SHOTCRETE PRACTICE IN UNDERGROUND CONSTRUCTION

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16. Abstract

This report describes the use and procedures for placement of wet- and dry-mix shotcrete in underground rock excavations. Its purpose is to serve as a guide for designers and contractors in selecting, preparing and applying shotcrete of acceptable quality in the variety of ground conditions encountered in underground work. The contents of this report include design considerations, engineering properties, shotcrete equipment, application techniques and quality control. Specifications for shotcrete are treated as well. The appendices provide supplemental information dealing with the use and engineering properties of fiber and regulated-set cement shotcrete, capabilities and specifications of shotcrete machines and some recommended guidelines for placing shotcrete underground.

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DEDICATION

This work is dedicated to

JAN A. BLANCK

for his technical and editorial assistance as our technical consultant for this report and for his outstanding leadership and contributions in shotcrete practice and tunnel engineering. Jan provided information and data that cannot be found in the literature but rather can only be acquired by many years of practical experience. He reviewed the text and made many comments that have been included in the report verbatim.

Jan was born in Stockholm, Sweden. He graduated from Stockholm Technical College in 1959 and was employed by Sentab on several construction projects overseas including Africa and Hong Kong. In 1966 he was a consultant as a shotcrete specialist on the Vancouver Railway Tunnel, the first large-aggregate shotcrete project in North America. The success of shotcrete on this project was instrumental in the acceptance of shotcrete for tunnel support in the U.S. Subsequently, Jan worked on several shotcrete tunnel and mining projects including the Balboa Outlet Tunnal and the Tehachapi tunnel. More recently he was a Senior Engineer for A. A. Mathews, Inc., as a shotcrete specialist on tunnel construction for the Washington, D. C. Metro. For the last two years, Jan has been employed as a project engineer/manager on several rock tunnel projects for DiMambro-Majestic Construction Company.

Jan has been called in as a consultant on many projects to solve problems dealing with the use, application, and quality of shotcrete. Because of his success in solving problems and his knowledge and experience in shotcrete work, Jan has won the respect of both contractors and engineers. He is recognized as one of the foremost authorities on underground shotcrete work. Jan has been an inspiration to those of us who have been fortunate enough to be closely associated with him. He has been a constant source of information and encouragement in setting up the shotcrete program at the University of Illinois and in the field tests and shotcrete instrumentation work conducted by the University on the Washington Metro project.

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PREFACE

The report was prepared in the Department of Civil Engineering of the University of Illinois at Urbana-Champaign. The work was sponsored by the Federal Railroad Administration, Department of Transportation through Contract No. DOT FR 30022, under the technical direction of Mr. William N. Lucke, who suggested that this report be prepared. Most of the work was completed in approximately one year, and as a result, there was not sufficient time to fully develop all of the topics included herein. Additional information, particularly in the use and design of shotcrete linings will be provided in subsequent reports.

Many individuals contributed to the writing of this report and without their help this undertaking would not have been possible. Special recognition is given to Dr. Ralph Peck, Dr. Ron Heuer and Mr. Jan Blanck for their technical and editorial contribution to the entire work. Dr. Ron Jones wrote a summary of the available literature on many of the topics covered herein; portions of this summary have been directly incorporated into this report. Many helpful suggestions on the use, design considerations, and safety aspects of shotcrete were provided by Dr. Don Deere and Dr. Ed Cording. Mr. Warren Alvarez contributed much information on chapters dealing with production of shotcrete, shotcrete equipment, nozzling and training of nozzlemen. Mr. Loren Lorig, Mr. I. Shimada and Mr. Gabriel Fernandez, research assistants in the Department of Civil Engineering, helped collect data and summarized protions of the available literature on shotcrete. Editorial

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A	area of cone, pull-out test
a	size of block
B	width of opening, width of shear zone
c	cohesion
d	diameter of Gillmore needle tips
FS	factor of safety
f'_a	adhesive strength
f'_c	compressive strength
f'_t	tensile strength
L	rock load per unit length of tunnel
M/bt^2	normalized moment, moment-thrust interaction diagram
MDR	material delivery rate
p (kg/cm^2 or psi)	pressure in air line entering shotcrete machine
P (kg or lb)	pull-out force
P/bt	normalized load, moment-thrust interaction diagram
P_i	internal pressure
P_N	normal force
P_o	free field stress
P_s	radial pressure
P_1	pressure in air line just before it enters the barrel of the shotcrete machine
P_2	air pressure in line at beginning of material hose
q_u	unconfined compressive strength
R (m or ft)	radius of yielded zone

R (kg or lb)	resultant force
r	radius of tunnel
RRR	rebound rate ratio
S	shear force
$T_{(0-t_1)}$	time to shoot entire, full-thickness rebound test
t	thickness of shotcrete layer
th	lateral thickness or extent of shotcrete layer
t_1	average thickness of shotcrete on wall at end of rebound test
W	weight of rock block
W_r	net weight of rebound in rebound test
W_{r_1}	net weight of rebound lost during Phase 1
W_w	net weight of shotcrete on rebound test wall
W_{w_1}	net weight of shotcrete on rebound test wall after Phase 1
w/c	water-cement ratio
Δr	displacement of tunnel surface
γ	unit weight of rock
ϕ(deg.)	angle of internal friction
ϕ_r	residual angle of internal friction
ϕ(mm or in.)	diameter
σ_r	radial stress
σ_t	tangential stress
σ_v	vertical stress
σ_θ	circumferential stress
θ	angle of block side with vertical, angle of nozzle with horizontal

CHAPTER 1

INTRODUCTION

Since the mid-1960's, shotcrete has been used more frequently in the United States on underground mining and civil engineering projects. The literature on shotcrete has expanded rapidly with its increasing use. Recently (1973), the ASCE and ACI co-sponsored a specialty conference devoted entirely to the use of shotcrete for underground structural support. Many excellent papers which contributed significantly to tunnel and shot-crete technology were presented at this conference. Nevertheless, the proceedings of the conference as well as past publications do not provide enough continuity or information to stand alone as a guideline for design and construction of shotcreted openings. There is a need to summarize the available information in a form that is useful to designers and contractors and that can be followed from conception to completion of the project.

1.1 Purpose and Scope

The purpose of this report is to present the design and construction information needed for successfully selecting and applying shotcrete in underground work. The aim is not to provide a comprehensive treatment of shotcrete but instead to provide designers and contractors with the basic information needed for using shotcrete in tunnels. Thus, specialty topics such as instrumentation of shotcrete liners will not be included. Since shotcrete is employed primarily in rock excavations, its use in soil tunnels will not be discussed; however, the information is directly applicable to underground soil excavations, particularly those that are hand mined.

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1.2 Source of Information and Contents of Report

Since shotcrete design and application is primarily an art rather than a science, the practical aspects of shotcrete will be described. The information contained herein is a summary of the available literature, of the experience of qualified consultants in shotcrete and tunnel engineering and of results of shotcrete tests conducted at the University of Illinois. In addition to these sources, data obtained from the instrumentation program carried out in the shotcreted tunnels and stations of the Washington, D. C. Metro will be used.

The report is divided essentially into two parts; the first part treats the use of shotcrete in underground excavations, whereas the second part is devoted to the production, application, and quality control of shotcrete in underground work. Chapter 2 contains criteria for selection or rejection of shotcrete as a means of controlling tunnel ground behavior in rock excavations and includes design considerations which should be used if shotcrete is chosen as a support element. Mix design and engineering properties of shotcrete are given in Chapters 3 and 4, respectively. Chapters 5 and 6 deal with production of a shotcrete program and shotcrete equipment. Techniques for placing high quality shotcrete and procedures for quality control are discussed in Chapters 7 and 8. Specifications are treated in Chapter 9. The appendices include descriptions of the material properties of special shotcretes (fiber and reg-set), a summary of commercially available shotcrete machines, and some guidelines for shotcrete practice in underground work.

1.3 Definitions

The term shotcrete used in this report is compatible with the definition

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adopted by the ACI (1966) and refers to any pneumatically applied concrete or mortar placed directly onto a surface. This definition is used to distinguish shotcrete from pneumatically placed concrete in which all or some of the material must be moved into position after it is extruded from the nozzle. Gunite is shotcrete which contains primarily sand-size aggregate.

Two basic means are used to place shotcrete: the dry-mix and the wet-mix processes. In the dry-mix process, cement and moist aggregate are mixed and placed into a shotcrete machine which projects the materials through a hose and out of a nozzle onto the surface. Water is added under pressure at the nozzle. In the wet-mix process, the cement, aggregate, and water are mixed and then pumped through a hose to the nozzle. At the nozzle air is injected to break up the slugs of material and to accelerate the wet-mix toward the surface. In underground work accelerator is added to either the dry-mix or wet-mix materials when a rapid initial set and early strength gain are needed.

This report deals primarily with coarse aggregate, wet- and dry-mix shotcrete; however, the use and some of the pertinent engineering properties of experimental materials, such as fiber and reg-set shotcrete are discussed as well.

CHAPTER 2

USE AND DESIGN OF SHOTCRETE LININGS IN UNDERGROUND OPENINGS

A major consideration in the design and construction of underground
openings is the need for and selection of tunnel support. The need for
support depends on the ground behavior and on the geometry of the opening.
In tunnels requiring ground control, the first step in the selection of
support is to assess the effectiveness of the various support methods in
controlling the anticipated or actual ground conditions. This assessment
is based on the nature of ground behavior, the capacity, stiffness and
ductility of the support, and the support-medium interaction. The installa-
tion procedures for each type of support system must be considered and
will depend heavily on ground behavior. The second step is to check the
compatibility of those supports which are judged capable of controlling
the ground conditions with the method and sequence of excavation. The
optimum support system is then chosen and its installation procedures
established.

Shotcrete is only one of many support elements which can be used
to control ground behavior in tunnels. It has been tried with varying
degrees of success in nearly all types of ground conditions. Failures with
shotcrete stem largely from its misuse in certain ground conditions and
from deficiencies in shotcrete quality. A common abuse of shotcrete has
been its application in thin layers 5 cm (2 in.) as the sole method of
tunnel support. In this respect shotcrete has been "oversold" by both
contractors and engineers. Despite its shortcomings, shotcrete has performed

satisfactorily and has been economical in many underground situations. Shotcrete has proven particularly useful as a remedial support in a number of cases.

This chapter considers the use of shotcrete in underground openings for initial ground control, for supplemental support, and as a permanent lining. The ground conditions in which shotcrete is appropriate, and those conditions in which shotcrete is inappropriate or is marginally adequate,are emphasized in this section. Design considerations and requirements are given for those ground conditions in which shotcrete can be used either as sole support or as one part of a composite support system. Economic considerations of shotcrete as well as its compatibility with the methods of excavation are described in the last two sections of this chapter. This chapter is directed toward the use of shotcrete in rock excavations ; however,much of the dis- cussion is also applicable to hand-mined,soft ground tunnels.

2.1   Initial Ground Control

Shotcrete used for initial ground control is placed in or close to the heading usually in layers 5-10 cm (2-4 in.) thick. In most cases shotcrete in this thickness does not act as a structurally continuous lining but rather as a membrane or a mortar placed between the rock blocks. In other cases, however, it may act as a structurally continuous lining when placed as a thin layer in an opening having a smooth perimeter or when applied in sufficient thickness to fill in the irregularities and form a structurally continuous arch or ring. The use, design, and performance of shotcrete depend largely on the rock behavior and water conditions. The ground conditions requiring control in tunnels are one or more of the following: loosening, overstressed, swelling, or slaking ground; and water inflows.

Shotcrete has been most successful in treating problems associated with loosening ground and air slaking. The only cases where shotcrete should be used as sole support are when a good shotcrete-rock bond can be obtained, when the shotcrete is thick enough to act as a structurally continuous lining, or when air slaking is the only ground problem. In any other cases, shotcrete should be employed together with some other support elements (e.g., rock bolts, steel ribs, etc.).

The design considerations for shotcrete linings include: thickness, strength, ductility, time and location of shotcrete applications, and use of other support elements. At present the design of thin shotcrete linings is based on empirical rules and/or on analytical models of shotcrete-rock behavior. Empirical design is based upon actual tunnel experience. The analytical models have been developed from observation of shotcrete cracking or failure in the field. In analytical models the support requirement is calculated assuming a loading condition, failure mode, and a set of shotcrete properties. As seen later, both of these approaches have certain advantages and drawbacks and should be used together as the basis for design and implementation during construction.

In addition to ground and structural behavior, the performance of the shotcrete depends upon the quality of the in-place materials. Shotcrete quality is treated in subsequent chapters.

2.1.1 Loosening Ground Conditions

Mechanics of Loosening

In loosening ground, rock blocks tend to separate from the surrounding rock mass and move toward the opening due to gravity (Figs. 2.1 and 2.2).
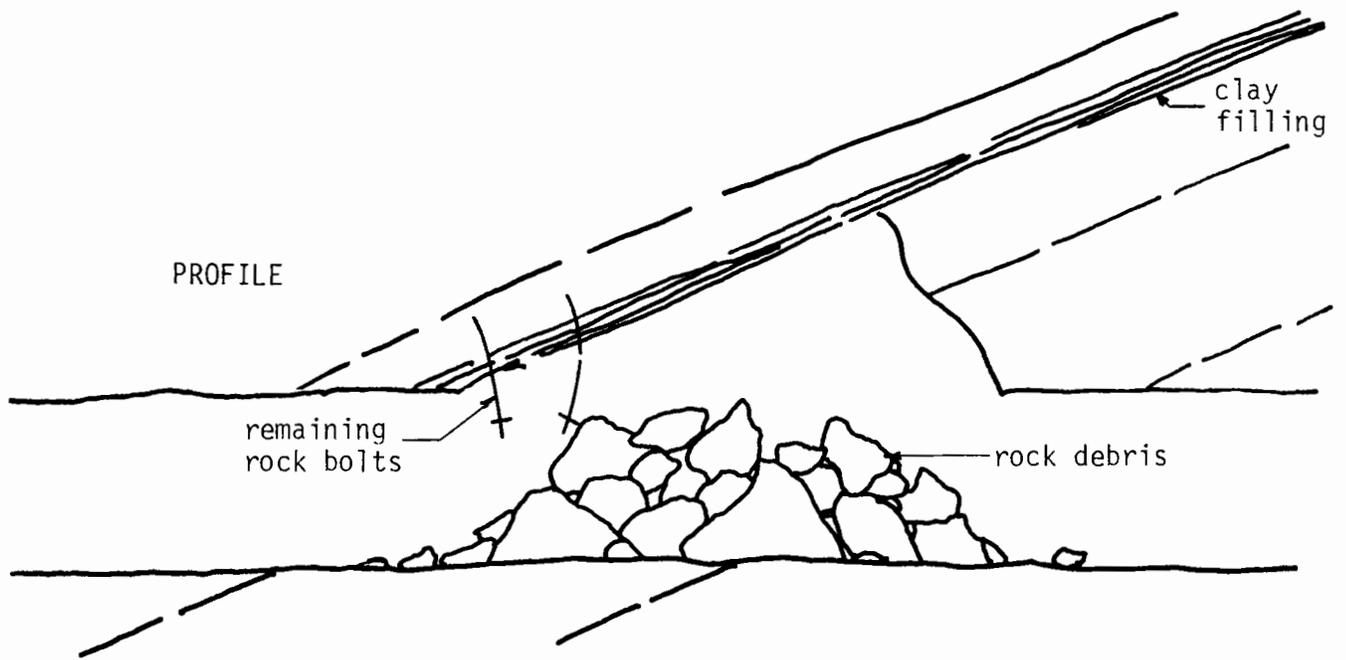
FIG. 2.1 TUNNEL FAILURE CAUSED BY LOOSENING GROUND (CECIL, 1970).
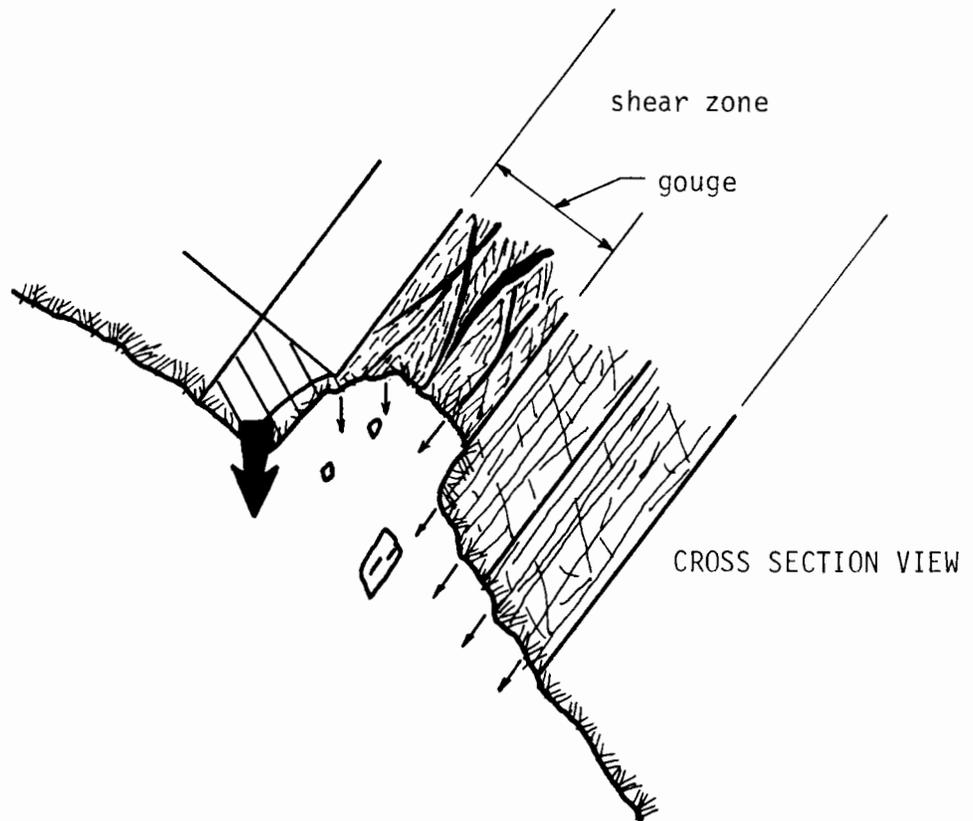
FIG. 2.2 LOOSENING OF SMALL ROCK FRAGMENTS - RAVELLING.

These movements may involve very large, individual wedges, or small fragments (ravelling). Most rock loosening occurs along natural geologic discontinuities present in the rock. The most serious loosening problems develop in rock containing shears and shear zones and/or well-developed joint sets. Highly weathered intact rock can also cause serious ravelling problems. Loosening ground conditions are common in most tunnels, regardless of depth, and are responsible for one of the most frequent ground support problems·

The mechanics of loosening of rock blocks in a tunnel crown were described by Cording (1967) and are illustrated in Fig. 2.3. Movement of the block is restrained by the shear strength along the sides of the block. With displacement the friction angle (ϕ) decreases after peak strength is reached and approaches $\phi_{residual}$. The normal force also decreases with increasing displacement. Thus, the effect of displacement in loosening ground is to reduce stability and to increase loads on the support system. The most efficient supports for loosening ground act to prevent or minimize rock displacements and maximize the self-supporting capability of the rock. Shotcrete containing accelerators has this capability when applied in the heading shortly after excavation.

Mechanics of Shotcrete Support in Loosening Ground

Thin shotcrete linings act to prevent rock displacements by:

1. stiffening and strengthening the rock mass by filling open joints and fractures (Fig. 2.4),

2. transferring the rock load to adjacent stable rock through adhesion or shear (Fig. 2.5), and
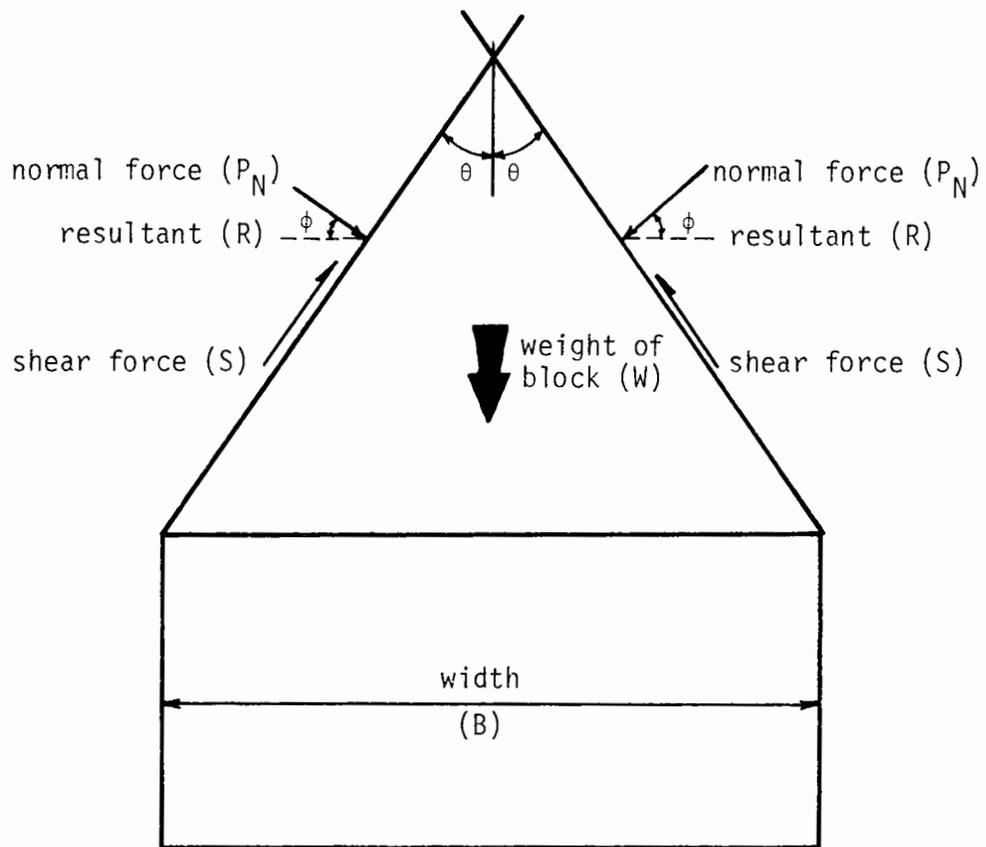
FIG. 2.3 MODEL OF ROCK LOOSENING IN A TUNNEL CROWN
(CORDING, ET AL., 1971).

shotcrete
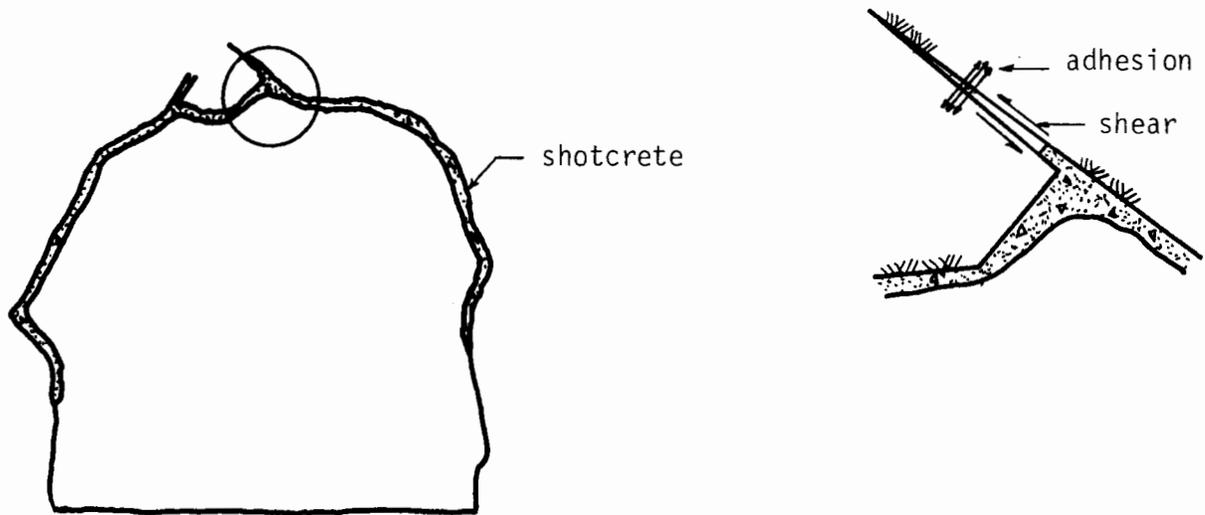
adhesion

shear

FIG. 2.4 INFILLING OF OPEN JOINTS WITH SHOTCRETE

shotcrete
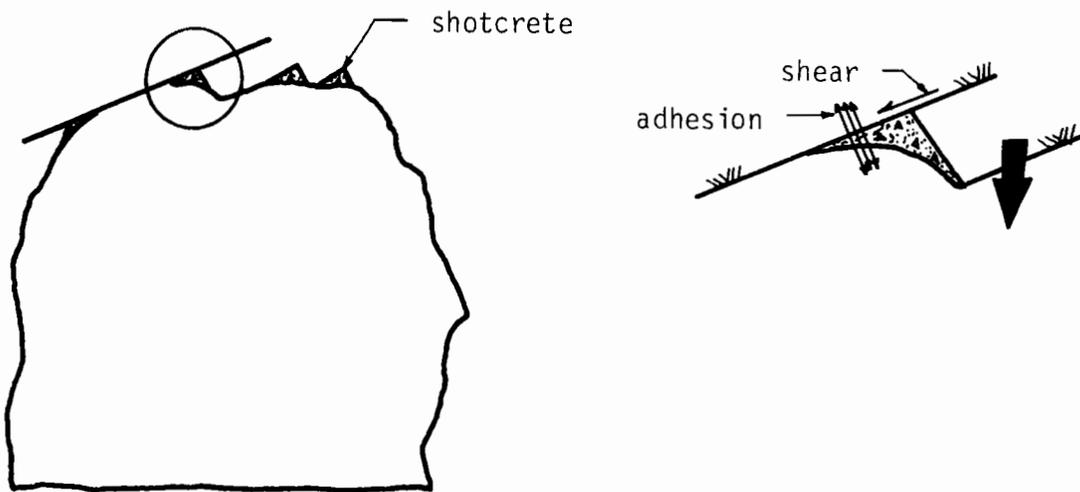
shear

adhesion

FIG. 2.5 SHOTCRETE ACTING TO TRANSFER ROCK LOAD
BY ADHESION AND SHEAR.

Table 2.1 Empirical rules for design of shotcrete linings in loosening ground.

Alberts (1965)	
Swedish rules from local experience	
Criteria	Thickness
Initial application immediately after blasting if the rock is heavily jointed.	3-8 cm (1-3 in.)
Total thickness applied if roof falls or deterioration is observed	10-15 cm (4-6 in.)

Kobler (1966)	
Experience from large highway tunnels	
Condition	Applied Shotcrete Thickness
Normal	15 cm (6 in.) thick at crown and tapered out below springline.
Side pressures	Same as above plus 5-10 cm (2-4 in.) carried down the walls.

Cecil (1970)		
Rock Quality Parameter		
RQD	Average discontinuity spacing	Support requirements
< 60%	<30 cm (<12 in.)	Maximum: multiple shotcrete application (1); cast concrete arches; combinations with spot bolts.
60-80%	30 cm - 1 m	Intermediate: medium (2-5 m) (6.5-16 ft) to closely (<2m) (<6.5 ft) spaced spot bolts; single shotcrete application; combined spot bolts and one shotcrete application.
80%	>1 m (>3 ft)	Minimum: unsupported or medium (2-5 m) (6.5-16 ft) to widely (>5 m) (>16 ft) spaced spot bolts.

(1) A single shotcrete application is a 4-6 cm (2 in. ±) thickness; multiple applications refer to a repeated application of layers of this same thickness.

Table 2.1 (continued)

Heuer (1974)
TEMPORARY SUPPORT UNDER LOOSENING LOADS (1)

GROUND CONDITION	SHOTCRETE APPLICATION
1. Good ground: Where support problems are minimal, but for one reason or another a "bald-headed" tunnel is considered unacceptable. RQD commonly > 75%.	5 cm (2 in.) shotcrete in arch above springline
2. Fair ground: Where the rock is more closely jointed or broken and the arch definitely needs some support, but sidewalls are stable. Ground allows good bond of shotcrete to excavation perimeter. RQD commonly 50 to 75%.	7-8 cm (3 in. ±) shotcrete in arch, feather out below springline
3. Poor ground: Where tunnel walls tend to ravel some, or where a good shotcrete bond to rock cannot be achieved. RQD commonly 25 to 50%.	8-10 cm (3-4 in.) shotcrete in arch. 7-8 cm (3 in. ±) shotcrete on walls. Carry to base of walls in horseshoe tunnels. On circular tunnels, wall coverage required depends on quality of shotcrete bond to rock. If bond is of fair quality, may need only upper 270° shotcrete coverage. If bond is very poor, need full 360° coverage.
4. Very poor ground: If support problems are truly loosening loads, treat as above for poor ground but add another 2-3 cm (1 in.) of shotcrete, giving 10-12 cm(4-5 in.) in arch, 10 cm ± (4 in. ±) on walls.	

(1) For tunnel diameters of 4-6 m (15-20 ft)

3. acting as a membrane in bending or tension when shotcrete-
    rock bond is low and the shotcrete layer is continuous
    (Fig. 2.6).

Shotcrete in thin linings having poor shotcrete-rock bond does not have
the capacity to carry the full gravity load of large wedges but may provide
enough support to reduce displacement and thus help maintain the self-
supporting capability of the rock.

Design of Thin Shotcrete Linings

Design Based on Empirical Rules. The design of thin shotcrete linings
in loosening ground is presently based on empirical rules developed from
observations of actual shotcrete performance underground. Several different
empirical rules for estimating shotcrete thicknesses are presented in Table
2.1. The formulation of empirical rules is the first step in the develop-
ment of rational design criteria; however, these rules have serious
limitations. The thickness criteria given in Table 2.1 are based on case
histories in which shotcrete did or did not fail. For cases where shotcrete
did not fail, the actual extent to which support was required is unknown and
the factor of safety may have ranged from very high to near unity. In
instances where the shotcrete did fail the amount of additional support
needed to stabilize the opening is unknown and may have ranged from minimal
to very large.

The earliest empirical guidelines were developed from local experience
usually involving only one geologic setting and one type of construction
practice. Use of these criteria for tunnels in other geologic and/or
construction conditions can lead to inadequate results because of changes
in geology or in construction practice. Later researchers such as Deere,

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shotcrete

low bond
strength

adhesion

moment

tension

shear

moment
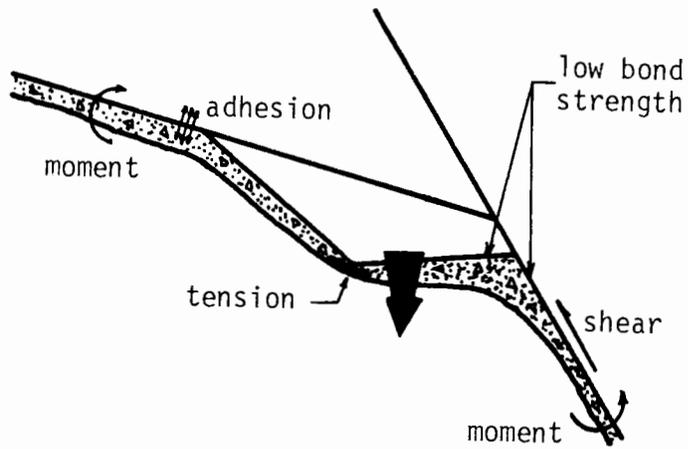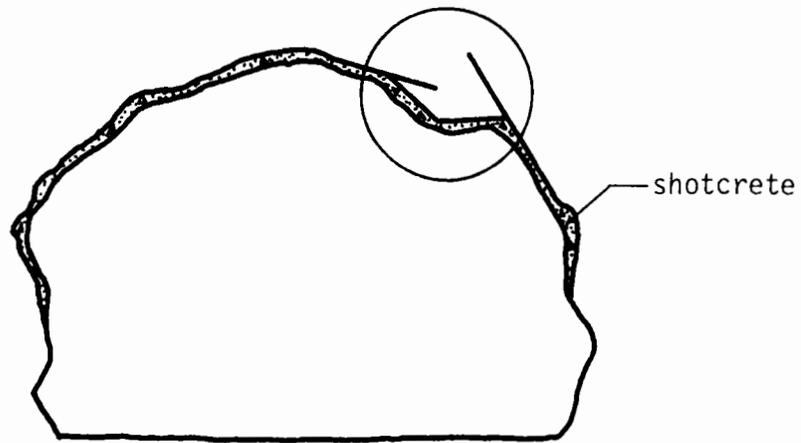
FIG. 2.6 SHOTCRETE ACTING AS A MEMBRANE.

et al. (1969) and Wickham (1974) have used rock indices such as rock quality designation (RQD) and rock structure rating (RSR) to correlate shotcrete experience in different ground conditions and have provided a better means for evaluating past experience with shotcrete performance. The rock index method has limitations, however, since the factor of safety is unknown and the rock indices are often not sensitive to subtle changes in geology or to changes in construction which can produce a large change in the need for support and the capacity of the shotcrete. The empirical rules based on rock indices can be used to provide an estimate of shotcrete thickness requirements, bid quantities, and support requirements during construction.

Design Based on Analytical Models. A second method of estimating shotcrete thickness for initial support involves use of analytical models of shotcrete behavior. In this approach, the shotcrete thickness needed to support a given assumed wedge is calculated on the basis of an assumed mode of shotcrete failure.

Determination of shotcrete thickness for a flat-roof tunnel by using models and analyses suggested by Cecil (1970) is illustrated in Fig. 2.7. In this model it is assumed that the geometry of the rock block is known, that the rock is much stiffer and stronger than the shotcrete, that no displacement occurs in the rock mass adjacent to the moving block, that the moving block undergoes only vertical displacement, and that the shotcrete strength is known. The thickness needed to support the full gravity weight of the block is estimated by assuming a diagonal tension or bond failure. As a limiting condition the shotcrete may be designed to carry the full weight of the block, since the strength along the joint surfaces is unknown. The calculated required shotcrete thickness at failure times an appropriate factor of safety would be used as the approximate design thickness of the

TUNNEL
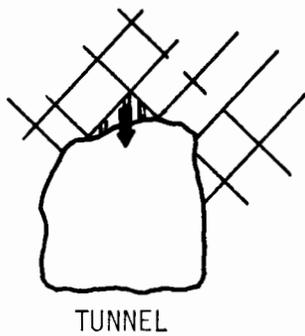
Assume:

Size of block: $a = 100$ cm

Unit wt. of rock: $\gamma = .0027$ kg/cm^3

Adhesive strength: $f_a' = 10$ kg/cm^2

Tensile strength: $f_t' = 20$ kg/cm^2
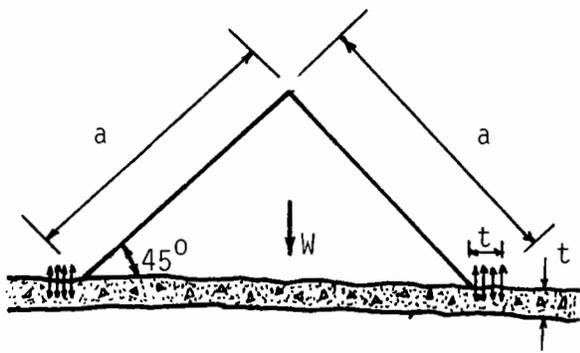
Driving force $= 1/2\ a^2\ \gamma$

Resisting force $= 2 \times 1/2\ f_a'\ \times\ t$

$$t = \frac{1/2\ a^2\ \gamma}{f_a'}$$

$$\underline{t = 1.4\ cm}$$
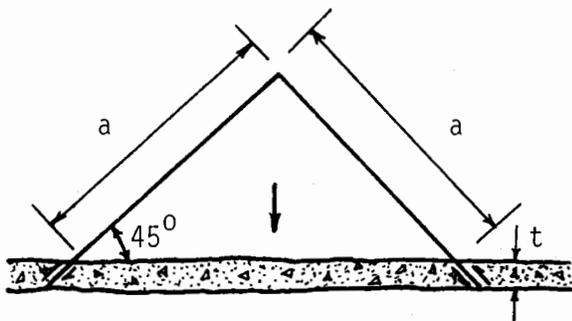
Driving force $= 1/2\ a^2\ \gamma$

Resisting force $= 2\ (1.4\ f_t'\ \times\ t)$

$$t = \frac{1/2\ a^2\ \gamma}{2.8\ f_t'}$$

$$\underline{t = .25\ cm}$$

FIG. 2.7 SHOTCRETE THICKNESS REQUIRED TO SUPPORT THE FULL GRAVITY
WEIGHT OF A BLOCK IN A FLAT-ROOF TUNNEL WITH GOOD
SHOTCRETE-ROCK BOND (CECIL, 1970).

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initial shotcrete layer. A thickness greatly different than that estimated
from the empirical rules given in Table 2.1 should not be used without
strong justification. For example, the initial layer of shotcrete should
not have a nominal thickness of less than 5 cm (2 in.) regardless of the
calculated value, since thinner layers are likely to undergo cracking and
deterioration as a result of shrinkage, water seepage, or construction
activity.

At present, the analytical approach is not used in determining thick-
ness requirements for structurally discontinuous shotcrete linings.
Actual modes of failure have not yet been well established from field
investigations, and information from most case histories is not detailed
enough to assess the failure mechanism. In order to use the analytical
approach the rock loads, nature of the rock block movement, geometry of the
tunnel perimeter, and the surface characteristics of the natural geologic
structures must be known, as well as the engineering properties of the
shotcrete. When shotcrete is used for initial support, the time-dependent
changes in the properties must also be considered. In addition to the above
limitations, many details of shotcrete support capacity such as the distri-
bution of adhesion and shear stress along the shotcrete-rock interface are
difficult to analyze. Present methods of site investigation do not give
sufficient information to allow the analytical approach to be used prior to
actual tunnel experience at the site. The analytical method may be of use in
special cases where detailed studies of tunnel and shotcrete performance
have been made in adjacent areas having similar conditions (Heuer, 1974).
During construction it is one of the best means of evaluating shotcrete
failures and modifying shotcrete applications where needed in the remainder

of the tunnel. The analytical method shows great promise since it requires determination of the behavior of the rock and shotcrete and incorporates the pertinent details affecting their interaction. It should not be used alone but rather in conjunction with the empirical rules. At present, more confidence should be placed in these rules than in the analyses, particularly in pre-construction design.

Shotcrete Thickness During Construction

The adequacy of the shotcrete thickness actually used should be assessed in light of careful observations of actual rock conditions and shotcrete performance encountered during construction (Cording, 1974). This is true not only for loosening conditions but also for other types of ground behavior in tunnels. The design assumptions made regarding rock indices, rock block movements, and shotcrete performance must be checked throughout construction, particularly during initial excavation when the geology is first exposed. If the actual conditions are more adverse than anticipated (e.g., gouge is present on the joint surfaces), then the thickness and/or application of the shotcrete must be modified and consideration given to the use of other support elements. Critical observations needed to assess the adequacy of shotcrete support in loosening ground are summarized in Table 2.2. The most direct observations of the adequacy of support are the movements of rock wedges and deformations in the shotcrete lining. Instrumentation, particularly the use of extensometers, is extremely valuable in measuring rock block displacements and in determining the effectiveness of the support in restraining their movement. Additional shotcrete support, if needed, can be estimated by using rock index correlations or from analytical models based on shotcrete-rock behavior. Observations

Table 2.2 Observations of geologic conditions and
shotcrete performance during construction.

Geology   Shotcrete

rock quality (RQD)   cracking and spalling as re-
                                           lated to rock block movements

size of wedges

nature of wedge movement

planarity, slickness, and filling
  along joint and shear surfaces

geometry of overbreak

presence of water in and behind
  joints and shears

of shotcrete-rock behavior must be continued in problem areas to insure that the support is adequate and to establish initial support requirements. The contract specifications should be written to provide for placement of additional quantities of shotcrete in the headings, without incurring exaggerated cost overruns. During the pre-bid phase of the project the contractor must be made aware of the possibility for additional material requirements and delays in his tunnel cycle. The contract must be written to provide fair compensation for these delays and additional materials.

Application of Shotcrete in Loosening Ground

Time of Application. Because of the nature of rock loading in loosening ground, shotcrete should be applied to the freshly exposed rock surfaces as soon as possible after excavation. In drill and blast tunnels the shotcrete application should begin no later than one hour after blasting and should be completed as rapidly as possible. In most conventionally driven tunnels, shotcreting can be started within one-half hour after blasting. The initial layer must be completed before the next round is advanced. In machine-bored tunnels, the initial layer of shotcrete should be applied as close to the cutter head or shield as possible. In the Heitersberg Tunnel, shotcrete was placed approximately 1 m (3 ft) behind the tail of the shield (Alberts, 1974). The initial layer of shotcrete placed in bored tunnels must be applied as rapidly as possible not only to prevent loosening but also to keep pace with machine excavation.

Early Strength Gain. In loosening ground conditions the strength gain in the initial layer of shotcrete should be as rapid as possible. When shotcrete is first applied to the tunnel surface it actually reduces the

stability of the arch by adding weight (150 kg/m^2[30 lb/ft^2] for a 5 cm [2 in.] layer) to the bottoms of the rock blocks. Many cases were observed in the Washington Metro tunnels where small rock blocks were brought down from the arch by the weight of the shotcrete alone during or shortly after gunning, even though water could not be seen in the vicinity of the blocks. Once the shotcrete becomes self-supporting the additional strength gain inhibits rock displacement and helps to maintain the strength along the sides of the blocks. Rapid strength gain in shotcrete is achieved by adding accelerator to the materials just before or during gunning. The time period shortly after application of the shotcrete (8 hours) is usually most critical since the shotcrete is weakest and most ductile during this period and many of the workmen are likely to be present in the heading installing other supports or preparing for the next advance.

