4870	33.6	460	3.2	9	5
28	1	4290	29.6	-	-	-	2
	7	4150	28.6	-	-	-	2
Ave. Mix. 28		4220	29.1	410	2.8	7	4
29	4	4450	30.7	420	2.9	9	4
30	10	3550	24.5	-	-	-	2
33	3	3990	27.5	300	2.1	7	4
33A	4	3740	25.8	400	2.8	11	4
34	4	3670	25.3	190	1.3	5	4
38	1	3630	25.0	230	1.6	6	4
39	2	4640	32.0	610	4.2	13	4
	3	3730	25.7	-	-	-	1
	5	3700	25.5	-	-	-	1
Ave. Mix 39		4330	29.8	670	4.6	15	6
40	1	4410	30.4	530	3.7	12	4
42	3	3630	25.0	370	2.5	10	4
	9	3650	25.1	310	2.1	8	4
Ave. Mix 42		3640	25.1	310	2.1	9	8
45	6	3740	25.8	360	1.8	7	4

TABLE D.16

MODULUS OF ELASTICITY RESULTS AT SIX MONTHS

Mix	Panel	Mean 10^3 Psi	Mean GPa	Std. Dev. 10^3 Psi	Std. Dev. GPa	Coef. of Variation,%	No. of Specimens
23	6	3890	26.8	410	2.8	10	21
26	6	4550	31.3	780	5.4	17	4
28	8	4460	30.7	320	2.2	7	5
29	10	4520	31.1	-	-	-	2
30	7	3705	25.5	220	1.5	6	4
39	1	4060	28.0	540	3.7	13	21
	6	3950	27.2	870	6.0	22	10
	7	4115	28.3	850	5.9	21	9
Ave. Mix 39		4050	27.9	690	4.8	17	40
40	4	4310	29.7	460	3.2	11	10
	5	4080	28.1	660	4.5	16	7
Ave. Mix 40		4220	29.1	540	3.7	13	17
42	9	3000	20.7	-	-	-	1
45	3	3880	26.7	330	2.3	8	3

TABLE D.17

RESULTS OF MOMENT-THRUST INTERACTION TESTS, PANEL 23-13

Specimen	No. of samples	Thickness t inches (cm)	Width b inches (cm)	Eccentricity e inches (cm)	Increase in eccentricity Δe inches (cm)	Maximum load P_{max} kips ($N \times 10^4$)	Moment in.-kips ($N\text{-}m \times 10^2$)	Normalized to thickness: P/bt ksi (MPa)	Normalized to thickness: M/bt^2 ksi (MPa)	Normalized to compressive strength, σ_{c180}: $\frac{P/bt}{\sigma_c}$	Normalized to compressive strength, σ_{c180}: $\frac{M/bt^2}{\sqrt{\sigma_c}}$ $\sqrt{psi}$ ($\sqrt{MPa}$)
23-13 ave	8	-- (--)	-- (--)	0 (0)	0 (0)	-- (--)	0 (0)	6.07 (41.82)	0 (0)	1.0	0 (0)
23-13-6	1	2.82 (7.16)	2.98 (7.57)	0.3 (0.76)	0.07 (0.18)	40.25 (17.90)	14.89 (16.82)	4.79 (33.02)	0.63 (4.34)	0.78	8.27 (0.67)
23-13-2	1	2.3 (5.84)	2.95 (7.49)	0.35 (0.89)	0.11 (0.28)	19.25 (8.56)	8.86 (10.01)	2.84 (19.58)	0.57 (3.93)	0.46	7.48 (0.61)
23-13-3	1	2.28 (5.79)	2.97 (7.54)	0.45 (1.14)	0.12 (0.30)	28.25 (12.57)	16.1 (18.19)	4.17 (28.75)	1.04 (7.17)	0.68	13.64 (1.11)
23-13-5	1	2.29 (5.82)	2.97 (7.54)	0.7 (1.78)	0.14 (0.36)	16.88 (7.51)	14.18 (16.02)	2.48 (17.10)	0.91 (6.27)	0.41	11.94 (0.97)
23-13-7	1	2.5 (6.35)	3.03 (7.70)	1.0 (2.54)	0.12 (0.30)	15.5 (6.89)	17.36 (19.61)	2.04 (14.06)	0.92 (6.34)	0.33	12.07 (0.98)
23-13-1	1	3.51 (8.92)	3.0 (7.62)	1.25 (3.18)	0.03 (0.08)	4.25 (1.89)	5.44 (6.15)	0.56 (3.86)	0.29 (2.00)	0.09	3.80 (0.31)
23-13-4	1	2.27 (5.77)	2.99 (7.59)	∞ (∞)	0.015 (0.04)	0.89 (0.40)	2.07 (2.34)	0 (0)	0.134 (0.92)	0	1.76 (0.14)

TABLE D.18

RESULTS OF MOMENT-THRUST INTERACTION TESTS, PANEL 28-2

Specimen	No. of samples	Thickness t inches (cm)	Width b inches (cm)	Eccentricity e inches (cm)	Increase in eccentricity Δe inches (cm)	Maximum load P_{max} kips ($N \times 10^4$)	Moment in.-kips ($N\text{-}m \times 10^2$)	Normalized to thickness: P/bt ksi (MPa)	Normalized to thickness: M/bt^2 ksi (MPa)	Normalized to compressive strength, σ_{c180}: $\frac{P/bt}{\sigma_c}$	Normalized to compressive strength, σ_{c180}: $\frac{M/bt^2}{\sqrt{\sigma_c}}$ $\sqrt{psi}$ ($\sqrt{MPa}$)
28-2-ave	7	-- (--)	-- (--)	0 (0)	0 (0)	-- (--)	0 (0)	7.11 (49.02)	0 (0)	1.0	0 (0)
28-2-3	1	2.5 (6.35)	2.98 (7.57)	0.38 (0.97)	0.09 (0.23)	25.25 (11.23)	11.87 (13.41)	3.39 (23.37)	0.64 (4.41)	0.48	7.59 (0.63)
28-2-6	1	2.89 (7.34)	3.0 (7.62)	0.71 (1.80)	0.1 (0.25)	28.75 (12.79)	23.29 (26.31)	3.32 (22.89)	0.93 (6.41)	0.47	11.03 (0.92)
28-2-7	1	2.87 (7.29)	2.95 (7.49)	0.94 (2.39)	0.06 (0.15)	8.0 (3.56)	8.0 (9.04)	0.94 (6.48)	0.33 (2.28)	0.13	3.91 (0.33)
28-2-8	1	2.88 (7.32)	2.95 (7.49)	0.94 (2.39)	0.09 (0.23)	18.0 (18.01)	18.54 (20.95)	2.12 (14.62)	0.75 (5.17)	0.30	8.89 (0.74)
28-2-5	1	2.79 (7.09)	2.91 (7.39)	1.05 (2.67)	0.08 (0.20)	9.0 (4.00)	10.17 (11.49)	1.11 (7.65)	0.45 (3.10)	0.16	5.34 (0.44)
28-2-4	1	2.58 (6.55)	2.92 (7.42)	1.28 (3.25)	0.03 (0.08)	3.75 (1.67)	4.91 (5.55)	0.5 (3.45)	0.25 (1.72)	0.07	2.96 (0.25)
28-2-[illegible]	1	2.66 (6.76)	2.94 (7.47)	∞ (∞)	0.027 (0.07)	1.05 (0.47)	2.45 (2.77)	0 (0)	0.118 (0.81)	0	1.40 (0.12)

TABLE D.19

RESULTS OF MOMENT-THRUST INTERACTION TESTS, PANEL 39-4

								Normalized to thickness		Normalized to compressive strength, σ_{c180}	
Specimen	No. of samples	Thickness t inches (cm)	Width b inches (cm)	Eccentricity e inches (cm)	Increase in eccentricity Δe inches (cm)	Maximum load P_{max} kips ($N \times 10^4$)	Moment in.-kips ($N\text{-}m \times 10^2$)	P/bt ksi (MPa)	M/bt^2 ksi (MPa)	$\frac{P/bt}{\sigma_c}$	$\frac{M/bt^2}{\sqrt{\sigma_c}}$ $\sqrt{psi}$ ($\sqrt{MPa}$)
39-4-ave	5	-- (--)	-- (--)	0 (0)	0 (0)	-- (--)	0 (0)	6.61 (45.54)	0 (0)	1.0	0 (0)
39-4-1	1	2.62 (6.65)	3.04 (7.72)	0.26 (0.66)	0.1 (0.25)	41.25 (18.35)	14.85 (16.78)	5.18 (35.71)	0.71 (4.89)	0.78	8.73 (0.72)
39-4-6	1	2.62 (6.65)	2.99 (7.59)	0.3 (0.76)	0.12 (0.30)	41.75 (18.57)	17.54 (19.82)	5.33 (36.75)	0.75 (5.17)	0.81	9.22 (0.77)
39-4-4	1	2.56 (6.50)	2.99 (7.59)	0.52 (1.32)	0.14 (0.36)	26.25 (11.68)	19.95 (22.54)	3.43 (23.65)	0.97 (6.69)	0.52	11.93 (0.99)
39-4-7	1	2.57 (6.53)	2.98 (7.57)	0.7 (1.78)	0.13 (0.33)	20.05 (8.92)	16.64 (18.80)	2.62 (18.06)	0.85 (5.86)	0.40	10.5 (0.87)
39-4-3	1	2.65 (6.73)	2.93 (7.44)	1.07 (2.72)	0.12 (0.30)	11.83 (5.26)	14.08 (15.91)	1.52 (10.48)	0.68 (4.69)	0.23	8.36 (0.69)
39-4-2	1	2.6 (6.60)	3.03 (7.70)	1.25 (3.18)	0.1 (0.25)	10.46 (4.65)	14.12 (15.95)	1.33 (9.17)	0.69 (4.76)	0.20	8.49 (0.70)
39-4-5	1	2.56 (6.50)	3.0 (7.62)	∞ (∞)	0.17 (0.43)	1.375 (0.61)	3.2 (3.62)	0 (0)	0.16 (1.10)	0	1.97 (0.16)

TABLE D.20

RESULTS OF MOMENT-THRUST INTERACTION TESTS, PANEL 39-10

Specimen	No. of samples	Thickness t inches (cm)	Width b inches (cm)	Eccentricity e inches (cm)	Increase in eccentricity Δe inches (cm)	Maximum load P_{max} kips ($N \times 10^4$)	Moment in.-kips ($N\text{-}m \times 10^2$)	Normalized to thickness: P/bt ksi (MPa)	Normalized to thickness: M/bt^2 ksi (MPa)	Normalized to compressive strength, σ_{c180}: $\frac{P/bt}{\sigma_c}$	Normalized to compressive strength, σ_{c180}: $\frac{M/bt^2}{\sqrt{\sigma_c}}$ $\sqrt{psi}$ ($\sqrt{MPa}$)
39-10-ave	2	-- (--)	-- (--)	0 (0)	0 (0)	-- (--)	0 (0)	6.77 (46.67)	0 (0)	1.0	0 (0)
39-10-6	1	2.47 (6.27)	3.0 (7.62)	0.25 (0.64)	0.16 (0.41)	34.5 (15.35)	14.15 (15.99)	4.74 (32.68)	0.79 (5.45)	0.7	9.60 (0.80)
39-10-1	1	2.44 (6.20)	3.04 (7.72)	0.49 (1.24)	0.15 (0.38)	23.0 (10.23)	14.72 (16.63)	3.14 (21.65)	0.83 (5.72)	0.46	10.09 (0.84)
39-10-3	1	2.32 (5.89)	3.00 (7.62)	0.7 (1.78)	0.20 (0.51)	10.1 (4.49)	9.09 (10.27)	1.48 (10.20)	0.58 (4.00)	0.22	7.05 (0.59)
39-10-7	1	2.4 (6.10)	2.99 (7.59)	0.96 (2.44)	0.16 (0.41)	7.0 (3.11)	7.84 (8.86)	0.98 (6.76)	0.46 (3.17)	0.15	5.59 (0.46)
39-10-5	1	2.41 (6.12)	3.0 (7.62)	1.2 (3.05)	0.1 (0.25)	4.4 (1.96)	5.72 (6.46)	0.61 (4.21)	0.33 (2.28)	0.09	4.01 (0.33)
39-10-ave	2	2.27 (5.77)	3.02 (7.67)	∞ (∞)	0.03 (0.08)	0.9 (0.40)	2.39 (2.70)	0 (0)	0.115 (0.79)	0	1.40 (0.12)