Application of Shotcrete in the Tunnel Perimeter. In tunnels where shotcrete is actually needed for initial support it should be placed across the full arch. Application of shotcrete into the recesses between rock blocks should be made only to support local wedges (less than 1.2 m [4 ft] in dimension) bounded by clean, rough joints (Fig. 2.8). In tunnels where major support problems are likely to develop, clay coatings and slicken-sides are normally present on the joint surfaces. Clay and the slick surfaces associated with them prevent good bonding. In such cases, shotcrete sprayed only in the recesses provides essentially no resis-tance to rock block movement. When shotcrete-rock bond is poor, the shot-crete must be sprayed across the arch to form a continuous membrane. As a

recess

joint surface:
clean & rough
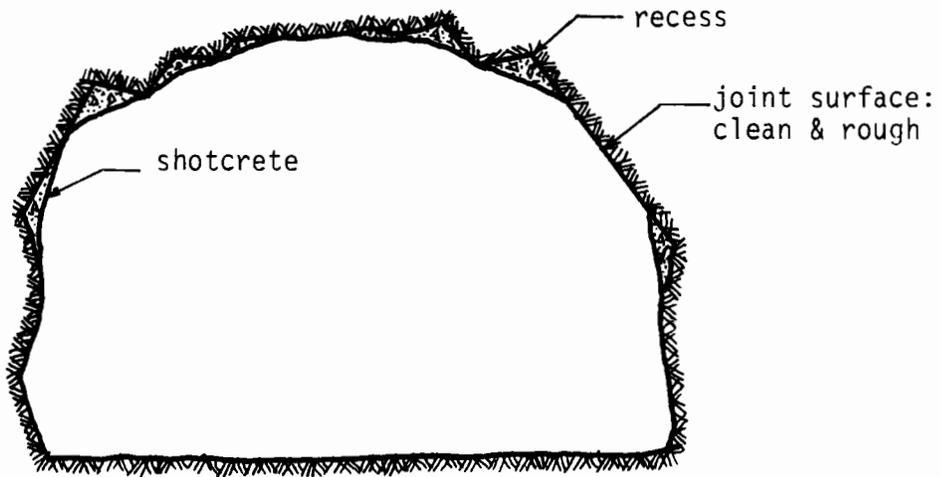
shotcrete

FIG. 2.8   USE OF SHOTCRETE IN RECESSES BETWEEN ROCK BLOCKS.

rock
bolt

gouge

gouge

shotcrete
membrane

②

①
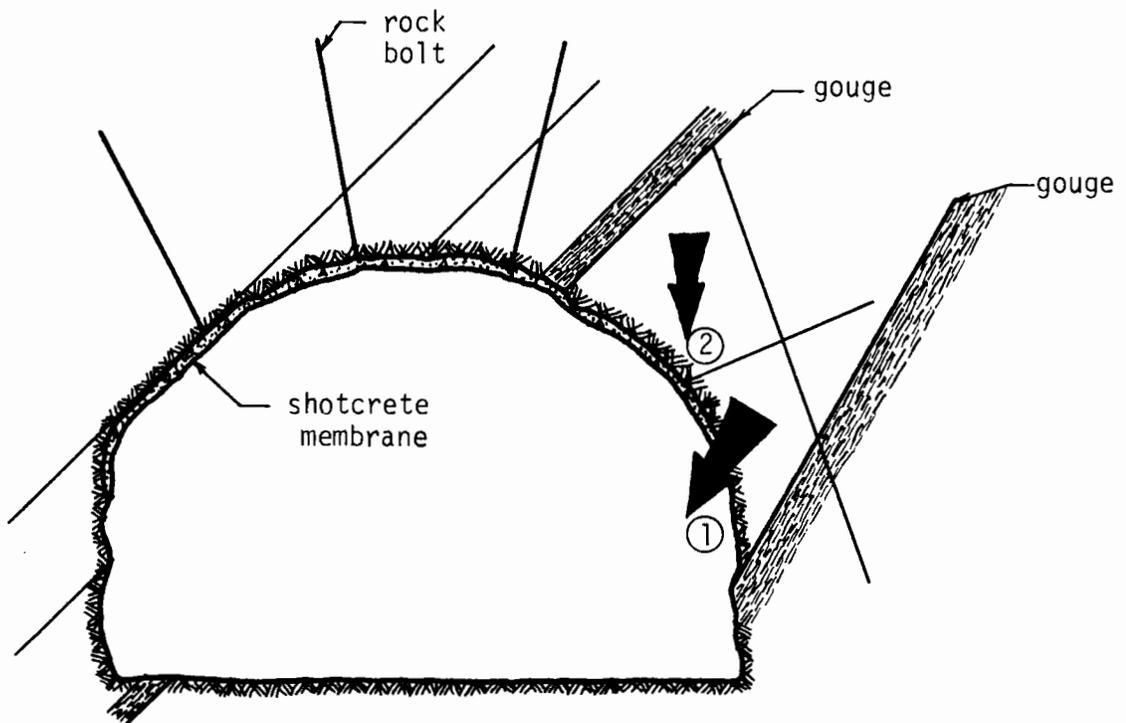
FIG. 2.9   ROCK BLOCK MOVEMENTS IN THE SIDEWALL
AND ITS EFFECT ON ARCH STABILITY.

membrane, the tensile and flexural capacity of the shotcrete resists rock movement. In 6-9 m (20-30 ft) diameter tunnels driven in blocky rock containing clay seams, the minimum thickness of the initial layer of shotcrete should be at least 5 cm (2 in.) particularly over the apices of rock blocks where tensile stresses are likely to concentrate.

Many support problems which have been encountered in rock tunnels and chambers have stemmed from inadequate support of vertical to near-vertical side walls. Inadequate support of sidewalls can produce deep sidewall movements which not only threaten the safety of the opening but also can jeopardize the stability of the arch (Fig. 2.9). Rock blocks in the arch derive support from the haunches and side walls. If the rock in the sidewalls is allowed to move, blocks above the arch lose their underlying support (Fig. 2.9). Shotcrete can be used to reduce or prevent block displacements in the sidewalls and maintain rock integrity. In very blocky ground a thin shotcrete membrane should not be used alone as support for vertical sidewalls over 3 m (10 ft) high (Cording, 1974).

Use of Thin Shotcrete Membranes as Sole Support

Thin membranes of shotcrete should be used as sole support in loosening ground only under the following conditions:

1. the diameter of the opening is less than 9 m (30 ft).

2. the joints are rough and clean.

3. rock blocks are less than 1.5 m (5 ft) in size and no large wedges are present.

These conditions are present in many tunnels, some of which have been solely supported with shotcrete.

2-20

Shotcrete can also be used to control ravelling ground provided the block movements are progressive and involve only small individual or groups of fragments (Fig. 2.10). If the blocks and fragments act as one large wedge a thin shotcrete layer alone will be inadequate (Fig. 2.11). Supplementary support is often desirable in ravelling ground, particularly if blocky rock adjoins the low quality zone. A thin layer of shotcrete was very effective in preventing ravelling of 2-5 m (6-15 ft) wide foliation shear zones encountered in the Washington Metro tunnels. Initial support in these tunnels consisted of rock bolts and shotcrete or steel ribs and shotcrete.

Shotcrete can be used alone as initial support in loosening ground, or as well, in almost any ground condition, if it is applied in sufficient thickness to act as a structurally continuous lining, and the excavation progress is slow enough to give the shotcrete ample time to gain strength. In loosening ground, the thickness of the shotcrete layer must be great enough to carry the full rock load. If tunnel progress is rapid or the shotcrete cannot support the heading, other support elements must be installed to give the shotcrete time to gain sufficient strength to carry the rock load. Shotcrete placed as a continuous arch is commonly used as sole support of small diameter tunnels (3 m [10 ft] or less) since rock loads and required shotcrete quantities are usually small. However, rock loads in some small tunnels may be relatively large as evidenced by roof collapses involving heights of rock more than one-half the width of the opening. In these cases a thin shotcrete membrane would not have been adequate to prevent failure.
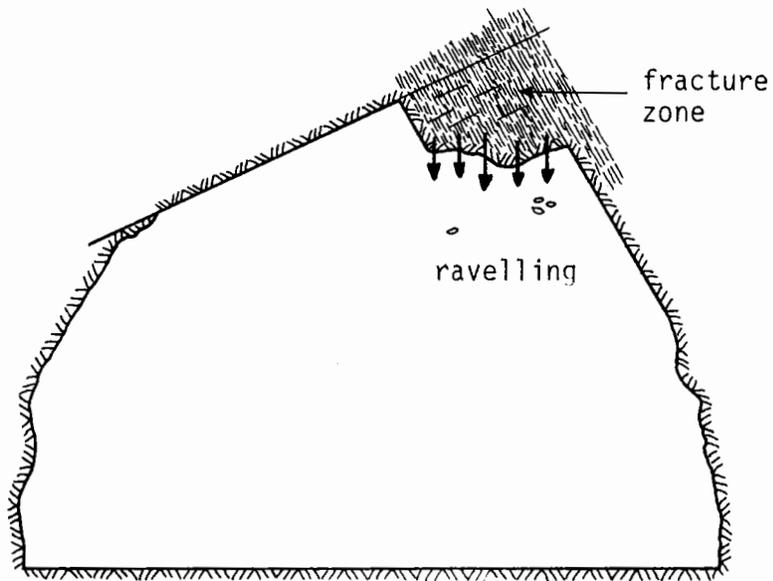
FIG. 2.10   SHOTCRETE MEMBRANE ADEQUATE FOR SUPPORT.
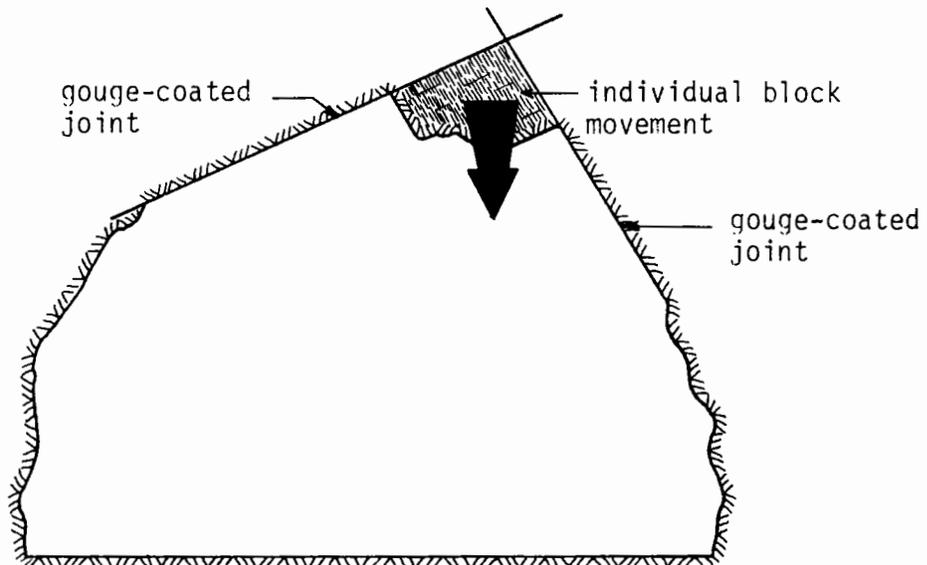
FIG. 2.11   SHOTCRETE MEMBRANE INADEQUATE AS SOLE SUPPORT.

Need for Other Support Elements

A thin layer of shotcrete used as initial support should be supplemented by other tunnel support elements when joint surfaces are continuous, smooth, and coated with clay. These conditions are often present in blocky and seamy rock and can cause poor shotcrete-rock bond with intermediate to large rock loads. Thin shotcrete layers used alone are generally not adequate since they do not have the capacity to support the rock blocks which tend to fall in the heading. The shotcrete layer if used alone must provide the required support immediately after it is placed since the stand-up time of large rock wedges in loosening ground can be very short. This is not possible with freshly gunned shotcrete because of the time required for it to gain strength. Even if the shotcrete is given sufficient time to gain most of its strength (7 days), a thin membrane cannot provide enough resistance to carry large rock loads since its capacity is governed by its low tensile and flexural strength, where shotcrete-rock bond is poor. These strengths range between 1/10 to 1/5 of the shotcrete compressive strength (f_c'). Shotcrete with regulated-set cement shows great promise for providing a very rapid gain in early strength (Appendix A); however, this shotcrete is only experimental and has not been used in actual underground construction.

Shotcrete should generally be supplemented with other supports in a flat-arched opening (rise/width $\leq$ 1/4). On flat horizontal surfaces, the capacity of the shotcrete is low even for good shotcrete-rock bond. In such situations, the shotcrete layer behaves as a beam rather than an arch. If rock bolts are used, the shotcrete can function efficiently in support of rock blocks between the bolts.

Reinforcement of Thin Shotcrete Membranes

Conventional reinforcement such as steel reinforcing bars or wire mesh placed near the outer fiber of the shotcrete layer should improve the tensile and flexural strength and the ductility of the shotcrete. Steel bars and mesh reinforcement are not placed in the initial layer because of delays in the heading, the danger of working beneath unsupported ground, and the questionable benefit of improving the flexural and tensile capacity of a thin layer. Steel fiber shotcrete shows promise for improving the post crack resistance (ductility) of the initial shotcrete layer (Appendix A). Flexural strength tests on samples of steel fiber shotcrete do not show a significant increase in flexural strength over conventional shotcrete (Parker, 1975). The increased ductility would be advantageous, however, since the layer could provide significant resistance to rock loads after initial cracking. Cracks in the shotcrete caused by rock loads could be used to monitor the stability of the opening, and remedial support could be placed under the protection of the fiber shotcrete. The use of steel fiber would reduce chances of catastrophic failure without warning. Field research is now being conducted on the use and performance of fiber shotcrete in mines (Parker, 1974). These studies should provide data on its capacity, material properties, and construction requirements which are needed to appraise its use in other types of geologic settings and underground works.

2.1.2. Overstressed Ground

In overstressed ground the stresses around the tunnel exceed the intact strength of the rock and cause a zone of yielding to develop around the opening. Failure of rock within this zone can involve brittle fracturing or plastic squeezing, depending on the degree of overstressing and on the ductility of

the rock (Figs. 2.12 and 2.13). In some materials such as shales both squeezing and slabbing (brittle fracturing) can occur adjacent to the opening. Some of the most difficult tunneling has been in heavily squeezing ground. Overstressed ground conditions are usually associated with weak materials such as shales or fault gouge at intermediate to great depths. These conditions can also occur in tunnels close to the ground surface in rocks having high residual horizontal stresses.

Rock behavior adjacent to the tunnel in overstressed ground progresses from yielding to loosening as illustrated in Fig. 2.14. Initially rock stresses adjacent to the opening are high and cause slabbing or squeezing of the material. As the rock at the tunnel surface yields the stresses around the opening are reduced. The reduction in stress and the inward displacement of the tunnel perimeter cause a reduction in the normal force and shear strength along the sides of blocks and slabs close to the opening. The loosened blocks adjacent to the opening tend to fall into the tunnel under the influence of gravity. Yielding and loosening of rock at the perimeter reduce the confinement of rock further from the opening, thus reducing its strength and allowing yielding to occur at greater depths. This process of yielding and loosening continues until equilibrium is achieved.

Support Requirements in Overstressed Ground

The support requirements in overstressed ground depend on the displacement at the tunnel perimeter as depicted in Fig. 2.15. Initially, the internal pressure required for support of the opening is large and much of the rock stress is mobilized by driving of the opening. As displacements increase the rock stresses on the support elements are
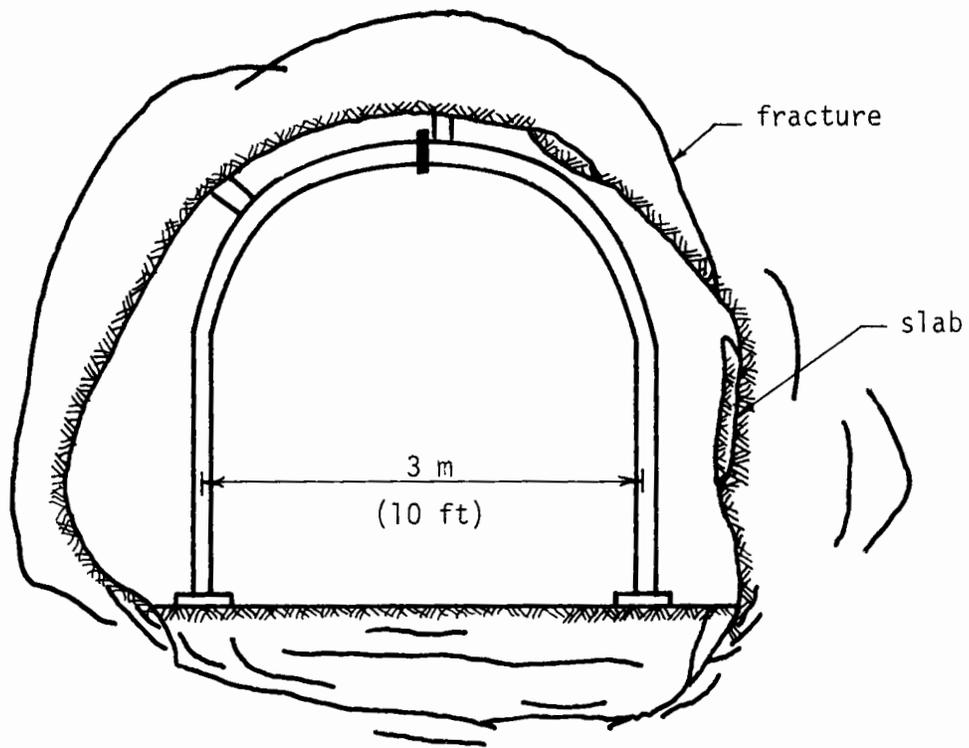
FIG. 2.12   BRITTLE FRACTURE OF ROCK IN OVERSTRESSED GROUND
            (CORDING, 1967).

shear zone

initial
excavation
surface

excavation surface after
inward plastic squeeze

shear zone
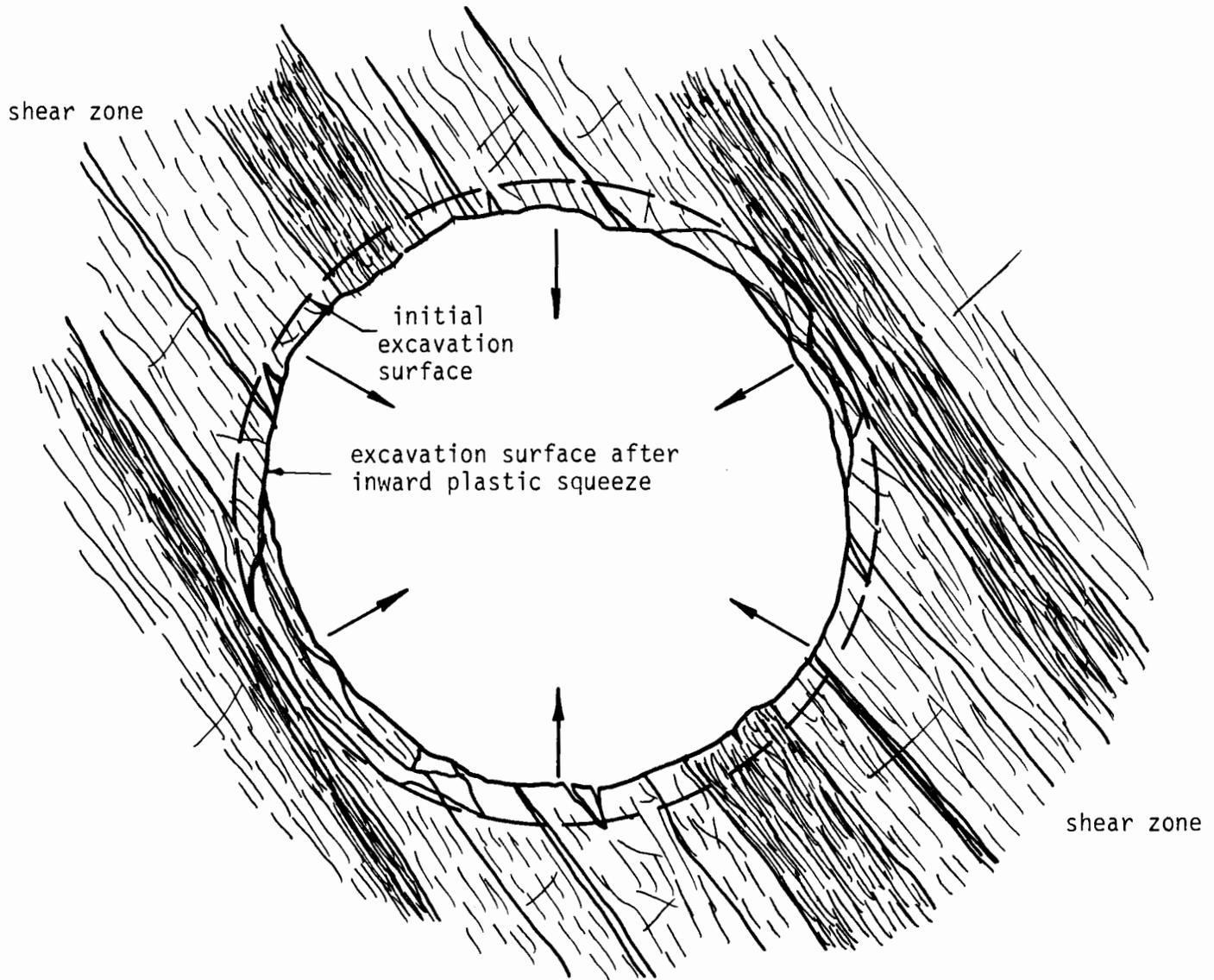
FIG. 2.13 PLASTIC SQUEEZE IN OVERSTRESSED GROUND.
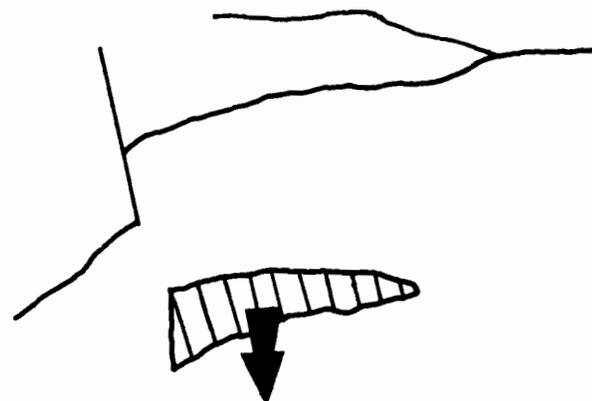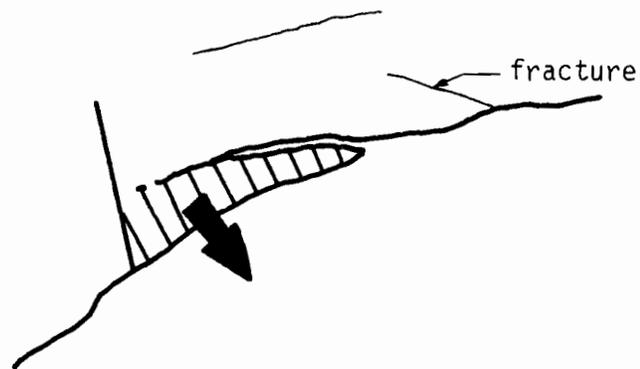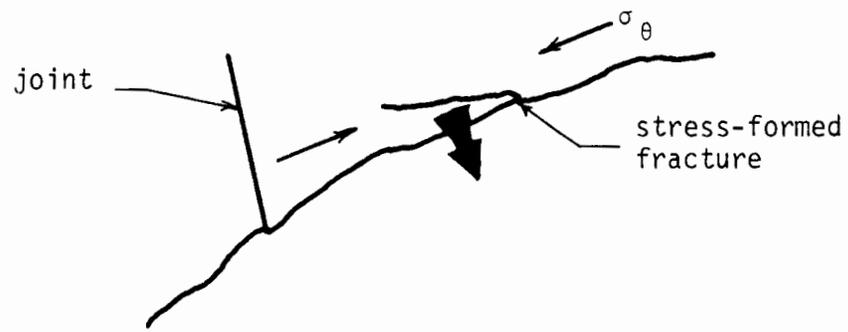
FIG. 2.14   PROGRESSIVE CHANGE FROM OVERSTRESSED TO
LOOSENING BEHAVIOR.
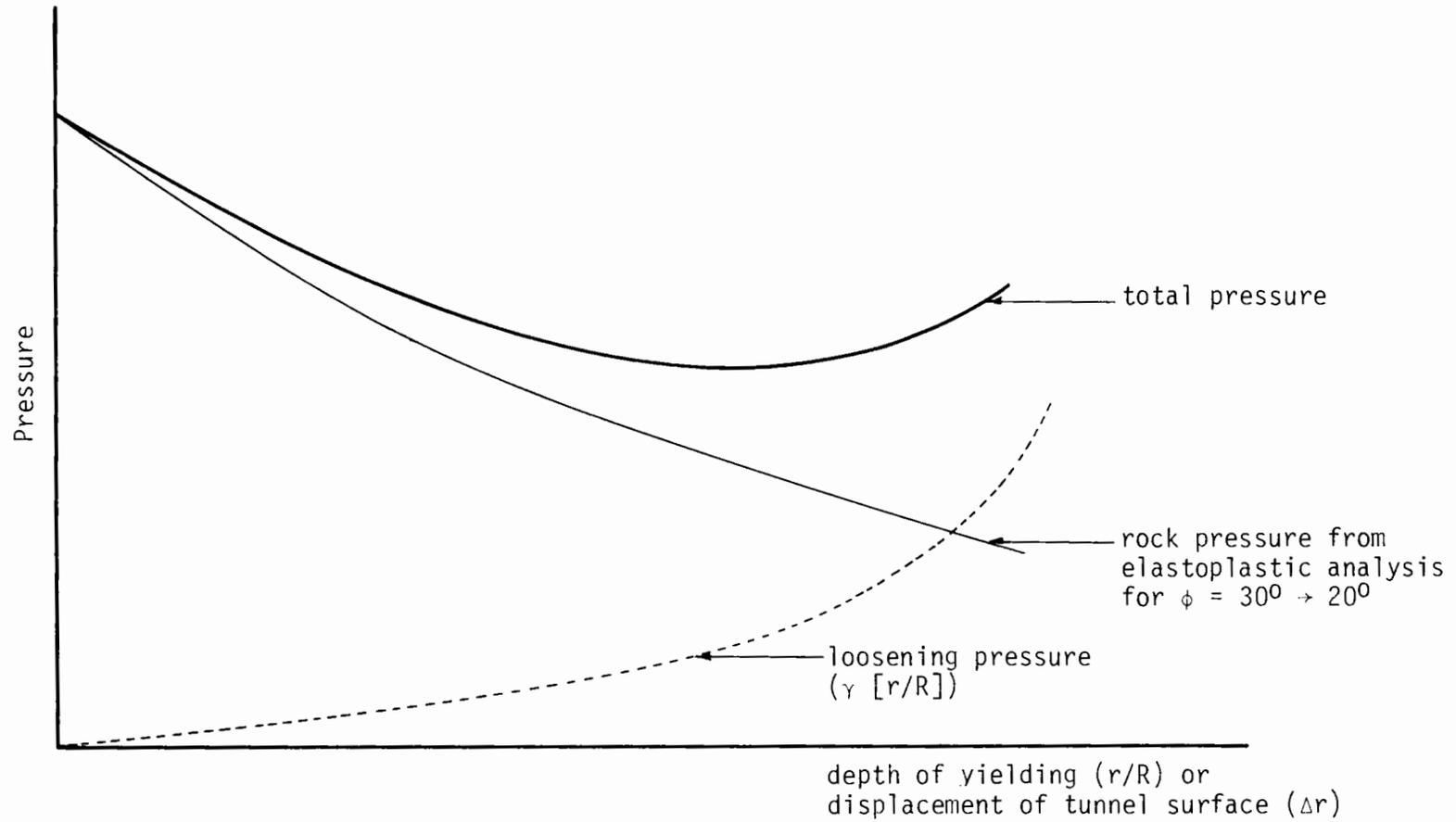
FIG. 2.15 RELATIONSHIP BETWEEN ROCK PRESSURE, LOOSENING PRESSURE AND TOTAL PRESSURE, AND THE DEPTH OF THE YIELDED ZONE OR THE DISPLACEMENT OF THE TUNNEL SURFACE (AFTER WAGNER, 1970).

reduced; however, the loosening loads are increased. The total support requirements, which consist of the squeeze pressure and loosening load, decrease at first and then increase with displacement at the tunnel perimeter. Thus, while required support pressure tends to decrease with initial displacement of the perimeter and growth of the yielded zone, the required support pressure will sharply increase if excessive displacement and loosening develops.

In tunneling through overstressed ground, some of the deformation and displacement should be allowed to reduce the amount of required support but must be controlled in order to prevent possible collapse of the opening and to maintain the strength of the rock. Many of the tunnel failures which have occurred in overstressed ground were caused by inadequate control of the loosened zone. In addition, the long-term creep loads on a lining in overstressed ground depend on the deformation and resultant loss in rock strength; higher ultimate loads are associated with greater deformation (Wagner, 1970 and Semple, 1973). Control of rock movement is achieved by placing support immediately after excavation in the heading and later, as required, to maintain the stability of the opening. The initial support should have a high strength to resist the rock stresses yet be sufficiently ductile in order to yield without permitting collapse of the opening.

Behavior of Shotcrete in Overstressed Ground

Shotcrete may be used in overstressed ground to resist rock stresses and to control rock loosening. Shortly after the shotcrete is applied, it acts to prevent yielding and loosening because of its intimate contact with the rock and its rapid gain in stiffness and strength. If the rock at the tunnel surface is yielding at the time of shotcrete application, relatively

high loads may develop in the shotcrete layer. Reduction in rock stress around the opening cannot occur until the shotcrete has deformed. Shotcrete used to resist squeezing or deep stress slabbing must be placed as a continuous ring around the full perimeter of the opening. Since high quality shotcrete is difficult to place in the invert, a reinforced, pre-cast concrete segment is often used to close the invert (Fig. 2.16). As a closed ring the shotcrete will behave similarly to a concrete lining except that in most cases the shear stresses between the shotcrete and the rock will be higher. Otherwise, for a given magnitude and distribution of load, the shotcrete should have approximately the same thrusts, moments, and shears as a comparable concrete lining. With small deflections, the shotcrete lining will tend to develop a relatively uniform, circumferential pressure (Cording, 1974). If a loosened zone has developed in the arch or walls, the shotcrete acts to hold the rock blocks and fragments in place in the same manner as described in the previous section on loosening ground.

Use of Shotcrete in Overstressed Ground

Heavily Squeezing Ground. The thickness and time of placement of shotcrete required in slabbing and squeezing ground depend primarily on the degree of overstressing and on the shotcrete-rock bond. Small diameter tunnels in heavily squeezing ground are successfully driven as circular openings by allowing some controlled yielding of the rock with subsequent placement of a full ring lining behind the face. Closed steel ribs and lagging are most commonly used to carry the initial squeeze pressures and are installed in the heading. Rock bolts may also be placed at the face to reduce rock loads on the ribs, to help maintain the integrity of the rock, and to provide a more uniform distribution of rock load. Shotcrete can be
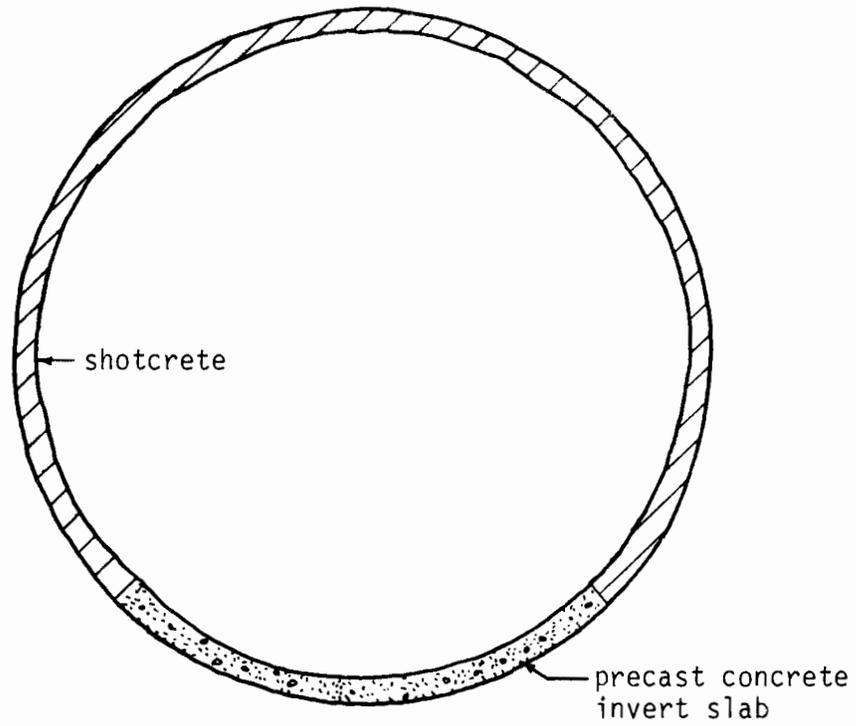
FIG. 2.16 USE OF A PRECAST CONCRETE SLAB TO CLOSE
THE INVERT OF A SHOTCRETE-SUPPORTED
TUNNEL IN OVERSTRESSED GROUND.

used to construct a full ring lining behind the face to carry the long-term creep and loosening loads (Fig. 2.17). Although it can be placed as a permanent lining at the face, this is rarely done because of the large thicknesses needed to resist the high initial rock stresses encountered in heavily squeezing ground. Shotcrete can also be used as remedial support to prevent collapse of the opening if the steel ribs are inadequate. In this case the shotcrete should be placed as a full ring lining. If shot-crete is applied in thin layers for initial support it is likely to undergo extensive cracking and slabbing and become a safety hazard itself. Use of shotcrete in thin layers as initial support in heavily squeezing ground is not recommended unless the stand-up time of the rock is very short. In this case it can be applied to prevent ravelling and fallouts during installation of the steel ribs. The blocking of the ribs should be adequate to prevent later fallout of shotcrete slabs. Shotcrete is sometimes used as lagging behind and between steel ribs but in such cases generally requires extensive repair.

Several investigators including Rabcewicz (1964-1965) report extensive cracking of shotcrete linings in heavily squeezing ground. In almost all of these cases it appears that the shotcrete did not have adequate thickness or reinforcement to carry the rock stress. Nearly all of these linings did not collapse completely because either a portion of the lining along the crack remained in compression and continued to carry load, or remedial support was placed. In most cases where thick layers of shotcrete were placed as remedial support the lining showed no additional cracking. Field observations indicate that squeezing pressures commonly develop gradually and that extensive yielding occurs before the lining collapses. This

A
A'
B
B'
fully grouted or driven spiling
face
shotcrete
lagging
steel rib

lagging
3 m
(10 ft)
rib
shotcrete

Section A-A'
Section B-B'
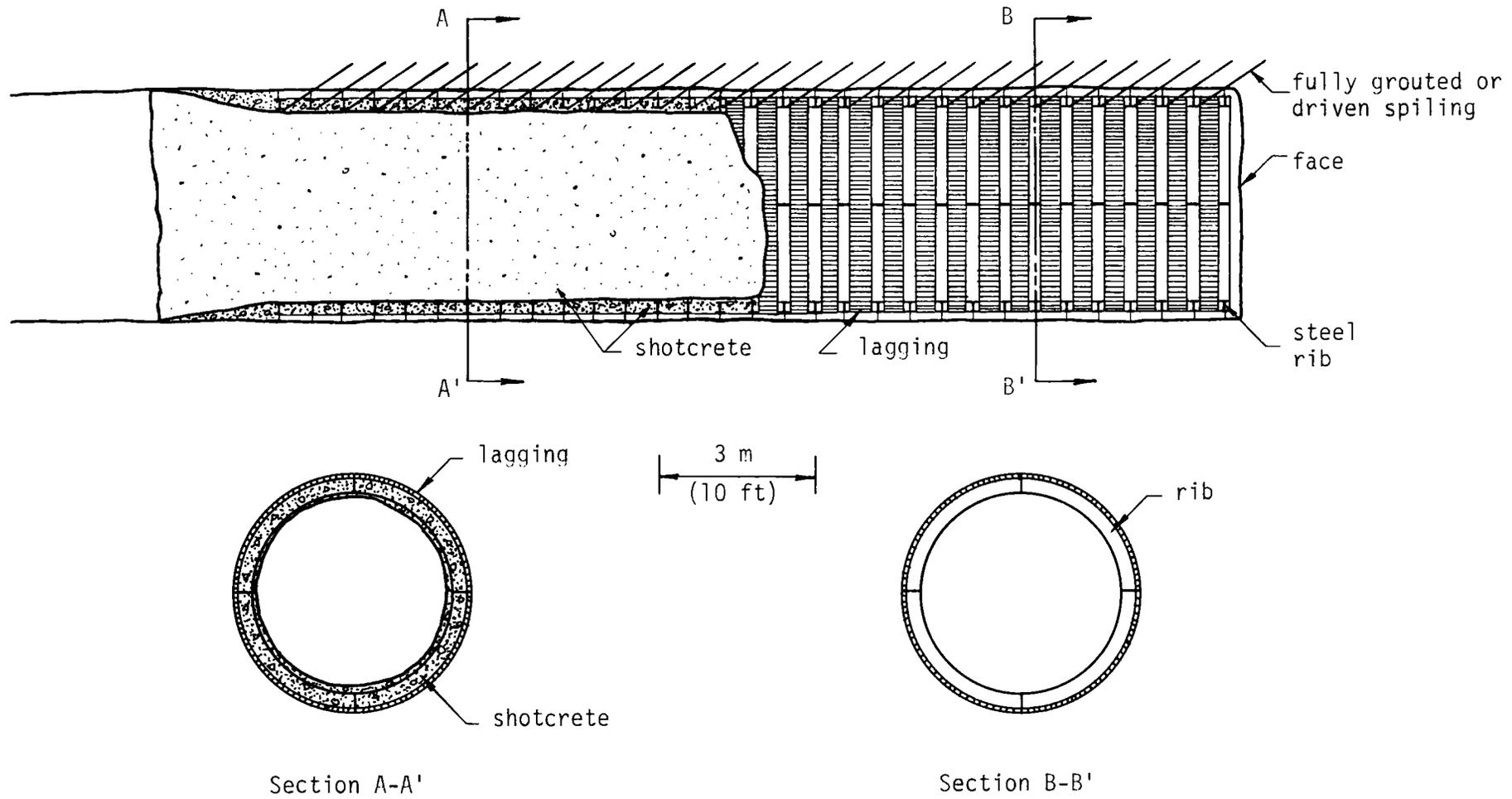
FIG. 2.17 USE OF SHOTCRETE IN SQUEEZING GROUND.

yielding provides early warning of impending failure and gives time for placement of remedial support.

Bursting Ground. Use of shotcrete to treat highly overstressed, brittle rock which exhibits popping or bursting behavior should be approached with caution or avoided if possible. Because of the brittle character of the shotcrete, failure will be instantaneous with both shotcrete and rock blown into the opening. In severe cases tunnels are usually driven through such ground by allowing or inducing rock deformation and stress release rather than by lining the opening. Shotcrete applied to bursting rock may aggrevate the problem by causing a high concentration of stress near the tunnel surface. Shotcrete has been used successfully in controlling mildly popping rock (Alberts, 1965 and Deere, et al., 1969) but may undergo excessive deformation if it is applied in too thin a layer. Where shotcrete is used as initial support in popping rock it must have sufficient capacity to withstand the rock stresses.

Slightly Overstressed Ground. In slightly overstressed ground ($\sigma_v/q_u \simeq 5$, Cording, et al., 1975) shotcrete can be applied as initial support in the heading. It is most effective in controlling slightly squeezing ground where full ring support is needed. Rock bolts are much more efficient than shotcrete for initial control of slabbing ground, but shotcrete may be of some value in preventing yielding and loosening of the rock between the bolts (Fig. 2.18). If the shotcrete-rock bond is poor or the rock stresses are high, the shotcrete must be placed as a continuous membrane.

Thickness Requirements for Shotcrete Linings in Overstressed Ground

Elastoplastic Analysis. Several two dimensional analytical methods have been proposed for estimating the internal pressure (P_i) on a circular

shotcrete

bolt

stressed-formed
fracture
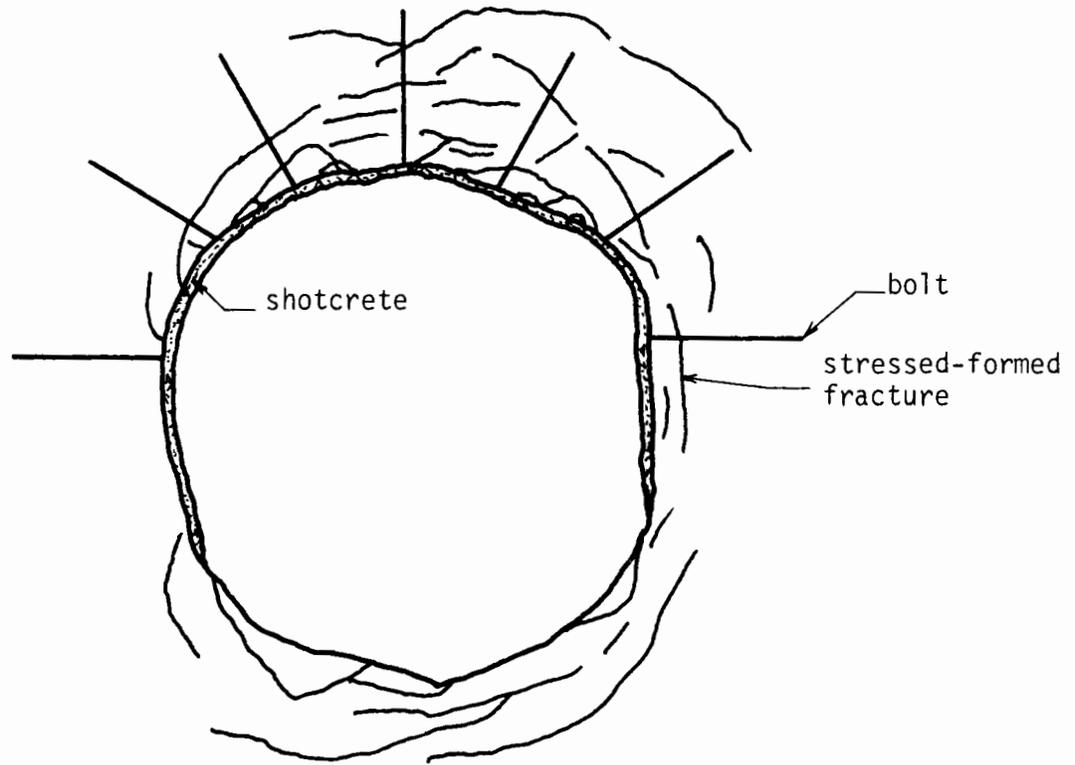
FIG. 2.18   USE OF SHOTCRETE AND ROCK BOLTS IN MILDLY SLABBING GROUND.

lining in overstressed ground. These methods assume development of a plastic continuum in a hydrostatic state of stress. One method was developed by Westergaard (1940) and Terzaghi (1943) and later applied in the design of thin shotcrete linings by Rabecwicz (1964-1965). In this method the internal pressure (P_i) needed to prevent development of the plastic zone beyond a given depth (R-r) is calculated from equations of equilibrium assuming a Mohr-Coulomb yield criterion (Fig. 2.19). This internal pressure (P_i) is calculated from the equation (Rabcewicz, 1964-1965):

$$P_i = -c \cot \phi + P_o[c \cot \phi + (1-\sin \phi)](r/R)^{\frac{2 \sin\phi}{1-\sin\phi}} \qquad (2.1)$$

where the terms are defined in Fig. 2.19. For c = 0, Eq. 2.1 simplifies to

$$P_i = P_o (1 - \sin \phi) (r/R)^{\frac{2 \sin\phi}{1-\sin\phi}} \qquad (2.2)$$

The validity of the assumptions in using this elastoplastic analysis for designing tunnel linings to carry rock stresses has been described by Hopper, Lang and Matthews (1972). In most geologic settings, (1) rock is neither isotropic nor homogeneous, (2) the state of stress is not hydrostatic and (3) rock does not behave perfectly plastic. The elastoplastic analysis is most valid when used to design linings for deep tunnels driven through fault zones containing a high gouge content or through highly weathered or altered rock.

Recognizing the errors associated with estimating the rock properties and the states of stress, Eqs. 2.1 and 2.2 can be used to estimate the

σ_r	Radial stress
σ_t	Tangential stress
P_o	Free field stress
P_i	Internal pressure
c	Cohesion
ϕ	Angle of friction
R	Radius of the yielded zone
r	Radius of tunnel
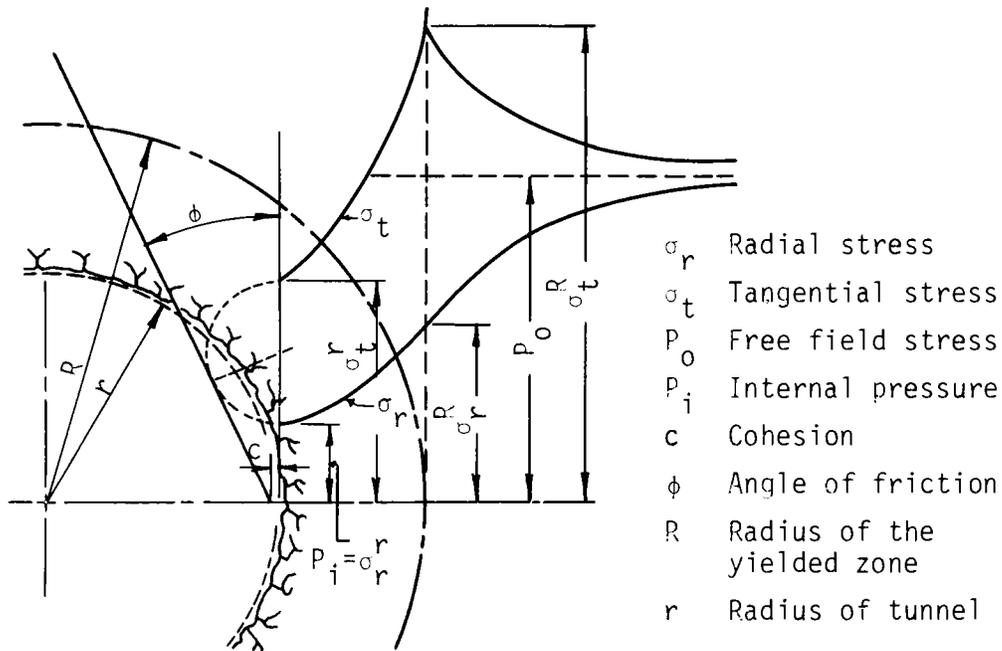
FIG. 2.19   STATE OF STRESS AROUND A CIRCULAR TUNNEL IN AN ELASTIC-PLASTIC (MOHR-COULOMB) MEDIUM AND A UNIFORM STRESS FIELD (AFTER KASTNER, 1962).

thickness of a shotcrete lining needed to resist rock stresses. These equations do not include rock loads associated with other types of ground behavior (swelling or loosening ground). If the full lining is placed at the face the r/R value used in the equations must be close to unity and the internal pressure will be high. If r/R values much smaller than 1.0 were assumed in calculating lining thickness, the required internal pressure would be low but may not be adequate to carry the loosening loads in the yielded zone. Thus, if the shotcrete is placed some distance

behind the heading, care must be taken so that the plastic zone is not allowed to develop to such a depth that the loosening pressures exceed the capacity of the initial support.

The equations describing elastoplastic behavior have been modified by Hopper, Lang and Matthews (1972) to include loosening loads associated with development of the yielded zone. The modified form of the elasto-plastic equation for c = 0 is

$$P_i = P_o (1 - \sin \phi) (r/R)^{\frac{2\sin\phi}{1-\sin\phi}} + \gamma(R-r) \qquad (2.3)$$

where γ is the unit weight of the rock. The internal pressure estimated using this equation is conservative in terms of the loosening loads since the full gravity weight of rock in the yielded zone, particularly near the elastoplastic boundary, would not be acting on the lining. In spite of the difficulties in estimating rock parameters and the discrepancies between assumed and actual conditions, Eq. 2.3 can be used to assist in design of shotcrete linings placed in ground exhibiting overstressed and loosening behavior.

The required thickness of shotcrete is determined by using the calculated value of P_i and assuming the shotcrete lining acts as a compression ring with a compressive shear mode of failure. The required effective thickness of the shotcrete lining is determined by:

$$t = \frac{P_i \times r}{f'_c} \times FS \qquad (2.4)$$

where P_i is the internal pressure, r is the radius of the opening, f'_c is the compressive strength of the shotcrete and FS is the factor of safety (2-3)

(Heuer, 1974). The thickness given in Eq. 2.4 includes only that portion of the lining forming a relatively smooth ring and does not include that required to fill the irregularities in the tunnel perimeter (Fig. 2.20). The assumption of a compressive shear failure mode appears to be valid from observation of cracking of tunnel linings in overstressed ground (Fig. 2.21).

Elastoviscous Analysis. The elastoplastic analysis for estimating the internal pressure does not include the time-dependent properties of the rock. Experience in heavily squeezing ground suggests that the initial squeeze movements are usually noticeable within a few hours or days after excavation and can continue for weeks or months. Semple (1973) has provided an analytical method in which the time-dependent properties of the rock are considered in estimating the internal pressure. The parameters used to describe the time-dependent behavior of the rock were determined from undrained, constant load, triaxial creep tests on samples of fault gauge. These parameters were used in a continuum analysis of closure of a circular tunnel in an elastoviscous material subjected to a hydrostatic state of stress. The nonlinear differential equations developed by Semple were solved using numerical techniques and a parameter study was conducted to determine the internal pressure needed to support tunnels in squeezing ground. Figures and tables are provided for estimating the internal pressure and lining thickness in creep sensitive materials. The results indicate that for materials of different strengths, the short-term loads on a lining (1 yr) are likely to range between 0.1 to 0.3 of the overburden pressure (P_o), whereas long-term loads are likely to be between 0.3 to 0.5 P_o (Semple, 1973).
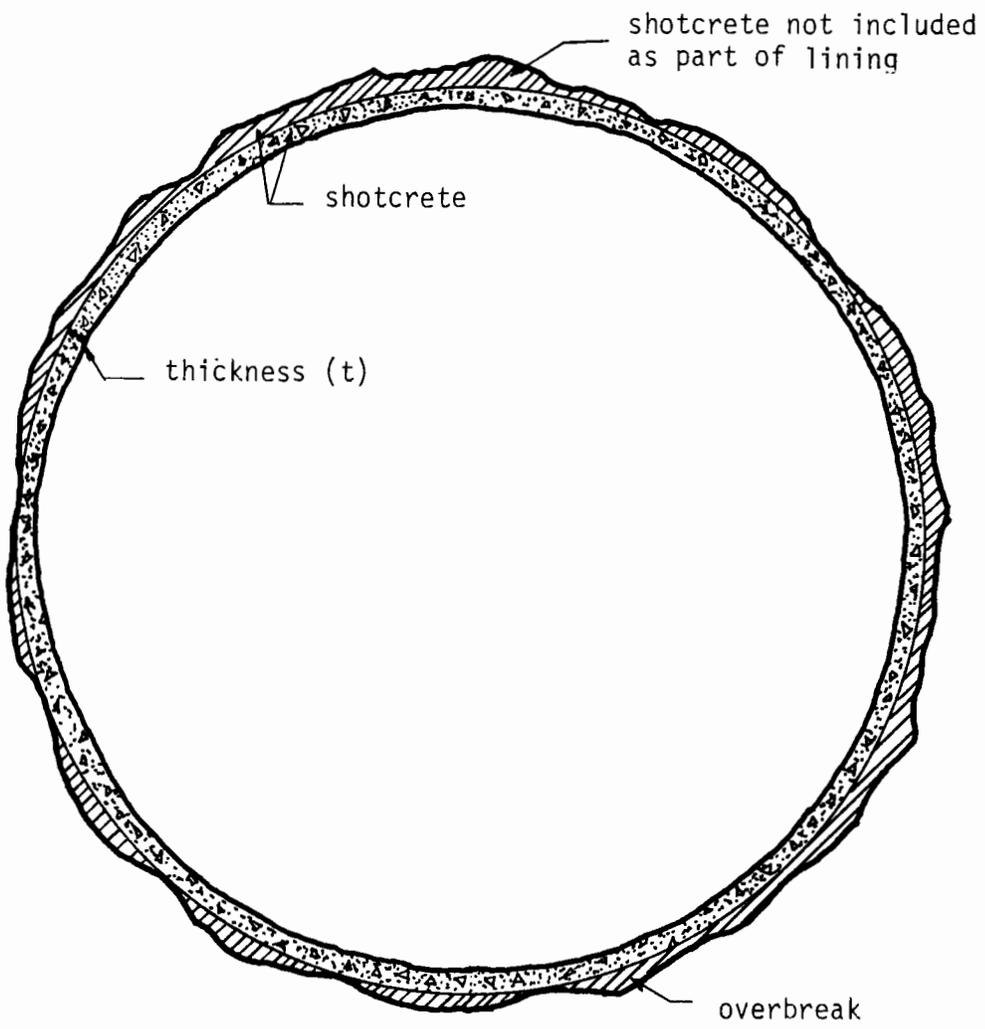
FIG. 2.20 THICKNESS OF A SHOTCRETE LINING USED
FOR DESIGN PURPOSES.

The actual thickness and time of placement of shotcrete in the tunnel must be determined by careful observation of ground behavior and deformation of the support. Shotcrete used to assist in initial or supplementary support is applied to the desired thickness at the face or a certain distance behind the heading depending on the ground movements and deformation of the initial support. If the lining cracks, additional support is placed until the deformation stops or is brought under control. In heavily squeezing ground, if steel ribs are used for tunnel support during the initial period of heavy squeeze and shotcrete is placed only to carry ultimate creep loads, the shotcrete is applied after the rate of closure of the opening levels off.
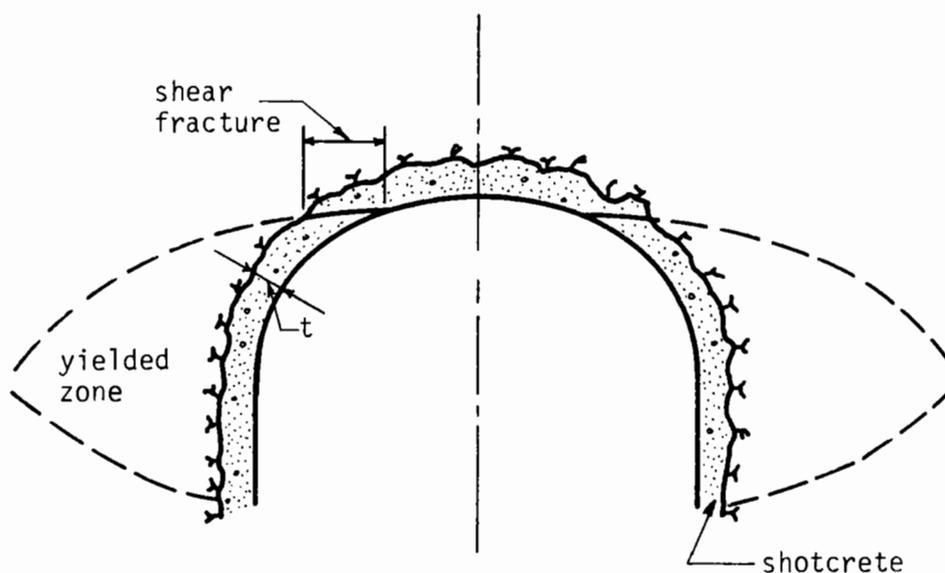
FIG. 2.21 COMPRESSIVE SHEAR FAILURE OF A TUNNEL LINING IN OVERSTRESSED GROUND (AFTER RABCEWICZ, 1969).

The same design considerations given for loosening ground are also applied when thin shotcrete layers are used to support overstressed brittle rock, except that the shotcrete is usually placed behind the heading.

Use of Shotcrete as Sole Support in Overstressed Ground

Shotcrete should not be used as sole support in overstressed ground and in most cases should not be placed as a thin lining. If placed as a closed ring, shotcrete will not permit yielding and relief of ground stresses. Thus, the shotcrete will be overloaded and may fail if it is not placed in sufficient thickness. Since loosening loads in overstressed ground can develop quickly even near the heading, other supports must be placed to provide sufficient time for the shotcrete to gain strength. In thin layers the shotcrete is not likely to form a structurally continuous lining because of the irregularity of the tunnel surface. If used alone these thin layers do not have sufficient capacity to carry large loosening loads, particularly where shotcrete-rock bond is poor. Shotcrete placed in thin layers may be of value to help support slightly overstressed brittle rock or its accompanying shallow loosened zone.

Preparation of the Tunnel Surface to Receive Shotcrete

In placing shotcrete in overstressed ground, the tunnel perimeter should not be scaled unless there is imminent danger of a rock fall. Scaling, particularly in squeezing ground, causes excessive overbreak and usually does not improve shotcrete-rock bond. Where extensive scaling is done, the thickness of the liner must be adequate to carry the high, external radial stresses associated with little or no development of a plastic zone. Many shotcrete failures have occurred because of extensive rock scaling and inadequate thickness or continuity of the layer.

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Placing of the shotcrete without scaling should be done carefully, particularly in the arch where spalls are likely to occur. The initial layer should not be more than 5 cm (2 in.) thick when clay is present on the joint surfaces.

Reinforcement of Shotcrete

The ductility of the shotcrete can be significantly improved by adding steel fiber to the mix. After cracking, fiber shotcrete provides a much greater resistance to loosening pressures and further movement than conventional shotcrete.

2.1.3 Swelling Ground

The stresses around an opening in swelling ground are caused by absorption of water by expansive materials, generally active clay minerals such as montmorillonite. These minerals are usually found in weathered volcanic ash deposits (e.g., Mexico City), in shales containing volcanic ash, and in faulted and weathered, feldspar- and mica-rich granites and gneisses. It must be remembered, however, that swelling conditions can occur in any rock type even though it does not contain minerals which weather into active clays (Brekke, 1972). Expansive materials can occur in thick layers and zones over long portions of the tunnel or as individual seams in blocky or fractured rock. Swelling can also develop in tunnels driven through anhydrite deposits. Swelling materials have access to water from drainage in the tunnel invert, from rock adjacent to the swelling materials, from water movement within the materials themselves, or from moisture in the tunnel air.

Swelling ground often appears quite similar to squeezing ground, and the two behaviors may be difficult to distinguish. Loads on a tunnel

lining due to swelling ground usually develop slowly and the rate of loading decreases with increasing deformation of the swelling materials. However, when large volumes of water come in direct contact with materials having a high swell potential, high pressures can develop quickly (Selmer-Olsen, 1971). The potential swelling pressures which can develop around an opening depend on the composition, the initial moisture content, and the relative percentage of swell-sensitive material in the rock, and upon the availability of water. Selmer-Olsen (1971) reports that in cases where the rock was initially dry and the swell-sensitive materials were at low moisture contents, no problems with swelling developed where the tunnel surfaces were adequately sealed.

Squeezing and Loosening Behavior Associated with Swelling

Swelling ground is often associated with overstressed and/or loosening ground. Materials which are susceptible to swelling often have low strengths compared with most intact rock. Swelling and overstressed ground are most likely to occur together in rocks containing a relatively high percentage of active clay minerals, such as thick sequences of weathered and interbedded shales and rhyolites, and thick fault zones containing montmorillonite. Swelling and loosening conditions can occur at any depth and are most prominent in fault zones and jointed rock containing seams of swelling clay (Fig. 2.22). The combination of swelling and loosening is one of the most difficult and hazardous conditions encountered underground and has caused some of the largest fallouts recorded in tunnel construction. Swelling materials usually have low frictional resistances ($\phi_r = 5\text{-}10^\circ$) and thus do not provide adequate shearing resistance on the sides of blocks to hold them in place. Shear failures and loosening may develop not only
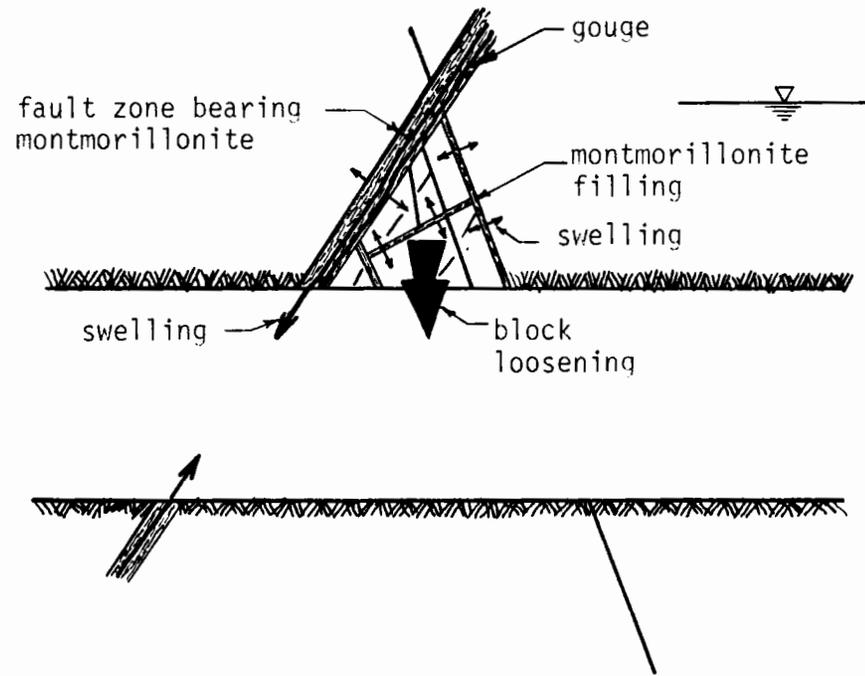
FIG. 2.22 SWELLING AND LOOSENING GROUND.

because of gravity-induced block movements, but also because of swelling and subsequent squeezing of the clay toward the opening. When they swell, active clays in flat-lying joints may actually pry blocks loose from the overlying rock mass (Fig. 2.23).

Use of Shotcrete in Swelling Ground

Shotcrete as a Sealent. Swelling ground is generally treated by using one of two techniques: 1) sealing the tunnel surface immediately after excavation or 2) allowing some of the swelling deformations to occur and then placing a lining behind the heading. The first method can be used only when the tunnel is dry, the water content of the swell-sensitive material is low, and the source of water is moisture in the tunnel air. The seal must be placed as quickly as possible, since some swelling materials with low moisture contents will readily absorb moisture from the air (Selmer-Olsen, 1971). The lining should be installed around the full perimeter of the excavation (Fig. 2.16), and must extend onto non-swelling rock at least one tunnel diameter on both sides of the zone of swelling materials. The thickness of the lining should be adequate to prevent shrinkage cracks or defects caused by construction activity (at least 5 cm [2 in.]). These steps are taken to prevent water in the air or in adjoining sections of the tunnel from coming into contact with the swell-sensitive materials. If cracks occur in the shotcrete or if the invert is not properly sealed, water will eventually reach the materials and cause swelling and the spalling of the lining. Shotcrete having a thickness of 5-10 cm (2-4 in.) has been used successfully as initial support when the tunnel was dry or when the amount of swelling material was small in comparison with the amount of

2-47
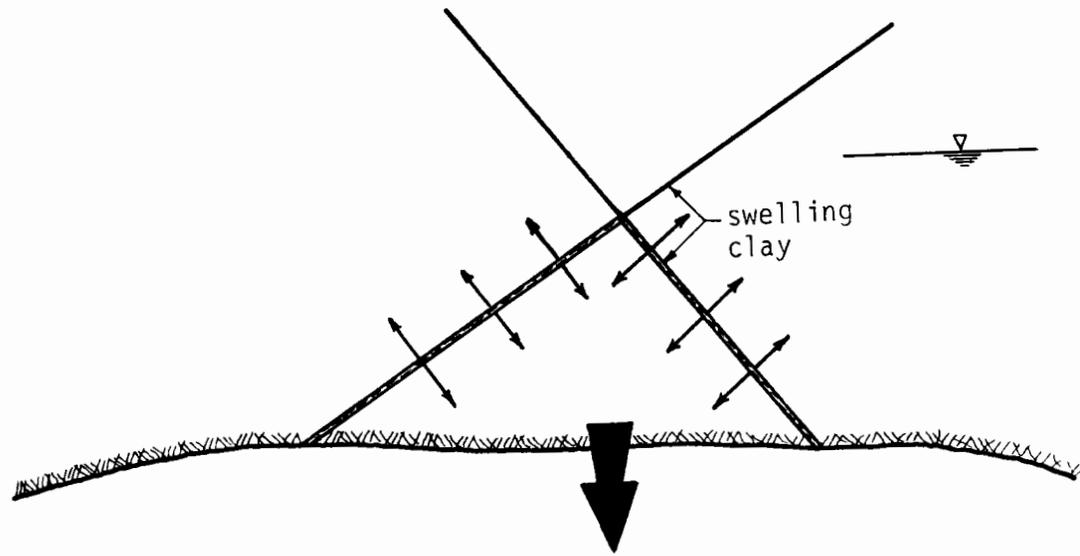
FIG. 2.23 BLOCK DRIVEN INTO OPENING BY SWELLING CLAY.

non-swelling rock (Selmer-Olsen, 1971). Consideration should be given to reinforcing the shotcrete with steel bars, wire mesh, or steel ribs to improve its ductility and resistance to bending. Rock bolts and/or steel ribs should be installed if the ground exhibits intermediate to deep loosening as well as swelling behavior.

Thin shotcrete membranes used alone as initial support have generally performed poorly in swelling ground where water was present in the rock (Selmer-Olsen, 1971). In this application the shotcrete is placed before the swelling has occurred and becomes subjected to high swell pressures. Water generally reaches the active clay through defects in the shotcrete or by migration toward the opening in clay seams and in open joints and fractures. The resultant swell pressures crack and spall the thin shotcrete layer.

Shotcrete as Continuous Ring Support. This method has been the most successful for driving tunnels through swelling ground except when ground conditions or the size of the opening require multiple excavations. It is nearly identical to that used in heavily squeezing ground. Steel ribs and lagging and, in cases of mildly squeezing ground, rock bolts are installed as initial support. These support elements permit some swelling movement and relief of swell pressure yet help to minimize the depth of the loosened zone. If the ground is not supported, rock movement caused by loosening and/or overstressing will allow the water to penetrate deeper into the swell-sensitive materials and further magnify the problems. Shotcrete may sometimes be used as initial support between the bolts and the ribs but can be expected to crack severely and require considerable maintenance and repair unless it has sufficient thickness to bear the swell pressures. The thickness of shotcrete needed to support the full potential swell pressure is generally economically prohibitive. In tunneling through heavily swelling ground, a shotcrete or

concrete lining is commonly placed at some distance behind the heading after some swelling deformation and relief of pressure has occurred. This lining should be structurally continuous and form a closed ring (Fig. 2.20). The required thickness of the lining will depend on the amount of swelling that has been allowed to develop before its installation. If the lining is placed close to the face (within 24 hours after excavation - Deere et al., 1969), the required thickness is estimated by assuming a uniform radial pressure (P_s) acting on a continuous ring:

$$t = \frac{P_s \times r}{f'_c} \times FS \qquad\qquad (2.5)$$

The swell pressure is estimated by performing confined swell pressure tests on undisturbed samples of the swelling materials. If some swelling relief is permitted before the liner is installed, the swell pressure will be much lower than that estimated from the confined swell tests. Experience with swelling seams in Scandinavian tunnels indicated that a volume change of 5% in a depth of 3 times the width of the swelling materials (Fig. 2.24) produced a permanent reduction in swell pressure of roughly 75% (Brekke and Selmer-Olsen, 1965). The actual thickness and time of placement of the lining must be determined during construction; however, the analyses using swell pressure tests and one dimensional volume expansions to reduce pressure provide initial guidelines for placement of the lining in the tunnel. If nearly all of the swelling pressure is dissipated by expansion, thin shotcrete layers can be used to prevent slaking of the clay. The same considerations regarding scaling and use of fiber given for overstressed ground apply as well in swelling conditions.
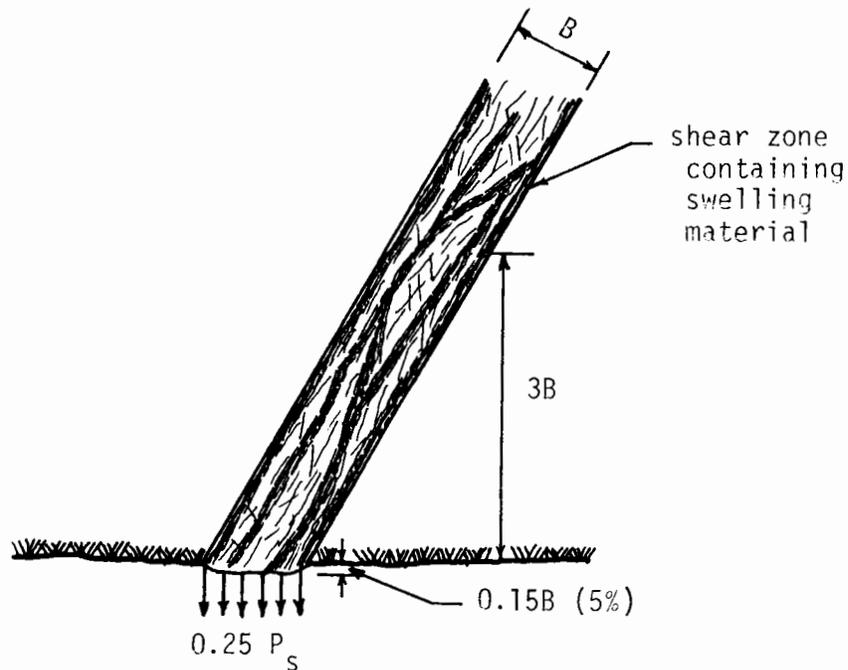
FIG. 2.24   REDUCTION IN SWELL PRESSURE CAUSED BY VOLUME CHANGE.

Brekke and Selmer-Olsen (1965) have described a method for using shotcrete to seal thin seams of moderately swelling material (< 30 cm[12 in.] thick) present between competent rock (Fig. 2.25). The clay and fragmented rock at the surface are removed and a layer of rockwool placed against the seam. The rockwool is covered with a fine mesh and then a layer of shotcrete. The rockwool allows the clay to expand without damaging the lining. The entire seam should be sealed and the method should not be used for very active clays or seams with a high clay content (Selmer-Olsen, 1971).

seam of swelling clay
and fragmented rock

25 mm (1 in.)
net

rockwool

rock bolt

reinforcing
steel

shotcrete
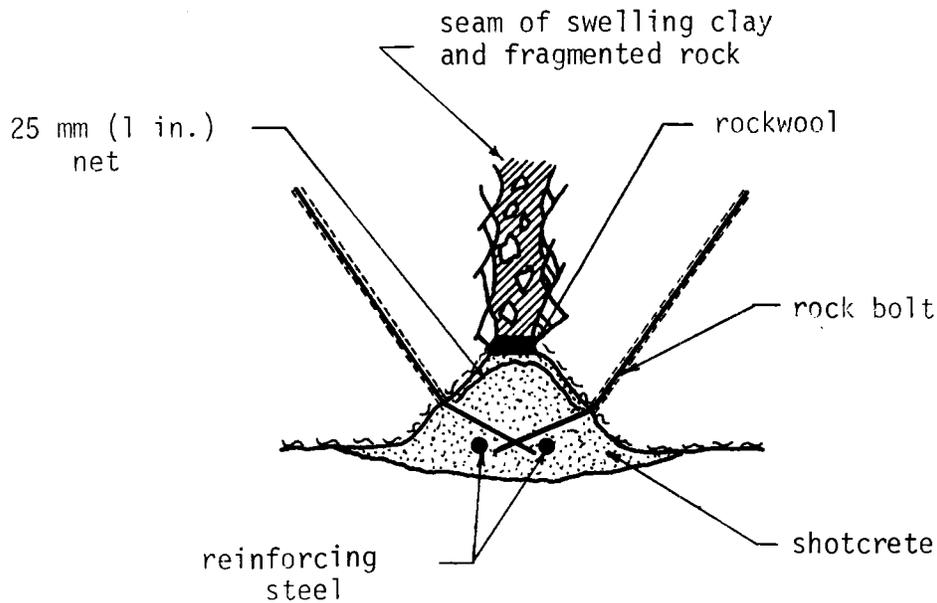
FIG. 2.25 METHOD FOR SEALING THIN SEAMS OF SWELLING MATERIALS
BETWEEN GOOD QUALITY ROCK (BREKKE AND SELMER-OLSEN, 1965).

2.1.4 Slaking Ground

In slaking ground, the rock deteriorates at the surface of the tunnel
by undergoing a brittle tensile failure and usually involves slow
ravelling or sloughing of small fragments into the opening (Fig. 2.26).
Slaking is caused by stress relief or by changes in the moisture content
of the materials. These changes include both drying and alternately
wetting and drying without appreciable softening. Wetting can result from
moisture in the tunnel air or from groundwater in and adjacent to the
slaking materials. Slaking is most likely to occur in shales,particularly
those which are carbonaceous or weathered (such as clay-shales and under-
clays), in some siltstones and in fault gouge. Slaking causes a general
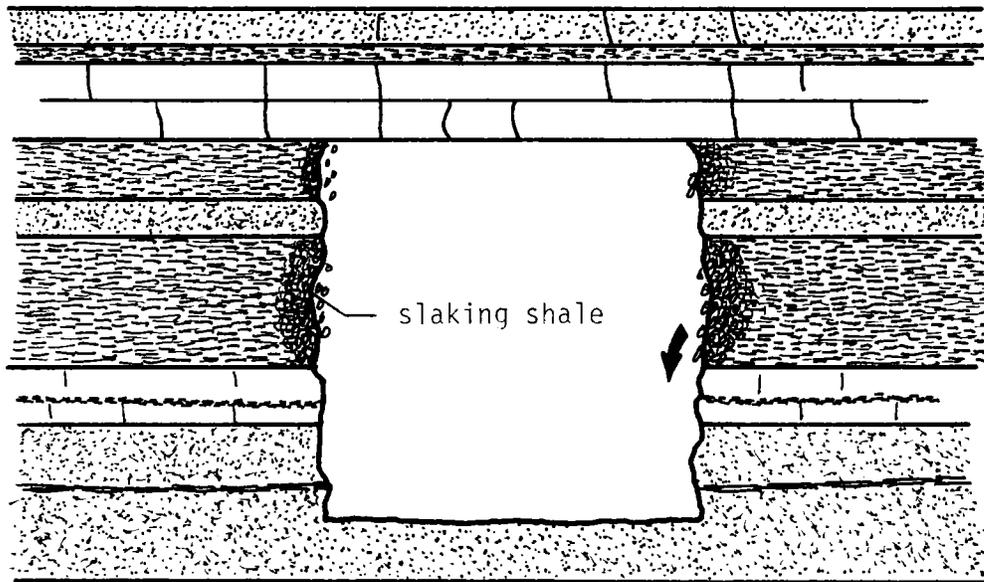
FIG. 2.26 SLAKING GROUND IN PENNSYLVANIAN SHALES.

and progressive deterioration of rock in the vicinity of the tunnel and can lead to loosening or overstressing problems.

Treatment of Slaking Ground

Thin layers of shotcrete are generally helpful in controlling slaking caused by stress relief and drying. In these conditions, the shotcrete is applied over the slaking material and is extended well onto competent rock on both sides of the zone of slaking (Fig. 2.27). If water is present in the tunnel, the full perimeter of the opening should be sealed (Fig. 2.28). In horseshoe-shaped tunnels sealing the invert may not be required, provided slaking materials are not present in the lower portion of the sidewall or in the invert (Fig. 2.29). Short rock bolts should be used near the base of the shotcrete lining if shotcrete-rock bond is low. If slaking materials are present in the invert a crushed stone base should be placed to protect
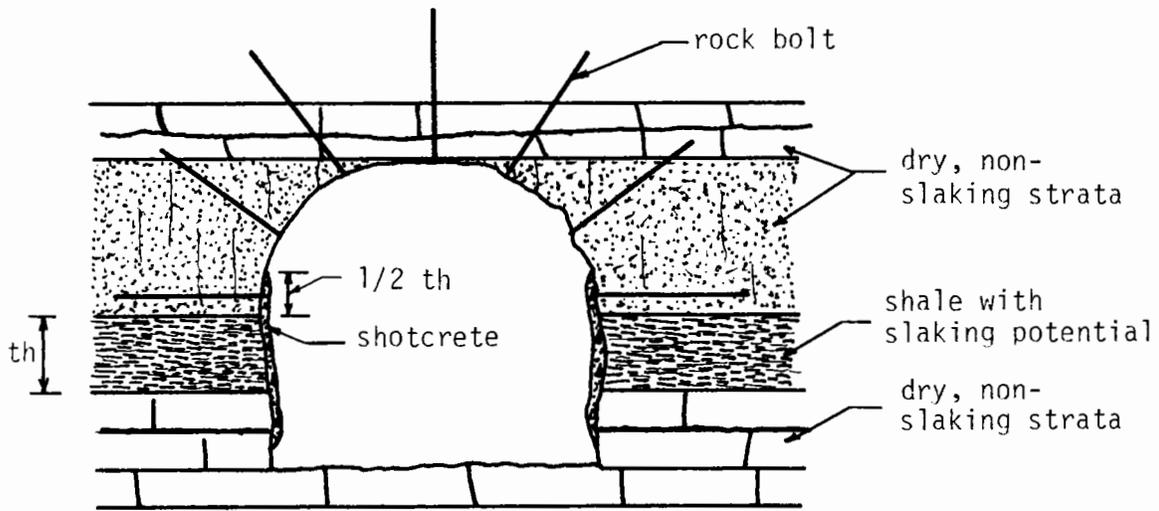
FIG. 2.27   USE OF SHOTCRETE TO PREVENT SLAKING CAUSED
BY STRESS RELIEF AND DRYING.
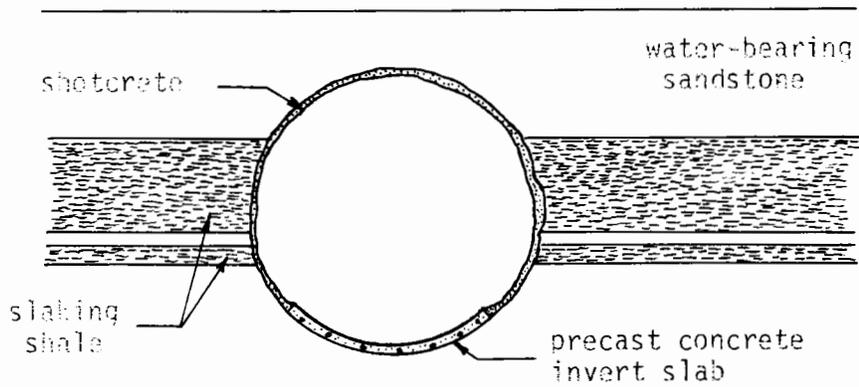
FIG. 2.28   USE OF SHOTCRETE TO CONTROL SLAKING WHERE
SHALES ARE IN CONTACT WITH WATER.
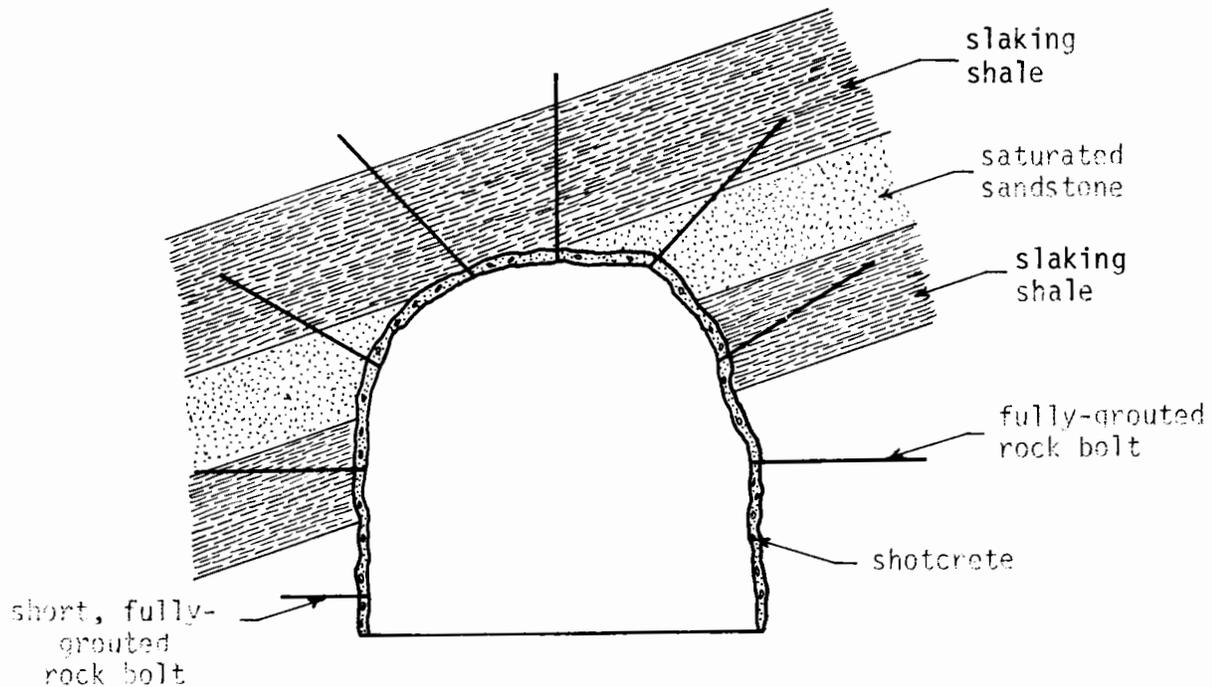
FIG. 2.29 USE OF SHOTCRETE FOR INITIAL CONTROL OF SLAKING GROUND.

the invert from construction traffic. Precast concrete invert segments may

serve the same purpose. In treating slaking ground, shotcrete must be

applied in the heading as soon as possible after excavation. The thickness

of the shotcrete should be adequate to prevent formation of through-going

shrinkage cracks and damage from tunneling operations. A minimum thickness

of 5 cm (2 in.) is usually adequate (Heuer, 1974); however, in some cases

layers as thin as 2.5 cm (1 in.) have proven helpful.

Many materials that slake are also susceptible to swelling. In

tunnels where slaking and mild swelling occur, the shotcrete lining should

be reinforced with wire mesh or chain link fence and rock bolts installed

to maintain the integrity of the lining and control spalling of the shot-

crete (Heuer, 1974).

2.1.5 Water

Water flows in tunnels occur along joints and fractures, and sometimes in pores of intact rock such as in sandstones. Water can cause slaking or softening of the rock, rock block movements, and delays in tunneling if high flows and pressures are encountered. Slaking and softening are characteristic of shales, whereas high flows and pressures are associated with fault zones and with permeable aquifers such as sandstone, limestone and basalt. If the rock is extensively crushed or poorly cemented, water can produce flowing ground. In tunnels where water jeopardizes the stability of the opening or makes working conditions intolerable, the ground must be treated by drainage, by grouting, or by sealing the surface of the opening.

Use of Shotcrete Alone as a Surface Seal

Shotcrete has been used alone to seal tunnel surfaces from water but has worked best when pressures and flows were low. Mason and Mason (1972) report successful use of shotcrete in controlling water flows up to 50 liters/min (13 gpm) under low pressures (< 3 m [10 ft] head). Rabcewicz (1964-1965) mentions that shotcrete was used to seal a 20-mm (3/4-in.) water jet. In the same article he reports that shotcrete was the only successful means of stopping heavy water inflows from a crushed and altered gneiss.

To stop water, the shotcrete must contain a relatively high percentage of accelerator (6-15% by weight of cement) and should be placed with a low water/cement ratio. The required adjustments reduce the set time so that the shotcrete will quickly bond to the rock and will be less susceptible to erosion and sloughing (Fig. 2.30). Shooting with a low water content will allow the shotcrete to absorb some of the water from the rock. If
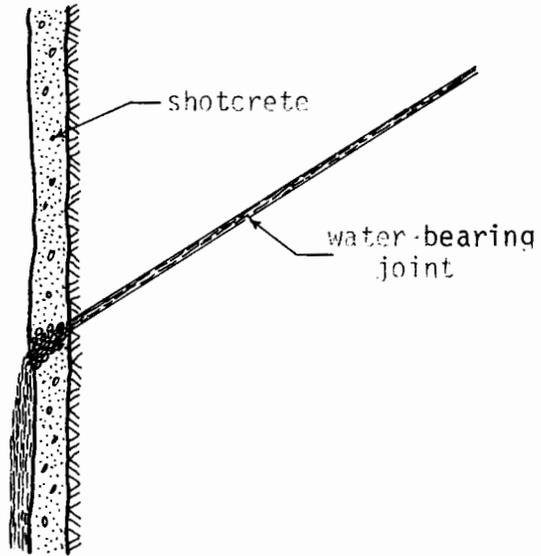
a. erosion
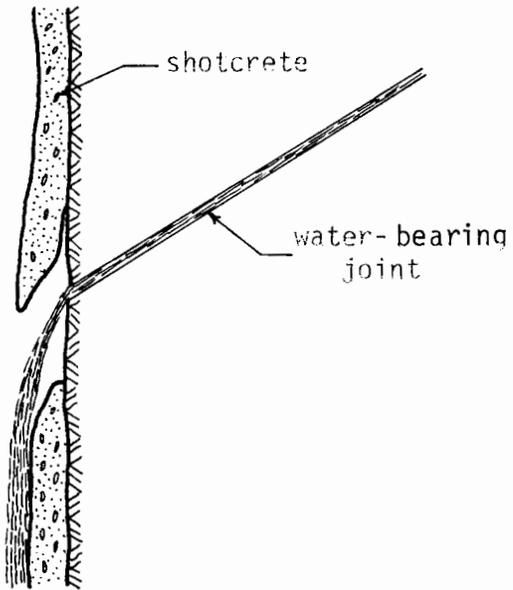
b. sloughing

FIG. 2.30   EROSION AND SLOUGHING OF SHOTCRETE CAUSED BY WATER.

the dry-mix process is used, the materials can be gunned without adding water at the nozzle, and the water on the surface of the rock will serve to hydrate the cement. Large amounts of accelerator are needed (up to 15% by weight of cement) if the wet-mix process is used to stop water flow. Laboratory studies of tensile bond strength indicate that the use of accelerators reduces the long-term bond strength of the shotcrete (Deere, et al., 1969 and Sandell, 1968). This reduction in bond strength may later cause spalling of the hardened shotcrete under water pressure. Thus the least amount of accelerator compatible with sealing requirements should be used.