TABLE D.21

RESULTS OF MOMENT-THRUST INTERACTION TESTS, PANEL 40-5

Specimen	No. of samples	Thickness t inches (cm)	Width b inches (cm)	Eccentricity e inches (cm)	Increase in eccentricity Δe inches (cm)	Maximum load P_{max} kips ($N \times 10^4$)	Moment in.-kips ($N\text{-}m \times 10^2$)	Normalized to thickness: P/bt ksi (MPa)	Normalized to thickness: M/bt^2 ksi (MPa)	Normalized to compressive strength, σ_{c180}: $\frac{P/bt}{\sigma_c}$	Normalized to compressive strength, σ_{c180}: $\frac{M/bt^2}{\sqrt{\sigma_c}}$ $\sqrt{psi}$ ($\sqrt{MPa}$)
40-5-ave	8	-- (--)	-- (--)	0 (0)	0 (0)	-- (--)	0 (0)	6.75 (46.51)	0 (0)	1.0	0 (0)
40-5-2	1	2.57 (6.53)	3.06 (7.77)	0.26 (0.66)	0.08 (0.20)	34.25 (15.23)	11.65 (13.16)	4.36 (30.06)	0.58 (4.00)	0.65	7.08 (0.59)
40-5-4	1	2.6 (6.60)	3.00 (7.62)	0.39 (0.99)	0.1 (0.25)	33.5 (14.90)	16.42 (18.55)	4.29 (29.58)	0.81 (5.58)	0.64	9.89 (0.82)
40-5-5	1	2.57 (6.53)	2.94 (7.47)	0.52 (1.32)	0.12 (0.30)	17.5 (7.78)	11.2 (12.65)	2.32 (16.99)	0.58 (4.00)	0.35	7.08 (0.59)
40-5-3	1	2.57 (6.53)	3.07 (7.80)	0.78 (1.98)	0.1 (0.25)	10.0 (4.45)	8.8 (9.94)	1.12 (7.72)	0.43 (2.96)	0.17	5.25 (0.44)
40-5-1	1	2.55 (6.48)	3.0 (7.62)	1.06 (2.69)	0.06 (0.15)	5.75 (2.56)	6.44 (7.28)	0.75 (5.17)	0.33 (2.28)	0.11	4.03 (0.34)
40-5-6	1	2.55 (6.48)	3.03 (7.70)	1.27 (3.23)	0.07 (0.18)	5.5 (2.45)	7.37 (8.33)	0.71 (4.89)	0.37 (2.55)	0.11	4.52 (0.37)
40-5-7	1	2.56 (6.50)	2.97 (7.54)	∞ (∞)	0.015 (0.04)	1.275 (0.57)	2.97 (3.56)	0 (0)	0.153 (1.05)	0	1.87 (0.15)

TABLE D.22

RESULTS OF MOMENT-THRUST INTERACTION TESTS, PANEL 42-9

Specimen	No. of samples	Thickness t inches (cm)	Width b inches (cm)	Eccentricity e inches (cm)	Increase in eccentricity Δe inches (cm)	Maximum load P_{max} kips ($N \times 10^4$)	Moment in.-kips ($N\text{-}m \times 10^2$)	Normalized to thickness: P/bt ksi (MPa)	Normalized to thickness: M/bt^2 ksi (MPa)	Normalized to compressive strength, σ_{c180}: $\frac{P/bt}{\sigma_c}$	Normalized to compressive strength, σ_{c180}: $\frac{M/bt^2}{\sqrt{\sigma_c}}$ $\sqrt{psi}$ ($\sqrt{MPa}$)
42-9-ave	9	-- (--)	-- (--)	0 (0)	0 (0)	-- (--)	0 (0)	4.91 (33.83)	0 (0)	1.0	0 (0)
42-9-1	1	2.48 (6.30)	3.03 (7.70)	2.64 (6.71)	0.08 (0.20)	22.25 (9.90)	7.57 (8.55)	2.96 (20.41)	0.41 (2.83)	0.61	5.86 (0.49)
42-9-2	1	2.5 (6.35)	3.01 (7.65)	0.38 (0.97)	0.11 (0.28)	24.0 (10.68)	11.76 (13.29)	3.19 (21.99)	0.63 (4.34)	0.65	9.01 (0.75)
42-9-4	1	2.48 (6.30)	3.07 (7.80)	0.53 (1.35)	0.11 (0.28)	11.25 (5.00)	7.20 (8.13)	1.48 (10.20)	0.38 (2.62)	0.30	5.43 (0.45)
42-9-7	1	2.52 (6.40)	2.83 (7.19)	0.78 (1.98)	0.11 (0.28)	14.0 (6.23)	12.46 (14.08)	1.96 (13.51)	0.69 (4.76)	0.40	9.87 (0.82)
42-9-5	1	2.47 (6.27)	3.05 (7.75)	1.04 (2.64)	0.09 (0.23)	5.13 (2.28)	5.80 (6.55)	0.68 (4.69)	0.31 (2.14)	0.14	4.43 (0.37)
42-9-6	1	2.48 (6.30)	3.03 (7.70)	1.3 (3.30)	0.06 (0.15)	3.25 (1.45)	4.42 (4.99)	0.43 (2.96)	0.24 (1.65)	0.09	6.15 (0.28)
42-9-3	1	2.47 (6.27)	3.02 (7.67)	∞ (∞)	0.014 (0.04)	0.94 (0.418)	2.18 (2.46)	0 (0)	0.118 (0.81)	0	1.69 (0.14)

TABLE D.23

UNIT WEIGHTS AT ONE MONTH

Mix number	Average unit weight, air dry	
	lb/ft^3	kg/m^3
23	148.3	2377
24	144.7	2319
25	147.0	2356
26	147.3	2360
28	145.9	2338
29	146.2	2343
30	146.0	2340
33	148.9	2386
33A	148.5	2380
34	146.7	2351
38	148.1	2374
39	149.5	2396
40	147.7	2367
42	145.3	2329
45	144.3	2313

APPENDIX E

PLOTTED RESULTS OF STRENGTH TESTS

The results of compression, flexural, and pull-out tests are presented in this appendix as a function of time in graphic form with time on a logarithmic scale. These semi-logarithmic plots permit the early strength results to be seen as clearly as the data for one month or older. The method of presentation is discussed in Section 8.5.2. After one month, the curing conditions changed significantly. Accordingly, two sets of graphs are given. One set, Figs. E.1 through E.18, contain all the test results for compression, flexural and pull-out tests up through one month. The second set, Figs. E.19 through E.27, contain just the compressive strength results up through six months. Note that the scale of logarithm of time is different between the two sets of figures.

Each point represents one strength test. The small number beside each data point indicates the panel number from which the specimen was cut. Hence, the reader may visually evaluate interpanel (between panels) and intrapanel (within panel) variations at a glance. The curves have been drawn visually on the basis of engineering judgment, with consideration of known strength-time relations and the results of the previous and subsequent test period. It includes a personal weighted evaluation of the scatter of the data in general. This best-fit strength time curve may not agree exactly with the data tabulated in Appendix D because the tabulated results are statistical averages based only on the data for the one test age.

The curves for compressive strength, σ_c, are solid; the flexural strength, σ_f, curves are dashed; and the pullout strength curves, σ_p, are dotted. In a few cases where there are so many tests at a given age that they would plot on top of each other, only the range and the average are shown.