Sealing the tunnel surface with shotcrete may cause fallout of large, marginally stable wedges because the sealing causes water pressures to increase behind the rock blocks (Fig. 2.31). The water pressures reduce the normal forces acting on the sides of the block, tending to hold it in place, and can also drive the wedge toward the opening. Block fallouts triggered by water pressures are most likely to take place in the heading shortly after gunning when the shotcrete has not had sufficient time to gain strength and resist the block movement. These fallouts can be prevented by pre-bolting and draining ahead of the face. Scaling in the heading will help reduce danger from fallouts but may not be adequate to dislodge large rock wedges. Surface drains are sometimes placed in the initial layer of shotcrete to prevent buildup of water pressures; however, installation of these drains in an unsupported heading is a dangerous and time consuming operation.

Shotcrete is most effective in sealing the tunnel surface when it is applied around the full perimeter of the opening, or is placed in the arch and walls and founded on an invert slab. Sealing of the full perimeter is
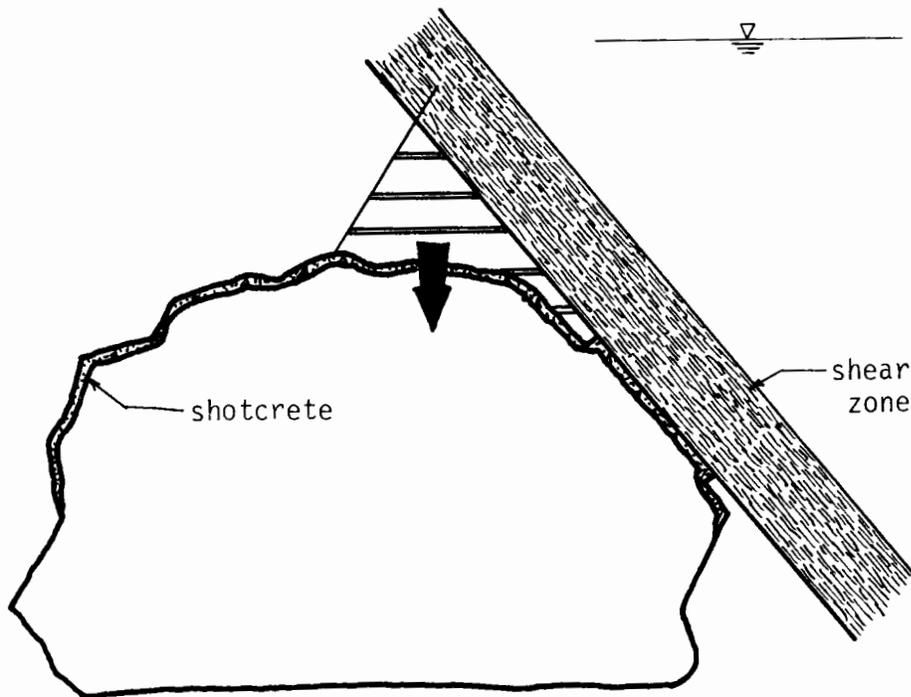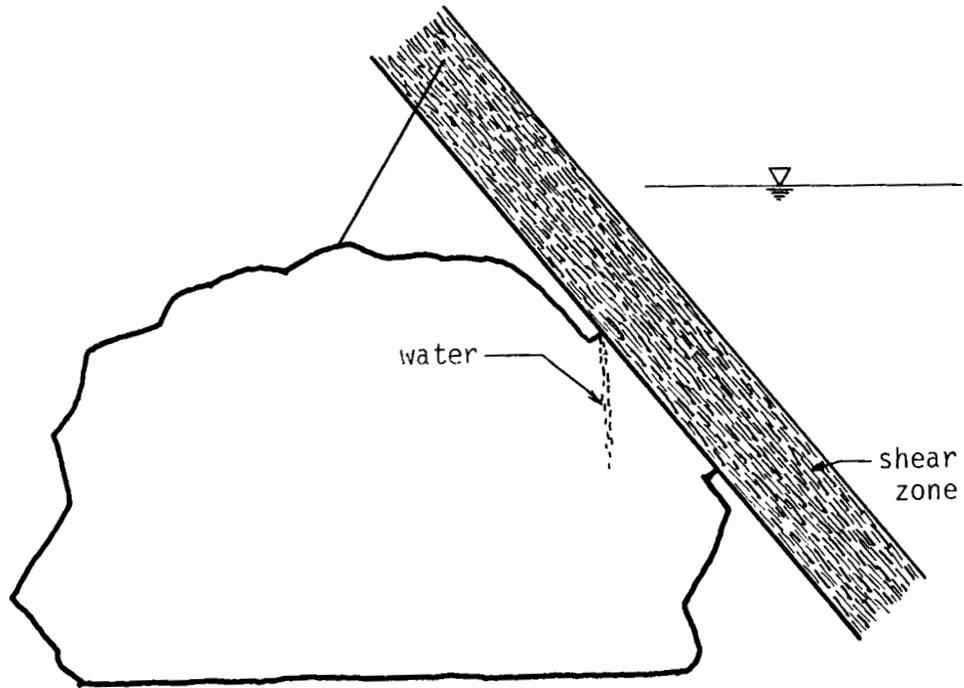
FIG. 2.31   ROCK BLOCK FALLOUT TRIGGERED BY SEALING OF THE TUNNEL SURFACE
WITH SHOTCRETE AND SUBSEQUENT BUILDUP OF WATER PRESSURE.

necessary when shotcrete is used to prevent water-softening of the rock.
If drainage is not provided, the lining must have sufficient thickness to
carry the full external hydrostatic pressure.

Treatment of Flowing Ground with Shotcrete

As a general rule, shotcrete is not the most effective means for
controlling flowing ground because of the difficulty of obtaining good
shotcrete bond. Moreover, the strength of the shotcrete immediately after
shooting may not be adequate to overcome the water pressure, and shotcrete
is likely to be brittle and susceptible to cracking as a result of rock loads
and construction activity. Narrow cracks even on the order of 2 mm (0.1 in.)
may be large enough to allow piping and lead to failure of the shotcrete and
subsequent filling of the tunnel with water and debris. On the other hand,
if flowing ground is encountered unexpectedly, shotcrete may be valuable in
stopping the flowing condition. In a sidewall of one of the Mexico City
Drainage Tunnels, shotcrete was successfully used to stop the flowing of a
thin seam (approximately 60 cm [24 in.] wide) of saturated, uncemented sand
(Mason and Mason, 1972). The shotcrete was sprayed in the arch and walls
and had a thickness of 10 cm (4 in.) except in the area of the flow, where
it was thicker. Once the flowing ground is brought under control other
types of ground treatment such as dewatering or grouting should be used to
prevent recurrence of the flowing condition.

Use of Drains in Placing Shotcrete in Water-Bearing Ground

Drains are used to improve shotcrete bond to wet rock and to reduce
water pressures acting on rock or behind the shotcrete support. When water
issues from an open joint or fissure, a pipe can be driven into the opening
to channel the water flow through the shotcrete lining (Fig. 2.32).
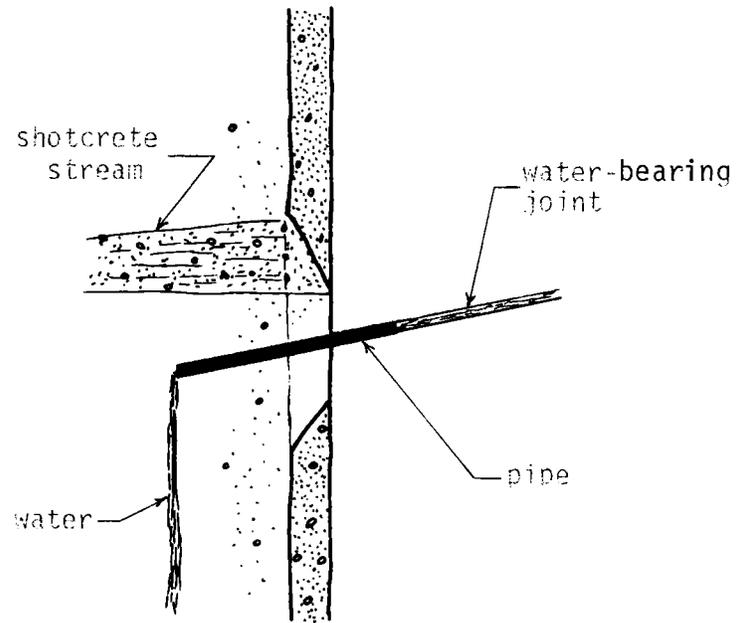
CROSS SECTION
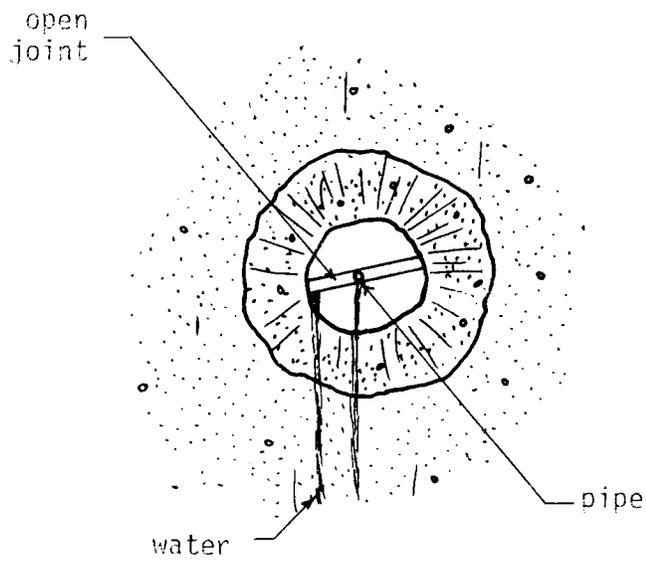
PROFILE

FIG. 2.32   SEALING WATER FLOW FROM OPEN JOINT USING A SURFACE
DRAIN AND SHOTCRETE (AFTER RYAN, 1973).

Shotcrete is built up around the pipe starting in sound rock near the edge of the flow. The shotcrete should be given time to gain enough strength to resist water pressures if the pipe is to be plugged.

Other types of drains are placed on the shotcrete surface before application of the final layers and are used for drainage of local water flows within the lining. These drains consist of rockwool or perforated plastic tubes protected by plastic foil or corrugated sheet metal (Fig. 2.33). Water in the rockwool drain is conveyed to the invert in a long plastic tube. Both the foil or sheet metal protection and the tube are encased in shotcrete except for the end of the tube which emerges at the invert. If a large number of drains are placed in a small section of the tunnel, they can reduce the structural integrity of the shotcrete lining. This practice should be avoided if possible.

Drill hole drains are used for both temporary and permanent drainage of the rock (Fig. 2.34). Such a drain consists of a drill hole containing a plastic pipe or tubing. This tube is covered with shotcrete except for the open end. When drill holes are used for permanent drains, the head of the plastic pipe must be removable so that the drain can be cleaned and maintained. Drill hole drains are the most reliable and permanent means of drainage and should be installed in areas of the tunnel having extensive seepage rather than surface drains.

Even with drains shotcrete is not effective in sealing water under high flows and pressures. When these conditions are encountered the rock must be allowed to drain or must be grouted to reduce both the flows and pressures. Shotcrete can then be applied to control the remaining water and to stabilize the ground. The amount of grouting or drainage needed in

8 mm (1/4 in.) φ
rebar — 2 perforated 40 mm (1-1/2 in.)
plastic tubes

3 mm (1/8 in.) φ
rebar 50 cm cc
(20 in. cc) — min. 8 cm (3 in.)
shotcrete

double plastic foil

galvanized wire net

7 cm (2-1/2 in.) rock wool

8 mm (1/4 in.) φ
rebar

3 mm (1/8 in.) φ
rebar — min. 8 cm (3 in.)
shotcrete

double plastic foil
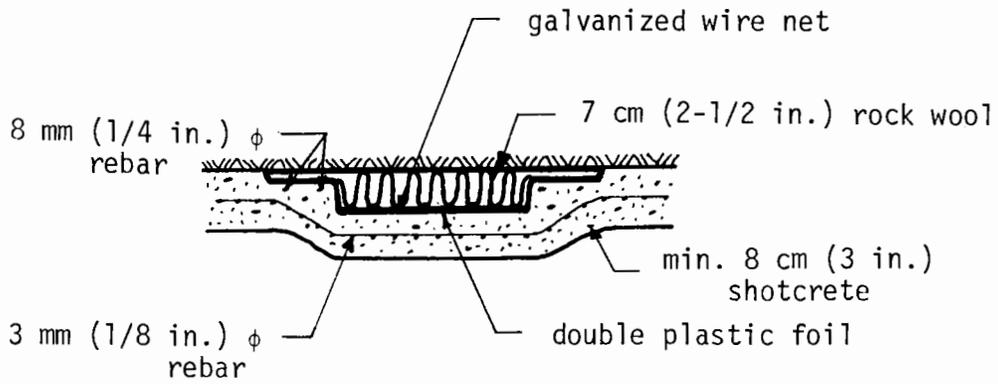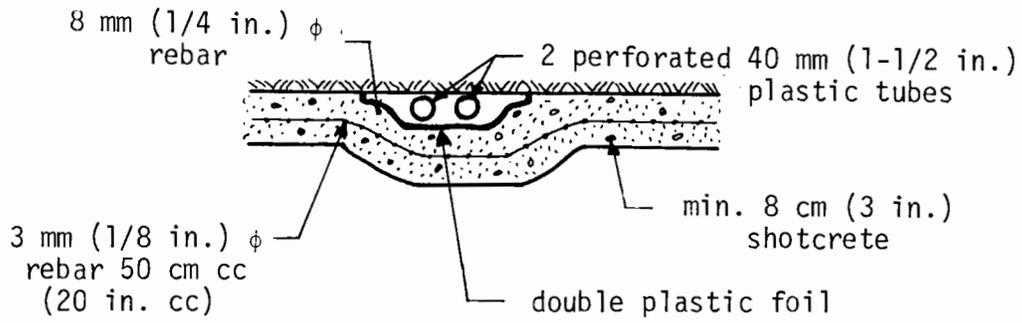
FIG. 2.33   LINER DRAINS USED FOR SHOTCRETING IN WET GROUND
(SANDELL, 1968 AND DEERE, ET AL., 1969)

perforated
plastic
pipe

water-bearing
joint

shotcrete

a. temporary drain

perforated
pipe

threaded
plug for
cleanout

drill
hole

shotcrete

plastic tube

b. permanent drain
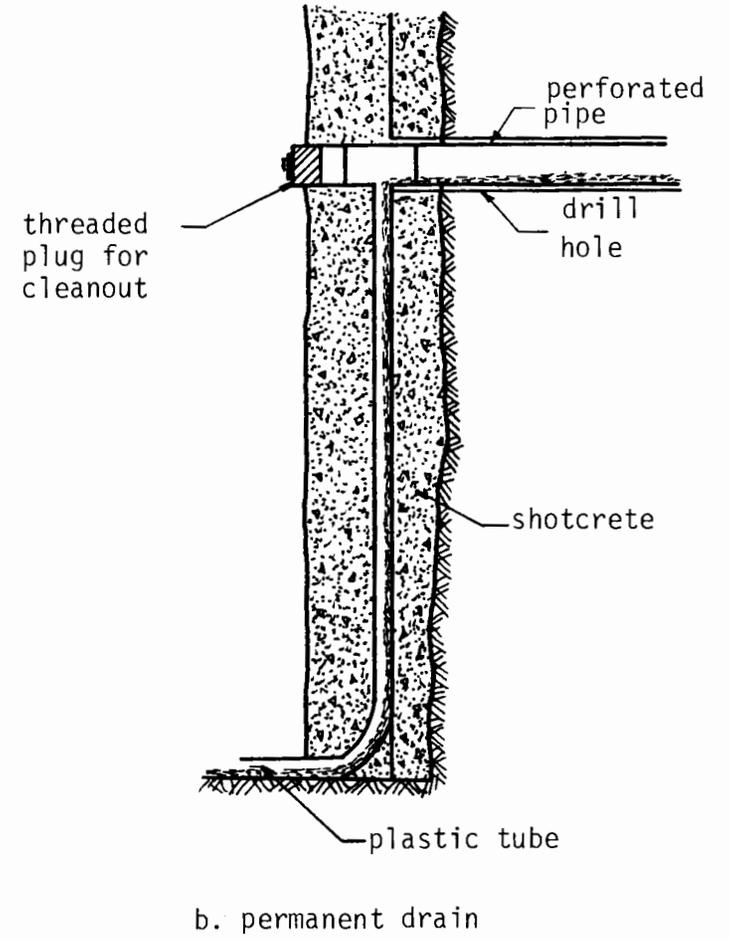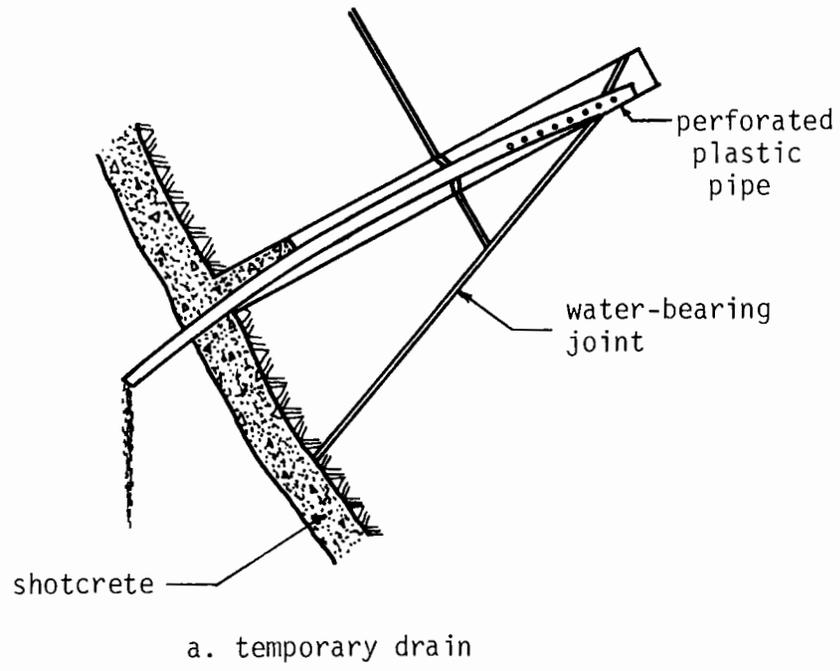
FIG. 2.34   DRILL HOLE DRAINS.

order to permit sealing of the surface with shotcrete must be determined during construction. Drains are installed before and after shotcrete application to prevent a buildup of water pressure which could cause the lining to fail.

2.2 Shotcrete for Supplementary or Remedial Support

Shotcrete is of particular value as a supplementary or remedial support material since it can readily be placed in areas of a tunnel requiring such support, without extensive preparation such as placing formwork required for concrete. It is used as supplementary support when it is applied to rock which must be excavated later or when it is placed between the initial support and the final lining. In this latter capacity, it not only serves as supplementary support of the completed excavation but also fills in overbreak and builds up the final tunnel lining. As remedial support shotcrete is applied to stabilize the opening where a support problem develops some time following excavation and placement of initial support.

2.2.1 Supplementary Support

Face Support

Shotcrete may be used to control rock movements in the tunnel face, and in the sidewalls and arches of intermediate drifts which will be incorporated into larger excavations. It has been applied on the faces of several tunnels in both loosening and overstressed ground (Cording, 1974 and Nussbaum, 1973). Face support problems involving loosening are most severe when joints and shears are oriented subperpendicular to the longitudinal axis of the opening. Shotcrete can be used to support local rock blocks which cannot be removed by scaling, provided a good bond can

be obtained. The same limitations for use of shotcrete as initial support in loosening ground apply. Cording (1974) describes the use of shotcrete to prevent fallout of rock blocks from the face of a drift which contained a previously driven pilot tunnel in its crown (Fig. 2.35). Rock blocks around the pilot tunnel were loose and exposed on two sides thus posing a serious hazard to workmen in the heading. A thin layer of shotcrete was applied on the face around the pilot tunnel to hold the blocks in place. In many locations the shotcrete actually penetrated between open joint surfaces and thus acted to cement the blocks together as well as to transfer the rock load to stable portions of the face. In squeezing ground, shot-crete has also been used to stabilize the face. Rock bolts should be installed along with shotcrete in squeezing ground (Fig. 2.36), as suggested by Deere, Merritt and Cording (1974).

In openings where advance is temporarily stopped, shotcrete has been used to stabilize the face and to prevent loosening ahead of the opening. If the height of the face is greater than 3 m (10 ft) and the rock is blocky and seamy, rock bolts should be used in addition to the shotcrete (Fig. 2.37). The face shown in Fig. 2.37 was approximately 13 m (44 ft) high and 10 m (33 ft) wide and contained at least two foliation shear zones. It was supported with about 15-20 cm (6-8 in.) of shotcrete and 4-m (12-ft) long, resin-encapsulated rock bolts. Both the shotcrete and rock bolts worked well to hold the face even when it was intersected by three other drifts in addition to the pilot tunnel (Fig. 2.38).

Supplementary Support of Arches and Sidewalls of Intermediate Drifts

Shotcrete has also served well as supplementary support of the side walls and arches of intermediate drifts which were later incorporated into

shear zone

pilot
tunnel

shotcrete applied
to hold loosened
rock blocks

face of
excavation

2m
(6 ft)
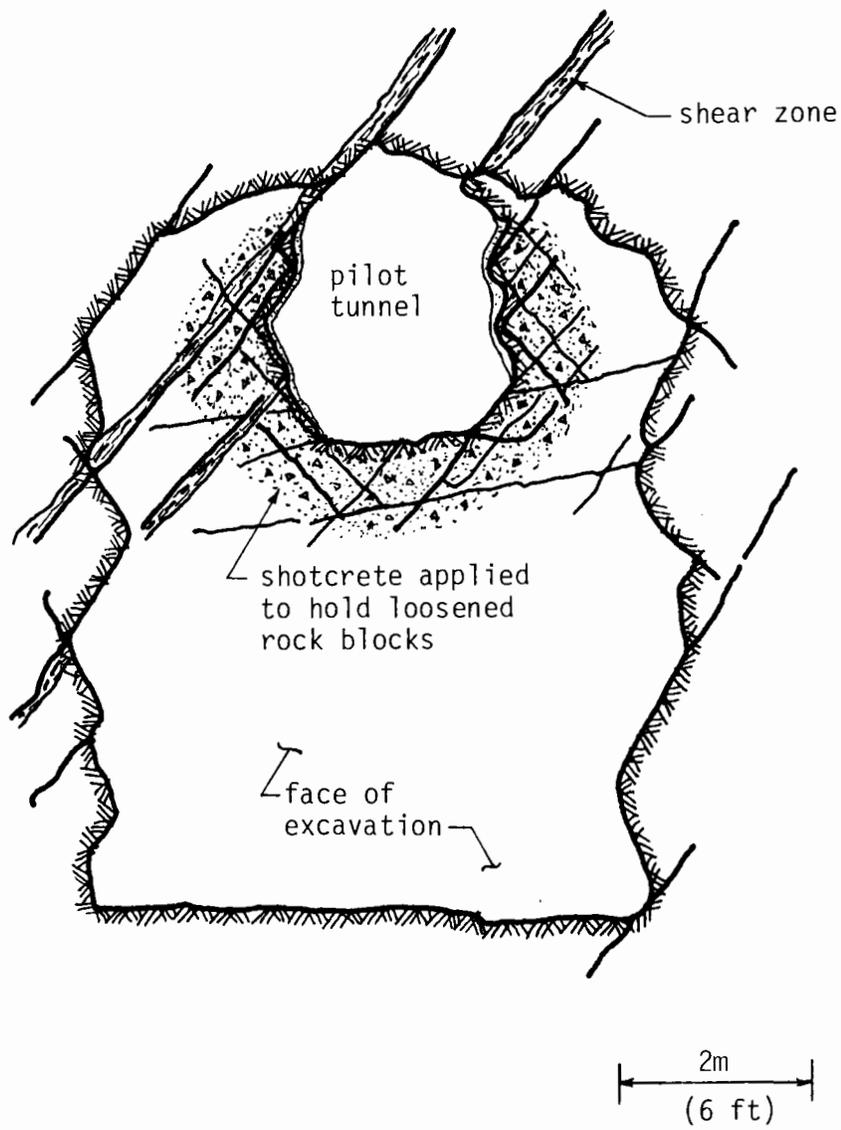
FIG. 2.35 SHOTCRETE SUPPORT OF TUNNEL FACE (CORDING, 1974).

shotcrete

fault zone

precast concrete slab

rock bolt

shotcrete

rock bolt

PROFILE

CROSS SECTION FACE
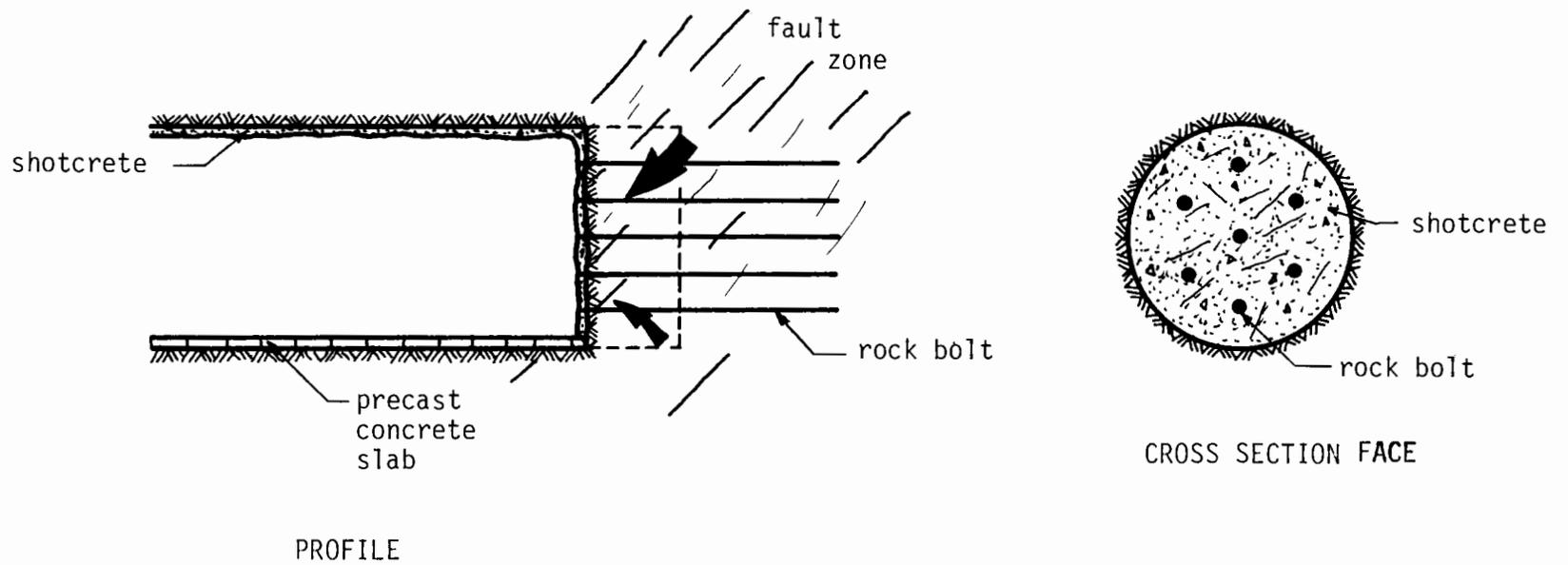
FIG. 2.36   USE OF ROCK BOLTS AND SHOTCRETE TO STABILIZE A TUNNEL
FACE IN SQUEEZING GROUND   (DEERE, MERRITT AND CORDING, 1974).

pilot
tunnel

CROSS SECTION

steel strap

rock bolt

shotcrete

shear zone

3 m
(10 ft)

steel
rib

shotcrete

shear zone

PROFILE
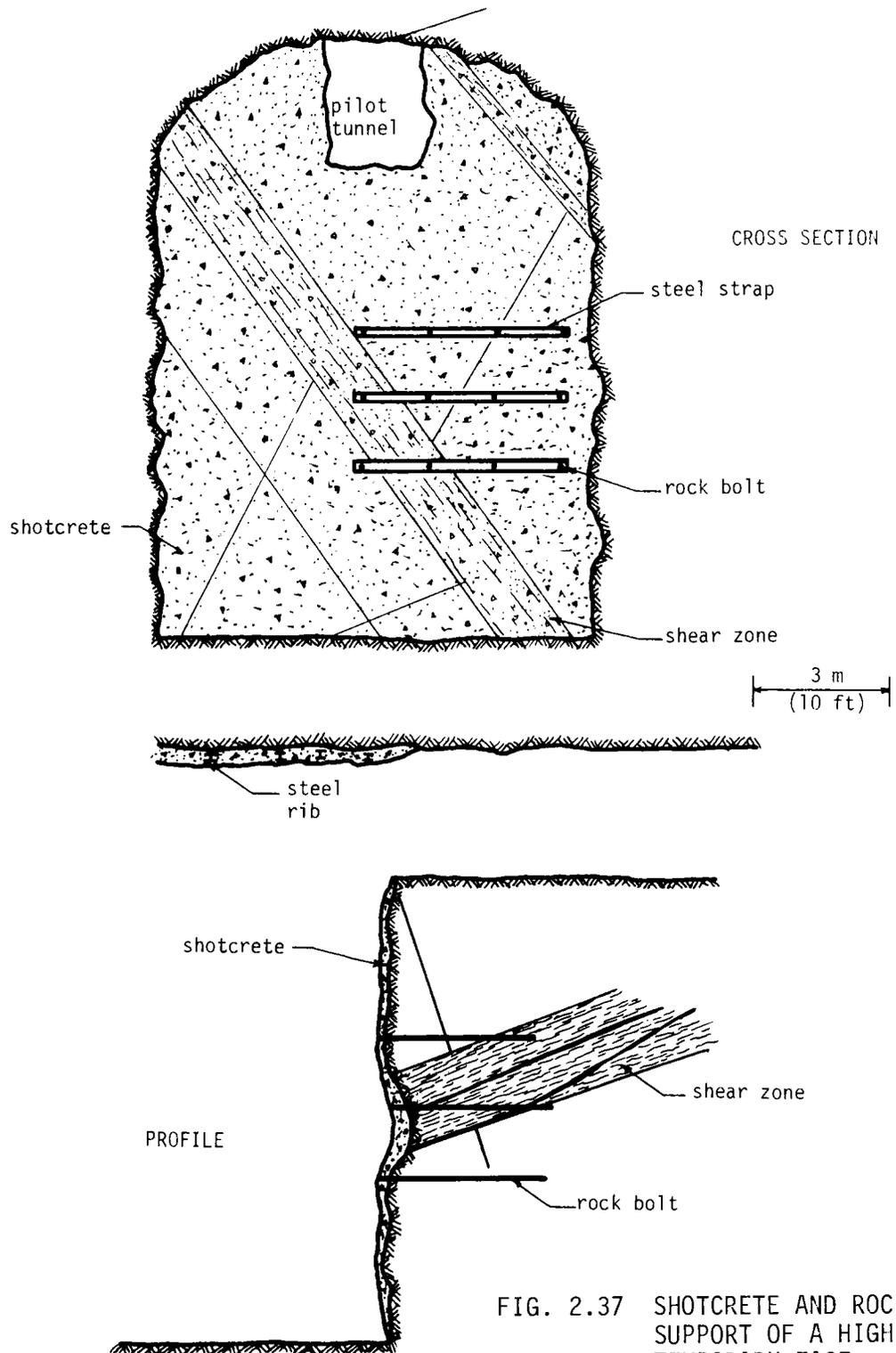
rock bolt

FIG. 2.37   SHOTCRETE AND ROCK BOLT
SUPPORT OF A HIGH
TEMPORARY FACE.

CROSS SECTION

drift

steel rib

drift

foliation
shear zone

shotcrete

rock bolt

crack, 10-20 mm
(1/4-3/4 in.) wide

drift

shotcrete

PROFILE

shotcrete

crack

foliation
shear zone

rock bolt

steel rib

FIG. 2.38 SHOTCRETE AND ROCK BOLT SUPPORT OF A HIGH VERTICAL
FACE INTERSECTED BY THREE DRIFTS.

larger openings (Fig. 2.39). The same considerations given in the previous section on initial ground control apply when shotcrete is used for such supplementary support. For example, the high (8 m [26 ft]), vertical side walls of the center drift shown in Fig. 2.39 were supported initially with a single layer of shotcrete. The shotcrete experienced cracking and spalling even where it was 20 cm (8 in.) thick (Fig. 2.40). These cracks resulted from rock block movements along the gouge-coated surfaces and poor shotcrete-rock bond. The rock movements were finally stopped by installing rock bolts on a regular pattern in the walls. Closing of the invert with shotcrete would not have improved the stability of the walls since most of the block movement was occurring on the walls between the invert and the crown. Shotcrete performed adequately as sole support of the 3-m (10-ft) wide and 3-m (10-ft) high wall plate drifts (Fig. 2.39). The shotcrete in the wall plate drifts showed little cracking and spalling, even when the pillars were excavated a few feet from the wall (Cording, 1974).

Supplementary Support of Thin Pillars

Thin pillars (height/width $>$ 2) are special cases of sidewall support problems (Fig. 2.41). Shotcrete can be used to maintain the integrity of the pillar, but in cases of high sidewalls or poor bond, it should not be used alone. The thin pillar shown in Fig. 2.41 was initially supported with resin-encapsulated rock bolts which in some places were spaced as close as 30 cm (1 ft) apart. The pillar was sheared and highly fractured and showed evidence of deterioration caused by overstressing of the pillar in compression between the crown and the invert, by gravity movements, and by blasting vibrations. Shotcrete was applied to the surface of the
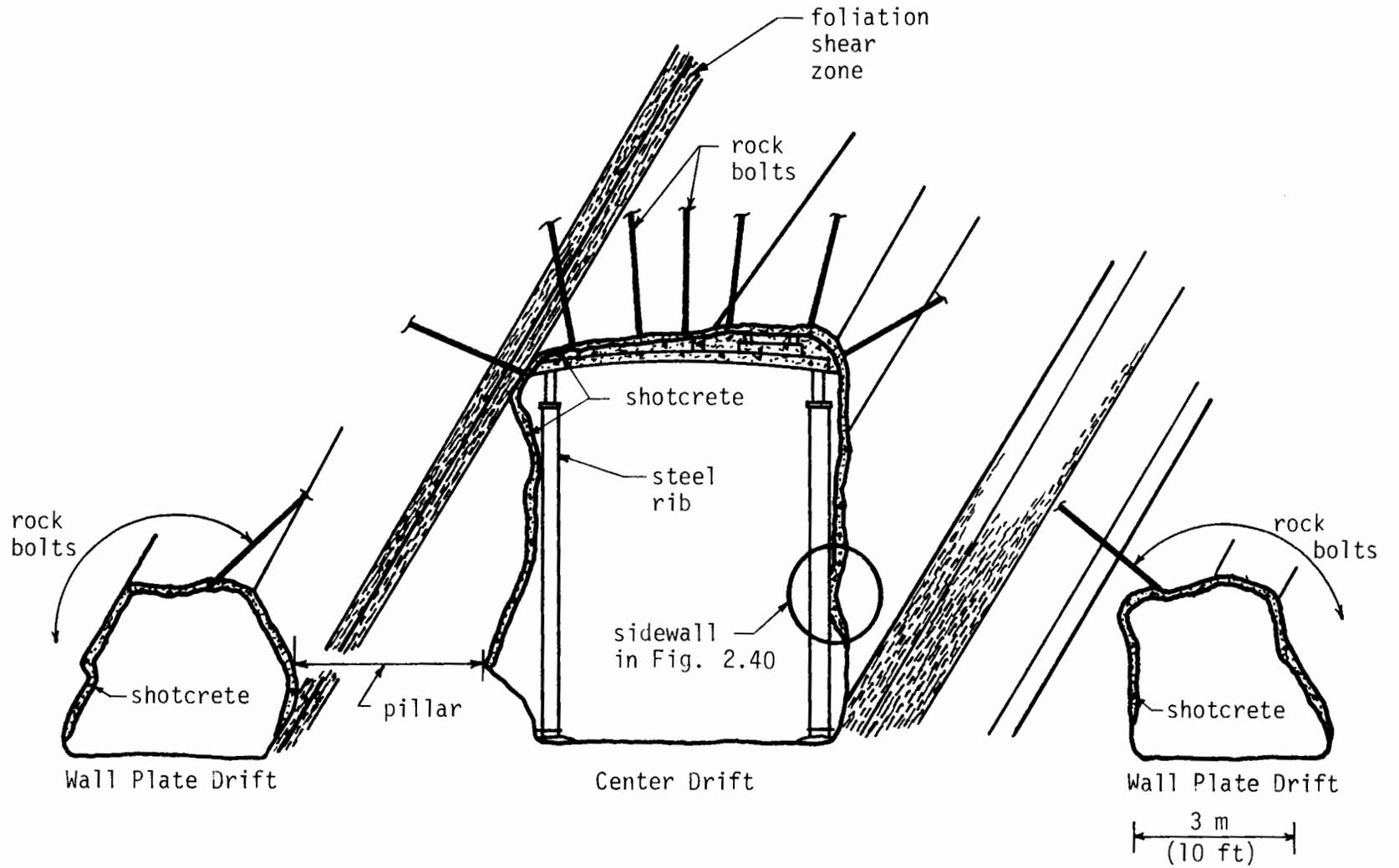
FIG. 2.39 SHOTCRETE SUPPORT IN MULTIPLE OPENINGS.

gouge

crack

CROSS SECTION

crack

$\begin{array}{c} 3 \text{ m} \\ (10 \text{ ft}) \end{array}$

steel
rib

PROFILE
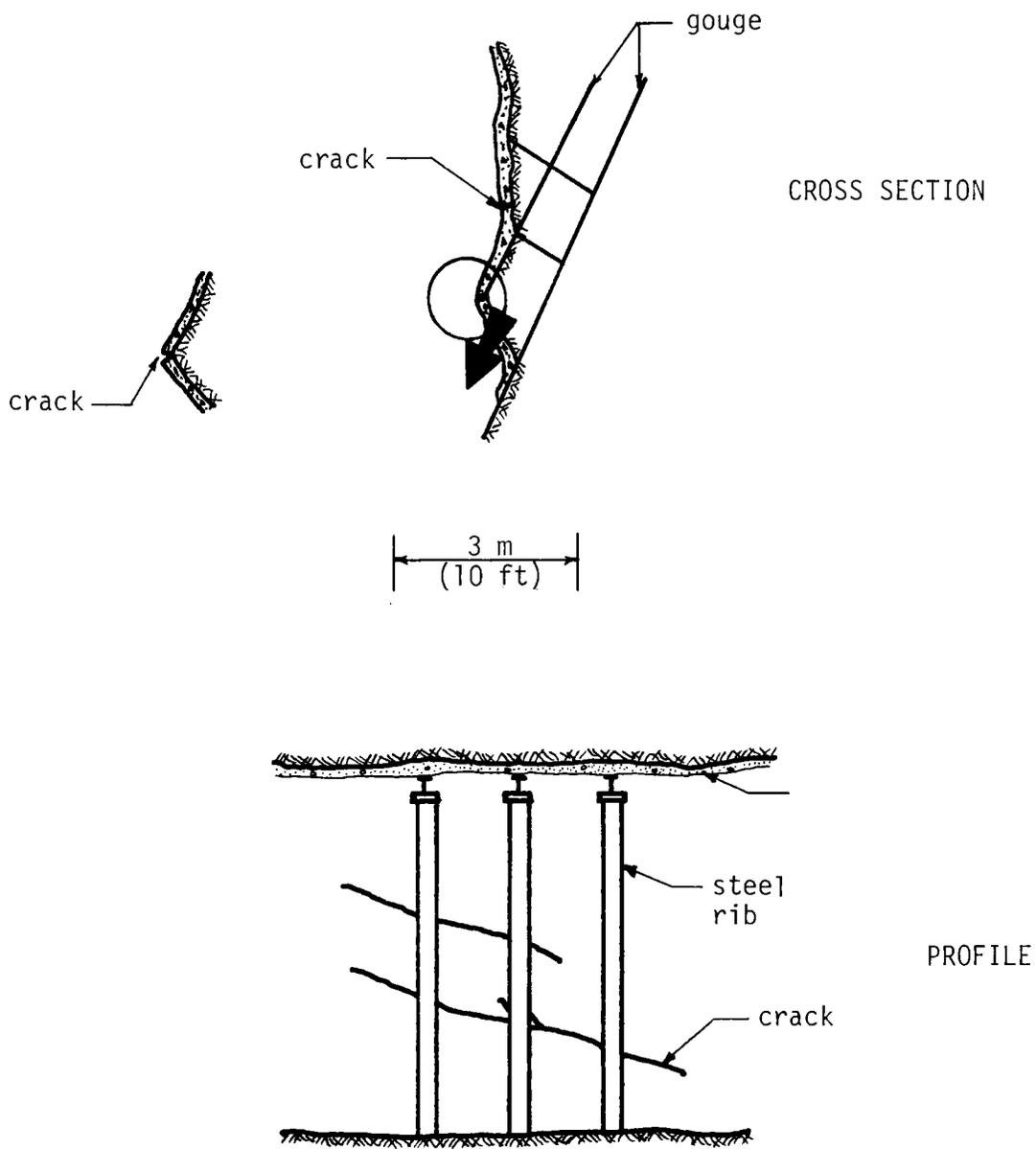
crack

FIG. 2.40 CRACKING OF SHOTCRETE ON HIGH VERTICAL SIDEWALLS.
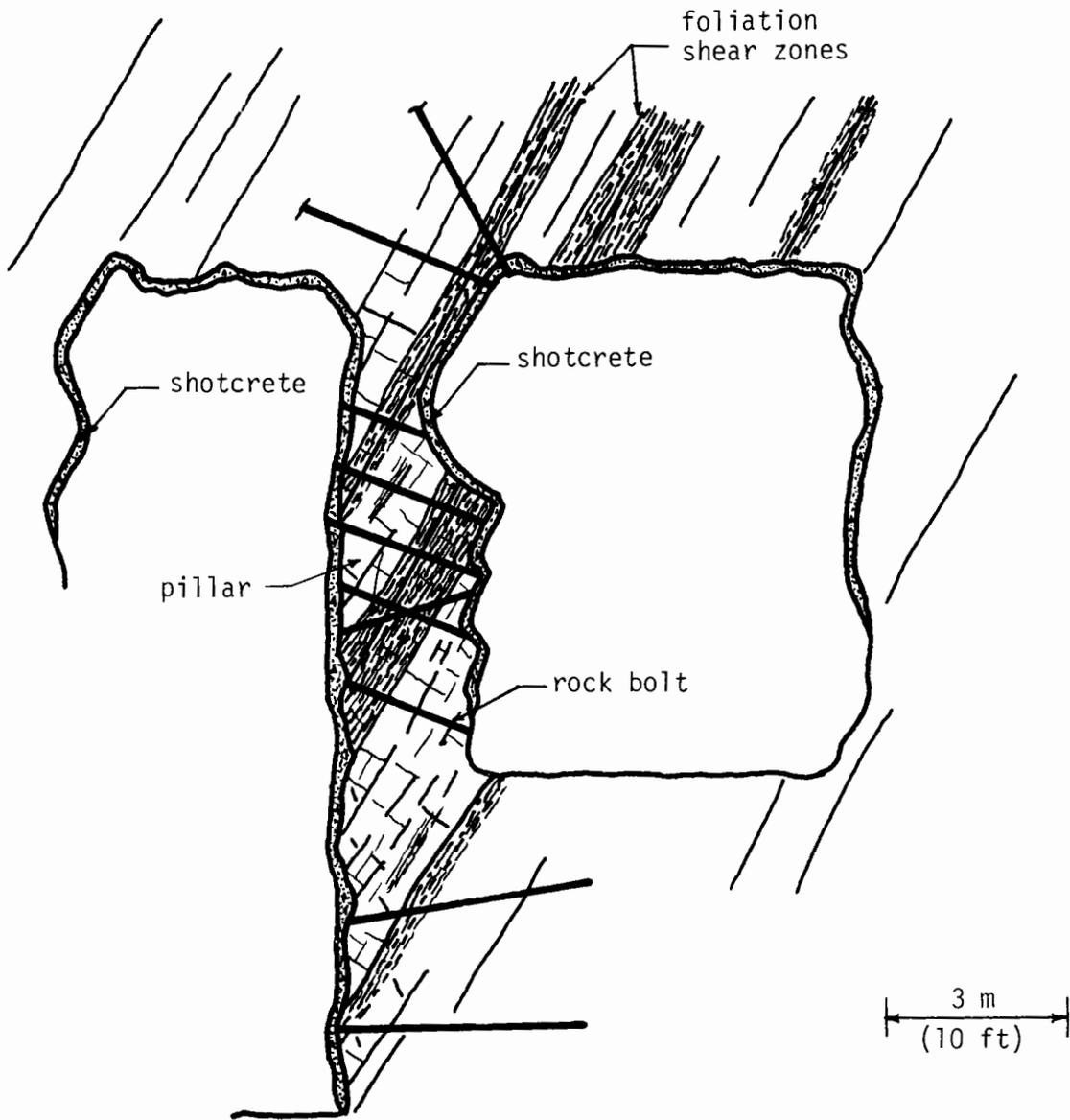
FIG. 2.41   USE OF SHOTCRETE AND ROCK BOLTS FOR SUPPORTING
THIN ROCK PILLARS (CORDING, 1974).

pillar to support the loosened rock between the bolts (Fig. 2.41). The
shotcrete stopped rock movement which the bolts alone could not prevent.

Supplementary Support Placed Behind the Heading

Finally, shotcrete is applied as supplementary support in full-sized
openings approximately 15-60 m (50-200 ft) behind the tunnel face. These
applications not only serve as support, but also smooth out the surface
of overbreak to facilitate placement of the final lining.

2.2.2 Remedial Support

Nearly all collapses of underground rock openings are at least partly
if not entirely caused by loosening behavior. Shotcrete has an excellent
performance record not only for preventing such collapses but also for
stabilizing the ground after a failure has occurred. Before collapse,
shotcrete can be used to block or stiffen existing supports or to place a
structurally continuous lining up to the face. The shotcrete can be sprayed
from secured areas even if the nozzle is hand-held, thus reducing danger
to workmen. The rapid gain in strength and stiffness of the shotcrete
allows it to minimize additional displacement and development of loosening
loads even shortly after the shotcrete is applied. In cases where complete
collapse has occurred, the shotcrete can serve to prevent additional
loosening and to protect workmen installing rock bolts and/or steel ribs
and cribbing in the collapse area. The rock conditions and nature of the
impending or actual failure must be understood in order to assess whether
or not shotcrete can be of benefit as remedial support and the manner in
which it must be placed. A few of the many cases in which shotcrete has
been used for remedial support are described in the following sections.

In one example a horseshoe-shaped tunnel was driven in blocky ground and supported by a thin layer of shotcrete (5 cm [2 in.]) and steel ribs (Fig. 2.42). The shotcrete was applied in the heading within two hours after blasting, and the steel ribs were installed at the face before drilling out the next round. The rock wedge outlined in Fig. 2.42 failed the thin shotcrete layer as a result of inadequate shotcrete-rock bond, and the wedge settled on to the lagging and steel ribs. Blocking above the springline was loose or absent, and the ribs deflected downward approximately 5-15 cm (2-6 in). Rock movement started at the face and progressed nearly 38 m (125 ft) back down the tunnel. After the initial large movements, the contractor placed posts at the quarter arch to prevent failure of the ribs (Fig. 2.43). Shotcrete was applied to the haunch and sidewalls to develop contact between the steel ribs and rock and prevent further outward deflection in the lower portion of the arch. Shotcrete was placed between the flanges to stiffen the ribs and improve their moment capacity. Shotcrete application was started in a stable section of the tunnel and advanced toward the face. Rock bolts were installed to prevent further loosening and to provide time for the shotcrete to gain strength. This remedial work was completed before face advance was resumed. The lining showed no measurable movement after the posts were removed and tunneling was resumed.

Mason and Mason (1972) describe the use of shotcrete in stabilizing rock and soil in a failed portion of the Emisor Tunnel in Mexico City. A roof collapse was caused by lack of initial support of swelling and overstressed volcanic tuffs present in the tunnel. After the failure occurred, the rock continued to ravel and spall. Shotcrete was applied to

2-76
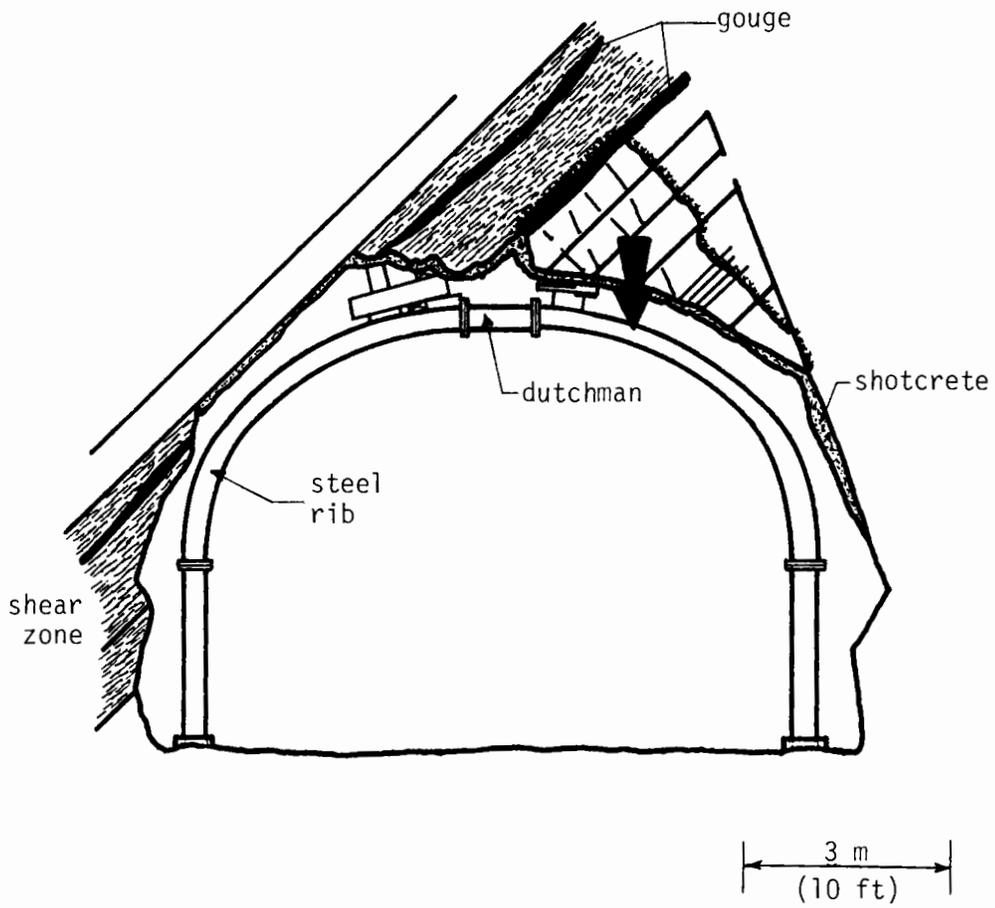
FIG. 2.42   ROCK BLOCK MOVEMENT CAUSING DEFLECTION OF TUNNEL CROWN.
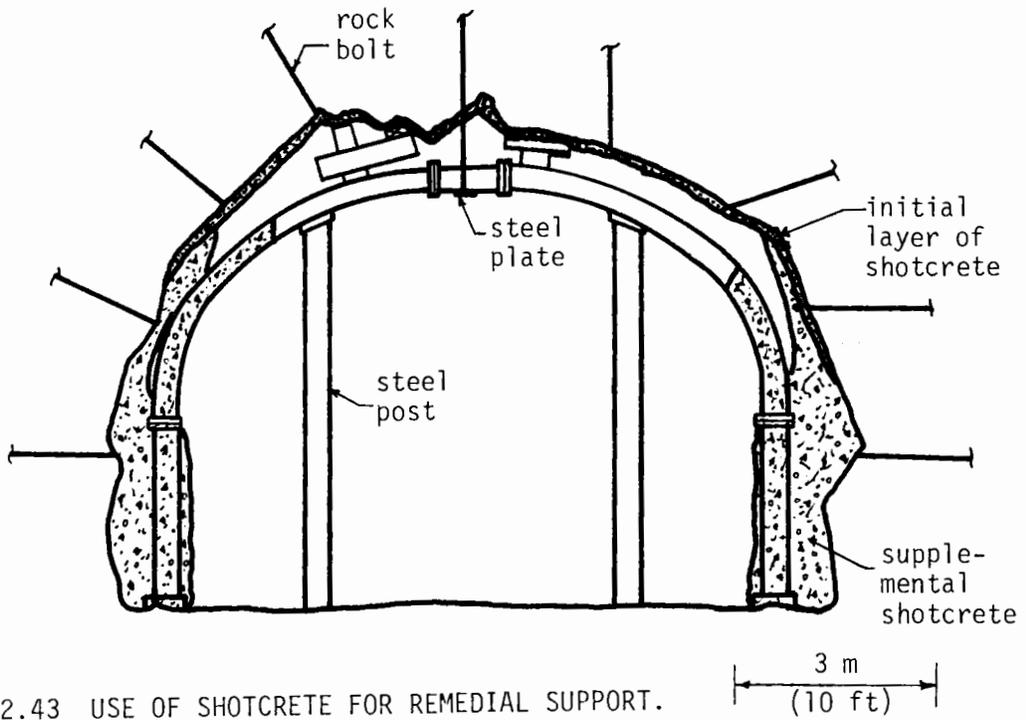
FIG. 2.43   USE OF SHOTCRETE FOR REMEDIAL SUPPORT.

the rock surface in the collapse area using a nozzle tied securely to a boom. The thin shotcrete layer prevented additional loosening and provided protection for the workmen (Fig. 2.44). Additional layers of shotcrete, some containing mesh reinforcement, were placed to increase the stability. Other case histories including Balboa Tunnel (Sutcliffe and McClure, 1969) have been described in which shotcrete was used to treat very poor tunnel ground after a collapse had occurred.

In another case shotcrete failed as a remedial support because of an incorrect interpretation of ground behavior and subsequent inadequate placement of the shotcrete. This case described by Rabcewicz (1964-1965) involved a horseshoe tunnel driven in weathered rock exhibiting squeezing behavior. The opening was advanced from the portal using a top heading and bench method of excavation. The top heading was supported with a thick (45-60 cm [18-24 in.]) reinforced shotcrete lining. After the heading was advanced a short distance from the portal, the bench excavation was started by first driving a center trench and then slabbing the walls to complete the opening. A short time after slabbing was started, shotcrete was placed on the side walls to arrest the soil and rock movement; however, the invert was not closed. The walls and lower arch squeezed into the opening leading to collapse of the arch (Fig. 2.45). The failed section was remined and supported with shotcrete in the walls and arch and a cast-in-place concrete slab in the invert. Fully-grouted bolts were installed in the arch for supplementary support until the sidewalls and invert were excavated and the shotcrete and concrete cured. This method was used successfully in driving the remainder of the tunnel in squeezing ground.

15 cm (6 in.)
of shotcrete

estimated
boundary
of fallout

rock bolt

3 m
(10 ft)
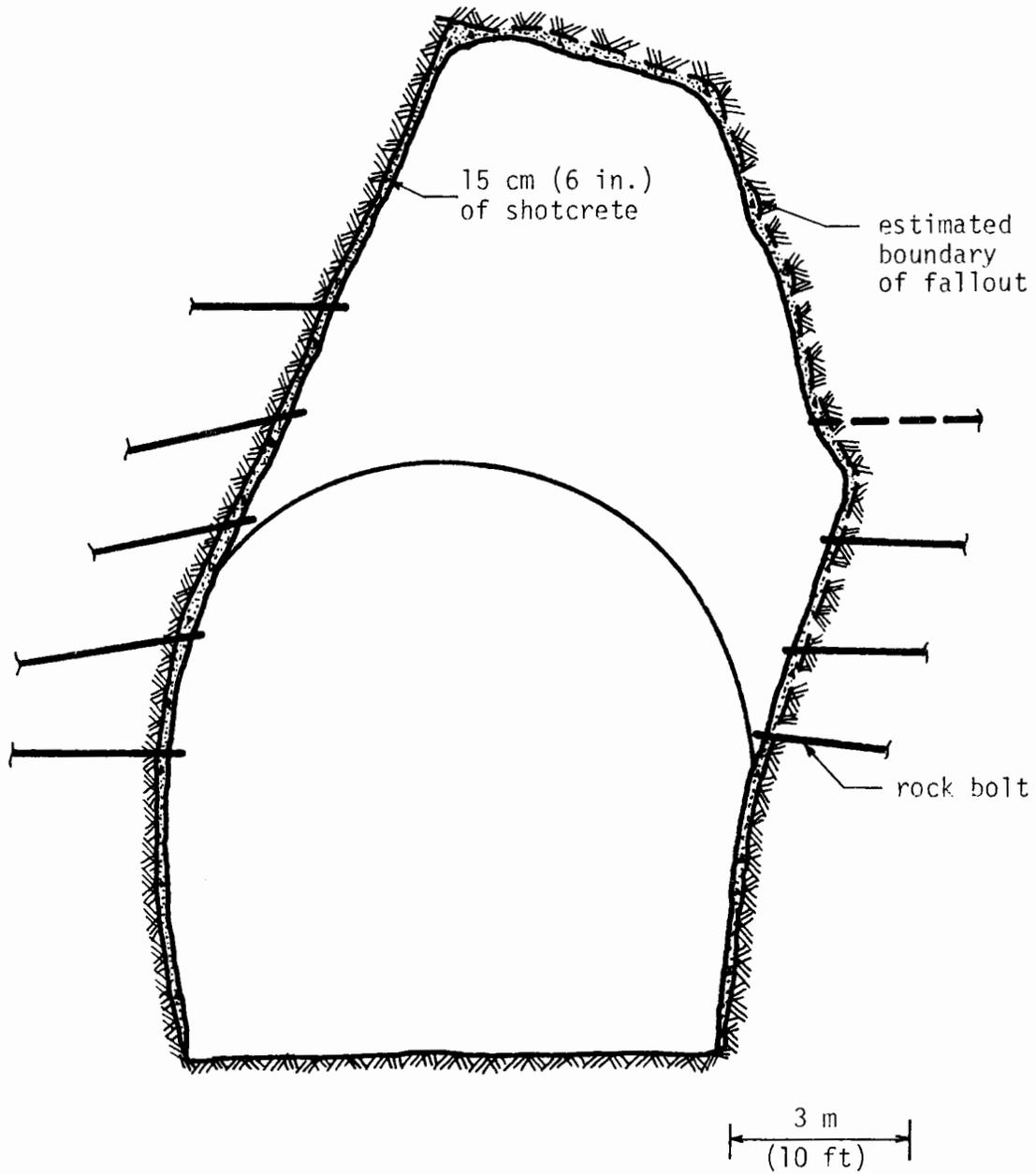
FIG. 2.44 USE OF SHOTCRETE AS REMEDIAL SUPPORT AFTER A ROOF COLLAPSE
(AFTER MASON AND MASON, 1972).

2-79
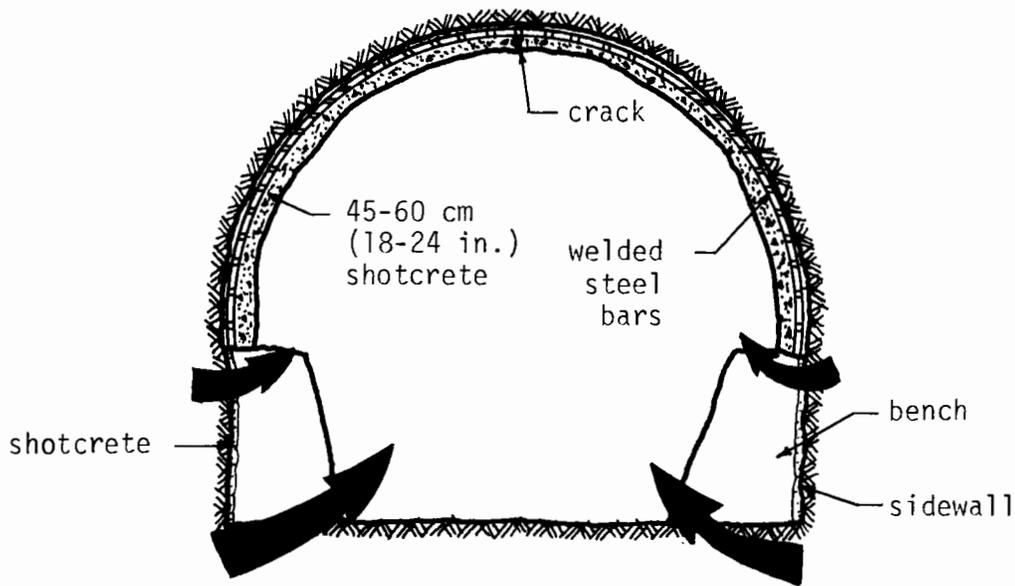
FIG. 2.45   FAILURE OF A TUNNEL IN SQUEEZING GROUND CAUSED BY INADEQUATE
SUPPORT OF THE SIDEWALLS AND INVERT (AFTER RABCEWICZ, 1964-1965).

The thickness of shotcrete and time of placement for remedial support
must be determined in the field. In general, movements are reduced by
developing a structurally continuous lining so that the shotcrete acts in
compression. In squeezing or swelling ground, the invert must be closed.
Measurements and observation of lining and rock movement must be made to
assess the adequacy of the remedial support. Additional shotcrete or other
supports must be placed in areas of the tunnel showing continuing distress.

2.3   Shotcrete for Permanent Support

2.3.1   Design of Permanent Shotcrete Linings

When shotcrete is used as a permanent lining, it may be designed by

the same methods used for concrete (Cording, 1974). In such cases the shotcrete must have sufficient thickness to be a structurally continuous arch (Fig. 2.20). In most tunnels excavated by drill and blast techniques at least 10-15 cm (4-6 in.) of shotcrete will be required to fill in the overbreak irregularities whereas in machine-bored tunnels 5-10 cm (2-4 in.) or less may be needed.

In designing large tunnels and chambers several analytical techniques are available for estimating the thrusts, moments, and shears in the permanent lining. Methods such as STRUDL and finite element techniques may be used for analyzing underground openings and linings. Finite element programs are more versatile than STRUDL and are available for analyzing elastic, elastoplastic, and viscous behavior and for gravity rock loads. When simulating shotcrete linings in rock, the shear stress along the lining-rock contact must be included in the analysis since shotcrete is usually in intimate contact with the rock and fills most of the overbreak spaces (Brierley, 1975). The analytical model should be verified by observations and measurement obtained from tunnels driven in rock exhibiting the same general behavior as that expected in the proposed opening, before the analytical results can be considered reliable. The results obtained from the analytical model will only be as good as the input data and the ability of the model to simulate the behavior of the real rock and the lining, and their interaction. The assumptions and limitations of the model must be carefully reviewed when the results are interpreted.

In tunnels subjected to concentrated loosening loads as in blocky ground, the thickness of lining must be adequate to prevent diagonal tension failures where discrete rock wedges are supported (Deere et al., 1969). The thickness needed to prevent a diagonal tension failure may

be determined by estimating the size of critical wedges located in the flat portion of the arch (Fig. 2.46). Experimental work at the University of Illinois indicates that a diagonal tension failure in a shotcrete lining commonly occurs at an angle of about 25° to the neutral axis of the lining. The minimum required thickness may then be determined by

$$t = .21 \ L/f_t' \qquad\qquad (2.6)$$

where L is the rock load per unit length of tunnel, and f_t' is the tensile strength of the shotcrete (0.05 to 0.1 f_c').

2.3.2 Time of Placement of a Permanent Shotcrete Lining

The time of placement of the permanent lining depends primarily on the ground behavior and on the adequacy of the initial support. In most tunnels the permanent lining is placed well behind the face after completion of the excavation. In such cases concrete is usually more economical than shotcrete. In heavily loosening ground, particularly in large, shallow openings, the permanent lining can and should be placed at the face. This lining replaces some of the heavy initial and supplementary support to which a thick permanent lining is added at a later time. An excellent example in which a shotcrete lining was placed at the face to prevent extensive loosening above a shallow rock chamber is the Dupont Circle Station in Washington, D. C. The permanent lining of the station was completed within 6 m (20 ft) of the face and 48 hours after excavation (Fig. 2.47). Steel ribs used for reinforcement and initial support did not require cribbing or blocking except for small, widely-spaced, wood blocks needed to erect and maintain the position of the ribs during shotcreting. The shotcrete was placed as a continuous lining developing

rock block

diagonal tension failure

shotcrete

assumed neutral axis of lining
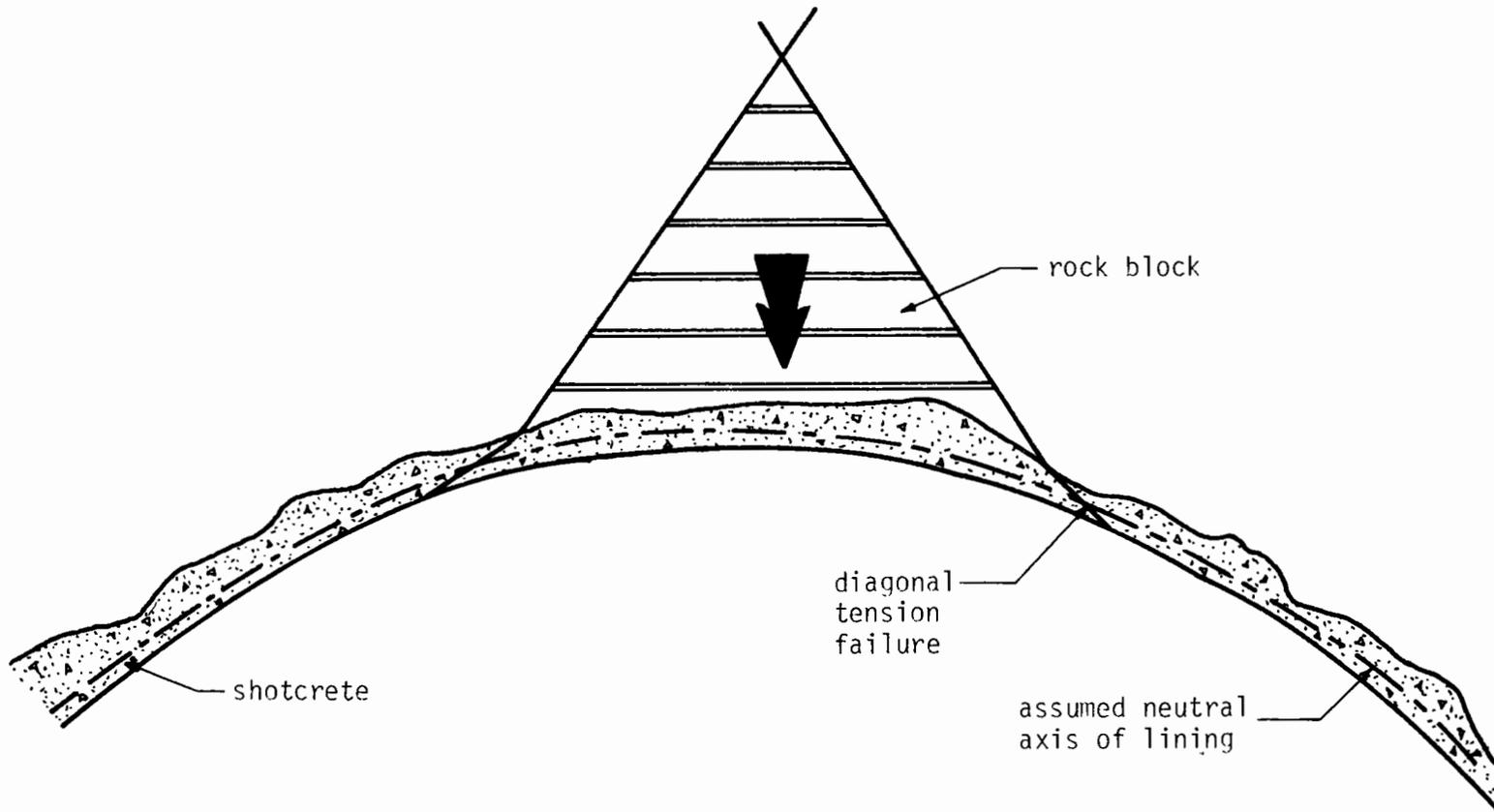
FIG. 2.46   DIAGONAL TENSION FAILURE IN A SHOTCRETE LINING.

steel beam

shotcrete

blocking

steel rib

concrete abutment

rock bolt

CROSS SECTION

3 m
(10 ft)
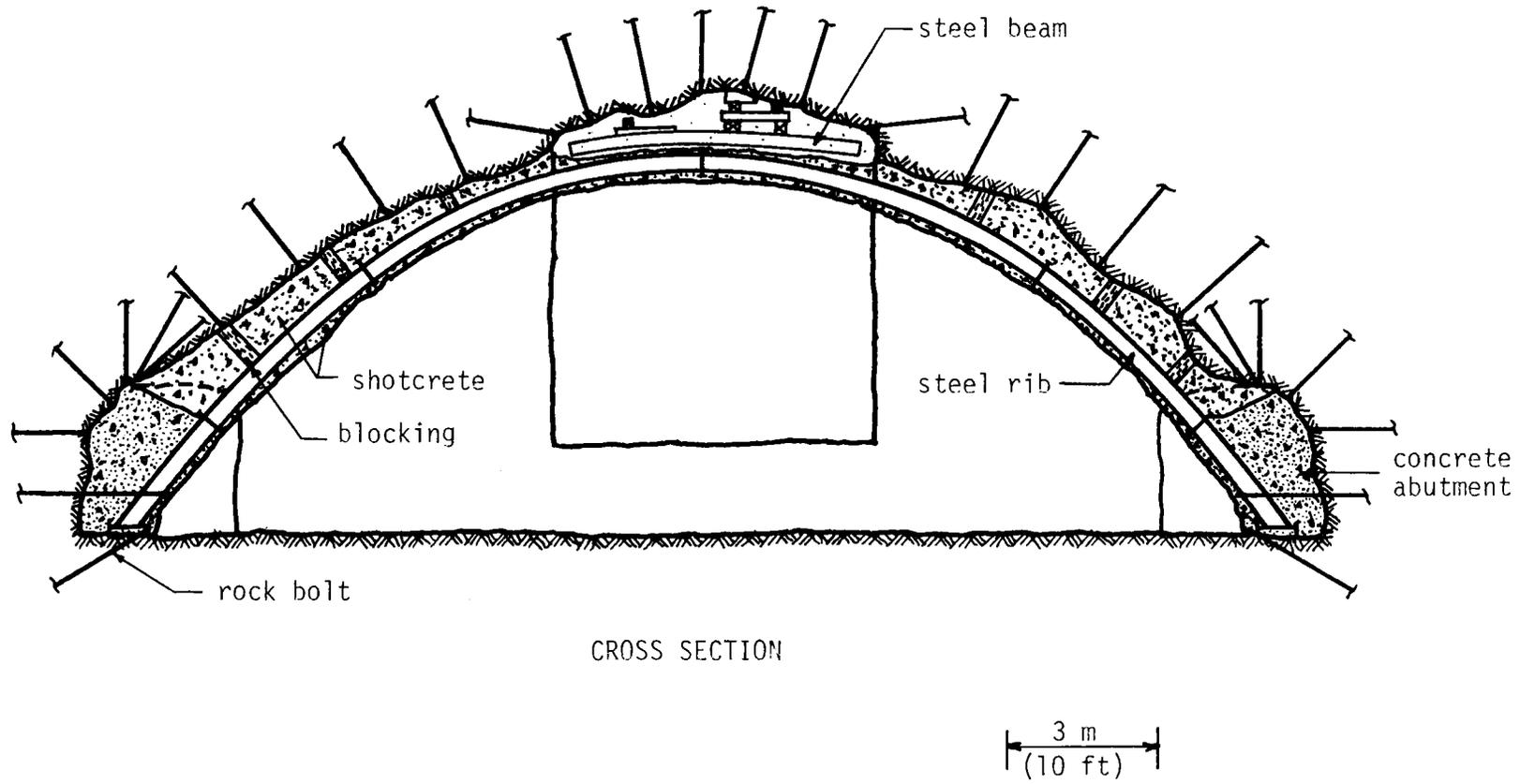
FIG. 2.47 USE OF SHOTCRETE AS PERMANENT SUPPORT.

intimate contact between the rock and the rib. This lining provided
adequate support and allowed only very small displacements of the overlying
rock mass. Placement of a permanent shotcrete lining at the face may be
more practical in large openings than in small diameter tunnels, because
of the lack of working room in small openings. In the crowded working
conditions of small tunnels, it is often more economical to install an
initial support system concurrent with excavation, and place the permanent
lining later. In other types of adverse ground, such as heavily squeezing
ground, the permanent lining may be placed close behind the heading or
after completion of the opening. In these cases, however, a cast-in-
place concrete lining is usually less expensive than a shotcrete lining.

2.3.3 Reinforcement

A permanent shotcrete lining is often reinforced to improve its
ductility and to provide a greater tensile and shear capacity than an
unreinforced lining. This reinforcement is usually located in the final
layers of shotcrete to resist bending moments which develop beneath rock
loads (Fig. 2.48). Several types of reinforcement including steel ribs,
deformed bars, wire mesh, and, more recently, steel fiber are used in
shotcrete linings. Steel fibers can be added to replace the mesh or some
of the deformed bars, but fiber shotcrete has a much lower post-crack
resistance and ductility than shotcrete reinforced with welded-wire mesh. The
amount of reinforcement may be determined by trial and error computations
in which the moments and thrusts in the liner are estimated for an assumed
reinforcement ratio and are compared with the failure envelope of the
interaction diagram for the section. The reinforcing must be adequately
encased in high quality shotcrete in order to prevent corrosion.
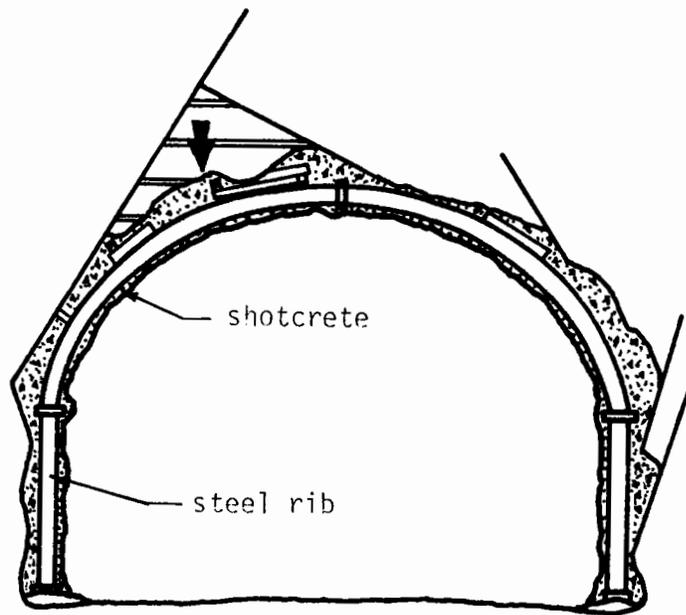
FIG. 2.48   USE OF A STEEL RIB FOR INITIAL SUPPORT AND REINFORCEMENT
OF A PERMANENT SHOTCRETE LINING.

Reinforcing not encased in shotcrete should not be included as part of the long-term support.

2.3.4 Long-Term Performance

Very little published information on the long-term performance of shotcrete linings is available. In some tunnels less than 10 years old, shotcrete has performed inadequately (Brekke and Selmer-Olson, 1965; Skogseld, 1966; Deere et al., 1969 and Cecil, 1970). Nearly all of these problems were associated with adverse groundwater chemistry, extremely harsh freeze-thaw cycles accompanied by seeping water, or from use of thin discontinuous linings in swelling ground. On the other hand, shotcrete and gunite have performed very well as permanent support in many other tunnels. In addition, shotcrete used to repair surface structures has remained in good condition after 30 to 40 years of service even where it has been

subjected to severe conditions of salt water and freezing and thawing (Blanck, 1974). If a low percentage of accelerator is used and the shotcrete is of good quality, it will have the same durability as a comparable concrete. Information on the long-term performance of shotcrete linings should be gathered and published in order to aid the designer in assessing the adequacy of shotcrete for permanent support when accelerators are used or adverse groundwater chemistry is encountered.

2.4 Compatibility with the Method of Excavation

The installation of the support system must be compatible with the method of excavation in order to prevent tunneling delays and possible instability problems and to reduce costs. When considering the use of shotcrete, these compatibility requirements are particularly important since considerable space and preparation are needed for its placement. Shotcrete has been used in both drill and blast and in machine-bored tunnels. At present it is much less compatible with tunnel boring machines, particularly if the shotcrete is placed in the heading. If shotcrete is to be used more frequently with tunnel boring machines, the machines must be redesigned to better accommodate shotcrete operations rather than simply adding shotcrete equipment as an afterthought. Shotcrete is much more compatible with the cyclic nature of a drill and blast operation.

2.4.1 Shotcrete in Machine Bored Tunnels

Space Limitations

If shotcrete is selected for support in a machine-bored tunnel, three major problems must be considered: 1) space limitations, 2) materials handling, and 3) clean-up of rebound. The space limitation is most

critical in small diameter openings when shotcrete must be placed in the heading. Adequate space is needed for both the shotcrete equipment and for the nozzling. The shotcrete equipment is usually located near the end of the boring machine and pumps or blows the material through hoses to the nozzle at the face. Sufficient space must be available for shooting at the proper angle and distance relative to the surface and for providing adequate coverage of the tunnel perimeter. The space required for nozzling behind the machine cutter head can be minimized by using remote nozzling techniques rather than hand-held methods (Fig. 2.49). The circular shape of the opening produced by the boring machine enhances automatic placement of shotcrete where the nozzle can be mounted on a boom, held perpendicular to the tunnel surface, and rotated through a radius smaller than that of the opening. Space limitations are not as critical when shotcrete is applied behind the boring machine or in large diameter openings. In large diameter openings, however, a high material delivery rate is needed to provide adequate coverage with shotcrete.

Materials Handling

Delivery of materials to the shotcrete machine must keep pace with excavation progress, and must have minimum interference with the mucking operation. Materials handling problems are most severe in small diameter bores where both mucking and material delivery are performed in one operation. In such cases, the supply of shotcrete materials is in direct competition with muck removal, which by itself can inhibit excavation progress. The shotcrete equipment can be pulled behind the machine and supplied by the muck train or it can be taken out and charged at the portal
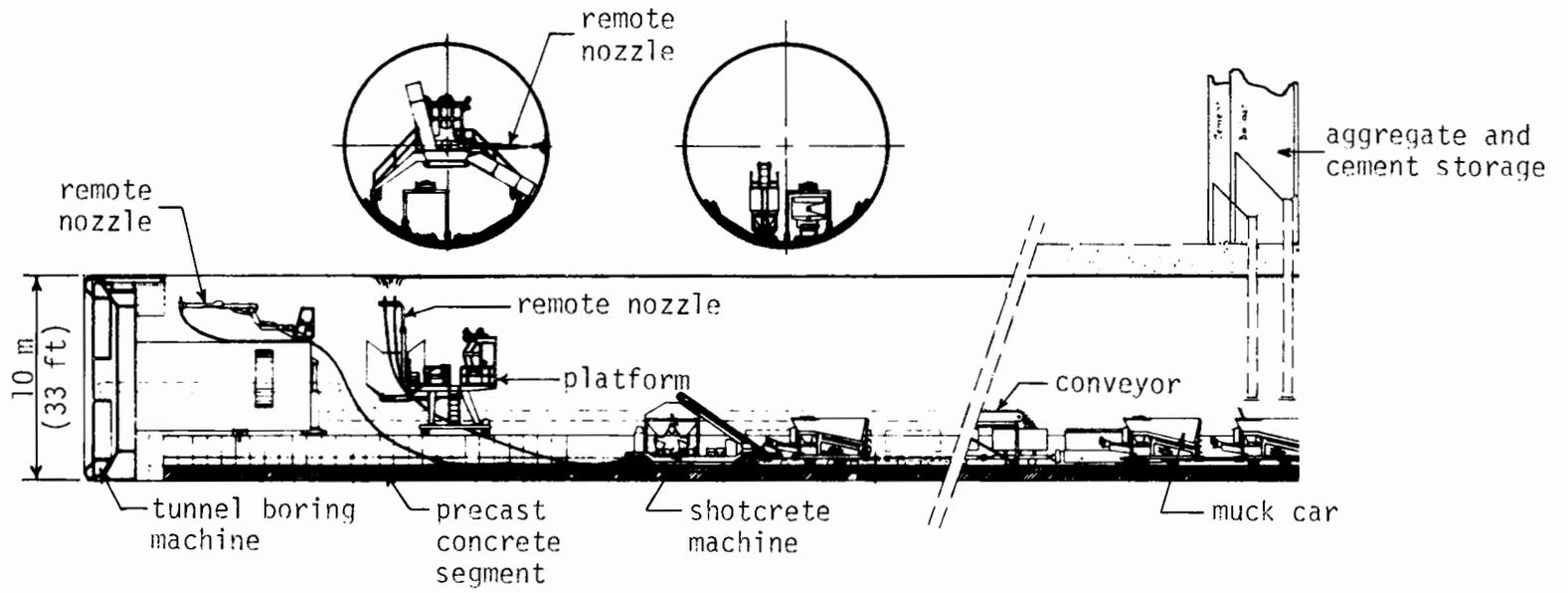
FIG. 2.49 USE OF SHOTCRETE IN A MACHINE-BORED TUNNEL (ALBERTS,1974).

or at a shaft. In the Balboa Tunnel, the materials were transported to the machine on the return (lower) position of the conveyor belt (Sutcliffe and McClure, 1969). In all cases, the supply must be adequate to provide the appropriate coverage at the desired thickness during tunnel advance. Mucking and materials supply can be done independently with less conflict in large diameter openings (Fig. 2.49). In large openings, the shotcrete equipment usually trails behind the boring machine and is continuously charged from a storage hopper. A separate set of equipment is used to bring the shotcrete materials to the heading. If space for only one haulage way is available, the mucking and supply operations must be coordinated to minimize interference.

Removal of Rebound

Rebound from the shotcrete operation must be removed in order to place invert slabs, to install track sections for the conveyance equipment, and to prevent the rebound from hardening in the invert. The rebound is usually collected independently of the normal mucking operation, and in most bored tunnels, the rebound is removed by hand and placed on the muck conveyor. The amount of rebound can be reduced by using the wet-mix process or by shooting dry-mix materials as wet as possible. Shotcrete having a high water content is also less likely to produce dust which can be detrimental to machine performance. In order to mechanize rebound removal, present machines must be modified to collect the rebound with the excavated rock or to catch the rebound during shooting. In small diameter tunnels, these modifications may reduce the available space so that placement of shotcrete is prohibitive.

Use of Precast Invert Slabs

A precast concrete slab is often placed in the invert to serve as a reaction for advancing the boring machine and to facilitate placement of a continuous ring when shotcrete-rock bond is poor. Boring machine grippers cannot be used when shotcrete is applied close behind the cutter head in front of the grippers, since the pressure of the pads can fail the fresh shotcrete. The invert slab may be designed to carry the full thrust of the machine. In soft rock, the cutter head may form a slick coating of dust or mud on the surface of the tunnel, interfering with formation of a good shotcrete-rock bond. In such cases, a continuous full perimeter lining is needed.