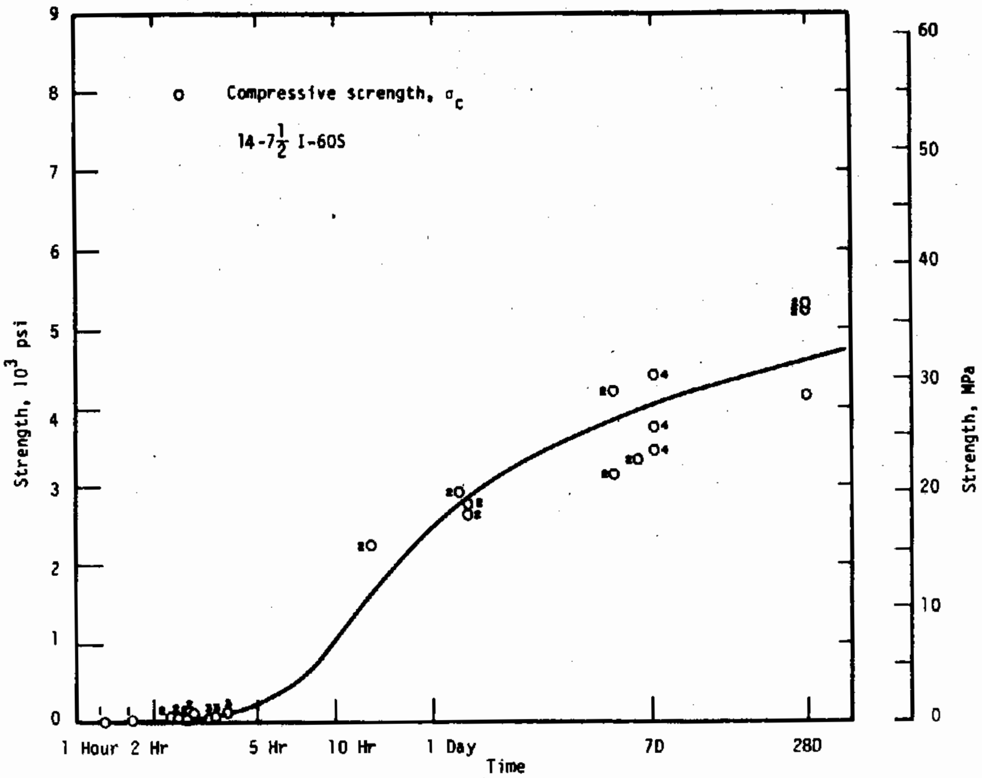

FIG. E.1 STRENGTH-TIME CURVES TO 28 DAYS, MIX 14

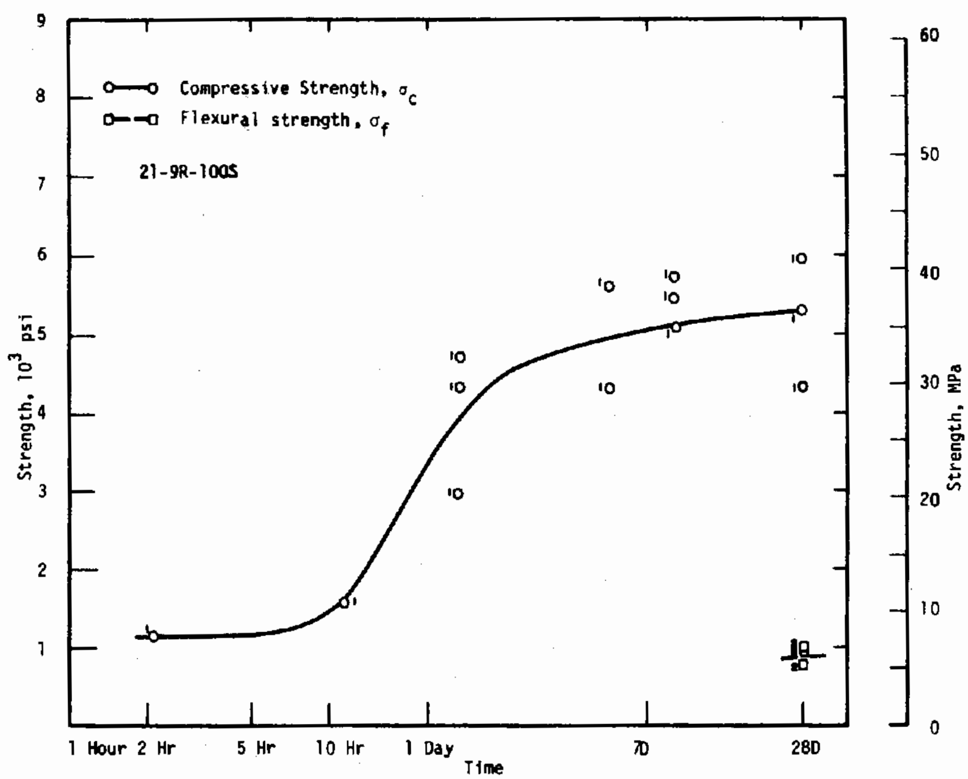

FIG. E.2 STRENGTH-TIME CURVES TO 28 DAYS, MIX 21

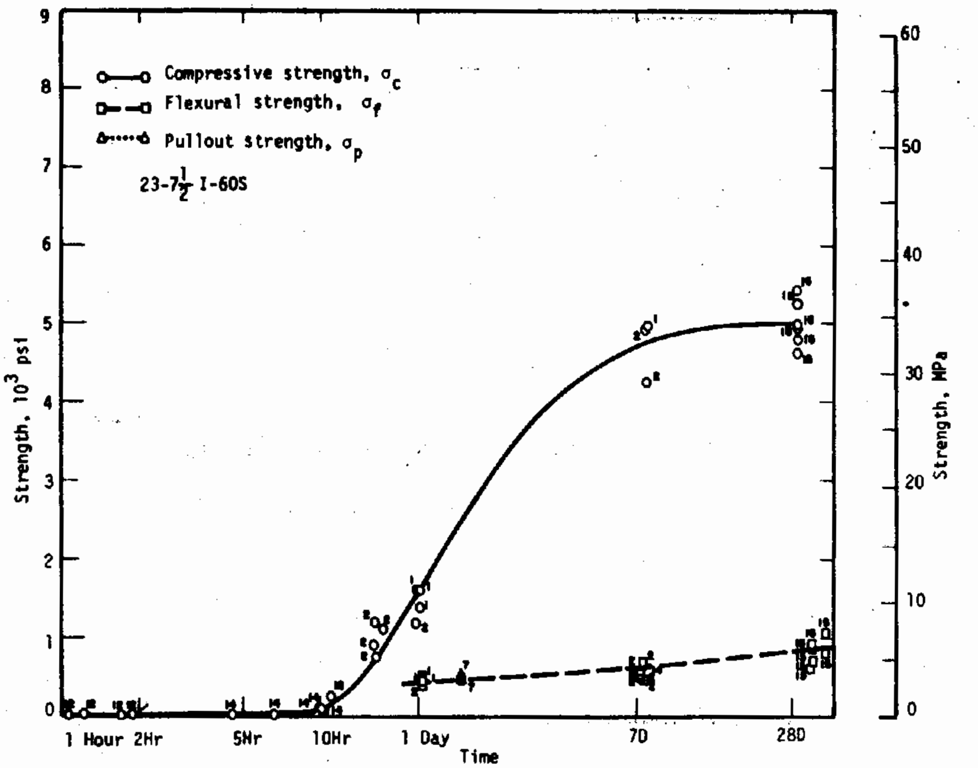

FIG. E.3 STRENGTH-TIME CURVES TO 28 DAYS, MIX 23

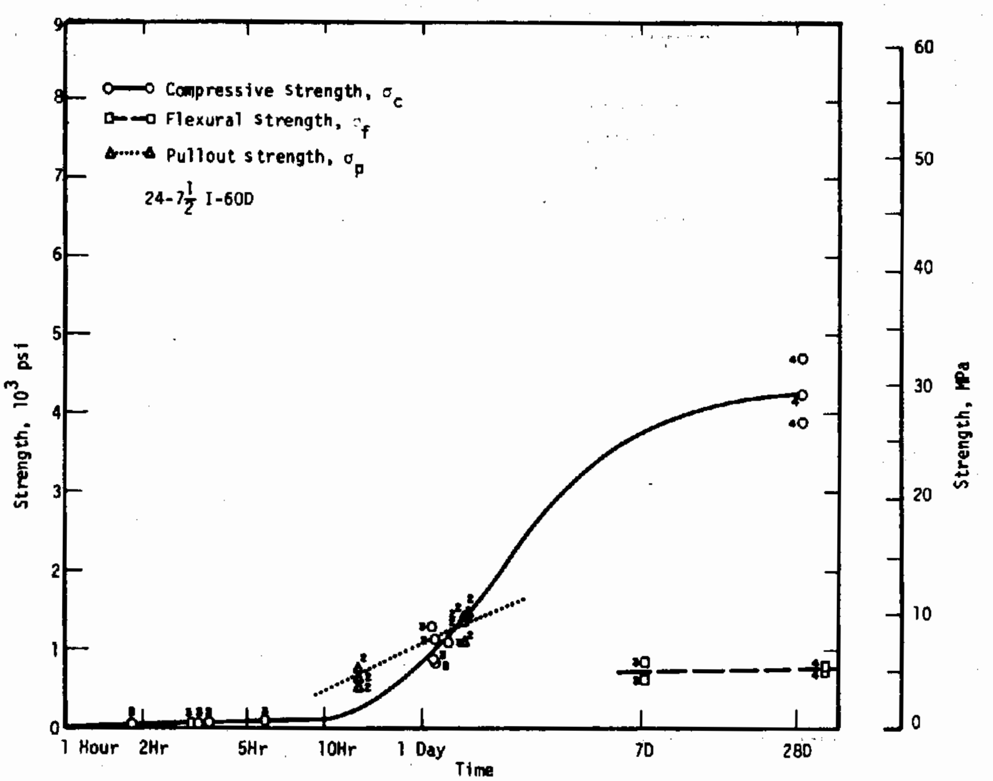

FIG. E.4 STRENGTH-TIME CURVES TO 28 DAYS, MIX 24

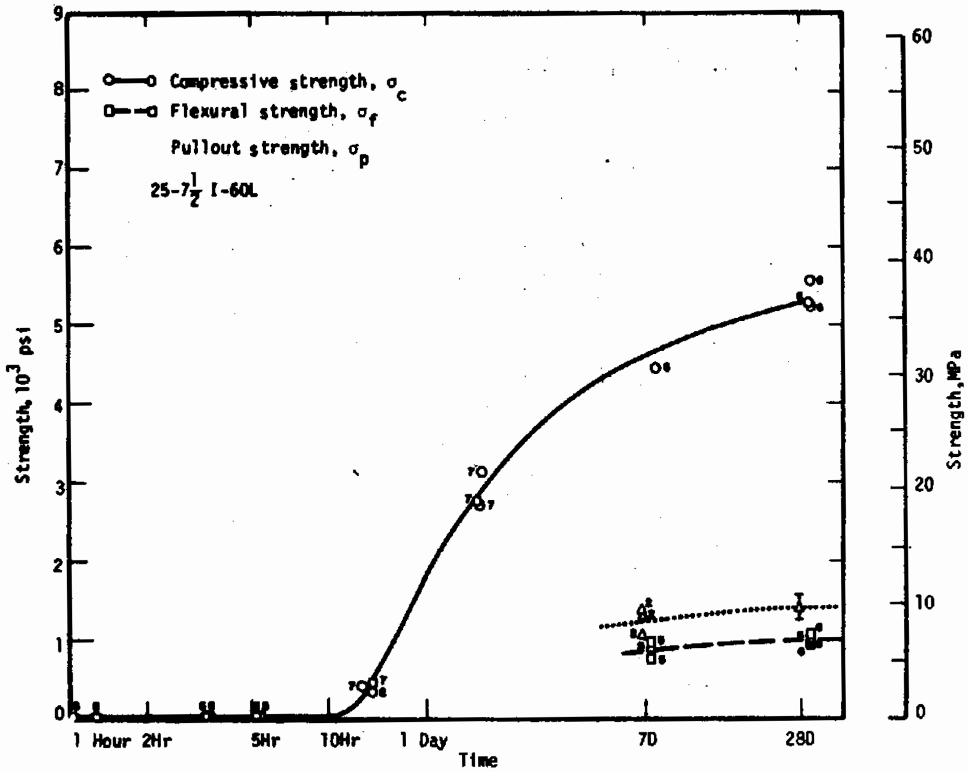

FIG. E.5 STRENGTH-TIME CURVES TO 28 DAYS, MIX 25

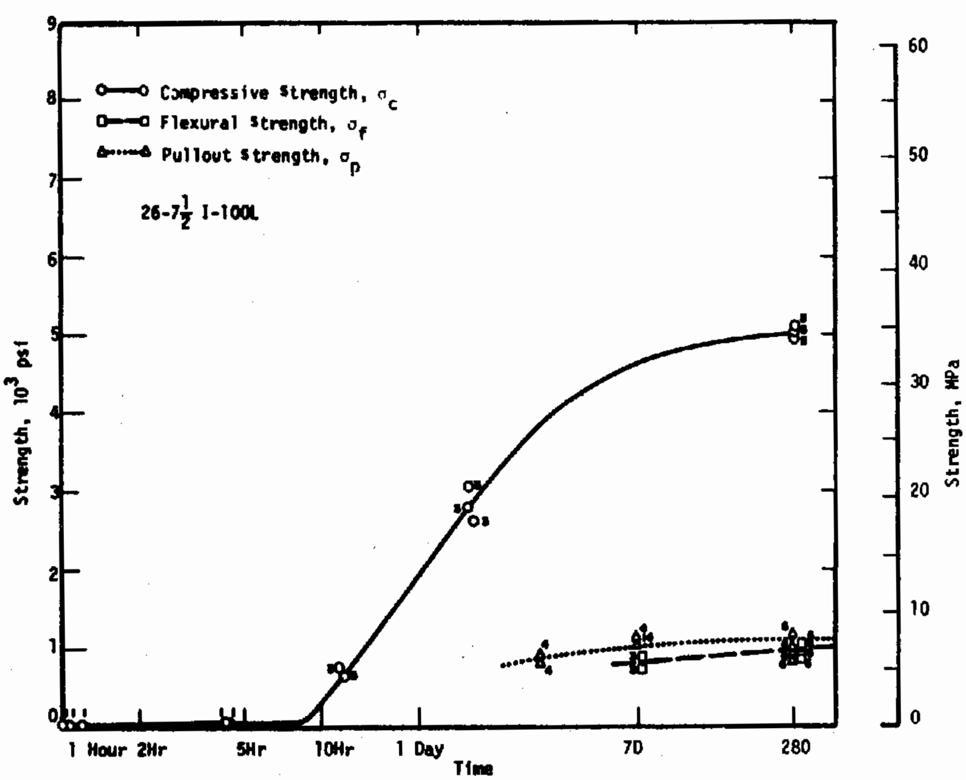

FIG. E.6 STRENGTH-TIME CURVES TO 28 DAYS, MIX 26

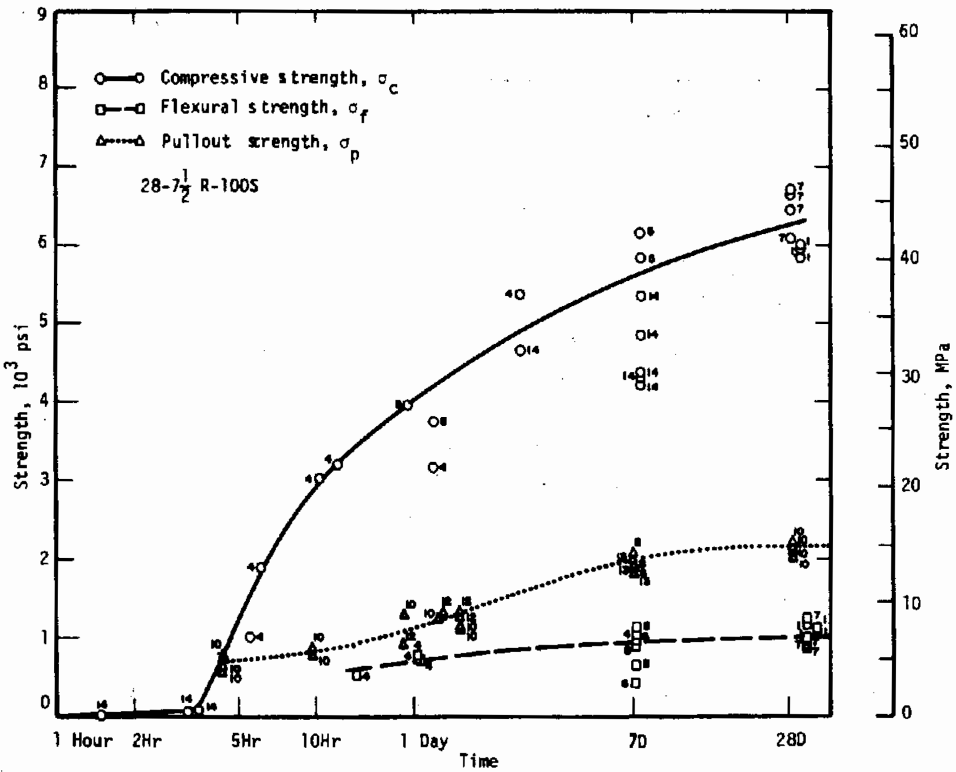

FIG. E.7 STRENGTH-TIME CURVES TO 28 DAYS, MIX 28

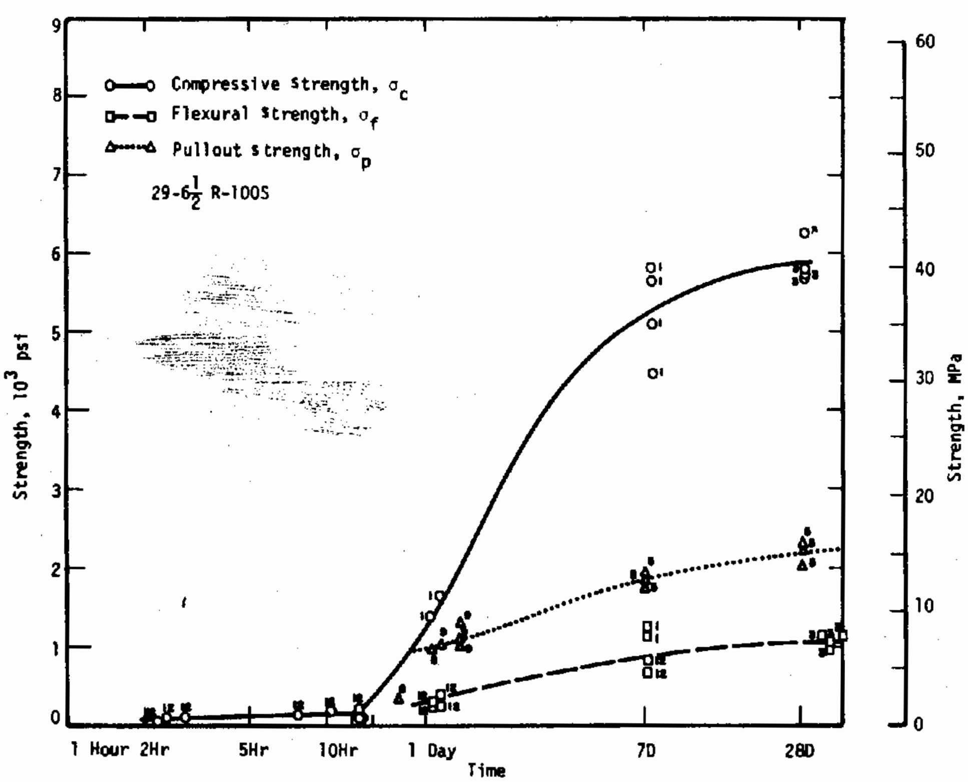

FIG. E.8 STRENGTH-TIME CURVES TO 28 DAYS, MIX 29

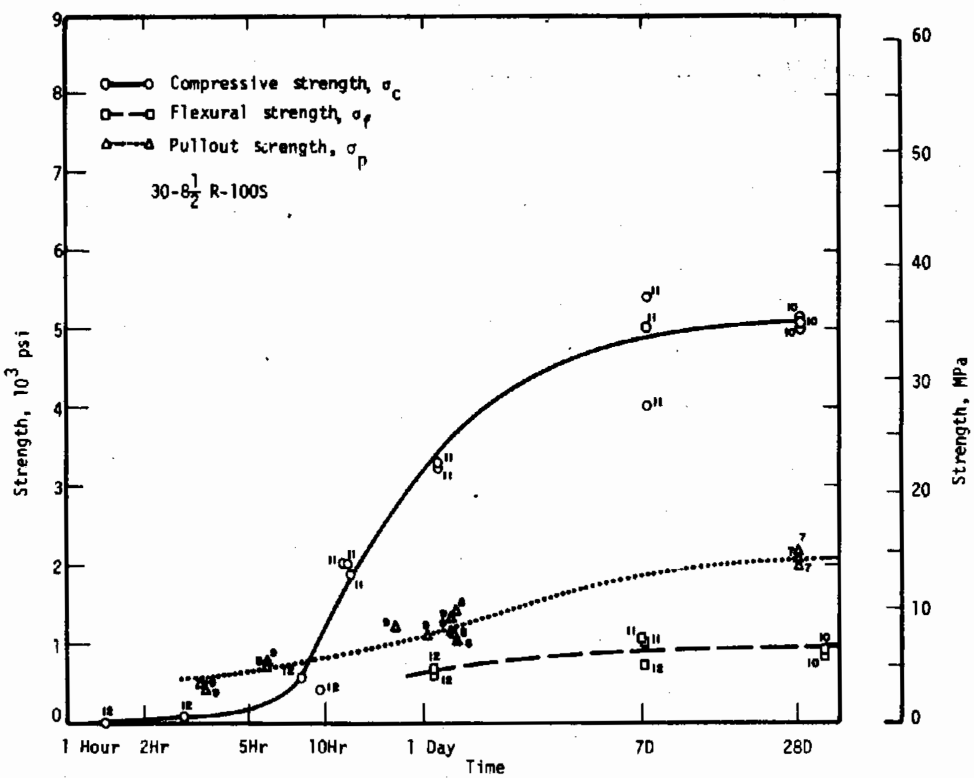

FIG. E.9 STRENGTH-TIME CURVES TO 28 DAYS, MIX 30

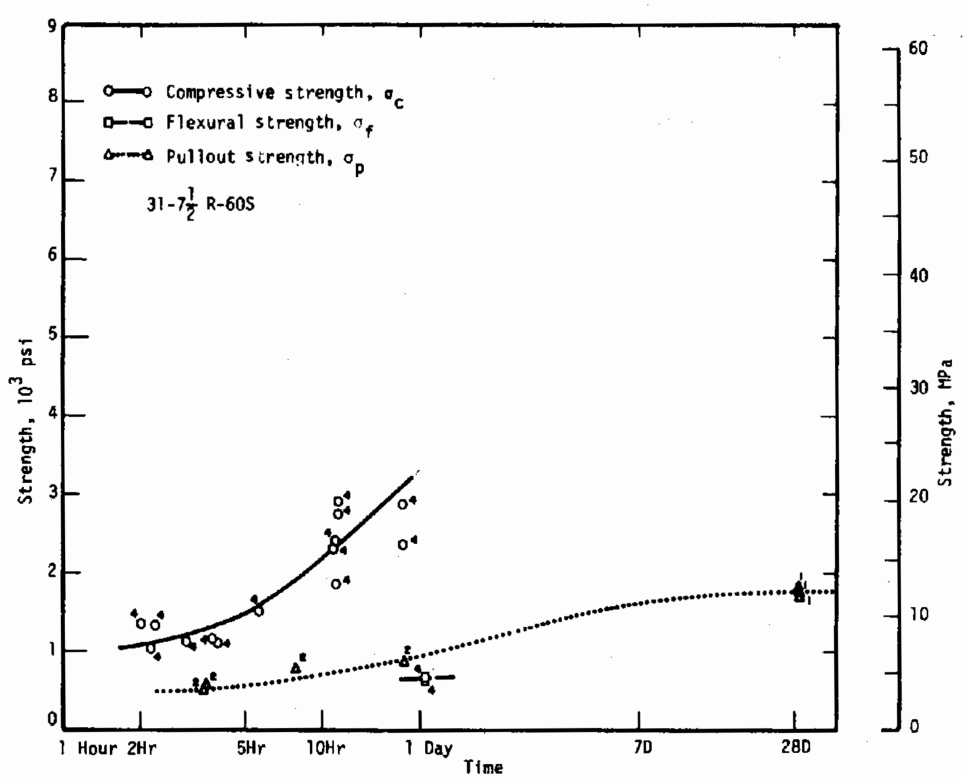

FIG. E.10 STRENGTH-TIME CURVES TO 28 DAYS, MIX 31

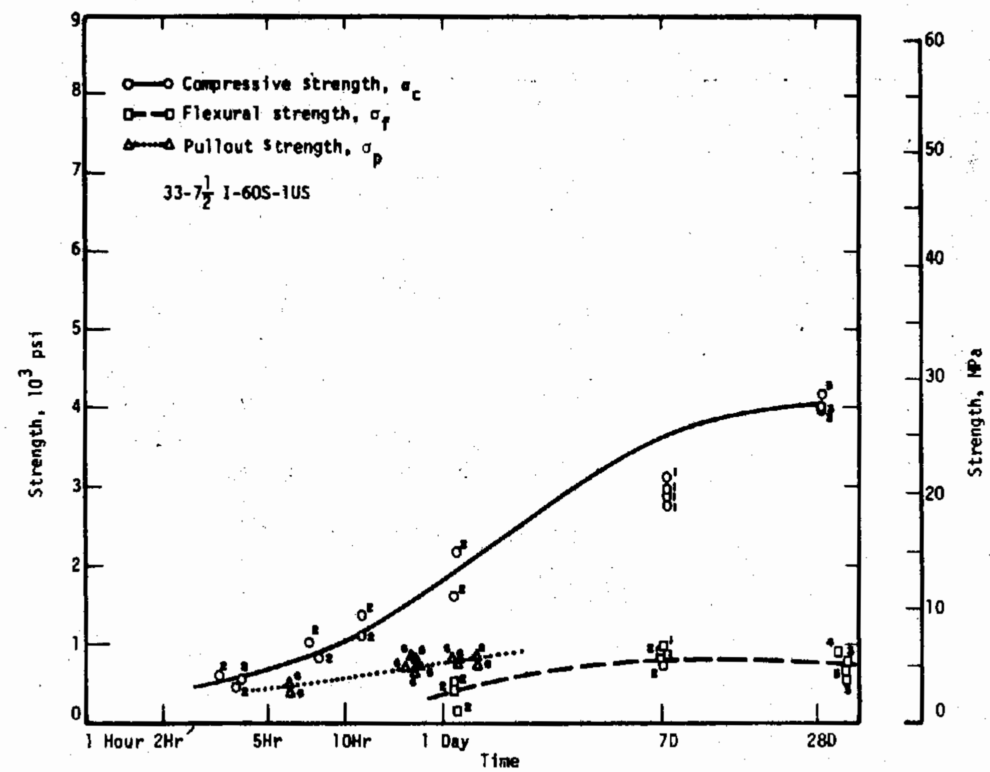

FIG. E.11 STRENGTH-TIME CURVES TO 28 DAYS, MIX 33

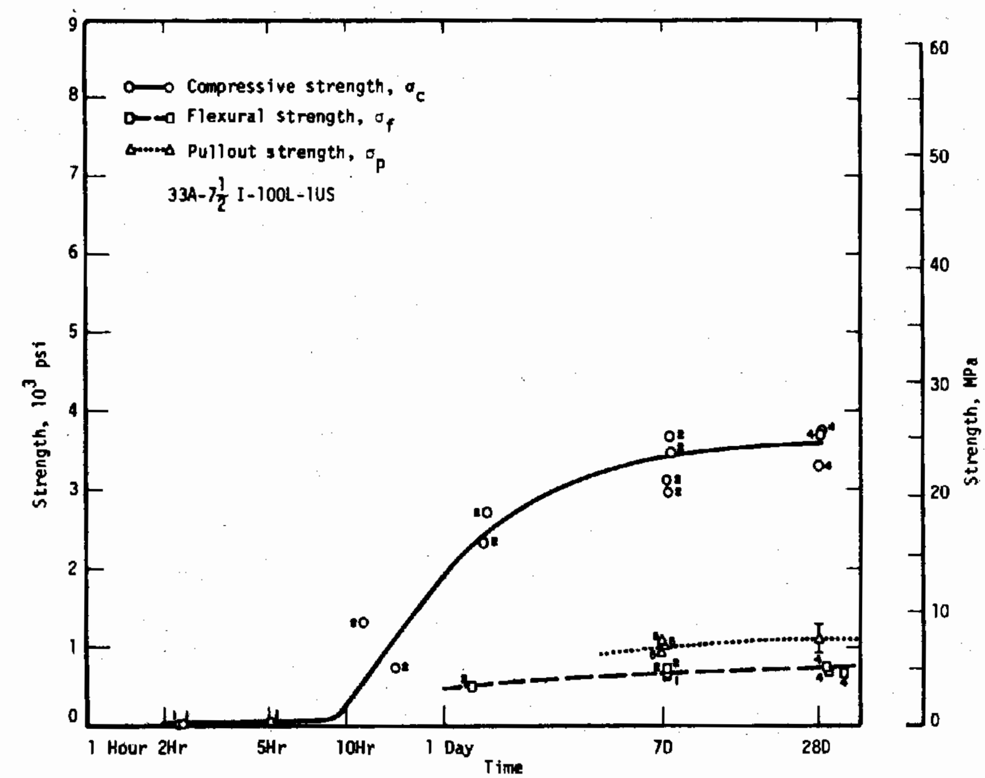

FIG. E.12 STRENGTH-TIME CURVES TO 28 DAYS, MIX 33A