Field Experience With Shotcrete in Machine-Bored Tunnels

In spite of these difficulties, shotcrete has been used with tunnel boring machines both in Europe and in the United States. Its first use with TBM excavation in the United States was in the Balboa Outlet Tunnel, where shotcrete was used as initial support of poorly cemented soils (Sutcliffe and McClure, 1969). Approximately 8 cm (3 in.) of shotcrete was applied immediately behind the cutting wheel using a hand-held nozzle (Witte, 1970). More recently shotcrete has been used to seal the tunnel surface in 3-m (10-ft) diameter water conveyance tunnels in Utah. One of the most successful applications of large volumes of shotcrete in machine bored tunnels was done in the Heitersberg Tunnel described by Alberts (1974) and shown in Fig. 2.49. In this tunnel, shotcrete was used as both initial and final support of the 10-m (30-ft) diameter opening and was applied using remote nozzling techniques and equipment developed by Alberts.

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2.4.2 Shotcrete in Drill and Blast Tunnels

Shotcrete in underground construction was developed and has been most frequently used in drill and blast tunnels. The cyclic nature of the drill and blast operation permits shotcrete to be placed as part of the tunnel cycle. In large openings (>6 m [20 ft]) mucking can be carried out at the same time as shotcreting. Removal of rebound is done as part of the normal muck removal operation (Heuer, 1974). The same problems of space limitations, materials handling, and delays in excavation encountered in TBM tunnels also occur in conventionally driven openings. However, the impact of these problems on tunnel progress is usually less severe in the drill and blast openings.

2.5 Economic Considerations

The cost of applying shotcrete underground is highly variable and depends primarily on the placement requirements and the quantities gunned at one time. Higher costs per unit volume are incurred where small quantities are placed at one time. Placement of small quantities is usually associated with shotcreting in small diameter openings before the tunnel is complete. These higher costs are usually reflected in the bid price, but do not have as great an effect on the bid price as the placement requirements. Placement of shotcrete in the heading is expensive since it usually causes delays in tunnel advance. If the shotcrete is applied some distance behind the heading, it is considerably cheaper since large volumes can be sprayed with a minimum interruption in the shotcrete operation or the tunnel advance.

When evaluating the cost of a support system, other factors must be considered in addition to the basic cost per unit area of support element. For example, the overall benefit to be gained from shotcrete may more than offset the high unit price of shotcrete when total costs are considered. The ability of shotcrete in preventing rock movement must be assessed even though its cost per unit volume may be higher than other support elements. Application of shotcrete may provide a more stable opening and reduce the permanent support requirements.

2.5.1 Typical Bid Prices

When shotcrete is considered for initial support, its cost is usually compared with steel ribs and lagging or rock bolts. In some cases, such as in ravelling ground, a combination of shotcrete and rock bolts is compared with steel ribs and lagging. The bid price for applying high quality shotcrete in the headings of tunnels for civil engineering purposes in the United States presently (1975) ranges between \$160-200/m^3 (\$25-150/ yd^3). This price is paid for material sprayed through the nozzle with no allowance for rebound. Although no published data are available, the cost of placing shotcrete at the face is likely to be comparable with concrete, since tunneling must be interrupted, forms must be placed, and individual pours do not involve large quantities of concrete.

When no support problems exist, placement of shotcrete behind the heading is usually not economically competitive with concrete. The bid price for shotcrete sprayed behind the heading is typically \$110-130/m^3 (\$80-100/yd^3) while cast-in-place concrete is usually \$80-110/m^3 (\$60-80/yd^3). In addition, a greater quantity of shotcrete would be

required for the same lining thickness because of rebound. Shotcrete may be economically competitive with concrete when its early support capability can be incorporated in design and the thickness of the permanent lining can be appreciably reduced relative to a cast-in-place lining.

2.5.2 Contractor Costs

The costs to the contractor for placing shotcrete fall into the following categories: material, equipment and maintenance, labor, and indirect costs. The material costs include the materials themselves as well as the expense in transporting them to the job site. These costs depend on the availability of acceptable materials and the distance of transport. Higher costs will be incurred if demand for materials is high, materials are scarce, or haulage distances are long. Equipment costs include purchase of the equipment needed to place shotcrete as well as setup, operation, and maintenance of this equipment. The equipment and setup costs typically range between $20,000 and $150,000 depending primarily on the sophistication of the materials handling system and the extra work needed to set up the equipment (such as excavating enlargements for placing the batching facility underground). The costs for operating the equipment, such as compressed air and electricity, usually constitute a small portion of the total expense since these are also needed for the tunneling operation and are readily available. Maintenance costs usually range between $1-8/m^3 (~$1-8/yd^3) and typically average $5/m^3 (~$5/yd^3). These costs include both repair and replacement of parts, but do not include labor. The labor costs include all manpower needed to prepare and convey the materials to the shotcrete machine as well as for the

placement of the shotcrete. These costs are determined by both the job requirements and the requirements imposed by the local labor union. Indirect costs are primarily for overhead and miscellaneous labor needed to assist in placing the shotcrete.

High costs to the contractor are associated with unacceptable mix design, poor selection of equipment, and excessive down time. Down time, particularly if it affects tunnel progress, is by far the most costly of these difficulties. It usually results from improper placement of equipment, scheduling of operations, and/or maintenance. Excess contractor costs can be drastically reduced or prevented by employing experienced shotcrete personnel having a diversified work record and by requiring preventive maintenance on all shotcrete-related equipment. The experienced shotcrete superintendent will be able to provide a mix design meeting specifications and will be able to select and set up the equipment to obtain maximum production and minimum interference with the tunneling operation.

2.5.3 Cost Overruns

Excessive cost to the owner for shotcrete application has resulted primarily from overruns in estimated quantities. These overruns are usually related to underestimating rebound, rock overbreak, and/or additional thickness needed to build up the lining if additional support is required. Most experienced contractors estimate 1.7-2.0 m^3 (1.7-2.0 yd^3) of material will be needed for each nominal cubic meter (cubic yard) of in-place shotcrete in a conventionally driven tunnel using the dry-mix process. In machine-bored tunnels where the rock surface is smooth,

approximately 1.5 m^3 (1.5 yd^3) is needed to place one cubic meter (cubic yard) of shotcrete on the tunnel surface. These figures should also be used by the designer in estimating shotcrete volumes. Material overruns caused by rock overbreak can be minimized by specifying maximum excavation lines beyond which no payment is made for shotcrete required to fill over-break. Further control of overbreak can be obtained by requiring use of smooth wall blasting techniques including specification of the spacing, loading, and delays of the perimeter holes. Extra quantities of shotcrete should be added to the bid estimate to cover additional material for filling of overbreak caused by poor rock conditions rather than by poor excavation techniques. Provisions must also be made in the contract documents for placement of extra quantities of shotcrete in areas requiring additional support. If steel ribs are specified as an alternative support, it is more economical to install a cast-in-place concrete lining rather than a shotcrete lining, provided permanent support is not needed at or near the face.

CHAPTER 3

SELECTION OF MATERIALS AND PROPORTIONING
OF COARSE AGGREGATE SHOTCRETE MIXES

Many aspects of the design of shotcrete mixes differ significantly from customary practices in concrete technology. The basic materials are the same but there are many additional, very demanding requirements on those materials or on their compatibility with other ingredients of the mix. This is particularly true of the compatibility between cement and accelerator which is a very sensitive relationship. There are no accepted mix design procedures for proportioning materials for the dry-mix process; proportioning methods used for concrete are applicable primarily to the wet-mix process. Usually the proportions are based upon previous experience and trial-mix methods.

Some of the standard tests for concrete materials can be used without modifications while others must be modified to accommodate the unique behavior of shotcrete. Quality control testing equipment and methods, though often similar to those for concrete, are usually more difficult and may require modification of test procedures.

This chapter describes the present state of knowledge of the factors involved in proportioning the mix. Where appropriate, the similarities or differences in characteristics between shotcrete and concrete are outlined. Those concepts and test methods for concrete which require modification for their application to shotcrete are discussed. The materials and the mix design affect the final product to a significant degree. The requirements and

typical usages of materials are presented followed by a discussion of the factors involved in mix design. Chapter 4 will then present typical values of the engineering properties together with a checklist and a discussion of possible factors that affect them which might cause a given engineering property to be lower than expected. The data in Chapter 4 provides input to the procedures described here.

3.1 Materials for Underground Support

3.1.1 Portland Cement

Types Available and Uses Underground

The most widely used variety of portland cement for shotcrete application is Type I. Type I cement is used where special properties of other cement types are not required and it is the most available cement. When special properties are required, other types of cement are used, but in most cases the special characteristics are gained at some sacrifice in strength gain for the shotcrete. For example, Type II (moderate sulfate resistance) and Type V (high sulfate resistance) may be desired where the soil, groundwater, or mixing water contain sulfates such as in the arid west but the rate of gain of strength of these cements is relatively slow. The composition and fineness of Type III cement provides a higher early strength. The rate of gain of strength of unaccelerated cement is, however, for underground work, less important than the overall behavior after the addition of the special fast-set accelerators. A new portland cement, regulated-set cement, has been

tested in the laboratory (Bortz, et al., 1973) and in the field (Parker, et al., 1975). Regulated-set cement is described in Appendix A. Because of the quickness of setting and the very fast rate of gain of strength even without accelerators, regulated-set cement has only been used for the dry-mix process; it might set in the lines of wet-mix equipment presently available.

In contrast to Type I cement, availability of these special-property cements is limited and varies with location. In some cases, they may be obtained only by special order from the manufacturer. The remaining types of cement specified in ASTM C 150, Type IV and the air-entraining versions of Types I through III, have had little use in underground shotcrete applications.

The most common practice is to use readily available Type I cement and rely on accelerating additives to achieve fast set and a higher initial rate of gain of strength. Accelerators are also used with Type II, III, and V. The ability of any given accelerator to be effective with any given batch of cement is a precise function of the chemistry of both ingredients. No matter what types of cement and accelerators are used, a series of tests is required to determine the compatibility of each proposed accelerating agent with each cement. These tests are discussed in more detail in Section 3.1.4.

The use of an accelerating additive places a special limitation on he type of cement that is acceptable: its compatibility with the accelerator must be proven and maintained. Before making the final order for cement, all available cements should each be tested for compatibility in terms of both early and ultimate behavior with a number of different accelerators. These tests should be performed at various temperatures which span the

anticipated range of material temperatures to be encountered for the duration of the project. Often only one combination of cement and accelerator will be compatible. If more than one combination is compatible, the combination giving the greatest latitude of compatibility should be selected. In all cases economy is an important consideration. However, a small savings in the cost of cement by using a marginally compatible cement may cost the contractor more in the long run because of extra rebound, delays and difficulties at the heading.

Slight variations in chemical composition from batch to batch are common even within a single brand of cement. Frequently, the variations significantly affect the reaction rates of cement and accelerator, invalidating the results of the original compatibility tests. Therefore, samples of materials tested before the cement order is made must be representative of the cement to be received. Samples of the actual cement delivered should be subjected to at least spot checks before the cement is accepted. Note, however, that changes in compatibility behavior may also be due to variations in the accelerator. Furthermore, a continuing series of tests is required to determine the proper proportion of accelerator to achieve the desired set time and early strength. On small jobs, problems with variations in compatibility can be minimized by obtaining all cement to be used on a shotcreting job from the same batch and stockpiling it until it is needed. The same should be done also for the accelerator once compatibility has been established. Otherwise, compatibility tests should be rerun periodically and the accelerator/cement ratio adjusted accordingly.

Applicable Standards

Portland cement used in shotcrete should conform to ASTM C 150, "Standard Specification for Portland Cement." This specification lists the standard and optional chemical and physical requirements for all five basic cement types plus the air-entraining varieties. In addition to listing the allowable values, the specification also indicates which tests should be performed to determine these chemical and physical properties. The specification also states that when requested by the purchaser in the contract or order, "a manufacturers' certification that the material was tested in accordance with this specification together with a report of the test results shall be furnished at the time of shipment" (ASTM C 150).

At present there are no standards for regulated-set cement; by varying the composition in the kiln, the behavior can be "regulated". Thus the chemistry and the behavior of the cement can vary between different sources and between different burns from the same source. Most regulated-set cement is probably adequate for shotcrete; however, the supplier should be consulted and the cement tested.

3.1.2 Aggregates

Aggregate Quality

Natural gravels are preferred over crushed stone, but otherwise, the quality of aggregate required for shotcrete is the same as for conventional concrete of good quality. Therefore, all aggregate used in shotcrete should

be clean, hard, tough, strong, and durable (Troxell, et al., 1968). Compliance with ASTM C 33, "Specifications for Concrete Aggregates" will assure that both fine and coarse aggregate will be of adequate quality.

Aggregates should not contain more than 2 percent passing the No. 200 sieve (0.075 mm) since the dust coats the aggregates and interferes with the bond between the aggregate and the cement and accumulates in the hoses and equipment. Aggregates should be free from an excess of silt, soft or coated grains, mica, harmful alkali, and organic matter. The maximum amounts of deleterious substances allowed under ASTM C 33 are shown in Table 3.1. In addition to those limits listed, the specification states that any concrete exposed to moisture for extended periods must not contain any materials that are deleteriously reactive with alkalies in the cement and accelerator in an amount sufficient to cause excessive expansion of the mortar or concrete. Alkali-reactive aggregates should not be allowed.

Other measures of aggregate quality, besides the concentration of deleterious substances, fall under the category of physical properties and include soundness and resistance to abrasion. Of these, soundness requirements apply to both coarse and fine aggregates, while requirements for abrasion resistance apply only to coarse aggregate. The limits for soundness and abrasion resistance for fine and coarse aggregate are shown in Table 3.2. The tests for measuring soundness (ASTM C 88) and abrasion resistance (ASTM C 131 and C535) are discussed briefly in Chapter 8.

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Table 3.1. Limits for deleterious substances in
fine and coarse aggregates

	Weight percent of total fine aggregate sample, max.	Weight percent of total coarse aggregate sample, max.
Clay lumps & friable particles	3.0	5.0
Material finer than No. 200 sieve	3.0[1]	1.0[2]
Coal and lignite	0.5	0.5
Chert[3]		
Severe exposure	N.A.	1.0
Mild exposure	N.A.	5.0

N.A. - Not applicable

[1]In the case of manufactured sand, if the material finer than the No. 200 (0.075 mm) sieve consists of the dust of fracture, essentially free from clay or shale, this limit may be increased to 5 percent.

[2]In the case of crushed aggregates, if the material finer than the No. 200 (0.075 mm) sieve consists of the dust of fracture, essentially free from clay or shale, this percent may be increased to 1.5.

[3]This applies only when chert appears as an impurity that will disintegrate in 5 cycles of the soundness test, or 50 cycles of freezing at $0°F$ ($-17.8°C$) and thawing at $40°F$ ($4.4°C$) in water; or that has a specific gravity, saturated surface dry, of less than 2.35. The limits listed in the table are not applicable to gravels that are predominantly chert. Limitations on soundness of such aggregates must be based on service records in the environment in which they are used.

Source: ASTM C 33-74

Note: These limits are subject to change periodically. Refer to the latest available ASTM specification for up-to-date requirements.

Table 3.2 Physical properties of coarse and fine aggregates

	Fine Aggregate	Coarse Aggregate
Soundness, loss in 5 cycles, max. weight percent:		
Sodium sulfate	10	12
Magnesium sulfate	15	18
Abrasion, max. loss, weight percent	N.A.	50

Source: ASTM C 33-74

Note: These limits are subject to change periodically. Refer to the latest available ASTM specifications for up-to-date requirements.

Crushed rock has been successfully used in shotcrete but it is more difficult to apply, creates additional wear on equipment and hoses, and results in an increase in rebound (Blanck, 1974). Crushed rock is also difficult to pump through the hoses in the wet-mix process.

Maximum Size of Coarse Aggregate

The maximum size of the coarse aggregate is dependent on the size of the equipment being used and on the preference of the user. Some shotcrete machines marketed today accept aggregate up to 32 mm (1.25 in.) in size, but, because of high rebound losses with large-sized coarse aggregate, the common practice on most U.S. shotcrete jobs is to limit the maximum aggregate size to 19 mm (0.75 in.) or less. A discussion of the factors involved in the selection of the maximum size is contained in Section 3.2.2.

Gradation of Fine and of Coarse Aggregate

The gradation of the shotcrete aggregates plays a critical role in a number of very important aspects of a shotcrete mix design: the pumpability, flow through hoses, hydration at the nozzle, and adherence to the area sprayed, as well as the density and economy of the final product (Blanck, 1974; Bawa, 1974). The final gradation is determined by two factors: 1) the gradation of the final stockpiles or sources designated as coarse aggregate and fine aggregate, and 2) the relative percentage of fine aggregate and coarse aggregate selected for the final mix design. The first factor is the subject of this section while the relative percentages are discussed in Section 3.2.2. To a degree, the two factors are interdependent since deficiencies in either coarse or fine aggregate sources can be compensated by processing, blending, or by varying the relative proportions in the final mix design.

The gradations recommended in ACI 506-66 are taken from ASTM C 33, "Specifications for Concrete Aggregates" and are reproduced here as Table 3.3 for fine aggregates and Table 3.4 for coarse aggregates. For maximum density, gap-graded aggregates should be avoided. Smooth gradation curves falling between the limits specified in ASTM C 33 will generally ensure that the aggregate is not gap-graded. All oversize pieces should be rejected by screening, since they are likely to cause plugging of the equipment or hoses. In order to ensure adequate bond between the cement and aggregate particles, material finer than the #200 sieve (0.075 mm) should be less than 2 percent (Kobler, 1966). A fineness modulus in the range of 2.4 to 3.2 is recommended for the

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Table 3.3. Fine aggregate gradation limits

Sieve	Percent passing, by weight
3/8 in. (9.5 mm)	100
No. 4 (4.75 mm)	95 to 100
No. 8 (2.36 mm)	80 to 100
No. 16 (1.18 mm)	50 to 85
No. 30 (0.60 mm)	25 to 60
No. 50 (0.30 mm)	10 to 30
No. 100 (0.15 mm)	2 to 10

Source: ACI 506-66 and ASTM C 33

Table 3.4. Coarse aggregate gradation limits

Sieve	No. 8 to 3/8 in. size	No. 4 to 1/2 in. size	No. 4 to 3/4 in. size
1 in. (25.0 mm)	--	--	--
3/4 in. (19.0 mm)	--	100	90-100
1/2 in. (12.5 mm)	100	90-100	--
3/8 in. (9.5 mm)	85-100	40-70	20-55
No. 4 (4.75 mm)	10-30	0-15	0-10
No. 8 (2.36 mm)	0-10	0-5	0-5
No. 16 (1.18 mm)	0-5	--	--

Source: ACI 506-66 and ASTM C 33

fine aggregates (Kobler, 1966). The fineness modulus is the sum of the cumulative percentages retained on the standard sieves divided by 100. The higher the fineness modulus, the coarser the aggregate.

3.1.3 Mixing Water

Water used in shotcrete should meet the same standards for water used in concrete. It should be clean and free from injurious amounts of oil, grease, salts, alkali, organic matter, or other harmful matter. Generally speaking, any water suitable for drinking and having no pronounced taste or odor is suitable. In addition, water of unknown quality may be used if mortar cubes made with this water have 7- and 28-day strengths equal to at least 90 percent of similar specimens made with drinkable water (PCA, 1975). Also, there should be no indication of unsoundness or marked difference in setting times between the two sets of samples (AASHTO T 26, "Quality of Water to be Used in Concrete").

3.1.4 Accelerators

General Composition and Characteristics

There are a number of circumstances where a rapid gain in early strength is desirable in shotcrete applications, especially underground. Special types of accelerating admixtures (or accelerators) provide the desired fast-set and high initial rate of gain of strength. The accelerator provides both fast-setting characteristics so that shooting conditions are improved (maximum layer thickness and low rebound) and rapid gain of strength beginning immediately

after shooting. These special types of accelerators are significantly different from accelerators for concrete.

Calcium chloride, normally used in conventional concrete, is not sufficiently fast-acting for most underground applications although it has been used (Reading, 1974; Jones, 1974). When batched in its usual proportions, less than 2 percent of the cement weight, it does not suitably accelerate the gain in early strength. Proportions on the order of 5 percent do provide a sufficiently quick set for shotcrete but the deleterious effects, primarily a decrease in ultimate strength, durability, and resistance to aggressive agents, become too great (Orchard, 1973). Consequently, new types of accelerators were developed for shotcrete purposes.

Shotcrete accelerators are faster acting than conventional concrete accelerators. The accelerators marketed for shotcrete purposes generally contain the following water soluble salts as active ingredients: sodium carbonate, sodium aluminate, and calcium hydroxide (Reading, 1974; Blanck, 1974). The proportions of these ingredients vary with each brand; in some cases only one of these active ingredients may be present. These alkaline chemicals give the accelerators their caustic characteristics and require that precautions be taken in handling them. "Low causticity accelerators" that take about twice the exposure time before burning a negligent worker have recently been marketed (Blanck, 1974). In addition to these, new liquid accelerators are presently (1975) being developed that are reported to be organic and noncaustic, but extensive field experience with these accelerators is lacking.

The accelerators are marketed in both liquid and dry powder form. The liquids are generally packaged in 190 to 210 ℓ (50 or 55 gallon) drums and

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some brands require dilution with water prior to use. The dry powder accelerators are packaged in sacks or boxes ranging in size from 11 to 36 kg (25 to 80 lb) each.

Preventing the powder accelerators from absorbing moisture is very important. The powders are typically batched from volumetric feeders, and the feeders require that the accelerator be dry and freely flowing for accuracy in batching. Even the small amount of moisture absorbed from the atmosphere can seriously alter the flow properties and lead to caking or bridging of the accelerator inside the feeder, so the dispensing rate can be seriously disrupted. In view of this extreme vulnerability to moisture, all packages of powder accelerator are lined with plastic to prevent moisture from entering. Care should therefore be exercised in handling and storing the accelerator so that it is stored in a dry place and that plastic liners are not ripped. Any sacks that have been opened and only partially used should be resealed carefully to minimize absorption of moisture.

Compatibility Requirements

The combined behavior of a cement-accelerator mixture is very sensitive to the exact chemistry of each of the constituents. Some combinations react favorably while others do not.

An accelerator is considered to be acceptable with a cement when the following conditions are met (Blanck, 1974):

1.   The initial set in the Gillmore Needles Test occurs within 3 minutes.

2. The final set in the Gillmore Needles Test occurs within 12 minutes.

3. Strength on the order of 500-1000 psi is attained after 8 hours.

4. The ultimate strength (28-day strength) should not be lower than 30 percent of the strength of an unaccelerated specimen. This usually restricts the accelerator dosage to 6 percent or less.

The ultimate strength (at 28 days) must be greater than the minimum called for in the specifications or by the mix designer. Further, these criteria should be met throughout the range of temperatures anticipated during the job.

A series of compatibility tests is required to determine if a cement-accelerator combination meets these criteria. The initial and final set times are usually determined by testing with Gillmore Needles (ASTM C 266). If other tests, such as the Vicat Needle, are used, the specified set times should be modified to obtain the same behavior or equivalent test times as those specified with Gillmore Needle Tests. A complete standard test procedure for the Gillmore Needles Test modified as it should be used for shotcrete accelerators is given in Appendix D.

Determinations should be made for accelerator concentrations of 1, 2, 3, 4, 6, and 8 percent of the cement content by weight. Suggestions for tabulating and plotting the results are given in Section 8.1.4. The data should be plotted on semi-log paper with time on the horizontal log scale and accelerator dosage on the vertical arithmetic scale (Fig. 8.1). An entire series of tests should be conducted using material temperatures that represent the range of

Legend:

O   All materials at room temperature

□   All materials 42°F (5.5°C)

Δ   Cement and Accelerator at room
           temperature, water at 110°F (43.3°C)

───►   Trend with colder temperatures

─ ─ ─►   Trend with hotter temperatures

✳   Possibly a false set; true set time
           believed to be less than 8 min.
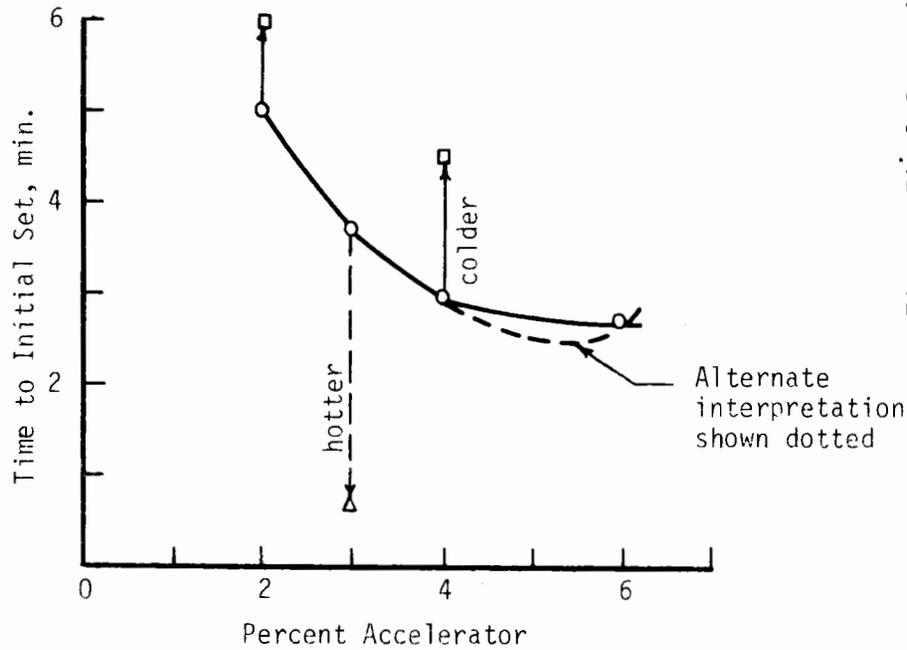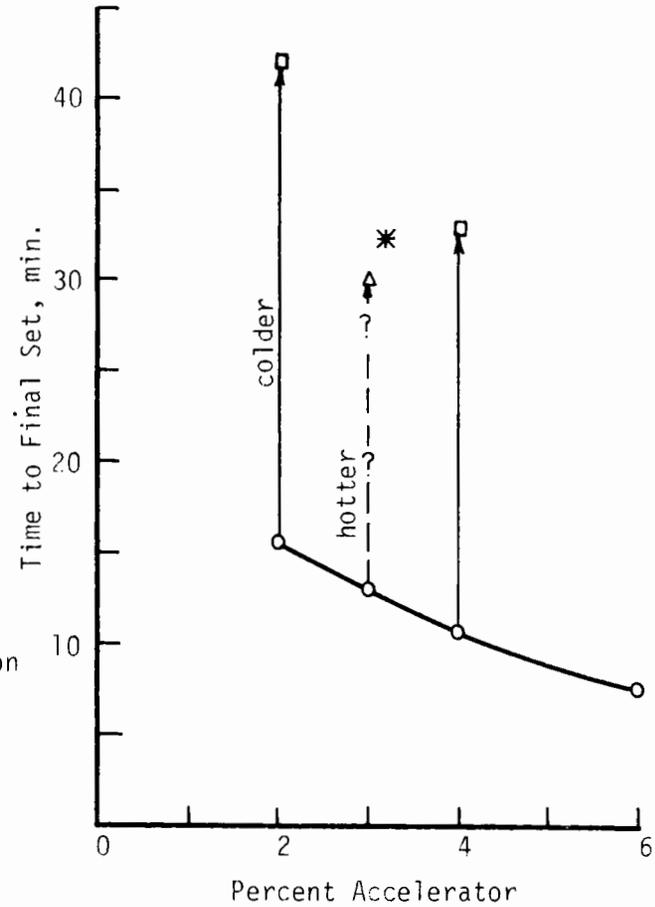
a) Initial Set   b) Final Set

FIG. 3.1.   TYPICAL EFFECT OF TEMPERATURE ON GILLMORE NEEDLE TEST RESULTS: TYPE I CEMENT
            (PARKER, ET AL., 1975)

temperatures anticipated throughout the duration of the project. This pro-
vides a family of curves from which the most economical compatible percentage
can be selected for any temperature encountered. Figures 3.1 and 3.2 are
graphs illustrating the typical effect of temperature on compatibility test
results for conventional and regulated-set cements respectively.
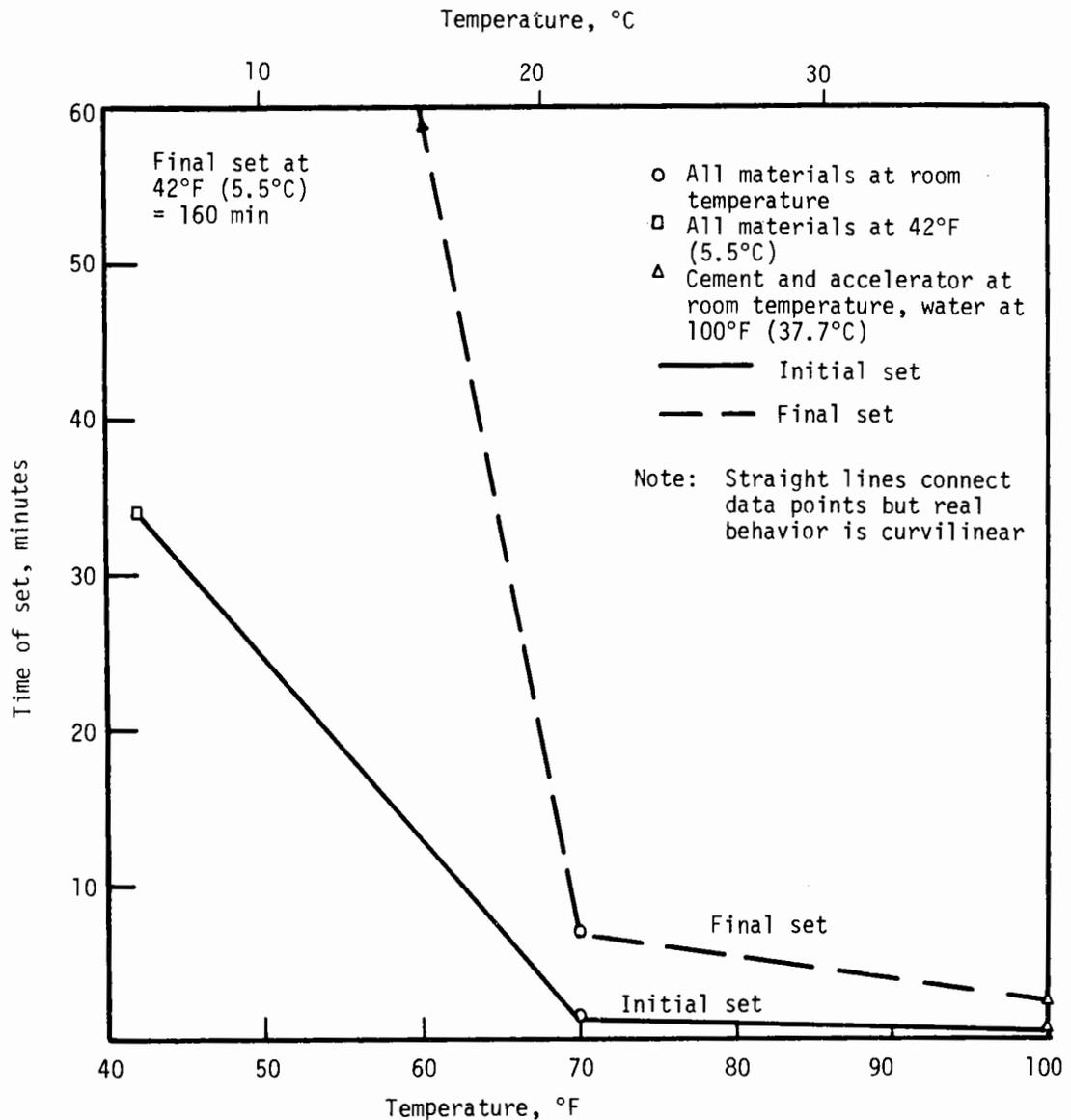
FIG. 3.2   TYPICAL EFFECT OF TEMPERATURE ON GILLMORE NEEDLES
           TEST RESULTS: REGULATED-SET CEMENT
           (PARKER, ET AL., 1975)

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An idea of the rate of gain of compressive strength at early ages can be determined by tests on mortar cubes in accordance with ASTM C 109 (Bawa, 1974). Cube tests (ASTM C 109) should be run at 28 days to determine the effect of the accelerator on ultimate strength. Ultimate compressive strength is determined by the test method called for in the project specifications but, prior to actual shotcrete production, cube tests (ASTM C 109) can be used for an indication of the accelerator's effect on ultimate strength. Any time cubes are molded, care must be taken that the method of preparation does not affect the results. Since the methods of placement and compaction of the cubes have no resemblance to shotcrete placement, the magnitude of the strength of the cubes bears only an approximate relation to the strength of shotcrete in-place.

Combinations of cement and accelerator which cannot produce set times within the allowable time limits stated above or which require high percentages of accelerator (i.e., exceeding about 6 to 8 percent accelerator by weight of cement) are discarded as unacceptable combinations. Also discarded are accelerators which result in excessive loss of ultimate strength. Samples containing accelerator should not exhibit a decrease in strength of more than 30 percent over mortar cubes with no accelerator.

Figure 3.3 is a typical graph of compressive strength vs curing time for two mixes with accelerators and one mix without. Both mixes with accelerators exhibit a rapid gain in early strength followed by a markedly lower ultimate strength when compared with a mix with no accelerator. Tests with accelerator concentrations in the range of 2-3 percent have shown that about a 25 percent reduction in compressive strength may be expected at 28 days (Blanck, 1974). With higher concentrations the ultimate strength penalties

Mix: 50% 1/2 in. Gravel + 50% Sand

Curve 1: 7 Bag Mix + 3% Accelerator A
Curve 2: 7 Bag Mix + 3% Accelerator B
Curve 3: 7 Bag Mix - No Admix

Shotcrete Compressive Strength, kg/cm²

Shotcrete Compressive Strength, psi

Time of Cure, Hours-Days

Hours

Days
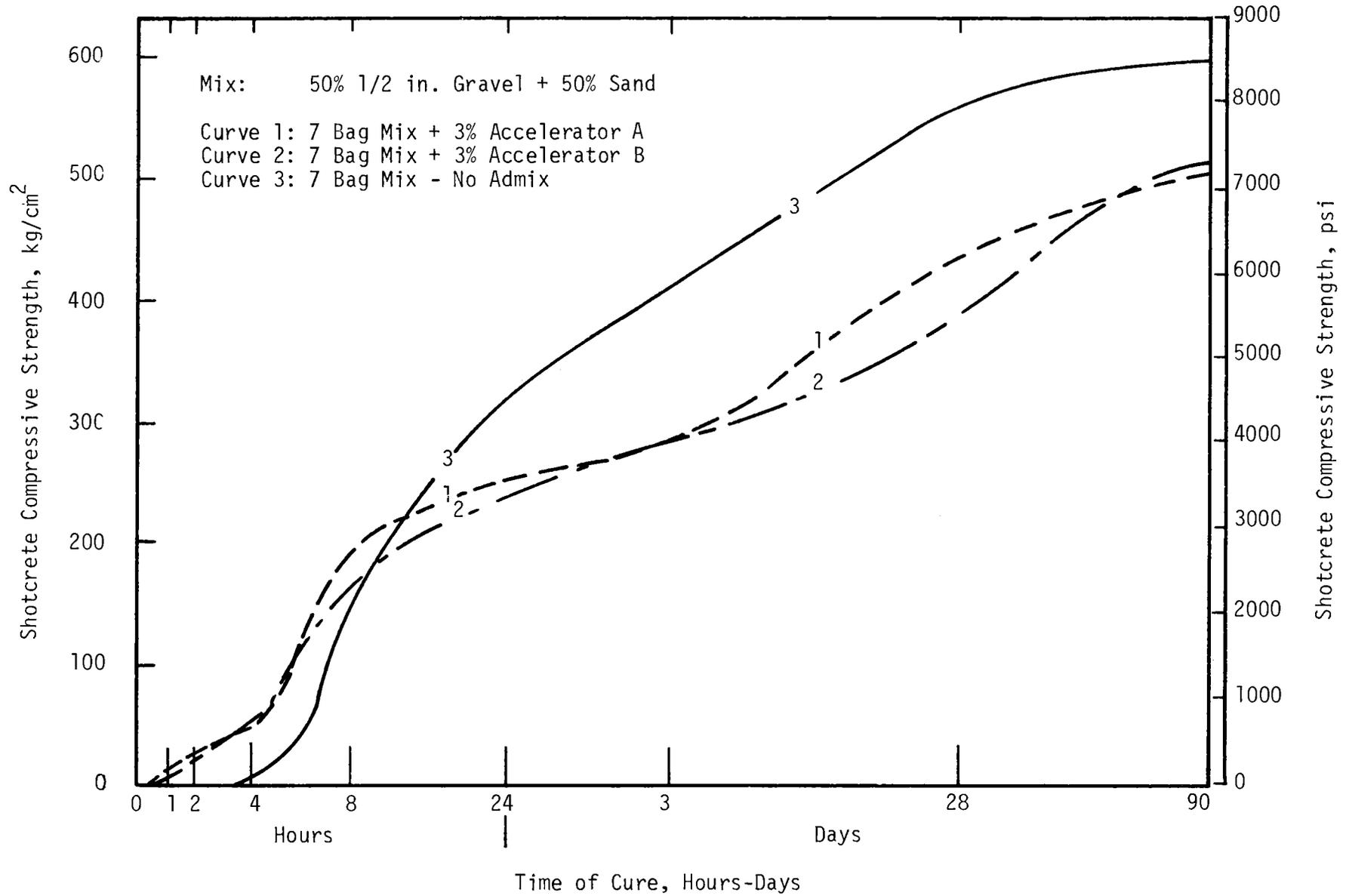
FIG. 3.3. EFFECT OF ACCELERATORS ON EARLY AND ULTIMATE STRENGTH OF SHOTCRETE
            (AFTER BLANCK, ET AL., 1974)

can be expected to be higher. However, in this respect liquid accelerators appear to have some advantage over the powdered variety. The liquid accelerators appear not only to give a smaller reduction in final strength, but they also give a higher initial strength (Sallstrom, 1970; Brekke, 1972). This is attributed to the more thorough mixing with cement than occurs with powder accelerators. The new generation of liquid accelerators are reported to have very little effect on the ultimate strength of shotcrete but they must be proven by extensive use in the field.

Applicable Standards for Accelerators

In the past, some project specifications for shotcrete have required that accelerators conform to ASTM C 494, "Standard Specification for Chemical Admixtures for Concrete". In fact, the ACI standard for shotcrete (ACI 506-66), which mentions this requirement, was prepared prior to the development of present day accelerators, and ASTM C 494 is now only partially applicable to these new additives. The specifications for uniformity, packaging, storage, sampling, and inspection are still pertinent to rapid set accelerators, but the specified testing methods were developed for much slower reacting additives. Consequently, the testing methods mentioned must be modified. Guidelines for cement-accelerator compatibility tests are contained in Appendix D.

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3.2 Mix Design

3.2.1 Overall Approach

This section treats the design of mixes containing coarse aggregate and fast-set accelerators. The process of mix design is a long, complicated process which is an integral part of the entire process of setting up the operation, selecting the materials and equipment, and training the crew. Any change in this process results in a change in the final product. A mix shot at a later stage of pre-construction testing will probably result in a significantly better product than the same mix shot at an early stage. However certain arbitrary assumptions in the mix design must be made at the beginning to get trial mixes started.

The process of mix design should be one of refinement; a mix should be determined as soon as possible which meets or exceeds the specification requirements and then refinements should be made to improve shooting conditions, reduce rebound, or to otherwise economize by reducing cement and/or accelerator content. There is usually an optimum mix design for a given set of conditions. It may be very difficult, however, to obtain that first acceptable mix that meets the specifications because of the complex interrelationships. Adding more cement or accelerator may not be enough; it certainly is not the most economical procedure.

The overall approach to the design of the mix is similar for both the wet- and dry-mix processes. However, there are important differences in the detailed procedures for selection of the requirements of the mix design depending on whether the wet-mix or the dry-mix process is to be used. Regardless

of the shooting process selected, the mix design must meet the following criteria:

1. Shootability

    Must be able to be placed overhead in layers as thick as specified with minimum rebound.

2. Early strength

    Must be able to hold ground loads at ages less than 4-8 hours. Usually a compressive strength at 8 hours is specified.

3. Long-term strength

    The specified 28-day strengths must be achieved with the dosage of accelerator needed to achieve the shootability and early-strength criteria.

4. Durability

5. Economy

    Low cost as batched and low rebound losses.

Environmental conditions are important to the behavior of shotcrete. The temperature and humidity under which trial mixes are shot and specimens cured should be representative of those anticipated during tunneling. It may be impossible to shoot and cure specimens in a tunnel except for those cases in which the new work represents an extension of an existing under- ground facility. It may then be necessary to create the same temperature and humidity in a curing room. At the very least, these differences must be recognized by the contractor and by the engineers. The inability of a

mix design to achieve the specified strength could be the result of poor curing conditions.

The mix design should be evaluated several times after construction begins especially during the early stages of construction, and when environmental conditions change significantly. Economy in the mix design should not be viewed as the cost of the materials which go into a given mix per unit volume or unit weight. Only "total project economy" can be used as a criteria for economic evaluations of different mix designs. The use of accelerators are a good example of this concept. The addition of accelerators increases the unit price of the materials but results in faster application times when support of the heading is crucial and is on the critical path. The overall rate of advance of the tunnel is then faster, resulting in savings many times greater than the cost of the accelerator. Thus, the cost of materials and even the total cost of application are not always adequate parameters for evaluation of the benefits of a given mix design. If it is judged that a given set of mix designs all have the same impact on the rest of the cost of the tunnel, then the total cost of application, including maintenance and rebound losses and removal, could be used as a rough guide to their relative economy. However, "total project economy" is the only reliable means for evaluation of the economic impact of a given mix design.

3.2.2 Procedure for Selecting Mix Design

Generalized Flow Path

There are no standard or generally accepted procedures for the detailed

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mix design of shotcrete. Mixes are more or less selected rather than de-
signed. Basically, the few concrete mix design procedures which remain
applicable to shotcrete are combined with the contractor's experience to
select a first trial mix. Different trial mixes are then made and shot to
select acceptable ones. Sometimes the experienced contractor may be able to
go directly to a trial mix.

The overall flow chart for mix design is shown in Fig. 3.4. The initial
steps are similar for both wet and dry processes. The purpose of the shot-
crete, the specified requirements, additional requirements demanded by con-
struction and shooting conditions, and the previous experience of the con-
tractor all combine to determine the desired engineering properties of the
final product. In cases where specifications are stringent, these may be
equivalent. In other cases, the contractor may recognize more demanding
requirements for his shotcrete than those specified.

The contractor's assessment of the overall construction project to deter-
mine the type of process and the equipment to be used affects the mix design.
Items like the rate of advance, the type of transportation scheme for handling
muck and incoming material, the location of batch plant, length of the tunnel,
and the desired capacity all go into the selection of the type of process and
the specific shooting equipment to be used. All these conditions and equip-
ment selection affect the mix design in the various ways shown schematically
in Fig. 3.4.

There are several aspects of mix design which are related to the selection
of equipment. There are other aspects related to the nature of the available
materials. These two factors, the nature of the equipment and of the available

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Purpose of Shotcrete

a) initial structural support
b) final lining
c) rehabilitation or repair
d) protective coating

Anticipated Shooting Conditions

a) % overhead
b) Water flow into heading
c) Temperatures
d) Stand-up time of rock

Specifications:
a) strengths:
   early
   ultimate
b) thicknesses
c) time limit for placement
d) other support systems in addition to shotcrete.

Previous Experience of Contractor

Overall Construction Conditions

a) Distance from source or mixing area to heading
b) Transportation problems and backup equipment
c) Material temperatures and moisture conditions

Determination of Required Setting Time

Desired or anticipated required setting time and early rate of gain of strength.

Desired Engineering Properties of Final Product

Volume to be Placed and Rate of Placement

a) Estimated Rate of Advance
b) Size of Tunnel

Selection of Wet Mix or Dry Mix Process

Required Rate of Delivery. Equipment Capacity. Number of guns needed.

Equipment Selection:

Gun, Backup, Mixing and Transporting Equipment

Aggregate Size and Gradation

Function of:
   available materials
   capability of equipment
   economy in rebound
   economy in cement
   desired compaction

Equipment Constraints on Mix Design

Max.-size aggregate pumpability (etc)

Estimated Range of Cement Content Necessary to Achieve Ultimate Strength

Test Cement-Accelerator Compatibility (see Figs. 3.6 & 3.7)

Decision of range of Cement and Accelerator content needed to achieve both setting characteristics and initial and final strengths

If Wet Mix-Use Concrete Mix Design Procedures For Pumpable Mixes

Initial Trial Shooting of Mix Designs covering a range of combinations of cement, accelerator dosage and aggregate gradations.

FIG. 3.4 OVERALL FLOW CHART FOR MIX DESIGN

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materials, are much more important to shotcrete mix design than they are

for ordinary concrete and because of these factors, there are more steps

to the design of a mix for shotcrete.

The obvious major difference in equipment is the distinction between

wet- and dry-mix equipment which requires different mix design procedures.

There are other equipment-related constraints to mix design, however. For

example, the shooting equipment and hoses can handle only certain sizes of

aggregate. The equipment thus limits the range of aggregate size to be

considered.

Decisions about the aggregate, maximum size, gradation, etc., and the

results of the cement-accelerator compatibility tests also go into the final

decision for the initial trial mix. Shotcrete with fast-set accelerators

requires compatibility between the cement and the accelerator. This adds

an extra step to the process of mix design and puts the design of the mix

within the constrains of the availability of compatible materials.

The mix design for the dry-mix process is usually a trial and error

process based on the contractor's experience. Subsequent sections will pro-

vide customary values for the various ingredients which can serve as a starting

point for the process of selection.

Concrete mix design procedures are more applicable to the wet-mix process

than to the dry-mix process. The initial detailed steps in designing wet-mix

shotcrete follow accepted concrete mix design procedures. However, the

design must always be pumpable through rather small diameter hoses. This

pumpability criterion is important to the successful application because a

properly designed mix will minimize plugs in the line. Later steps of wet-mix design also involve trial and error methods.

Once the input from the factors just discussed are evaluated, a decision on the range of cement and accelerator contents are selected. Then trial mixes are shot covering a range of proportions including various aggregate gradations. The strengths are then evaluated and additional trial mixes shot as necessary.

Depending on the conditions, the length of time required for the selection of materials and pre-construction testing could be several months long.

Guidelines for Proportioning Aggregates

The selection of aggregates is made according to the size and gradation available that will work in the equipment and that will achieve the desired final product. Often the aggregate to be used for concrete on other parts of the job will be acceptable. The coarseness of the aggregate or the ratio of coarse to fine aggregate may be dictated by the desire for certain properties of the final product. The decision to use large aggregate to obtain certain shotcrete properties may dictate the equipment which must be used.

Selection of Maximum Sizes. Selection of the maximum size aggregate is presently a controversial subject. Proponents of large-aggregate (13 to 25 mm [1/2 to 1 in.]) dry-mix shotcrete were largely responsible for the introduction and the successful application of shotcrete for underground support in the United States. Shotcrete for structural support of underground construction usually contains a significant percentage of gravel-sized coarse aggregate ranging up to 19 or 25 mm(3/4 to 1 in.). The use of larger sizes

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has been reported to result in better compaction and thus increased density, lower cement and water requirements, less shrinkage, and higher bond and flexural strength (Blanck, 1974; Kobler, 1966). However, there are conflicting opinions and some evidence that the use of very large aggregates does not provide as many benefits as originally believed. Certainly, the amount of rebound is substantially higher with the larger aggregates, and for this and other reasons, the present trend (1975) in the United States appears to be toward limiting aggregate sizes to 12 to 19 mm (1/2 to 3/4 in.).

Until conclusive results on the behavior of shotcrete with various proportions of aggregate become available, it is recommended that the initial trial mixes contain aggregate of at least 9 mm (3/8 in.) and up to a maximum of 12 mm (1/2 in.) in size. During the shooting of trial mixes, the maximum size can be varied between 9 and 19 mm (3/8 and 3/4 in.) if desired. Most dry mix equipment can easily handle aggregates of these recommended sizes. The maximum size in the wet-mix process strongly influences pumpability and smaller aggregates may be necessary to meet the pumpability criteria.

Relative Proportion of Coarse and Fine Aggregate. Typically, a mix for underground construction might be graded so that 40 to 50 percent of the combined aggregate is gravel sized, i.e., retained on the No. 4 sieve (4.76 mm) (Kobler, 1966). The aggregate source for fine aggregate and for coarse aggregate may both contain some sand-sized particles, the percentage of coarse and fine aggregates may be adjusted to obtain the desired percentage of gravel-sized material in the combined gradation. Blanck (1974) recommended the range of gradation shown in Fig. 3.5 for the combination of both sand and

3-27
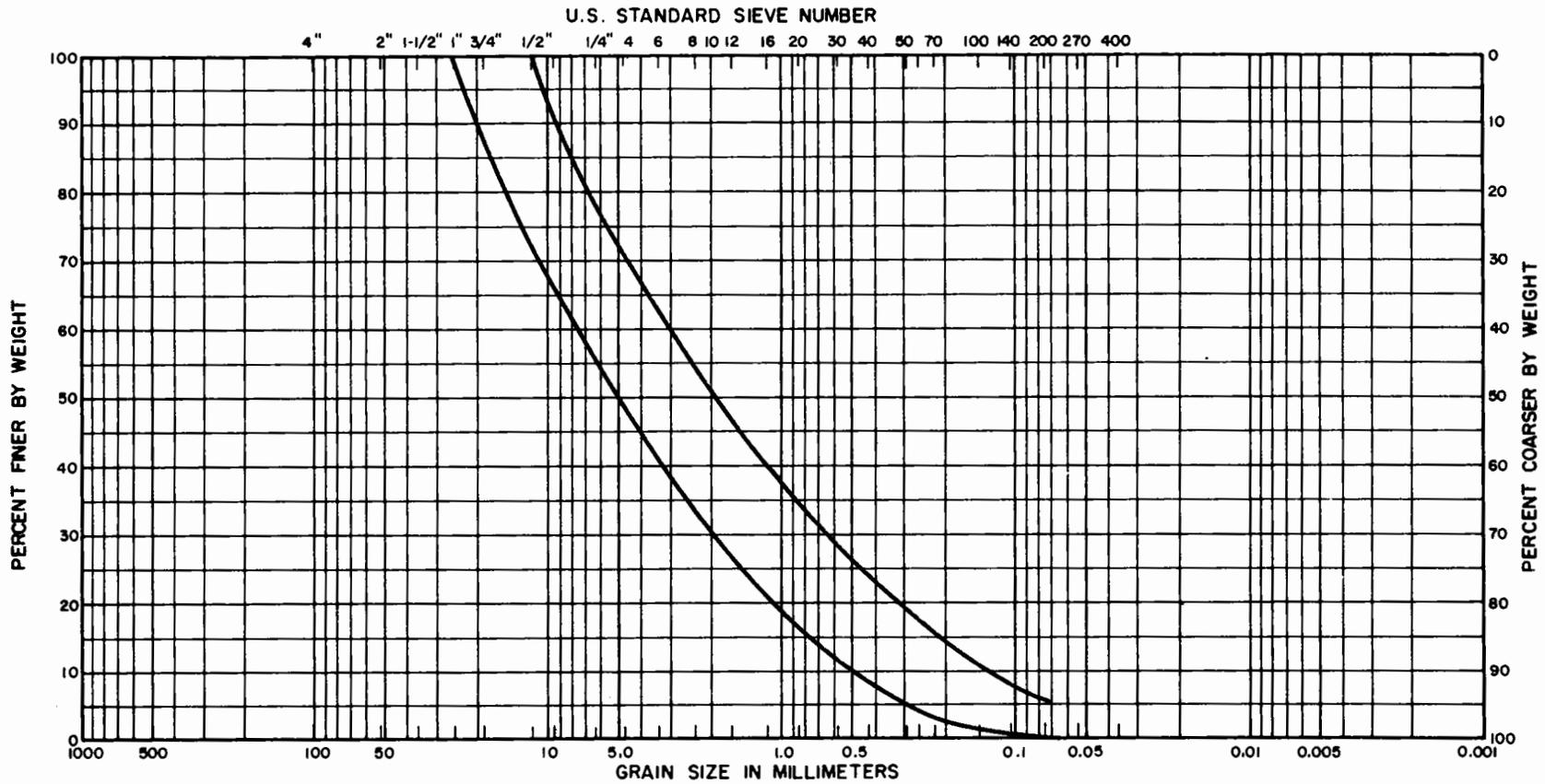
FIG. 3.5 RECOMMENDED GRADATION RANGE FOR COMBINED FINE AND COARSE AGGREGATE
(DATA FROM BLANCK, 1975)

gravel. Once the mix meets the criteria, the percentage of coarse aggregate may be adjusted in subsequent trial mixes to refine the design for economy and for superior engineering properties.

An increase in the percentage of the coarse aggregate fraction in the mix up to about 50 percent will affect the engineering properties of the shotcrete in the same way as an increase in the maximum size of coarse aggregate, but to a lesser degree. Thus one can expect better compaction, increased density, lower cement and water requirements, less shrinkage and higher bond and flexural strength with an increased percentage of coarse aggregate. One can also expect higher rebound percentages. However, a moderate increase in coarse aggregate percentage does not increase rebound as much as a moderate increase in maximum size.

The pumpability of wet-mix shotcrete is also strongly affected by the percentage of coarse aggregate. The higher the percentage of coarse aggregate, the more difficult to pump. However, most wet-mix equipment of the type and capacity needed for underground work should be able to handle up to 50 percent coarse aggregate which is well graded with a maximum of 1/2 in. (13 mm) size.

Guidelines for Selection of Cement and Accelerator

All available cements must be tested for compatibility with the available cements. A general flow path for this process of selection of compatible cement and accelerators is given as a hypothetical example in Fig. 3.6. Only cements combined with three powder accelerators and three liquid accelerators are shown but the flow chart can be expanded to any size. Cement
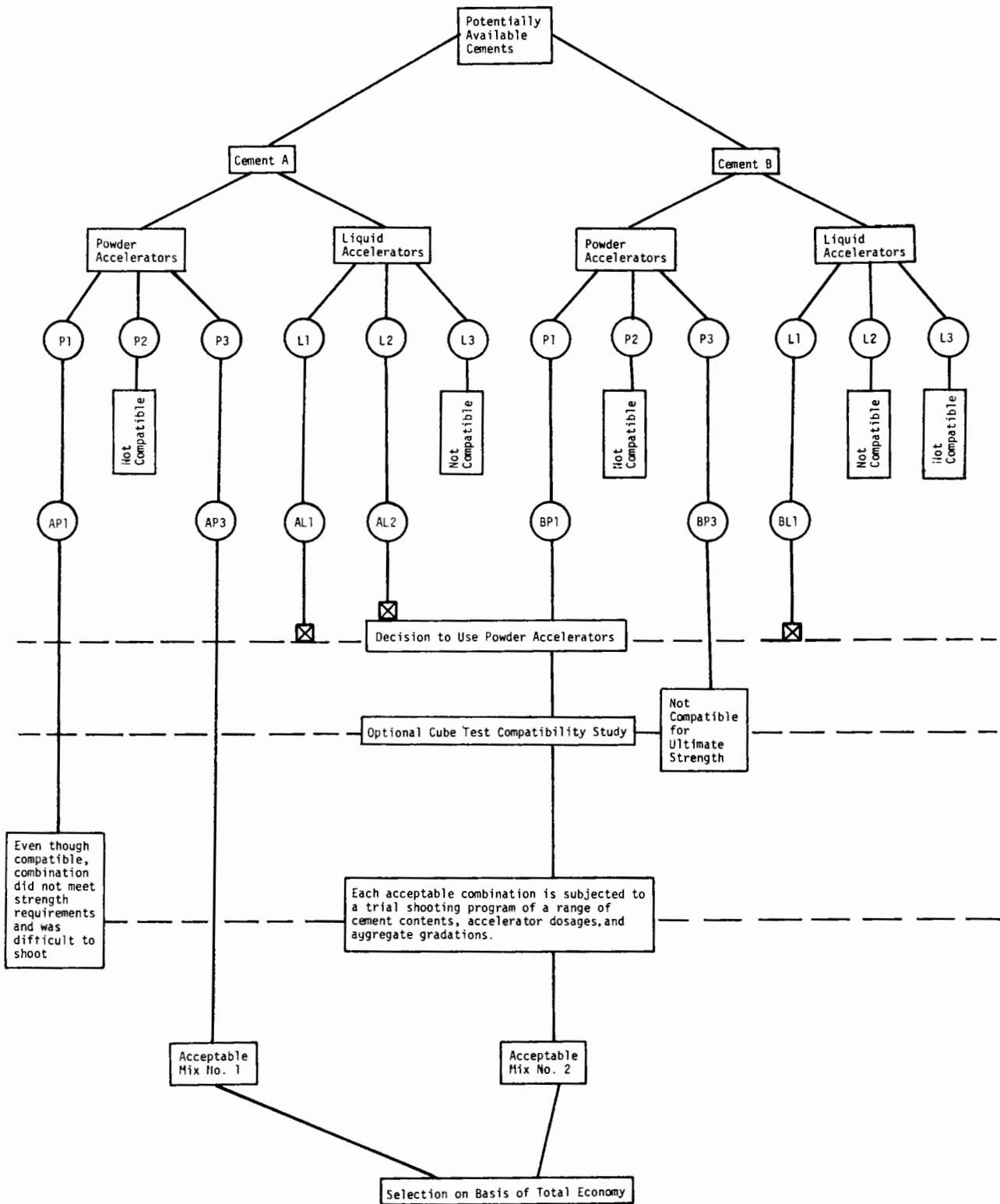
FIG. 3.6   FLOW CHART FOR SELECTION OF
CEMENT AND ACCELERATOR

brands are designated by capital letters. Powder accelerators are designated by P and a numeral, i.e., P1, P2, etc., and liquid accelerators are designated as L1, L2, etc. Compatibility tests in the form of Gillmore Needles Tests are conducted on the entire combination. A box-type summary table can be used to summarize these results as shown in the simplified hypothetical table in Fig. 3.7. Those combinations which are compatible, designated in Figs. 3.6 and 3.7 by the brand code and the accelerator code (i.e., AP1, AP3, etc.), may be continued for additional investigation. All those not compatible in Fig. 3.7 are cast out as shown in Fig. 3.6. Somewhere along the line, a decision concerning equipment might eliminate the need for either liquid or powder accelerators. Those mixes not needed may be cast out at that stage as shown in Fig. 3.6 (for liquid accelerators AL1, AL2, and BL1). The selection process to this point gives combinations that will be shootable and should also achieve an adequately fast set and rate of gain of strength.

Accelerators

	P1	P2	P3	L1	L2	L3
Cement A	AP1 3-4%	NC	AP3 2-5%	AL1 2-4%	AL2 3-6%	NC
Cement B	BP1 2-5%	NC	BP3 4-7%	BL1 1-3%	NC	NC

Note: NC = Not compatible for early set in Gillmore Needle Tests.
2. AP1 = Combination of Cement A with accelerator P1.
3. Percentage shown in box is range of accelerator dosage combination is compatible.

FIG. 3.7 EXAMPLE SUMMARY CHART FOR EVALUATION OF GILLMORE NEEDLES TESTS

At this stage, if batching and shooting equipment has not arrived or is not set up, a cube test program can be conducted to evaluate the relative rate of gain of strength and the relative potential effect of various dosages of accelerators on the ultimate strength of the shotcrete. No mixes should be cast out solely on the basis of cube tests as there is some danger that the test procedures may affect the test results. However when done properly, the cube tests can give vital information about the effect of accelerators on early and 28-day strength. To do this, cube tests should be made on mixes without accelerator so that a comparison can be made. If cube tests meet the early strength and the 28-day strength specification, it is likely that the mix could meet the specification if shot properly. If cube tests do not meet the specification, there is a chance that disturbance during preparation of the cubes may have reduced the strength. This is especially true if the cement and accelerator have a very short initial set time. Disturbance always acts to reduce the measured strength. No matter how it is done, the final selection and ordering of cement should not be made until it is proved through trial mixes or cube tests that there is satisfactory 28-day strength. Once the decision on the cement is made, the project is locked-in to a certain accelerator and a certain strength.

Special Considerations for Wet Mix

Wet-mix shotcrete is ordinary concrete which is pumped or blown through a hose to the nozzle where a metered dosage of accelerator is added. Since the process starts with a wet concrete mix, the procedures for mix design

of concrete are applicable. An assumed or desired water-cement ratio and cement content may be used to design a mix by the same procedures used for concrete (PCA, 1975; ACI, 1974). When using this procedure, the cement content on the wall may be assumed to be slightly higher than that batched.

The water-cement ratio (which determines slump), the cement content, and the aggregate gradation and size, etc., all must be selected so as to provide a "pumpable mix." The design of a mix to achieve pumpability is a difficult task. Guidelines for proportioning mixes for all aspects of pumping are given by ACI (1971).

Generally crushed stone is more difficult to pump than gravels. The cement paste content and the gradation of the aggregate are vital parameters to pumpability. A given gradation will have a certain void volume. Kempster (1969) reports that cement content should be equal to or greater than the aggregate void volume. Too much cement is also detrimental. The maximum aggregate size should be less than 1/3 of the smallest constriction in the hose line. ACI (1971) gives recommended aggregate gradations. If pumping difficulty still occurs, there are commercial admixtures which improve pumpability. If pumping admixtures are to be used, their effect on compatibility must be checked.

Trial mixes selected on the basis of experience can be used by those contractors who have the experience. After these mixes are selected, they must be checked in the field and varied by trial and error methods to optimize the desired characteristics.

Accelerator Combinations. Pre-construction compatibility tests answer two important questions. First, those accelerator-cement combinations which are clearly incompatible are identified. Second, the percentage of accelerator that will provide the shortest possible set time for each of the accelerator-cement combinations that are compatible will be determined for an entire range of temperatures. The most economical combination can then be selected. Unfortunately, in some geographical areas only one combination may be compatible and that one may only be marginally compatible. Obtaining proper compatibility is necessary in order to achieve a mix design that will produce the highest early strength and the least rebound. When the most favorable accelerator-cement combination is used with the optimum additive concentration, construction will be more economical since accelerator content can be held to a minimum and the shotcrete can be applied in thicker layers.

The optimum concentration need not be used for all applications, but the fast set and high early strength must be attainable when ground conditions so require. By minimizing the use of accelerators, reductions in ultimate strength are also minimized and less shrinkage is associated with the shotcrete in place (Blanck, 1974). Concentrations for powder accelerators are generally in a range of 3-6 percent of cement weight; liquid accelerators are batched in volume ratios to water ranging from 1:20 (very low) to 1:1 (Brekke, 1972). However, the various liquid accelerators have different concentrations of solids. This concentration must be taken into account when volume ratios are used.

Conditions Requiring Use of Accelerator. The considerable expense involved in using accelerator is reason enough to limit its use, but further reasons such as the lower ultimate strength and the safety hazard caused by its causticity can also be listed. Nevertheless, where quick-setting properties are required in order to permit a rapid buildup of shotcrete to the desired thickness, to develop very early strengths (to provide immediate support), and to seal off water leakage, use of an accelerator is indispensible (Reading, 1974). Thus, accelerators are normally used on all overhead work, on some vertical walls (especially where the shotcrete layer thickness is considerable) and in locations of high groundwater flows. Even when not needed for these purposes, however, accelerators are useful in preventing sagging and sloughing of the shotcrete during application and in reducing rebound.

Situations where a rapid gain in early strength is not required and where accelerators consequently need not be used include applying a reasonably thin layer on a dry and clean rock surface (Brekke, 1972), applying a layer of any thickness to the invert, and applying the final layer over a previously shotcreted surface (Kobler, 1966).

3.2.3 Shooting of Trial Mixes

Once the shotcrete equipment is set up and the crew adequately experienced, actual shooting of trial mixes may be conducted. If the cube test program indicates that one or two cement and accelerator combinations will meet both initial and final sets, and still achieve the specified early strength and 28-day strength, trial mixes may be made on these mixes.

Possibly a certain cement brand will be chosen on the basis of lowest material cost. Thus by the time shooting of trial mixes begin, only one cement and perhaps one or two accelerators may need to be tested. For some projects, it may be necessary to test three or four different combinations.

Variations in Trial Mixes

Several different trial mixes can be shot over the period of pre-construction testing and into the early stages of construction so that the optimum mix design can be determined. The first priority is the determination of a mix that achieves the specified strength requirements, etc., so that the beginning of tunnel construction will not be delayed. This goal might be achieved by shooting several trial mixes covering a range of cement contents and aggregate combinations. It is recommended that one aggregate combination be selected which provides about 50 percent gravel size (retained on the No. 4 sieve; 4.76 mm). Many mixes on different projects meeting this criterion have been satisfactory. Several mixes with a range of cement contents may be shot with this gradation. Variations in mix design may be made by trial mixes in one of the following ways:

a) Several trial mixes for each cement content may be shot, each having a different ratio of sand to gravel.

b) One or two cement contents that are expected to achieve the specified strength may each be subjected to several trial mixes having different aggregate ratios.

c) If time is available, a few mixes may be shot
    having a range of cement content and aggregate
    ratios. Strength tests are made frequently and
    plotted on strength-time curves. After about
    7 to 14 days, the 28-day strength can be
    extrapolated from the strength-time curves.
    Refinements in the mix can be made on the
    basis of these data and new trial mixes shot.
    The procedure could be repeated as necessary.

The shotgun approach in (a) is inefficient but may be useful if it is
impractical to wait until strength results are obtained. At the end of 28
days, the best mix is selected. In the limited approach in (b) there is a
risk that the initial trial mixes will not be satisfactory. The rational
approach in (c) uses the information obtained on previous trial mixes to
select the next series of trial mixes to be shot. Each time, the mixes shot
are refined so that the optimum mix can be determined.

Use of Strength-Time Plots

If there is any question that the mix design may not meet the required
specification for any given age, every effort should be made to test enough
specimens at frequent intervals so that a strength-time curve can be plotted
as shown in Figs. 3.8 and 3.9.

Figures 3.8 and 3.9 are hypothetical strength-time curves illustrating how
the data can be presented. Figure 3.8 is for a mix that achieves both the
assumed specified early and 28-day strength; Figure 3.9 is for a mix that

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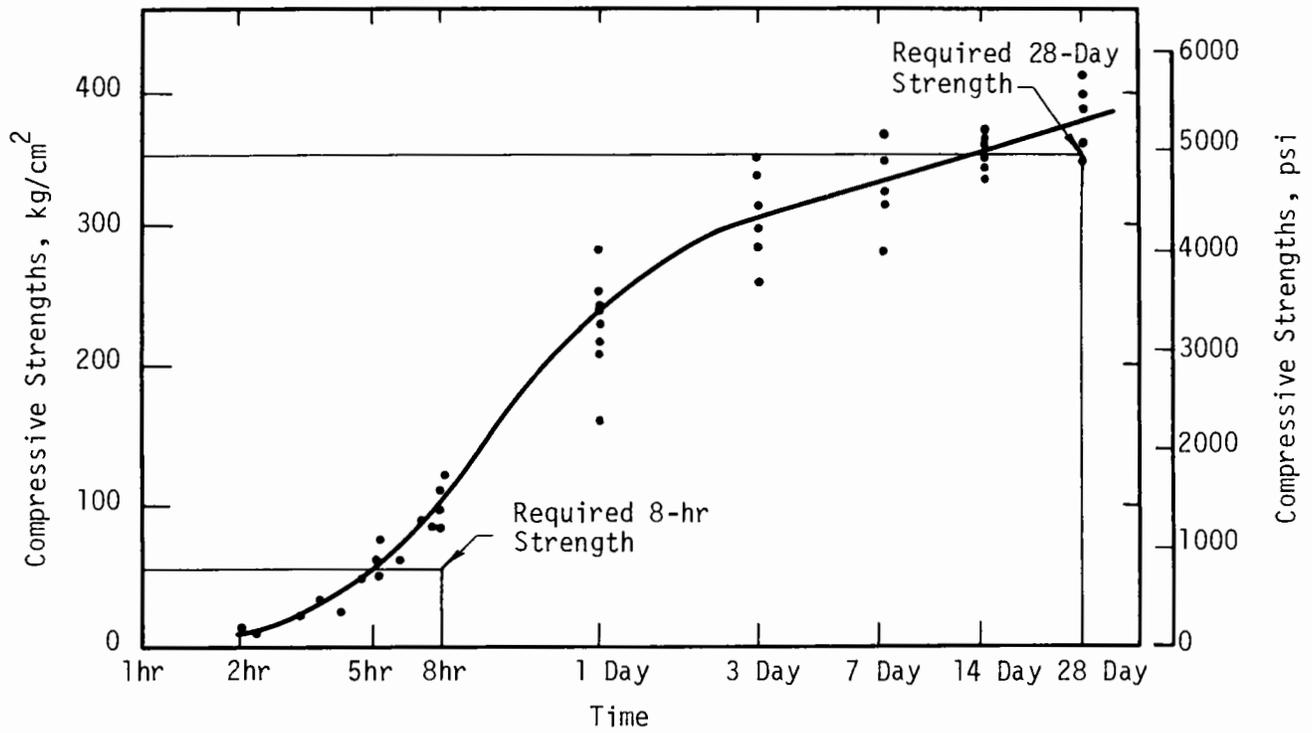
a) Semi-logarithmic plot
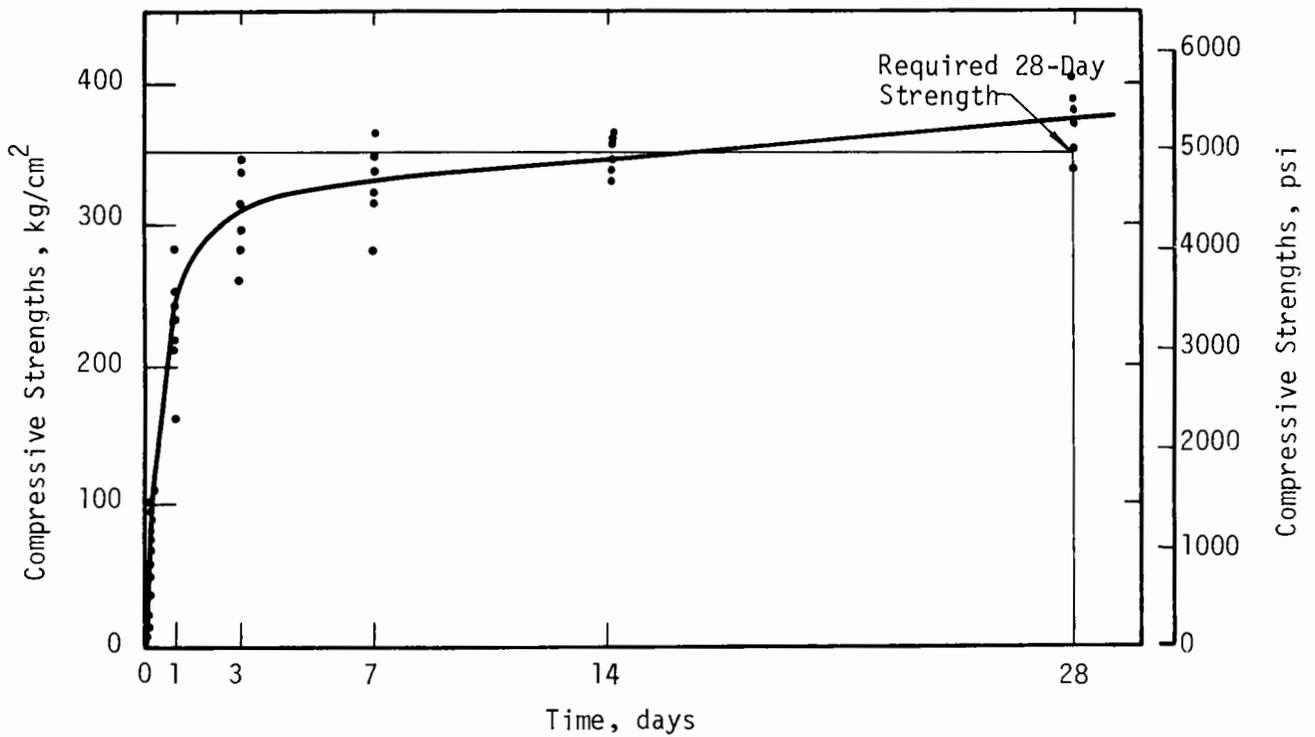
b) Arithmetic plot

FIG. 3.8.   HYPOTHETICAL STRENGTH-TIME CURVES FOR A MIX THAT ACHIEVES
            28-DAY STRENGTH CRITERION

3-38
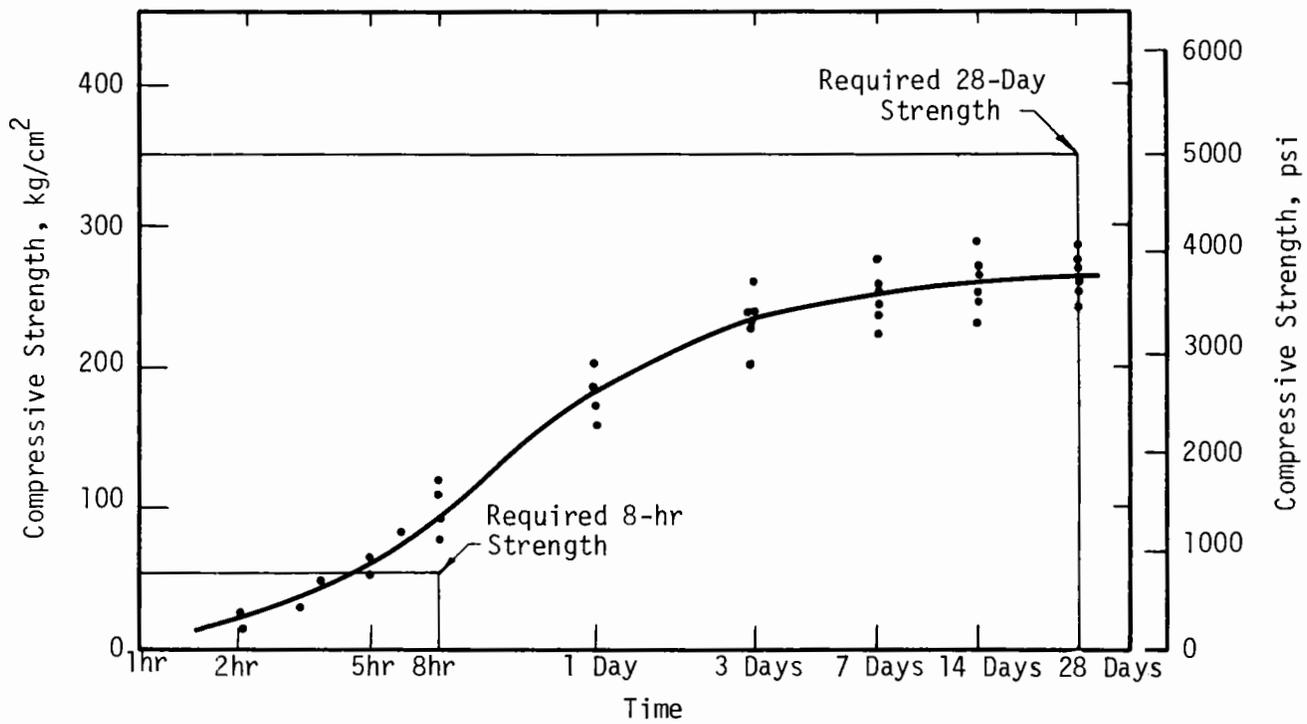
a) Semi-logarithmic plot.
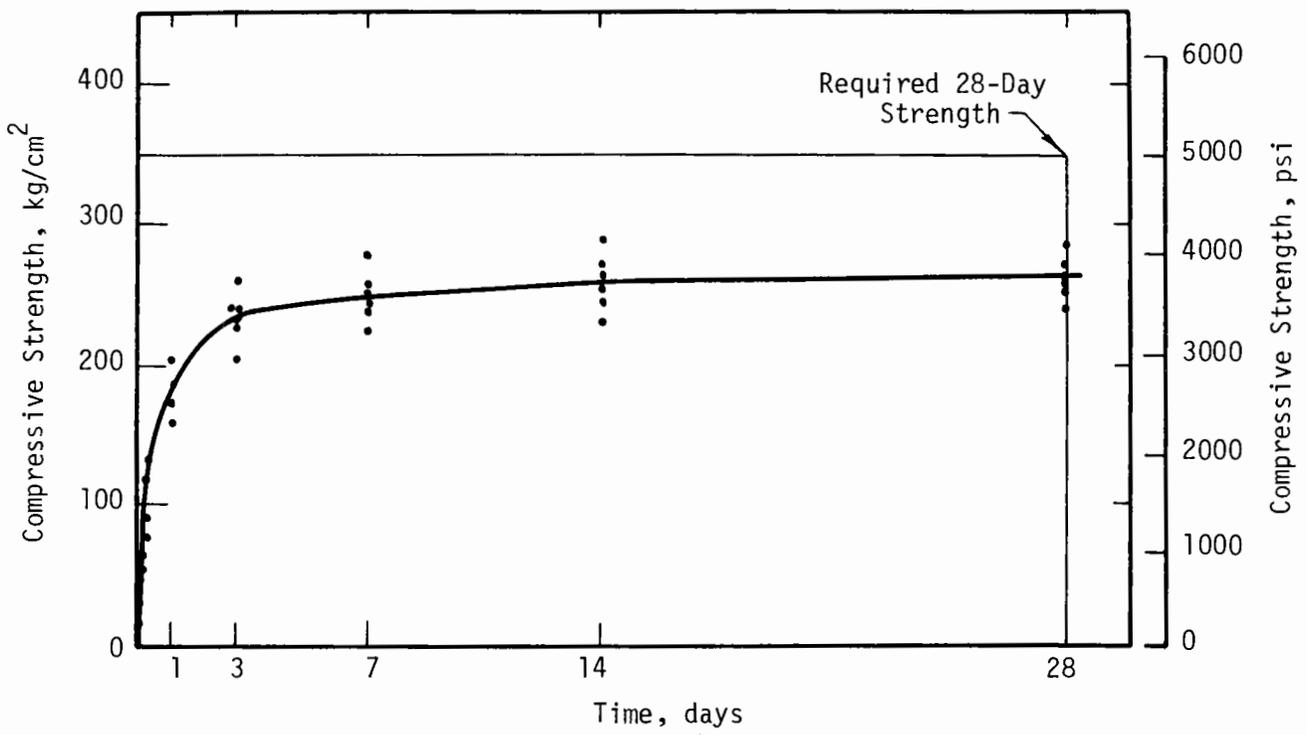
b) Arithmetic plot.

FIG. 3.9.   HYPOTHETICAL STRENGTH-TIME CURVES FOR A MIX THAT DOES NOT
ACHIEVE 28-DAY STRENGTH CRITERION

achieves the early strength criterion but not the 28-day criterion. The same data is plotted two ways in each figure. The upper diagram is a strength-versus-logarithm of time plot that can be used to show early and long-term strength with equal clarity. The slope of the curve of this logarithmic plot, however, is not the true rate of gain of strength as it is in the arithmetic plots shown in the lower diagram. The early strength behavior in an arithmetic plot can not be interpreted as well.

Each test result (not the average) should be plotted so that a visual impression of the average and of the scatter can be obtained. The data for each test period should also be evaluated statistically to determine the mean, standard deviation and the coefficient of variation. By plotting the data comparing the strength-time curve to strength-time curves from other projects or those shown in Chapter 4, one can extrapolate ahead to estimate the strength at some future time. In most cases, whether or not a mix will achieve the required 28-day strength will be known in about 7 to 14 days. If it appears the mixes will not meet the required strength (Fig. 3.9), there is no need to wait until 28 days to begin a new series of trial mixes.

The plotted strength-time curve is a very powerful tool in evaluating a mix. It is too difficult to see trends from tabulated data. It can be seen in Figs. 3.8 and 3.9 that the 28 day strength can be extrapolated with sufficient accuracy. The plotted strength-time curve also is useful in determining the early-strength behavior of shotcrete and the quality of testing. If the panels are sawed up into prisms with a masonry saw as described in Chapter 8, good specimens can be obtained of shotcrete with very low strengths.

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Prisms can thus be sawed and tested at 4, 8, 12 and 24 hours so that the curve of strength gain can be plotted. These curves are very useful in assessing the reasons why one design is satisfactory and another is not. In the case of early strength, only three tests are necessary at each age and each test should be plotted at its respective age at testing to the nearest 5 minutes.

Importance of Simulating and Documenting Conditions

Procedures for shooting panels during preconstruction testing are given in Chapter 8. It is important that the shooting conditions during these mix-design tests simulate the anticipated conditions during tunneling as closely as possible. This cannot be completely achieved but it is vital that the shooting conditions be documented accurately. A list of parameters that should be documented are given in Table 3.5. The purpose of this documentation is to aid the evaluation of the 28-day strength results. Without the records, no one will remember for sure what the weather was and how the panel was cured. These environmental conditions do affect the strength and the inability to achieve the desired strength may be due to factors other than the proportions of the ingredients.

Importance of Curing

It is very important to cure the test panels in a manner simulating anticipated conditions. At the very minimum, all test panels shot should be cured in exactly the same manner so that the strength of the panels can be compared to each other without the variable of curing conditions.

Table 3.5. Summary of information that should be recorded for each trial mix

---

Environment

  Temperature of all materials, cement, sand, water, accelerator
  Air Temperature
  Weather (Temperature and approximate humidity)

Shooting Conditions

  Material Delivery Rate (MDR)
  Water rate at one minute intervals
  Exact accelerator dosage (Requires weighing before and after shooting)
                         and, if dispensed uniformly in time,
                         correlation with the MDR
  Approximate length of time accelerator added to mix before shooting.
  Nozzle type - (include details of water ring)
  Water pressure
  Air pressure (Total length and diameter of hose)

Mixing Conditions

  Type of mixer
  Sequence of batching
  Length of time ingredients batched
  Batch proportions
  Moisture content of aggregates and dry-mix

Method of Transporting

  Elapsed time from adding cement to beginning and end of shooting,
      i.e., range of age of shotcrete at time shot.

  Observations on Shooting

    Range of nozzle distance
    Normal motion used by nozzleman:
      Range of angle of nozzle to work
      Nature of pulsations in air stream
      Tendency to entrap rebound pockets
      Nature of water in airstream

        a) Uniformly dispersed
        b) Heavy stream at top or bottom

    Abnormal dusting

  Any plugs or other temporary stoppages

  Exact time of shooting a given panel to nearest 5 min

Rebound

  Total thickness shot (very important)

At least 1.5 m^3 (2 yd^3) should be shot of each mix design. Several test panels should be shot during the latter half of the batch after the nozzleman has had sufficient time to become accustomed to the mix and has adjusted the water to his satisfaction. One m^3 (1.3 yd^3) is not enough preparation for test-panel shooting.

Sufficient test panels should be shot to permit testing of several samples at each of several selected time periods up to at least one month. There is too much at stake to base decisions on only 3 tests. A minimum total of 6 to 9 samples should be taken from at least 3 different panels so that a representative average of the true capabilities of the mix and of the nozzleman can be tested.

Rebound and Other Shooting Tests

Strength testing is only a part of the trial mix program during pre-construction testing. A standard rebound test (Appendix D) should be conducted for each trial mix so that relative rebound comparisons of the mix design can be determined.

In addition, the tests should include a careful evaluation of the ability of the mix design and of the nozzle to be able to place a substantial thickness of shotcrete on a wall and overhead. The maximum thickness of shotcrete that can be placed in one layer should be determined both for overhead and wall surfaces. The surfaces should simulate the anticipated shooting conditions in hardness and wetness. For a comparison of trial mixes for the mix design, it is important that the accelerator dosage be the same as that shot for the strength tests.

Nevertheless, it is also of interest to know how adaptable the mix design will be under severe shooting conditions. The maximum thickness of shotcrete that can be placed in one layer using whatever accelerator dosage necessary to achieve the maximum thickness is of practical interest to the contractor.

3.3 Typical Mix Proportions for Coarse Aggregate Shotcrete

There is no such thing as a definable "cubic meter" or a "cubic yard" in dry-mix shotcrete. The volumetric quantity as a specification and as a pay item is a good example of how nomenclature in one technology (concrete) can be misleading in another (shotcrete). There is no time in the life of dry-mix shotcrete that the quantity batched or shot can easily be measured in units of volume, even if it is batched by volumetric ribbon-feed methods. The dry-mix before shooting cannot be measured by volume because of bulking problems. During shooting, water is added and there are substantial losses to rebound. After shooting, the irregularities of the rock wall that was shot make measurements of the volume of in-place shotcrete difficult. Only in a smooth machined tunnel is measurement of in-place volume possible. Consequently, the specifications often define a "cubic yard" in terms of a total weight. Unfortunately the definition of a cubic yard varies on different projects from about 1590 kg (3500 lb) to more than 1730 kg (3800 lb). Cement content and other mix design parameters lose their importance unless reported in terms of percentage of total dry weight. Terms like bags per cubic yard are not as meaningful as in concrete.