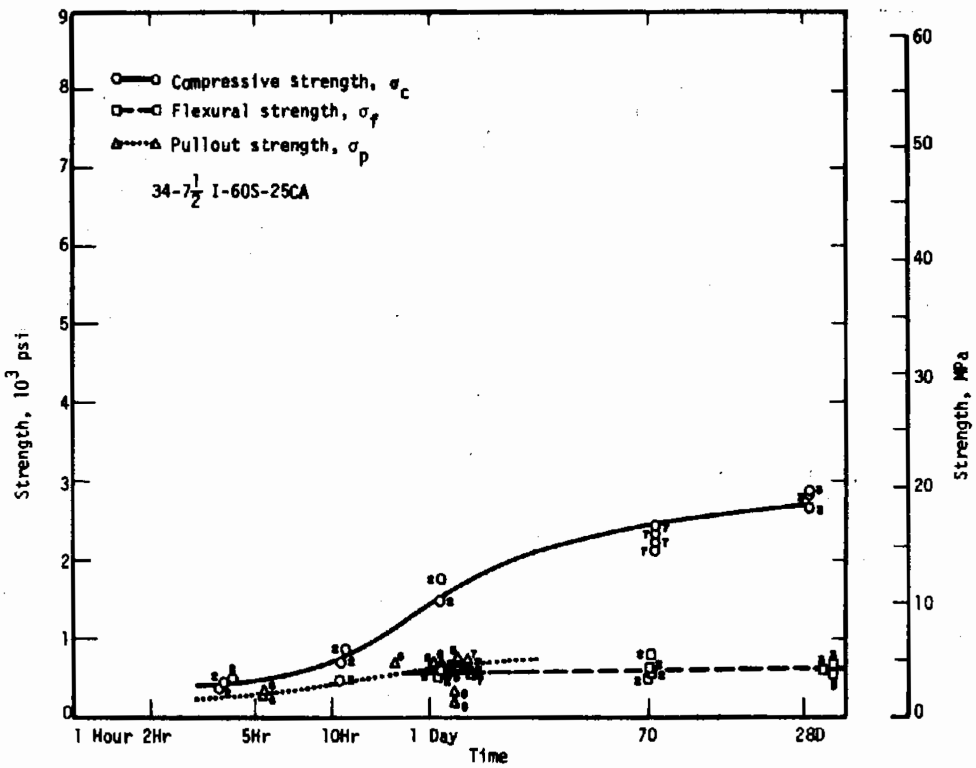

FIG. E.13 STRENGTH-TIME CURVES TO 28 DAYS, MIX 34

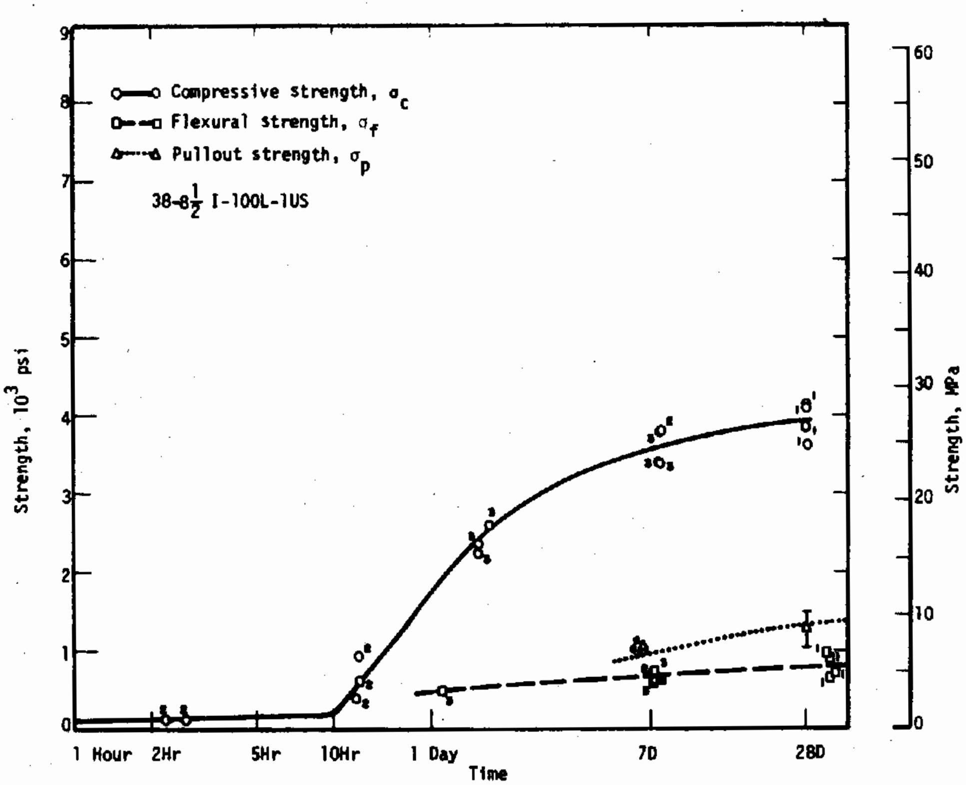

FIG. E.14 STRENGTH-TIME CURVES TO 28 DAYS, MIX 38

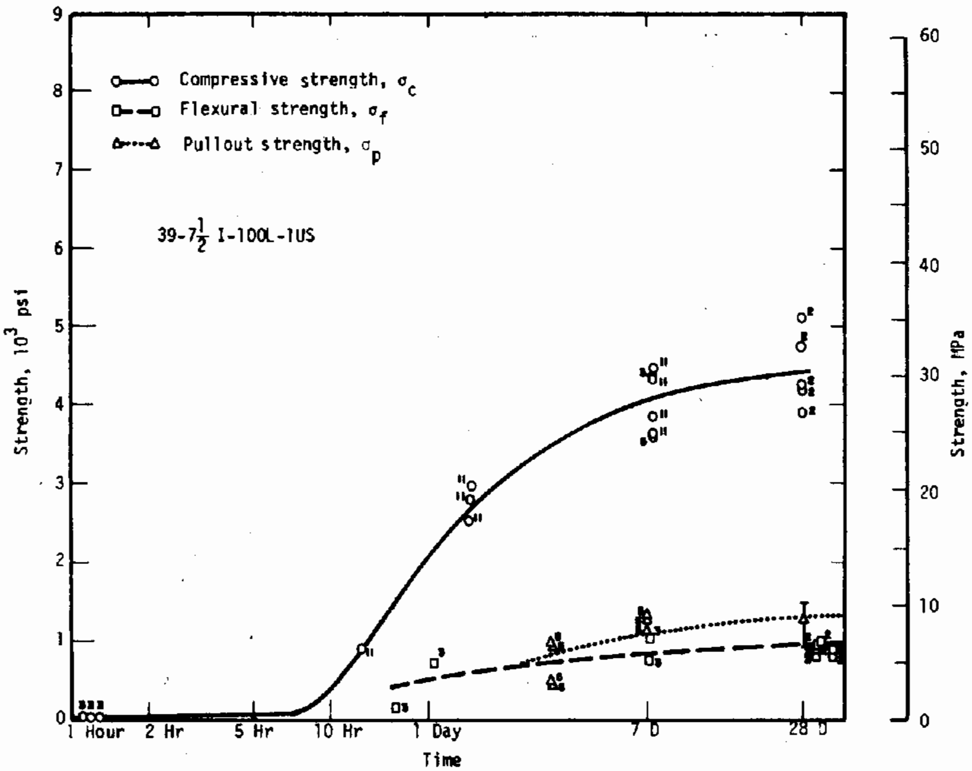

FIG. E.15 STRENGTH-TIME CURVES TO 28 DAYS, MIX 39

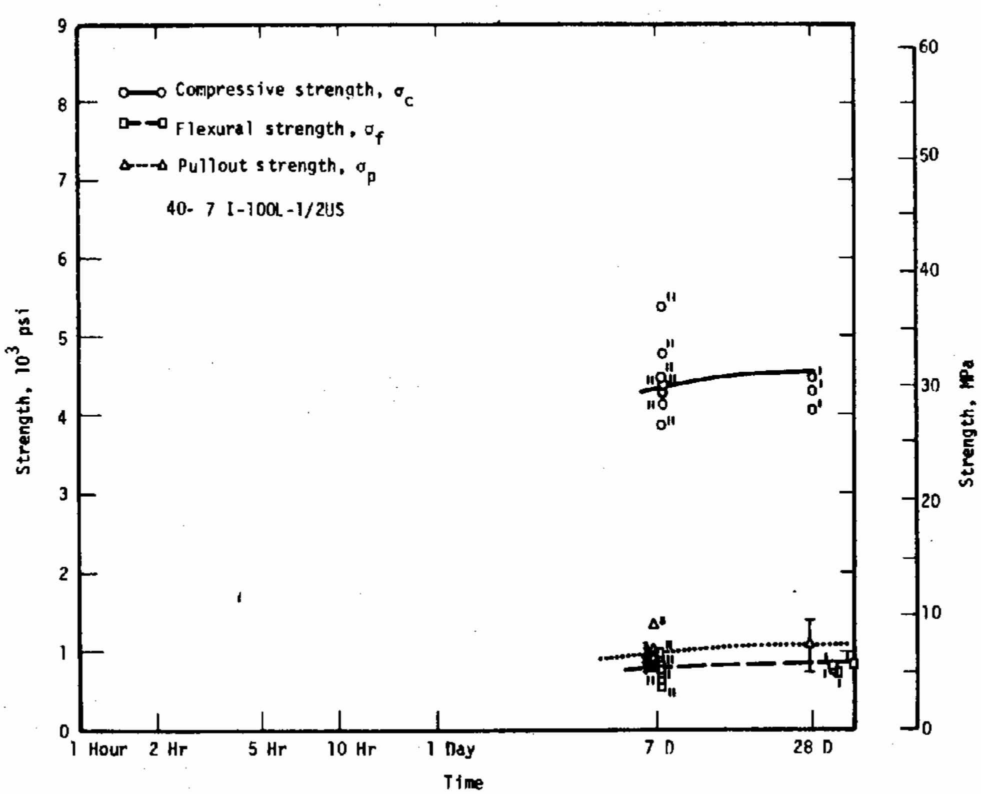

FIG. E.16 STRENGTH-TIME CURVES TO 28 DAYS, MIX 40

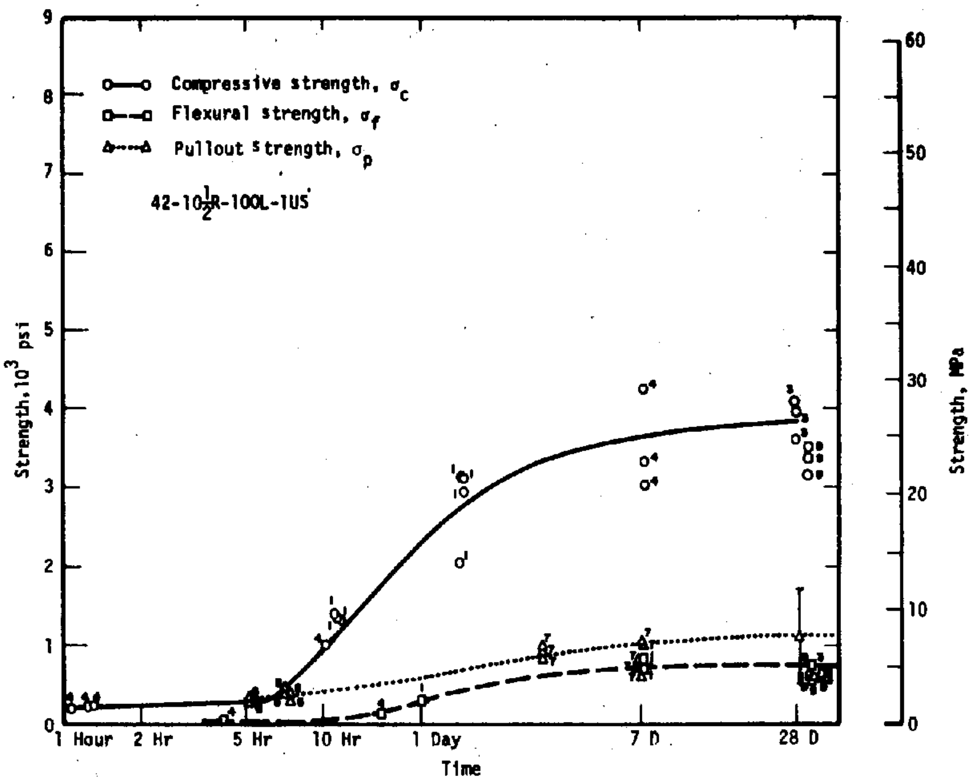

FIG. E.17 STRENGTH-TIME CURVES TO 28 DAYS, MIX 42

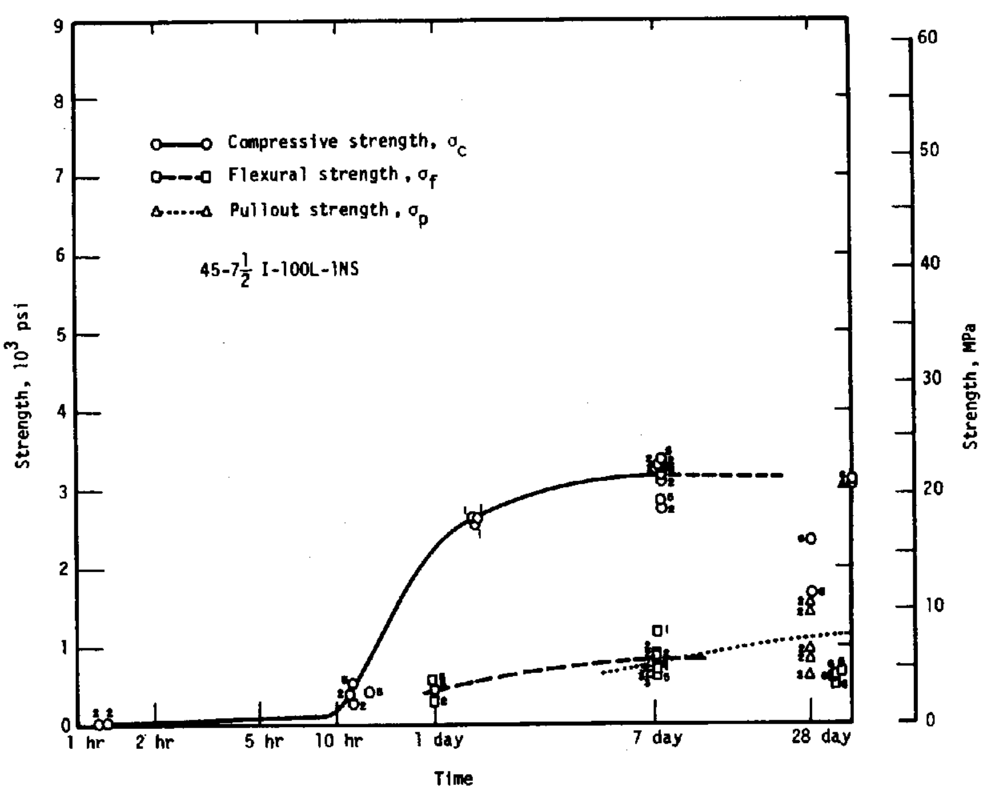

FIG. E.18 STRENGTH-TIME CURVES TO 28 DAYS, MIX 45

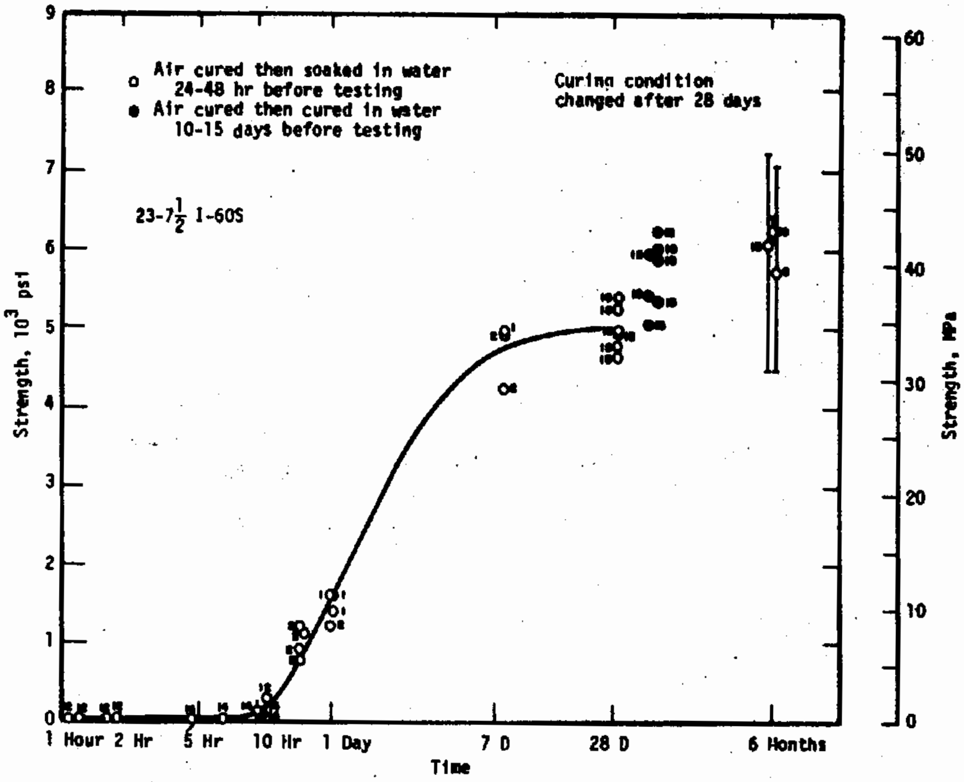

FIG. E.19 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 23

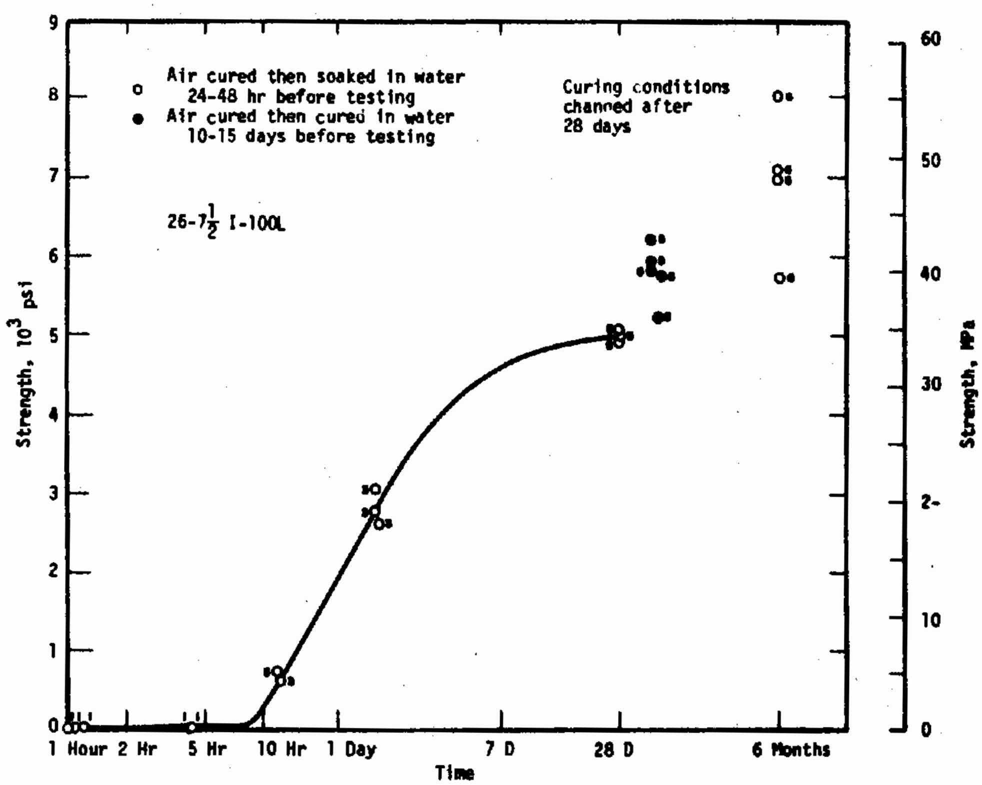

FIG. E.20 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 26

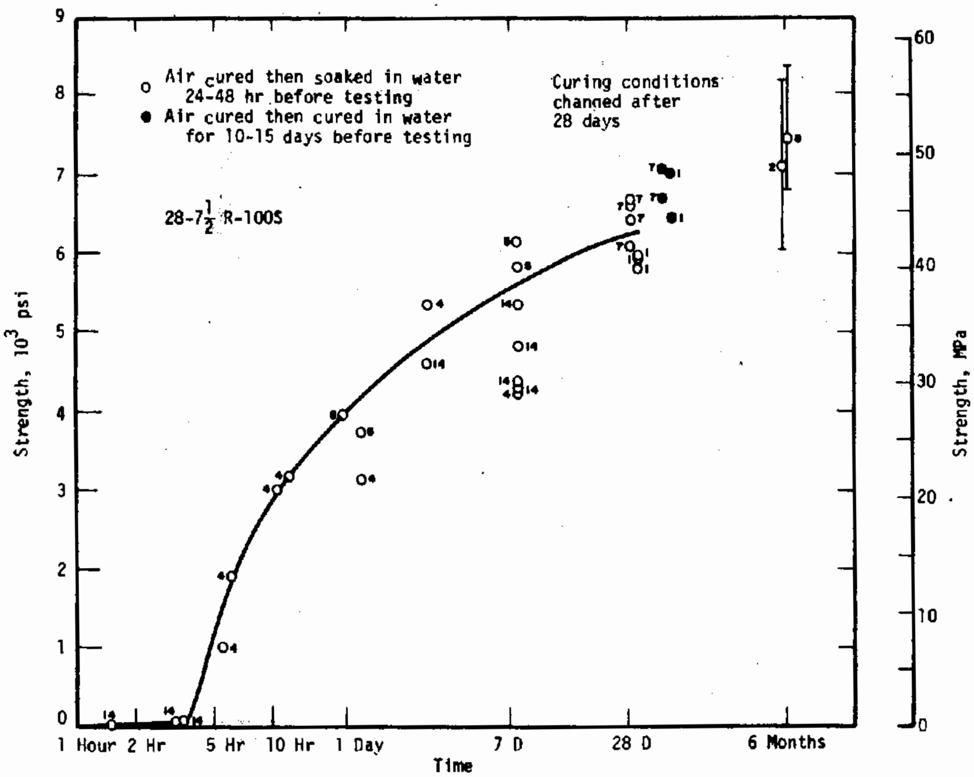

FIG. E.21 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 28

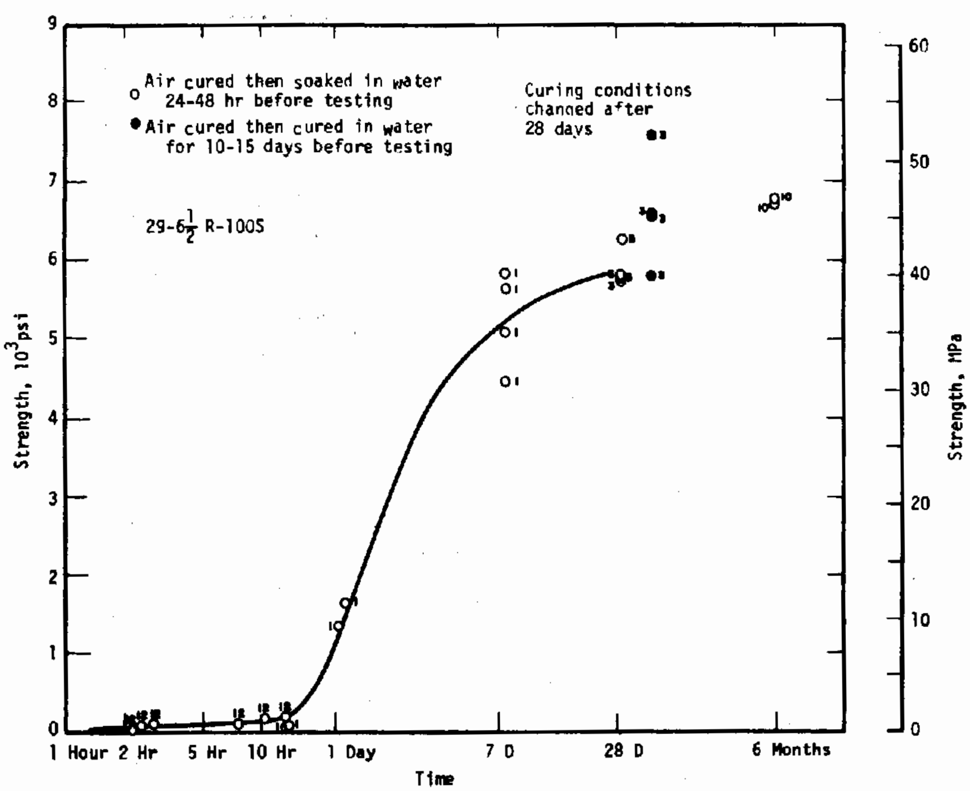

FIG. E.22 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 29

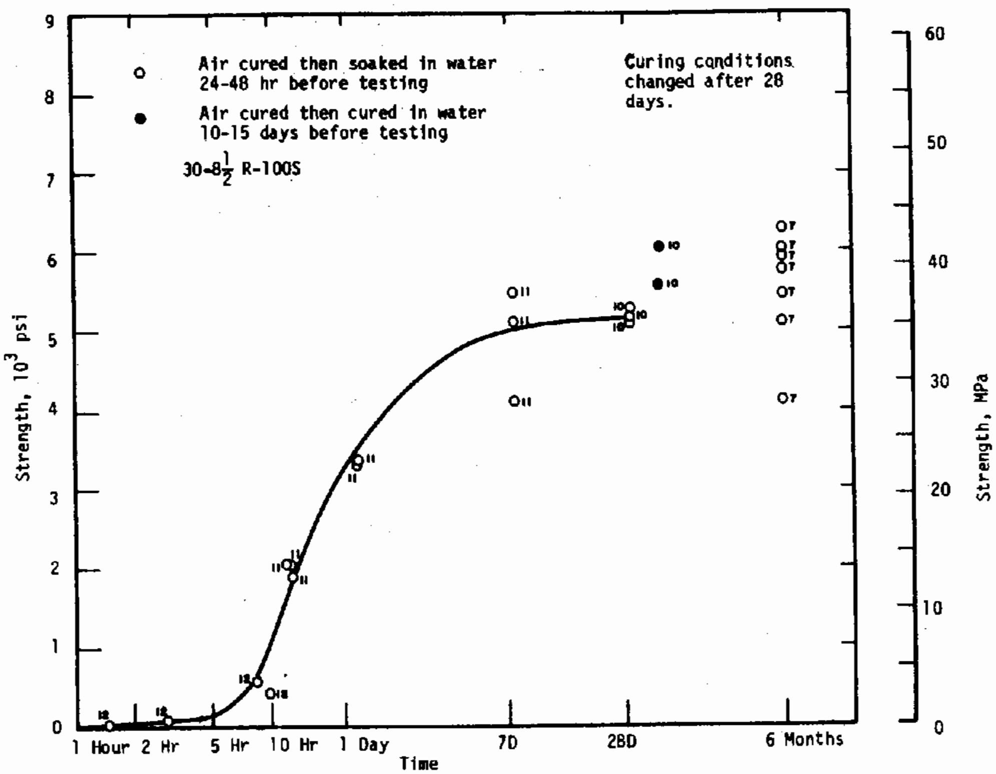

FIG. E.23 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 30

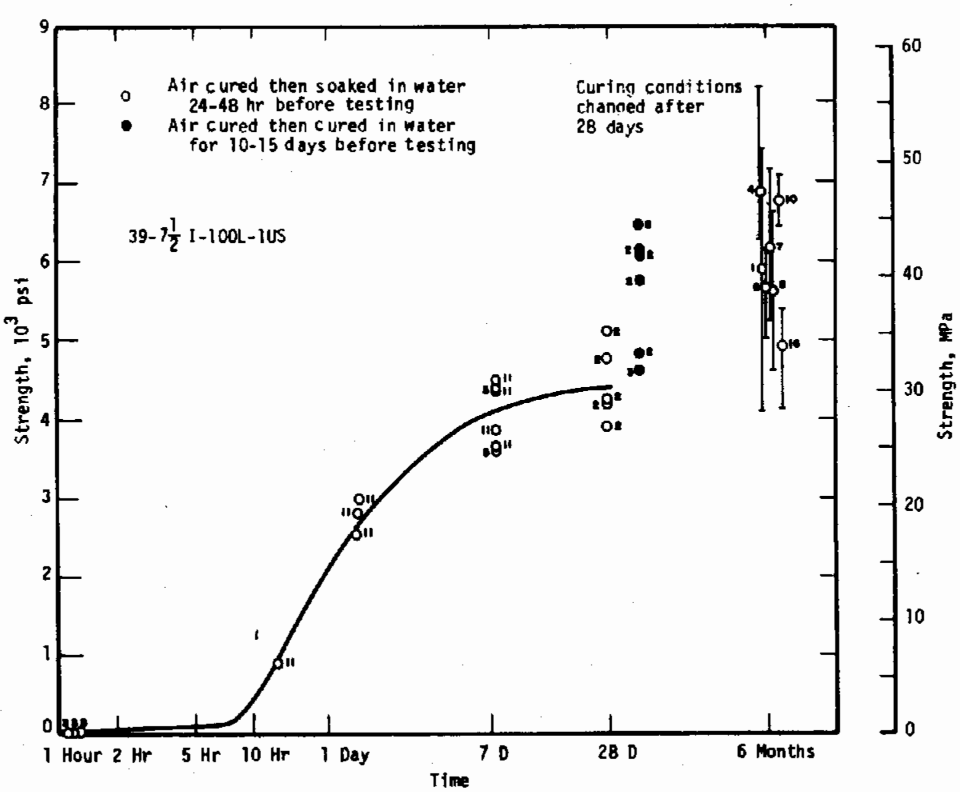

FIG. E.24 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 39

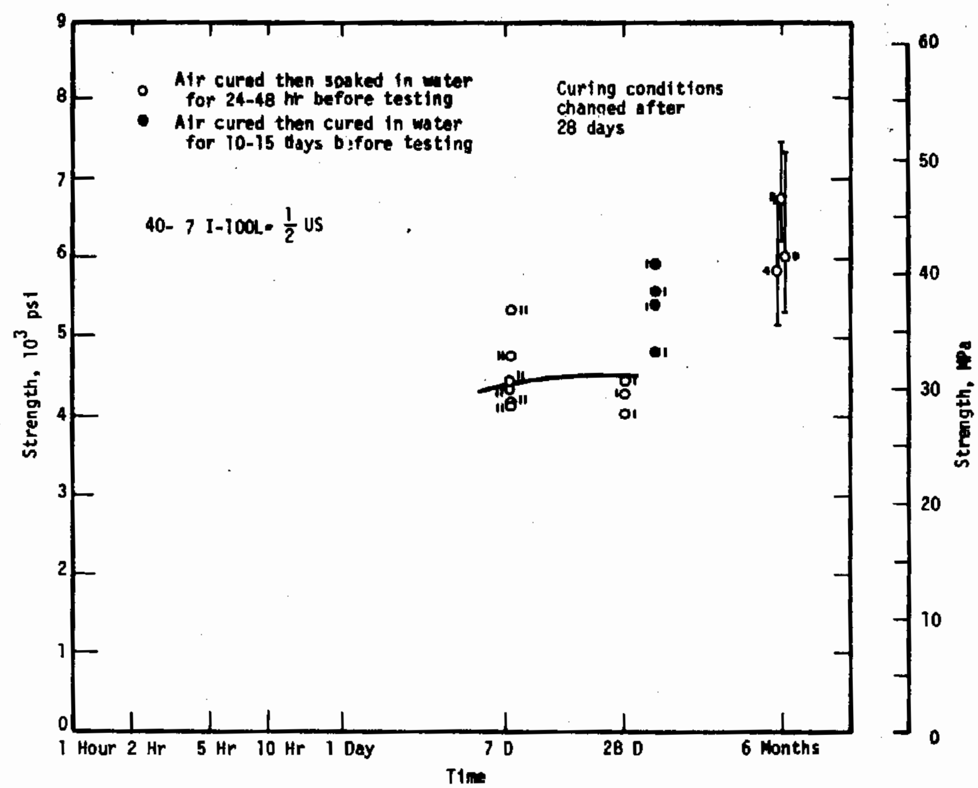

FIG. E.25 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 40

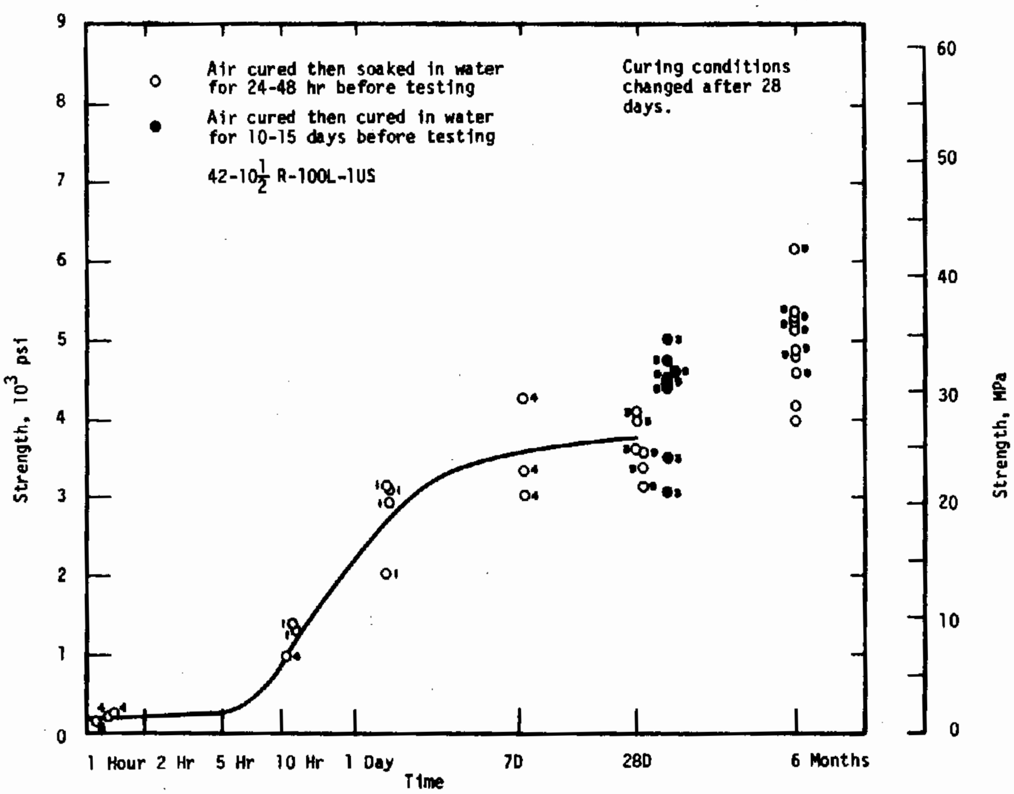

FIG. E.26 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 42

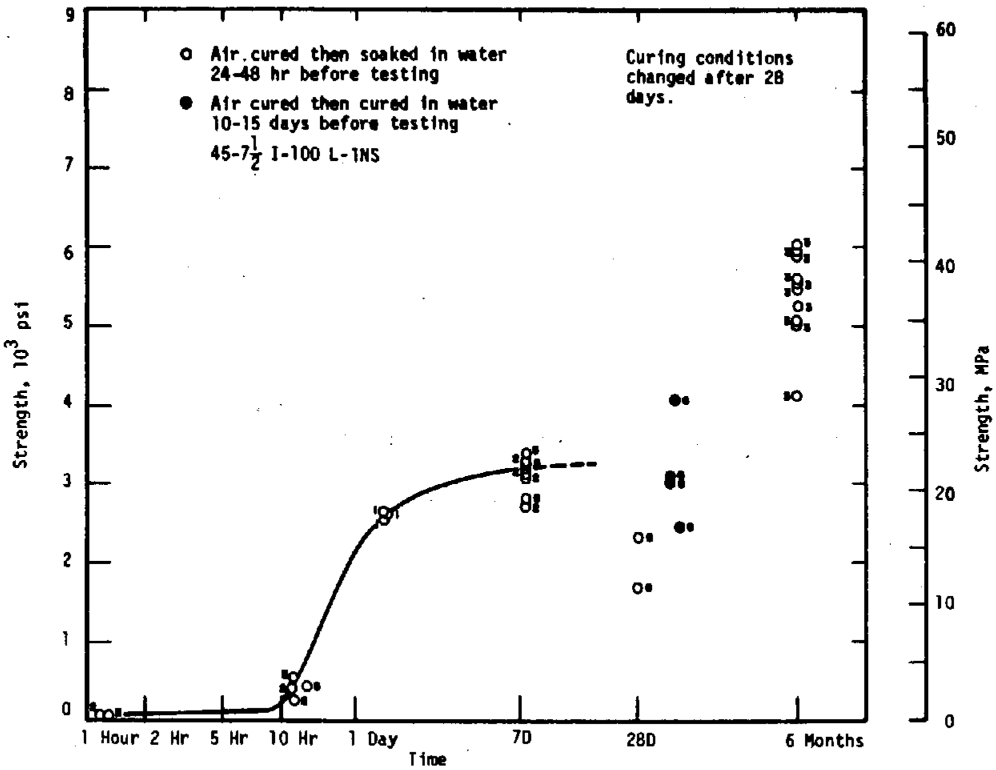

FIG. E.27 STRENGTH-TIME CURVES TO SIX MONTHS, MIX 45

APPENDIX F

THEORETICAL RELATIONSHIPS BETWEEN RRR, RAVE, THICKNESS, AND TIME OF SHOOTING

F.1 BACKGROUND

The concept of rebound rate ratio, RRR, and its relationship to average rebound, RAVE, was introduced in Section 4.2.2. RRR and RAVE were plotted with respect to thickness of shotcrete because the thickness plot is believed to represent the physical mechanism more accurately. However, an RRR curve is related directly to its corresponding RAVE curve only if both are plotted with respect to time of shooting. When the two curves are plotted with respect to thickness, the area under the RRR curve is directly related to RAVE only if RRR is approximated so that it varies incrementally, like a bar graph, and if RRR within the increment is constant. An inclined or curved RRR-versus-thickness plot is related non-linearly to the corresponding RAVE versus-thickness curve.

It was not necessary to complicate the introductory development of the basic concepts with this non-linear relationship. Accordingly, RAVE was defined in terms of RSUM and SSUM rather than in terms of the RRR curve. The developments of the relationship were discussed solely on the basis of plots of RRR or RAVE versus thickness. However, it must be understood that the area under the RRR-versus-thickness curve is not the ordinate of the RAVE-versus-thickness curve because time of shooting is not considered. Accordingly, the relationship between time of shooting and thickness is important. An equation relating RRR, RAVE, time, and thickness is developed in this appendix. The equation is based on simple assumptions that were verified experimentally. The relationship for losses during the establishment of the initial critical thickness (Phase 1) will be developed first, followed by the relationships for Phase 2. The development of a composite curve is discussed in Section F.4.

F.2 RELATIONSHIP BETWEEN RRR AND THICKNESS

The basic assumption in the derivation is that the RRR-versus-thickness curve can be idealized by a linear relationship as shown in Fig. F.1a up to the establishment of the critical thickness (Phase 1). The data presented in Chapter 4 supports this idealization. Beyond the critical thickness (Phase 2), RRR is essentially constant, and the two linear segments of the relationship intersect at the critical thickness t_c, which occurs at the critical time T_c. For convenience, RRR is assumed to be some finite value at zero thickness (RRR_0); this reasonable assumption implies that at least some small portion of the first material reaching the wall sticks to the wall. RRR_2 represent the constant RRR of Phase 2. The inclined line segment will be treated separately from the horizontal line segment, although once the RRR-versus-thickness curve is defined experimentally in more detail, a continuous non-linear equation could be substituted for the two-part curve used in this derivation.

The equation for the inclined line segment for losses during Phase 1 ($t \leq t_c$) is

$$RRR - RRR_2 = \frac{RRR_2 - RRR_0}{t_c} (t - t_c) \qquad (1)$$

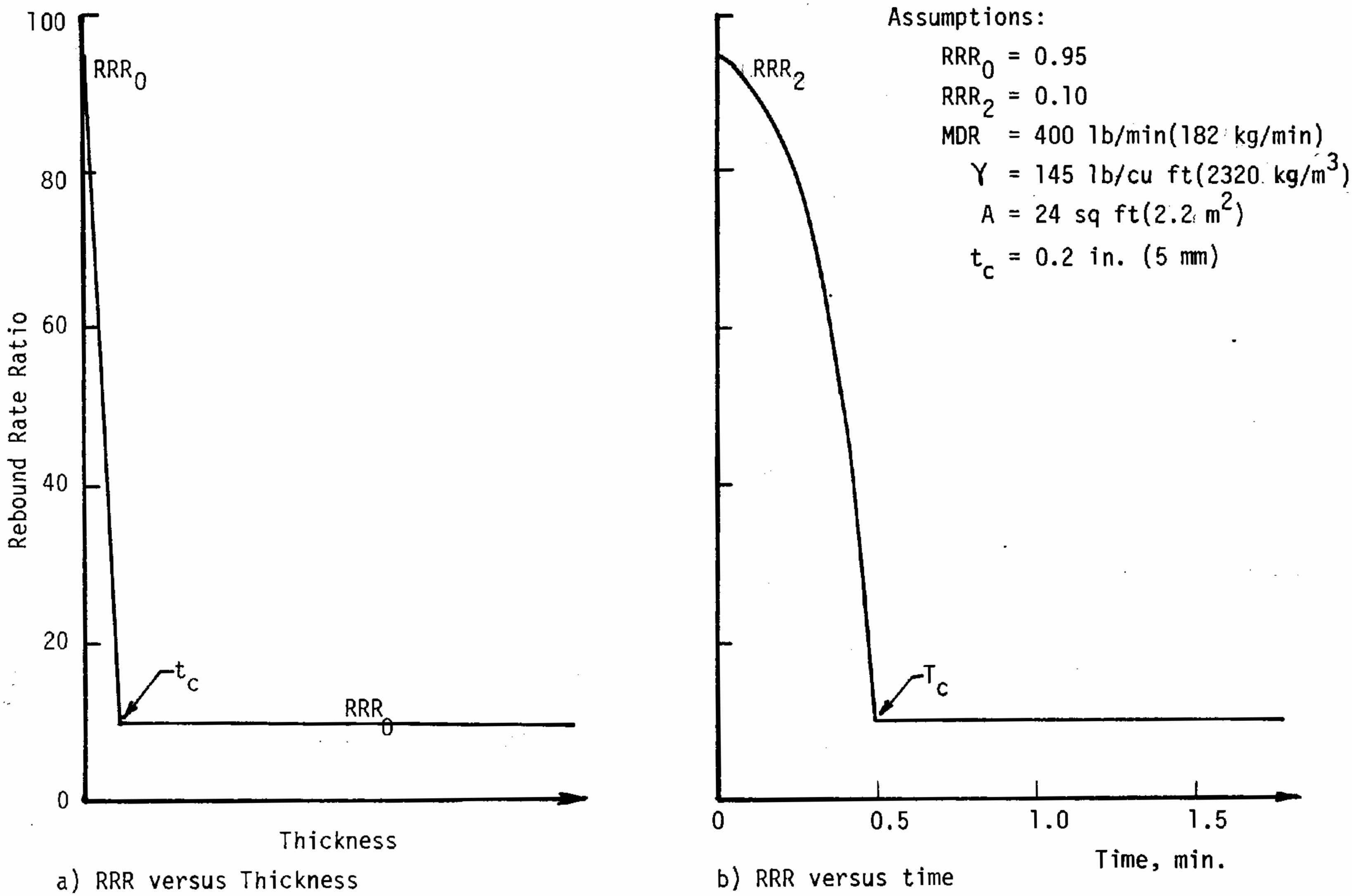

FIG. F.1 IDEALIZED RRR CURVES

where RRR = RRR for Phase 1 rebound, a variable

RRR_0 = RRR at zero thickness, a constant

RRR_2 = RRR for Phase 2, a constant

t = thickness

t_c = critical thickness.

Equation (1) can be simplified to

$$RRR = \frac{t}{t_c} (RRR_2 - RRR_0) + RRR_0 \qquad (2)$$

For the horizontal line segment $(t > t_c)$

$$RRR = RRR_2 \qquad (3)$$

F.3 RELATIONSHIP BETWEEN TIME AND THICKNESS

F.3.1 GENERAL RELATIONSHIP

Incoming material must either stick on the wall or rebound, so it follows that

$$MDR = YR + RR$$

or

$$YR = MDR - RR;$$

since $RR = MDR \cdot RRR$,

$$YR = MDR - MDR \cdot RRR = MDR\,(1-RRR). \qquad (4)$$

At any time, T, the weight of material on the wall in terms of time and material delivery rate is

$$YSUM_T = \int_0^T YRdT = \int_0^T MDR\,(1-RRR)dT. \qquad (5)$$

The weight of material on the wall, YSUM, can also be expressed in terms of its dimensions at any given time. If shooting is directed at one specific area, A, so the thickness is built up uniformly, the weight of material on the wall can also be expressed in terms of thickness, t, as:

$$YSUM_t = A \cdot \gamma \cdot t. \tag{6}$$

The two YSUM's in Equations 5 and 6 can be equated to determine a relation between the time, T, and thickness, t, so that:

$$\int_0^T MDR\ (1-RRR)dT = A \cdot \gamma \cdot t$$

Differentiation with respect to T gives

$$MDR\ (1-RRR)dT = A \cdot \gamma \cdot dt$$

and rearrangement of terms yields:

$$\frac{A \cdot \gamma\ dt}{(1-RRR)} = MDRdT \tag{7}$$

which is the basic relationship desired. Each of the two equations relating RRR and thickness for Phase 1 and Phase 2 derived in Section F.2 may be substituted into Equation (7) to develop the desired relation for each phase.

F.3.2 RELATIONSHIP DURING PHASE 1

Equation (2) is substituted into the term (1-RRR) and rearranged as follows:

$$(1-RRR) = 1-RRR_0 + \frac{t}{t_c}(RRR_0-RRR_2)$$

Accordingly, during Phase 1, Equation (7) becomes:

$$\frac{dt}{(1 - RRR_0) + (RRR_0 - RRR_2)\frac{t}{t_c}} = \frac{MDR}{A \cdot \gamma}\, dT, \tag{8}$$

Equation (8) can be integrated from 0 to t and from 0 to T, t being the corresponding thickness at any time, T, within the range of the critical thickness, t_c. Thus,

$$\int_0^t \frac{dt}{(1-RRR_0) + (RRR_0 - RRR_2)\frac{t}{t_c}} = \frac{MDR}{A \cdot \gamma} \int_0^T dT. \tag{9}$$

Integrating the equation results in the following equation:

$$\frac{t_c}{(RRR_0 - RRR_2)} \ln \left[(RRR_0 - RRR_2)\frac{t}{t_c} + (1 - RRR_0) \right]_0^t = \frac{MDR}{A \cdot \gamma} \Big[T \Big]_0^T \tag{10}$$

Simplifying, and solving for T gives the general equation:

$$T = \left[\frac{A \cdot \gamma \cdot t_c}{MDR}\right] \left[\frac{1}{RRR_0 - RRR_2}\right] \left\{ \ln \left[(1-RRR_0) + (RRR_0 - RRR_2)\frac{t}{t_c} \right] - \ln(1-RRR_0) \right\} \tag{11}$$

A plot of Equation (11) based on the assumptions given in the figure , is shown in Fig. F.1b where it is clear that the RRR curve has a logarithmic form with respect to time when it is assumed linear with respect to thickness. This form is reasonable physically. For any increment in thickness, it must take a longer time to shoot that thickness when most of the material is rebounding ($RRR \sim RRR_0$) than at the critical thickness when a greater proportion of the material shot is sticking to the wall. As soon as a given weight of material sticks to the wall, the thickness is greater so a greater percentage of the material being shot begins to stick to the wall. Thus, the percentage being retained increases with each increment and the corresponding time to shoot that increment decreases. Thus, it is reasonable for the rebound rate or rebound rate ratio to remain high for a short time, then begin to drop off rapidly as the cushion builds up. The true shape of the RRR-versus-time curve is more complex than for the simple assumptions made in this analysis. Near the critical thickness, the real curve would reverse its curvature and be continuous with a curve for Phase 2, that would also be more complex than the straight line shown.

Evaluation of Equation (11) for the critical time, T_c, yields:

$$T_c = \left[\frac{A\cdot\gamma\cdot t_c}{MDR}\right]\left[\frac{1}{(RRR_0 - RRR_2)}\right]\left[\ln(1-RRR_2) - \ln(1-RRR_0)\right] \quad (12)$$

which will be evaluated for its physical significance in the following treatment.

Since $(A\cdot\gamma\cdot t_c) = YSUM_{t_c}$ and $T_c\cdot MDR = SSUM_{t_c}$, Equation (12) can be simplified by transposing and substitution to:

$$SSUM_{t_c} = \left[YSUM_{t_c}\right]\left[\left(\frac{1}{RRR_0 - RRR_2}\right)\left(\ln(1-RRR_2) - \ln(1-RRR_0)\right)\right] \quad (13)$$

According to Section 4.7.1, the weight that must be shot, SSUM, is the weight in place, YSUM, multiplied by the overshoot factor, OSF. Accordingly,

$$SSUM_{t_c} = (YSUM_{t_c})\cdot(OSF_{t_c}) \quad (14)$$

and from Equation (13), at the end of Phase 1,

$$OSF_{t_c} = \left[\frac{1}{RRR_0 - RRR_2}\right]\left[\ln(1 - RRR_2) - \ln(1 - RRR_0)\right] ; \qquad (15)$$

and

$$RSUM_{t_c} = SSUM_{t_c} - YSUM_{t_c} = SSUM_{t_c} - \frac{SSUM_{t_c}}{OSF_{t_c}} . \qquad (16)$$

Since $RAVE = \frac{RSUM}{SSUM}$, it can be shown that:

$$RAVE_{t_c} = \frac{OSF_{t_c} - 1}{OSF_{t_c}} = \left[1 - \frac{1}{OSF_{t_c}}\right] \qquad (17)$$

into which, Equation (15) for OSF may be substituted for a theoretical calculation of RAVE at the critical thickness, t_c.

F.3.3 RELATIONSHIP DURING PHASE 2

Since the RRR-versus-thickness curve is assumed constant during Phase 2, the equations are simplified considerably. The relationship for RRR during Phase 2, Equation (3), can be substituted into the Equation for the basic relationship (7) and integrated from t_c to any final thickness t_f, and from T_c to the corresponding final time, T_f, as follows.

$$\frac{A \cdot \gamma}{MDR(1-RRR_2)} \int_{t_c}^{t_f} dt = \int_{T_c}^{T_f} dT ,$$

$$\frac{A \cdot \gamma}{MDR(1-RRR_2)} \left[t_f - t_c\right] = \left[T_f - T_c\right]$$

The term, $A \cdot \gamma\ (t_f - t_c)$, equals the weight retained on the wall only after Phase 2 begins and will be denoted as $YSUM_2$ and the term, $(T_f - T_c)MDR$, equals the weight shot during the same interval that will be denoted as $SSUM_2$. Thus, by substituting and rearranging,

$$SSUM_2 = YSUM_2 \left[\frac{1}{1-RRR_2} \right]$$

The factor $\left[\frac{1}{1-RRR_2} \right]$ is not an overshoot factor but rather is an overshoot rate for Phase 2. It defines the additional weight that must be shot to achieve a certain increase in weight on the wall after the critical thickness is established. The overshoot factor, OSF, defines the total weight that must be shot to achieve the total thickness. In this sense, the overshoot rate is a parameter analagous to RRR while the overshoot factor, OSF, is an average parameter analagous to and, in fact, related to RAVE. The next section provides information on the calculation of RAVE during Phase 2.

F.4 COMPOSITE RAVE RELATIONS DURING PHASE 2

The equations derived in Section F.3 for Phase 1 and Phase 2 may be used to develop useful theoretical equations for the calculation of RAVE, OSF, SSUM, RSUM, YSUM, etc., at any thickness greater than the critical thickness, t_c. Combining the equations results in an equation too complex to be practical. Hence, it is recommended that the theoretical RAVE curve be calculated incrementally according to the method recommended for multiple-tarp rebound tests given in Table 4.8. Real numbers should be used in the basic equation for RAVE defined as RSUM/SSUM so that the physical significance is appreciated. Accordingly, for a given area (it can be a unit area), the numerical value of $RSUM_{t_c}$ and $SSUM_{t_c}$ should be calculated in accordance with the equations given in Section F.3. The numerical values are necessary in the subsequent calculations. At the critical thickness, RAVE is defined as $RSUM_{t_c}/SSUM_{t_c}$. At any thickness greater than the critical thickness, RAVE can be calculated by the following formula.

$$RAVE_{t>t_c} = \frac{RSUM_{t_c} + RSUM_{(t_f-t_c)}}{SSUM_{t_c} + SSUM_{(t_f-t_c)}}$$

where

$SSUM_{(t_f-t_c)}$ = Weight shot during Phase 2 to any thickness t_f

$$= \frac{A \cdot \gamma (t_f - t_c)}{1 - RRR_2}$$

$RSUM_{(t_f-t_c)}$ = Weight rebounded during Phase 2 to any thickness, t_f

$$= RRR_2 \left[SSUM_{(t_f-t_c)} \right] = RRR_2 \left[\frac{A \cdot \gamma (t_f - t_c)}{1 - RRR_2} \right]$$

A curve of RAVE-versus-thickness can be developed by calculating RAVE for various thicknesses. This procedure was used to calculate theoretical RAVE curves from an assumed RRR-versus-thickness curve in the examples in Section 4.7.4. The procedure was used in Section 4.8 to calculate a theoretical RAVE curve that was shown to represent the experimental field RAVE values well. Accordingly, the derived equations appear to be satisfactory and may find value for a simple parameter study.

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