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The wet-mix process, on the other hand, is batched with all its mixing water which would permit easy measurement in terms of volume, as batched, provided the unit weight is determined.

Because of these problems, efforts will be made to present typical values in terms of percentages in addition to customary terms. One method in which the problem could be minimized in the future would be to adopt a defined standard batch weight industrywide. A weight equal to 1500 kg (3300 lb; 1-1/2 metric tons) would be a reasonable standard batch weight to adopt.

Table 3.6 summarizes the mix designs for several recent projects using dry-mix coarse aggregate shotcrete; Table 3.7 summarizes recent designs for wet-mix coarse aggregate shotcrete.

Cement contents generally are about 335 to 390 kg per m^3 (6 to 7 bags per yd^3). Since rebound produces an in-place cement content higher than the dry mix, a mix containing 335 to 360 kg per m^3 (6 to 6-1/2 bags per yd^3) is often considered adequate for a strength of about 350 kg/cm^2 (5000 psi) (Blanck, 1974). Measurements taken during a recent test program indicated that the process of rebound resulted in the cement content increasing from about 19 to 24 percent of the total dry weight of the mix or about 110 kg per m^3 (2 bags per yd^3) (Parker, et al., 1975).

For dry-mix shotcrete, the water-cement (w/c) ratio generally falls in the range of 0.32 to 0.40 by weight as reported by Kobler (1966), while Reading (1966) reports a somewhat larger range of 0.35 to 0.50. In dry-mix shotcrete, the amount of water added is controlled at the nozzle. Consequently, only indirect measurements have usually been made of the in-place

Table 3.6 Selected mix designs for dry-mix coarse aggregate shotcrete

Project	Ingredient (typical)	Batch weight		Percent of total batch weight	Reference and remarks
		kilograms	pounds		
Washington, D. C. Metro (General)					
	Cement (Type I)	298.5	658	18.7	Bawa (1974)
	Coarse Aggregate (13 mm, 1/2 inch)	649.0	1431	40.65	Some projects contained 320 kg (705 lb) cement
	Fine Aggregate	649.0	1431	40.65	Coarse aggregate/total
	Total	1596.5	3520	100.0	aggregate = 50%
New Melones Dam, California					
	Cement (Type II)	298.5	658	18.8	Corps of Engineers (1974)
	Coarse Aggregate	606.0	1336	38.17	Coarse aggregate/total
	Sand	683.0	1506	43.03	aggregate = 47%
	Total	1587.5	3500	100,0	
Vancouver Tunnel, Canada					
	Cement (Type I)	295.0	650	16.6	Mason (1970)
	Stone (19 mm, 3/4 inch)	408.	900	23.0	Coarse aggregate/total
	Stone (6 mm, 1/4 inch)	385.5	850	21.7	aggregate = 53%
	Sand	689.5	1520	38.7	
	Total	1778.0	3920	100.0	
IITRI Research Program (3 cement contents)					
	Cement (Type I)	213.0	470	13.5	Bortz, et al., (1973),
	Crushed Stone (13 mm, 1/2 inch)	500.5	1103	31.5	Singh and Bortz (1974) 5-Bag Mix
	Dry Sand	873.0	1925	55.0	Coarse Aggregate/total
	Total	1586.5	3498	100.0	aggregate = 36%
	Cement (Type I)	298.5	658	17.9	7-Bag Mix
	Crushed Stone (13 mm, 1/2 inch)	500.5	1103	29.9	Coarse aggregate/total aggregate = 36%
	Dry Sand	873.0	1925	52.2	
	Total	1672.	3686	100.0	
	Cement (Type I)	384.0	846	21.8	9-Bag Mix
	Crushed Stone (13 mm, 1/2 inch	500.5	1103	28.5	Coarse aggregate/total aggregate = 36%
	Dry Sand	873.0	1925	49.7	
	Total	1757.5	3874	100.0	
Waterways Experiment Station Research					
	Cement (Type II)	42.5	94	17.7	Tynes and McCleese, (1974)
	Coarse Aggregate (19 mm, 3/4 inch)	79.0	174	32.7	Coarse aggregate/total aggregate = 40%
	Sand	120.0	264	49.6	
	Total	241.5	532	100.0	
University of Illinois Research Program					
	Cement	113.5	250	18.4	Fernandez, et al., (1975)
	Coarse Aggregate (9 mm, 3/8 inch)	256.0	564	41.4	Coarse aggregate/total aggregate = 51%
	Sand	249.0	548	40.2	
	Total	618.5	1362	100.0	

Note: Batch weights shown are for saturated-surface dry aggregates. Actual batch weights are adjusted in the field to account for actual moisture content of aggregates.

Table 3.7 Selected mix designs for wet-mix coarse aggregate shotcrete

Project	Ingredients	Batch weight kilograms	Batch weight pounds	Percent of total batch weight	Percent of dry components	Reference and remarks
Lakeshore Project Hecla Mining Co.						
	Cement (Type II)	286.0	630	15.8	17.3	Chitunda, (1974)
	Coarse Aggregate (13 mm, 1/2 in.)	621.5	1370	34.5	37.6	Water-cement ratio = .53
	Fine Aggregate	744.0	1640	41.3	45.1	Coarse aggregate/ total aggregate = 45%
	Water	151.5	334	8.4	--	
	Total	1803.0	3974	100.0	100.0	
Waterways Experiment Station Research						
	Cement (Type II)	42.5	94.0	16.3	17.7	Tynes & McCleese, (1974)
	Coarse Aggregate (19 mm, 3/4 in.)	80.5	177.5	30.8	33.5	Water-cement ratio = 0.5
	Sand	117.5	258.9	44.8	48.8	Coarse aggregate/ total aggregate = 41%
	Water	21.5	47.0	8.1	--	
	Total	262.0	577.4	100.0	100.0	
IITRI Research Program (3 different Cement Contents)						
	Cement (Type III)	213.0	470	12.8	13.5	Bortz, et al., (1973)
	Crushed Stone (13 mm, 1/2 in.)	500.5	1103	29.9	31.5	Singh & Bortz (1974)
	Dry Sand	873.0	1925	52.2	55.0	5 bag mix
	Water	85.5	188.0	5.1	--	Water:cement ratio = 0.4
	Total	1672.0	3686.0	100.0	100.0	Coarse aggregate/ total aggregate = 36%
	Cement (Type III)	298.5	658	16.7	17.9	7 bag mix
	Crushed Stone (13 mm, 1/2 in.)	500.5	1103	27.9	29.9	Water-cement ratio = 0.40
	Dry Sand	873.0	1925	48.7	52.2	Coarse aggregate/total aggregate = 36 %
	Water	119.5	263	6.7	--	
	Total	1791.5	3949	100.0	100.0	
	Cement (Type III)	384.0	846	20.1	21.8	9 bag mix
	Crushed Stone (13 mm, 1/2 in.)	500.5	1103	26.2	28.5	Water-cement ratio = 0.4
	Dry Sand	873.0	1925	45.7	49.7	Coarse aggregate/total aggregate = 36 %
	Water	153.5	338	8.0	--	
	Total	1911.0	4212	100.0	100.0	
St. John's Abbey, St. Paul, Minn.						
	Cement (Type I)	256.0	564		16.4	Hoffmeyer, (1966)
	Gravel (16 mm, 5/8 in.)	517.0	1140		33.2	Coarse aggregate/total aggregate = 40%
	Sand	784.5	1730		50.4	
	Water	--	--		--	
	Total	1557.5	3434		100.0	
Henderson Mine						
	Cement (Type I)	295.0	650		17.8	Jones (1974)
	Coarse Aggregate (9 mm, 3/8 in.)	453.5	1000		27.4	Coarse aggregate/total aggregate = 33%
	Sand	907.0	2000		54.8	
	Water	--	--		--	
	Total	1655.5	3650		100.0	

w/c ratio, and this no doubt explains some of the variation. Further, because of rebound, the water-cement ratio on the wall may be lower than the water-cement ratio in the airstream (Parker, et al., 1975). Thus, the w/c ratio for dry-mix shotcrete probably lies within a range of 0.3 to 0.5 and must be adjusted by the nozzleman according to his experience and judgment to cope with the shooting conditions. Since the method of gunning dry mix shotcrete causes pulsations of dry mix in the hose, the final water-cement ratio in place varies somewhat throughout the material.

The water-cement ratio for wet-mix shotcrete generally ranges between 0.4 to 0.6. However, a major difference lies in the fact that the water is batched with the cement and aggregate before the material reaches the nozzle. Consequently, the w/c ratio is more uniform and it can be controlled. The slump of pumpable shotcrete mixes generally ranges from 1/2 to 2 in. (Fredericks, et al., 1966).

CHAPTER 4

ENGINEERING PROPERTIES OF COARSE AGGREGATE SHOTCRETE
WITH FAST-SET ACCELERATORS

When considering the engineering properties of shotcrete it is important
that careful attention be given to the possibility that certain accepted con-
cepts or techniques of concrete technology may be less applicable or inappli-
cable to shotcrete. Despite a great many similarities, shotcrete is not con-
crete. One should not be misled by the similarities in appearance of the
materials used and of the final product. Most of the ingredients are the same
but the method of placement and the effect of parameters that determine the
final product are substantially different in many ways. The method of place-
ment makes shotcrete potentially more variable and more anisotropic than con-
crete. Shotcrete is compacted by impact rather than by vibration. It is placed,
especially dry-mix shotcrete, at a different consistency and usually at a lower
water-cement ratio than concrete. It does not bleed in the normal sense of
concrete terminology. The individual constituents rebound at different rates
and, thus, the composition of the shotcrete in-place is substantially different,
usually finer and richer, from the composition as batched.

The development with time of the engineering properties, such as strength,
of shotcrete containing fast-set accelerators is drastically different from
concrete. The accelerators typically used in shotcrete for underground support
bear no relationship either in their composition or in their action to calcium
chloride, the most common accelerator used in concrete. Shotcrete accelerators
have an overpowering effect on the engineering properties throughout the life

of shotcrete. The effects are particularly noticeable during the very early and long-term stages. Generally, curing practices underground are substantially different from normal concrete practice.

These differences reduce the applicability of some, but not all, of the established concepts and rules of thumb in concrete technology. Certainly one must assess shotcrete technology and properties from a different perspective than customarily used for concrete. This is especially true of the degree to which a certain parameter governs the engineering properties. The effect of some mix design parameters that are important to concrete may be overshadowed by the shooting conditions in shotcrete and, thus, may have a reduced, complex, or illusive effect. It appears that parameters that have no clear optimum value in their normal range for concrete may have an optimum value in shotcrete, often dictated by shooting conditions. For example, in shotcrete, it has been observed that higher cement content results in higher strengths up to an optimum, above which, little increase or even lower strength results because of the effect of shooting conditions.

Nevertheless, shotcrete is a cementitious material and its behavior is governed by many of the same fundamental rules that govern the behavior of concrete. Where conditions are the same or when they result in the same compaction or degree of particle contact with similar cement content and curing conditions, the properties should be similar. It could be said that the fundamental rules of behavior are the same but the boundary conditions (methods of placement and curing) are often substantially different.

4.1 Factors Affecting Strength

The effect of time on the strength of shotcrete is generally to improve it. However, time is not a parameter, as is cement content or aggregate quality, that can be manipulated to achieve the desired results. Shotcrete, in some cases, is called upon to resist ground loads almost immediately. This contrasts with concrete practice where forms are left in place and loads are not applied until the concrete has cured. The time at which loads are applied to shotcrete is generally beyond the designer's or contractor's control, but it is often while the initial rapid rate of gain of strength is taking place. Development of adequate strength at an early age is a primary concern.

Because the initial shotcrete layer becomes a portion of the final support system, the ultimate strength is also important. The achievement of early strength conflicts with the achievement of long-term ultimate strength; factors that tend to improve the early strength of shotcrete generally have a detrimental effect on the ultimate strength. In summary, the development of strength in shotcrete is important throughout its entire life, but for underground support, particular emphasis is placed on the early stages.

Various factors affecting the engineering properties of shotcrete are categorized in Table 4.1. The table consists of ten major categories of problems regarding the engineering behavior of shotcrete. Various conditions or parameters that could cause the problem are listed for each major category according to the following subcategories: mix design, shooting conditions, curing conditions, testing errors, and ground conditions. The table may be

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Table 4.1 Factors affecting engineering properties of coarse
aggregate shotcrete with fast-set accelerators

Problem	Mix Design	Shooting Condition	Curing Condition	Testing Errors	Ground Conditions

I. Both early and ultimate strengths are low.	1. Low cement content.
	2. Mix has excessive dry-mix activity that causes pre-hydration.
	   Mix design parameters that affect dry-mix activity are:
	   a) high cement content
	   b) high potential of cement to set, such as higher fineness, or regulated-set or Type III cement characteristics or chemistry.
	3. Mix has excessive shooting activity; shooting after flash-set causes disturbance.
	   Mix design parameters that affect shooting activity are:
	   a) high cement content
	   b) high potential of cement to set quickly (see I,2b)
	   c) high degree of compatibility between cement and accelerator.
	4. Poor aggregate quality (affects ultimate strength only).
	5. Aggregate completely dry--can't get proper wetting.
	6. Poor water quality.
	7. Wet-mix batched at concrete batch plant may contain automatically dispensed additives that retard reaction (affects early strength only).
	8. Unburned oil or other contaminants in aggregate from improper drying operation.
		1. Mix has excessive dry-mix activity that causes prehydration.
		   Shooting conditions that affect dry-mix activity are:
		   a) high moisture content of dry-mix from excessively wet aggregate
		   b) high materials temperature during mixing and temporary storage before shooting
		   c) long storage times between mixing and shooting during which the cement is in contact with water in aggregates
		   d) any delay between addition of accelerator and shooting.
		2. Mix has excessive shooting activity; shooting after flash-set causes disturbance.
		   Shooting conditions that affect shooting activity are:
		   a) high accelerator dosage
		   b) high material and nozzle water temperatures
		   c) high environmental temperatures
		   d) lower water-cement ratio.
		3. Improper nozzling
		   a) low air pressure
		   b) insufficient water
		   c) water ring plugged
		   d) entrapment of air, rebound and laminations.
		4. Improper gun operation.
		5. Improper batching.
		6. Pumpability additive for wet-mix may be retarding cement-accelerator reaction (affects early strength only).
		7. Oil in water or compressed air lines.
			1. Humidity of tunnel too low and shotcrete allowed to dry out (affects only ultimate strength).
			2. Curing temperatures too low (affects both early and ultimate strength).
				1. Disturbance, while samples only a few hours old, to samples to be used for early and ultimate strength determinations.
				2. Samples for ultimate strength not cured in tunnel environment.
				3. See V.
					1. High sulfate concentrations in groundwater or soil(affects ultimate strength).
					2. Special chemistry in groundwater flowing into tunnel during shooting (acids, chemical wastes, etc.) can affect cement-accelerator reaction and thus early or ultimate strength.

Table 4.1   continued

Problem	Mix Design	Shooting Conditions	Curing Conditions	Testing Conditions	Ground Conditions
II. Low ultimate strength; early strength satisfactory.	1. Cement-accelerator compatibility using more accelerator than needed for the temperature. a) interpreted compatibility tests incorrectly b) batch to batch variations in cement and accelerator change compatibility c) increase in material or environmental temperatures. 2. Poor aggregate quality.	1. Actual accelerator dosage too high a) dispenser not set correctly b) dispenser out of adjustment c) material delivery rate lower than when dispenser calibrated. 2. Improper nozzling resulting in pockets and laminations (see I-3). 3. Improper or erratic gun operation. 4. Mix has high shooting activity. Activity is high enough to reduce ultimate strength but is still not high enough to cause flash-set (see Table 4.2, Part II). 5. Poor compaction; low air pressure.	1. Humidity of tunnel too low and shotcrete allowed to dry out. 2. Shooting in warm environment or with heated materials followed by curing at low temperatures.	1. See Part V.	1. High sulfate concentrations in groundwater or soil. 2. High inflow of water requiring high accelerator dosage.
III. Low early strength; ultimate strength satisfactory.	1. Cement-accelerator compatibility using less accelerator than needed for the temperature. a) interpreted compatibility tests incorrectly b) batch to batch variations in cement and accelerator change compatibility c) decrease in material or environmental temperatures. 2. Using slow setting cements like Type II and Types IV and V. 3. Poor water quality. 4. Wet-mix batched at concrete batch plant may contain automatically dispensed additives that retard reaction.	1. Accelerator dosage too low a) improper setting of dispenser b) dispenser plugged c) dispenser out of adjustment d) material delivery rate higher than when dispenser calibrated. 2. Shooting too wet. 3. Cement, accelerator, aggregates or water too cold. 4. Antifreeze additive to compressed air supply may be retarding cement-accelerator reaction. 5. Pumpability additive for wet-mix may be retarding cement-accelerator reaction.	1. Temperature too low for early strength gain.	1. Disturbance to early strength samples by rough handling or poor coring. 2. Testing equipment not calibrated in the low range necessary for early strength testing.	

Table 4.1 continued

Problem	Mix Design	Shooting Conditions	Curing Conditions	Testing Errors	Ground Conditions
IV. Erratic strength behavior					
a) high scatter in test results		1. Improper nozzling or gun operation. 2. Improper or erratic batching.	1. See Testing Errors	1. Testing methods not conforming to ASTM: a) specimen not centered in machine b) load rate too high, or too low or variable c) specimens not soaked properly or some soaked and others not d) poor caps. 2. Sample disturbance. 3. Samples not cured uniformly. 4. Direction of testing with respect to laminations not always the same. 5. Samples too small.	
b) low flexural strength or lower flexural strength than predicted from compressive strength.	1. Gradation of aggregates too fine.	1. Laminations from improper nozzle or gun operation.		1. Testing methods not conforming to ASTM. 2. Flexural specimens cured differently (drier and colder) than compression specimens.	
c) scattered zones of low strength		1. Non-uniform accelerator dosage a) erratic operation of dispenser. b) insufficient mixing after accelerator is dispensed c) accelerator caked into lumps. 2. Improper nozzling or gun operation. 3. Improper batching.		1. Bad samples; disturbance. 2. Not conforming to standard test procedures.	1. Scattered areas of high water flow requiring additional accelerator.
d) significant difference in strength between shifts		1. Improper nozzling or gun operation. 2. Improper batching.			
e) strength approximately similar for each shift but varies daily or weekly, etc.	1. Different batches of cement or accelerator having slight chemical or physical variations that affect compatibility significantly.		1. Overall changes in curing conditions periodically.	1. Not conforming to standard test procedures.	1. Variable conditions of water flow requiring changes in accelerator dosage.

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Table 4.1 continued

Problem	Mix Design	Shooting Conditions	Curing Conditions	Testing Errors	Ground Conditions
V. Test results appear too low.			1. See Testing Errors	1. Testing methods not conforming to ASTM: a) specimen not centered in machine b) load rate too slow c) load gage not calibrated d) poor caps. 2. Samples cured in colder and drier environment than tunnel conditions.	
VI. Test results appear too high.		1. Crew more careful when aware they are shooting strength specimens.	1. See Testing Errors	1. Samples cured in warmer and wetter environment than tunnel conditions. 2. Testing perpendicular to laminations. 3. Samples not soaked prior to testing. 4. Loading too fast.	
VII. Poor bond strength					
a) not sticking during shooting or immediately after shooting	1. Low cement content.	1. Accelerator dosage too low. 2. Surface not adequately prepared. 3. Improper nozzling procedure in diverting water flow. 4. Shooting too wet. 5. Layer too thick.	1. Dry tunnel above groundwater table resulting in poor curing conditions at interface.		1. Joint surfaces coated with clay gouge, highly slickensided, or airborne fines. 2. Excessive flowing water. 3. Absorptive rock tending to draw moisture from shotcrete into rock resulting in dry curing conditions in interface.
b) low early-bond strength	1. Low cement content.	1. Accelerator dosage too low. 2. Surface not adequately prepared. 3. Improper nozzling procedure in diverting water flow. 4. Shooting too wet.			
c) low ultimate bond strength	1. Gradation of aggregates too fine. 2. Low cement content.	1. Accelerator dosage too high.	1. Interface between rock and shotcrete permitted to dry during curing.		1. High sulfate in ground water or soil.

Table 4.1   continued

Problem	Mix Design	Shooting Conditions	Curing Conditions	Testing Errors	Ground Conditions
VIII. Durability unsatisfactory.	1. Poor aggregate quality. 2. Aggregates reactive to cement and accelerator.	1. Improper nozzling resulting in entrapped air and re-bound pockets, making the shotcrete more permeable. 2. Poor compaction. 3. Shooting excessively wet.	1. Poor curing conditions.		1. High concentration of sulfate in groundwater. 2. Other undesirable chemicals in groundwater including acid mine or chemical wastes. 3. Freeze-thaw conditions at tunnel portal or in short, well-ventilated tunnels.
IX. Too permeable.	1. Elongated aggregate particles interferring with compaction. 2. Poor aggregate quality. 3. Gap-graded aggregates. 4. Low cement content. 5. High water-cement ratio in wet-mix shotcrete.	1. Improper nozzling resulting in laminations, entrapped air, and rebound making it more permeable. 2. Poor compaction. 3. Shooting excessively wet.	1. Poor curing conditions.		
X. High shrinkage.	1. High cement content. 2. Poor aggregate quality. 3. High water-cement ratio or high cement content in wet-mix shotcrete.	1. Shooting excessively wet. 2. High accelerator dosage.	1. Low humidity.		1. Low bond strength to rock because of clay gouge on joint surface (reduces restraining effect of rock substrata). 2. Dry tunnel above groundwater table.

Note: Factors for VIII, IX, and X are expected to follow similar trends as concrete except for
      differences related to methods of placement at low water content, the fact that shotcrete
      does not bleed, and the typical nonuniformity of shotcrete.

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used as a trouble shooting guide. Selected aspects of Table 4.1 are discussed in more detail in the following sections.

4.1.1 Potential Activity of Mix and Shooting Conditions

Although changes in 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. The mix and the shooting conditions both can be described in terms of their "activity". Activity is defined as the potential for hydration, quick setting, and fast strength gain during early ages. Several factors are believed to have a combined effect on the potential activity of the mix. Some of the more important of these parameters are listed in Table 4.2. Each parameter affects the shotcrete differently depending on whether it is considered to act on the dry mix before shooting or on the shotcrete during or immediately after shooting. This difference is reflected in the table by separating Dry-Mix Activity in Part I from Shooting Activity in Part II. There are aspects of mix design as well as shooting conditions that affect Shooting Activity. The table illustrates how certain mix design and shooting conditions are interrelated.

The factors listed in Part I tend to promote premature hydration of the cement in the dry mix. Prehydration of the cement adversely affects the early and ultimate strength. Depending upon the activity, this may become noticeable whenever the dry-mix is allowed to sit for periods longer than about 1/2 hour before shooting. The moisture in the aggregate will cause the cement to begin to hydrate. A delay of just a few minutes between addition of accelerator and shooting of the mix also results in undesirable prehydration that strongly affects behavior. Subsequent shooting of any mix that prehydrated to any

Table 4.2 Factors related to activity of shotcrete mixes

I.   DRY MIX ACTIVITY

FACTORS THAT TEND TO PROMOTE PREMATURE HYDRATION OF DRY MIX BETWEEN TIME
OF MIXING AND TIME OF SHOOTING. (Premature hydration tends to promote
lower early and ultimate strength.)

A.   High moisture content of dry mix from excessively wet aggregate.

B.   High cement content.

C.   High potential of cement, itself, to set quickly without accelerators.

   1.   Higher fineness.

   2.   Regulated-set cement characteristics or chemistry.

   3.   Type III cement characteristics or chemistry.

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
shotcrete.

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.

degree serves to disturb the setting process. The factors in Part I should be kept within acceptable levels for the early and ultimate strength desired. Since the factors are interdependent, the magnitude of the effects are dependent, not upon the absolute level of any one factor, but upon the actual combination. For instance, if a dry 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. The concept can be applied qualitatively to wet-mix shotcrete.

The factors listed in Part II of the table tend to 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, their effect on ultimate strength can be detrimental even below the optimum value. For instance, below the optimum value, an increase in accelerator results in an increase in early strength but reduces the ultimate strength. Cement content and water-cement ratio are exceptions, 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 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 factors) 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. Any disturbance subsequent to this set is detrimental both to the initial rate of gain of strength and to the ultimate strength.

The rate of buildup of material (the material delivery rate) and nozzling technique may affect this phenomenon of shooting activity. It may be possible, to shoot a moderately active mix to the full thickness before the initial set takes place 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, 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 provides its own disturbance. Mixes and shooting conditions this active must be avoided. 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 and the set times begin to increase with higher accelerator dosage. Cement-accelerator combinations above this point of reversal are too active and could exhibit problems if shot in the field.

As with the factors in Part I of Table 4.2, the effects of the factors listed in Part II are interdependent. Each factor can be analyzed individually

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to determine a trend, but the combination of all the factors, not the absolute level of any one parameter, governs the overall behavior. 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. For instance, a high cement content and a low dosage of accelerator may be just as active as a low cement content and a high accelerator dosage.

There is a large number of combinations of factors that tend to promote higher rates of gain of strength during early ages. Accordingly, there is a large number of optimum combinations of factors beyond which the mix is too active and their combined result is detrimental. Any evaluation of the effects of mix designs and shooting conditions on strength should consider the entire spectrum of factors and combinations of factors that could affect the activity of the mix.

4.1.2 Effect of Shooting Conditions on Strength

Some of the shooting conditions that affect strength include the quality of nozzling, gun operation, batching operation, temperature of ingredients and environment, accelerator mixing, and prehydration.

Nozzleman

The nozzleman, especially in dry-mix shotcrete, is one major factor in controlling the quality of the final product. By making adjustments that account for conditions on the wall, the product can be improved substantially. The nozzleman has greater flexibility to account for these variations in the ground conditions with the dry-mix process than with the wet-mix process, but

his importance to strength should not be minimized in the wet-mix process. Poor nozzle techniques can cause the product to be completely variable with lower strength by entrapping rebound or by improper water control. He can overcorrect and shoot alternately too wet or too dry by too wide a margin, or not correct the water at all; both result in variable strength.

The nozzleman can shoot with a water content that creates the sheen or glossy appearance that has been reported to be close to the optimum density and strength (Zynda, 1966; Ryan, 1975), on the dry side of this water content, or on the wet side up to the wettest stable consistency (the water content that is at incipient sagging or slumping) where ultimate strengths are still acceptable.

Water Content

In concrete technology, water content or water-cement ratio is a mix design parameter that can be changed by the designer to control the strength of the concrete. In shotcrete technology, such control over strength is not exercised by adjusting water content, not even for wet-mix shotcrete. Shooting conditions tend to overshadow strength trends. In dry-mix shotcrete, even though the nozzleman controls the water added, the range of water content possible between too dry and slumping is actually fairly narrow. It appears there is an optimum water content for dry-mix shotcrete. Shooting wet of optimum tends to reduce ultimate strengths and to delay setting times or slow down the initial rates of gain of strength. Shooting too dry also appears to result in lower strength and the reduction in strength on the dry side appears to be greater than when shooting on the wet side. When shooting too dry, there is

a tendency for laminations to occur. These laminations are weak layers that generally affect long-term strength more than early strength because failure occurs along laminations and the strength is governed by the laminations, not the strength of the matrix. However laminations are not highly stressed in low strength shotcrete where their effect is not as prominent.

It appears that water content in the dry-mix process is not an independent variable. Instead the upper and lower boundaries of the range of water contents available to the nozzleman are dependent upon other mix and shooting conditions such as the cement content, gradation of the mix, temperatures, air pressures, etc.

In the wet-mix process, water content is also restricted to a specific range dependent on the shooting conditions even though water is added into the mix when it is batched. Too much water results in sloughing but a certain minimum water content is necessary to be able to pump it through the hoses. Again the range is fairly narrow although it can be extended somewhat by using additional accelerator. There should be a general tendency for strength to increase with decreasing water-cement ratio of wet-mix shotcrete given the same shooting conditions and provided shooting conditions do not cause disturbance because of high activity.

Other aspects of the nozzleman's performance are discussed elsewhere in this report. Clearly, the nozzleman is a major factor in governing the quality and thus the strength of the shotcrete. For wet-mix shotcrete, the nozzleman has less control on the final product, but low strengths can be traced directly to poor nozzling techniques.

Accelerator Dosage and Mixing

Accelerator dosage, and the all-important cement-accelerator compatibility, is a mix design problem discussed in detail in Chapter 3. However, the field control of accelerator dosage is often so poor that wide variation in early and long-term strength results. The proper accelerator dosage is a shooting condition that can be controlled by proper attention and inspection. The actual dosage is so closely related to strength that records of the actual accelerator dosage for each shift, and the location of shooting during the shift should be maintained. Such records may serve to explain anomalous strength results.

Inadequate mixing can result in pockets of accelerator concentrations higher or lower than the optimum dosage. Both can result in localized low-strength areas. The extreme susceptibility of the powders to moisture absorption can lead to irregular dispensing rates from the volumetric feeders. Ripped or damaged containers could be one source of moisture causing these problems. Any time lapse between the addition of accelerator and the shooting of the mix causes a strong tendency for prehydration of the mix that results in lower early and lower long-term strengths. This delay is a particularly important factor in determining dry-mix activity.

Temperature of Ingredients

Raising the temperature of the ingredients has the same effect as raising the curing temperature of the in-place mix during early stages of hydration, except for the material near the surface which is affected more by ambient conditions. For concrete, an increase in the curing temperature speeds up the

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chemical reactions of hydration and increases the early strength. A similar effect appears to hold true for shotcrete.

In order to attain a sufficient level of early strength, raising the temperature of the mix is frequently required for cold-weather shotcreting. Since water is easiest to heat, that is the method often chosen to raise the mix temperature, although heating the aggregate or cement is occasionally required also. A rule of thumb for concrete is that for each degree the water temperature is raised, the mix temperature is raised about 1/4 degree (Troxell, et al., 1968). This rule should be approximately correct for wet mix shotcrete; for dry mix shotcrete there is less water in the mix and, therefore, there will be less effect. Care should be taken, however, because heating the water too much may cause the shooting activity to be above optimum with the resultant flash set and disturbance from subsequent shooting.

4.1.3 Effect of Mix Design on Strength

Cement and Accelerator

The strength of shotcrete is not affected as strongly as concrete by the type of cement because the strength behavior is dominated by the cement-accelerator reaction. However, it is possible that it may be more difficult to obtain compatibility between any given accelerator and the slower-setting cements such as Type II, IV or V.

Low cement contents will result in low early and ultimate strengths. An increase in cement content increases early and ultimate strength up to an optimum cement content that is determined by the combined effect of the parameters that govern shooting activity. Further increases in cement content reduce early strength and ultimate strength because of disturbance after the flash set of the shotcrete on the wall.

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Increasing accelerator dosages increase early strength and reduce ultimate strength up to an optimum dosage determined by the combined effect of the parameters that govern shooting activity. Further increases reduce both early and ultimate strength.

Aggregate

Aggregates that are too wet tend to promote prehyaration of the cement in the dry mix which results in lower early and lower long-term strengths. On the other hand, if the dry mix is too dry, there may be insufficient cement adhering to the particles and an insufficient time for water to mix with the dry mix at the nozzle. Both result in lower early and ultimate strength.

Weak aggregates will lower the ultimate strength of shotcrete but will not have much effect on early strength since the aggregates are not highly stressed in low-strength shotcrete. Any impurities of harmful substances can be expected to have a detrimental effect on the general quality of shotcrete.

The gradation of aggregate in the mix affects pumpability, flow through hoses, hydration at the nozzle, adherence to the sprayed area, and strength (Blanck, 1974). Although grading of aggregate has little effect on compressive strength, mixes containing coarse aggregate of maximum size of 9 mm (3/8 in.) or greater have greater flexural strength, shear strength and bond qualities. It is believed that the presence of coarse aggregate increases flexural strength because the aggregate acts as a crack arrestor.

Flexural strengths can be expected to be higher with crushed rock (Troxell, et al., 1968). However, shotcrete mixes that contain crushed rock are more diffi-cult to apply and compressive strengths are similar to those with rounded gravel (Blanck, 1974).

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Other Additives

Chemical admixtures of any kind should not be used unless their effect on the cement-accelerator compatibility is checked. For instance anti-freeze additives for compressed air work at freezing temperatures may adversely affect compatibility. Pumpability aids for wet-mix shotcrete may have similar effects. Wet-mix batched in a routine concrete batch plant may contain typical water reducing or air entraining additives either because the operator neglected to turn off the automatic dispenser or because of equipment malfunction or carryover. These could also affect the cement-accelerator reaction and reduce early strength.

4.1.4 Curing

Although curing conditions are not usually controlled underground, they generally are favorable. This is fortunate because humidity and temperature play very important roles in the strength of shotcrete. In most tunnels, dehydration is seldom a problem because tunnel air typically has a high relative humidity. Yet, because shotcrete is produced in relatively thin layers and has large areas exposed to the air, the premature drying of the shotcrete can be a problem under certain circumstances especially since the low water-cement ratios contribute to dehydration on the outer surface. The air may be drier and the air circulation greater near tunnel portals. In areas where dehydration may be a problem the shotcrete layer should be cured in some manner compatible with tunneling operations and subsequent installation of final support. Proper curing of shotcrete allows proper chemical hydration which is important in gaining strength and producing durable shotcrete, and it delays and reduces the initial shrinkage. After a suitable period of curing (7 to 10 days)

the shotcrete has attained enough tensile strength that the possibility of shrinkage cracking is reduced.

With proper quality control cold weather shotcreting should present no major problems other than to reduce the early strength gain. Accelerators together with the low water-cement ratio characteristic of dry-mix coarse aggregate shotcrete facilitate shooting at temperatures near freezing. More accelerator is needed to combat the effect of low temperature on the reaction to provide the needed early strength. The use of admixtures to provide freezing resistance should be avoided because their presence in the mix may adversely affect the ultimate strength. In general, preheating of aggregates, heating the mix water, the use of space heaters, and other established procedures are helpful in preventing freezing. If freezing is prevented, the ultimate strength could be satisfactory, although if the entire curing period is cold, ultimate strengths will be lower.

Generally colder and drier curing conditions result in minimum early and ultimate strengths; the highest strengths can be expected for warm and moist curing conditions. Differences in curing conditions between in-place shotcrete and samples for testing can cause an erroneous assessment of strength as described in the next section.

4.1.5 Testing Errors and Variations in Strength

Significant variations in strength test results have been observed on shotcrete projects. These variations are the result of both the actual variations in the in situ strength of the shotcrete and the variations in test procedures.

Figure 4.1 is a graph of a typical distribution of 28-day compression tests on a major tunnel project over a period of 3 months (Blanck, 1974). The scatter between tests was traced mainly to the skill and performance of the application crew, especially the nozzleman.

Some of the causes of erratic observed strength behavior are listed in Part IV of Table 4.1. Shooting conditions that result in erratic strength behavior primarily involve improper nozzling and gun operation. These show up as significant differences in strength between shifts and excessive scatter in test results. Significant variations in flexural strength or flexural strengths that are lower than would be predicted for the compressive strength can often be traced to laminations during shooting caused by improper nozzling and improper or erratic gun operation because laminations reduce flexural strength more than
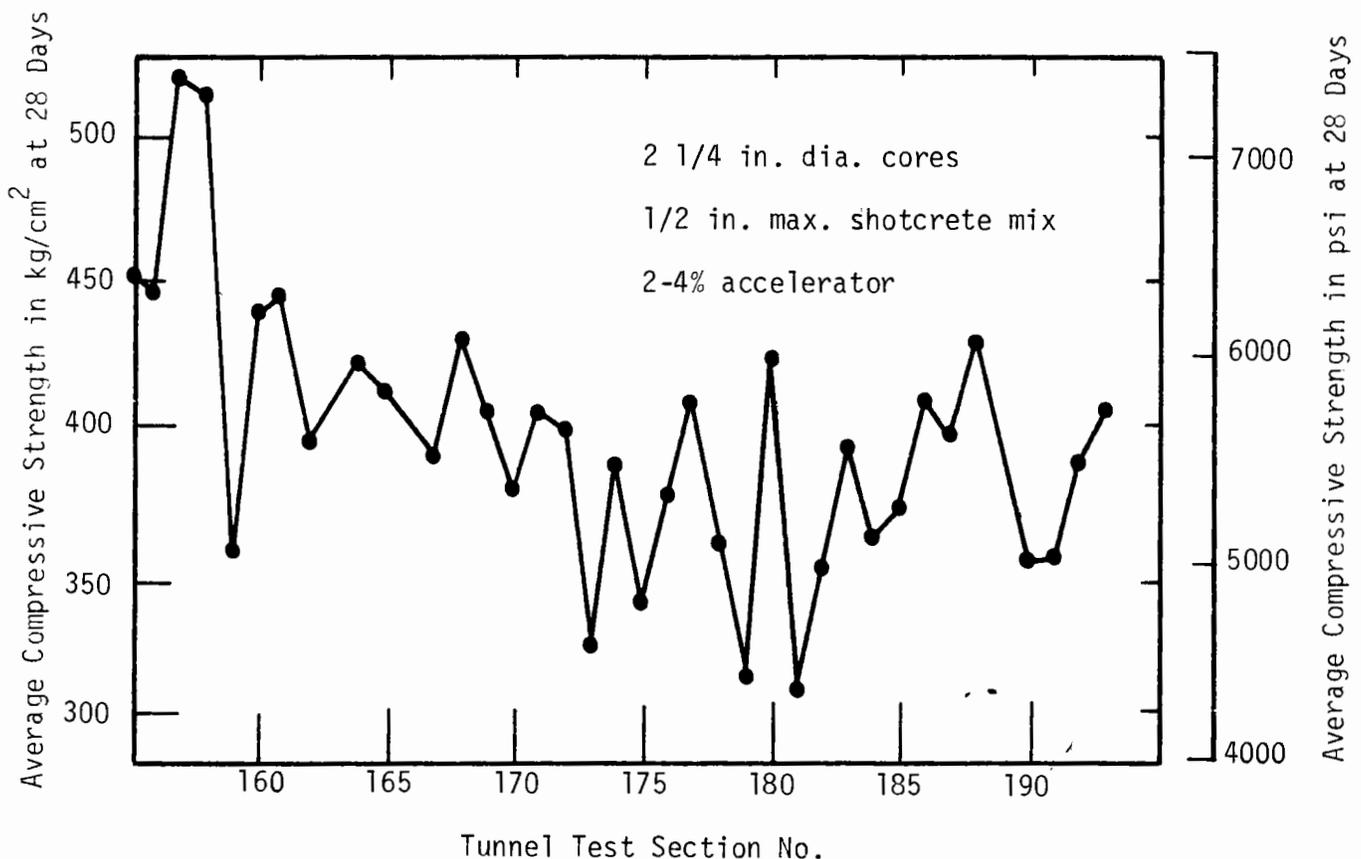
FIG. 4.1. TYPICAL VARIATION OF COMPRESSION TESTS OVER THREE-MONTH PERIOD (AFTER BLANCK, 1974)

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compressive strength. Scattered zones of low strength can result from laminations, pockets of rebound, and entrapped air as well as from non-uniform accelerator dosage. If the accelerator dispenser is operating erratically, strength variations will result. Improper batching and mixing can also show up as zones of varying strength.

If, however, the strength variations are daily or weekly, yet the strengths for each shift are approximately equal, other sources must be considered besides poor nozzling or gun operation. Periodic moisture and temperature variations may be the cause or the cause might be related to zones of high water flow that require additional accelerator. Records of actual accelerator consumption can explain such differences. Cement from the same mill exhibits some variation in chemistry and physical properties with time. Even small changes in cement chemistry can affect compatibility significantly, resulting in strength variations. Only spot checks on compatibility for each new supply of cement or accelerator will discover these variations.

Test errors or improper procedures or interpretation of test results usually increase the observed scatter. Testing must be done according to the applicable ASTM procedures. Particular problems with tests include: not centering a specimen in the testing machine, erratic or extreme loading rates, poor caps, and not orienting the specimen in the testing machine correctly. Disturbance to the delicate samples from rough handling or poor coring and load gages that are not calibrated specifically for low loads can introduce significant errors; disturbance always acts to reduce the strength.

It is possible for all these test variations to be overshadowed by more important considerations of sample curing. The samples must be cured in the

same environment (temperature & humidity) that exists underground or the test results have no meaning. It is possible for samples cured in a colder and drier environment to test at strengths quite low while the in-place strength can actually be higher than the specified strength. If this important difference in curing methods goes unnoticed, all efforts to improve the mix or shooting conditions will be futile.

There are also test conditions that give higher strengths than in situ. Samples cured in a warmer and wetter environment, such as in a curing room, will have higher strengths. In addition, the crew either consciously or subconsciously may be more careful when shooting shotcrete they know will be tested, resulting in test values higher than in situ.

Finally, no matter how good the testing and sampling, there are bound to be variations that could be somewhat larger than those normal for concrete. Fig. 4.2 shows all the compression test results from 21 specimens taken from the same panel. The specimens were prisms 7.6 by 7.6 by 17.8 cm (3 x 3 x 7 in.) that were tested to detect any difference in strength if the outer rough shotcrete surface remained (R) or was trimmed (T). These six-month tests were done carefully as part of a research program but the testing machine was a typical good-quality portable compression tester that might be found in any well-equipped lab. Considerable variations in results can be seen even for samples prepared identically, i.e., either all R or all T, including about 150.7 kg/cm^2 (2140 psi) between samples that shared a common side. Table 4.3 summarizes the results from this test panel averaged different ways. There was a tendency for interior specimens to have a higher average strength. However, in spite of the differences (large strength differences between adjacent samples; also

Average Strength Along Vertical Strip, 10^3 psi

kg/cm^2

kg/cm^2

| 404.2 (5740) | 405.6 (5760) | 409.2 (5810) | 431.7 (6130) | 367.6 (5220) | 391.5 (5560) | 411.3 (5840) |

T	R	T	R	T	R	T
367.6 (5220)	371.8 (5280)	460.6 (6540)	447.9 (6360)	350.7 (4980)	331.4 (4450)	409.9 (5820)

388.7 (5520)

R	T	R	T	R	T	R
435.2 (6180)	497.9 (7070)	417.6 (5930)	448.6 (6370)	375.4 (5330)	439.4 (6240)	444.4 (6310)

436.6 (6200)

LEGEND

T = Trimmed
R = Rough
kg/cm^2 ——→
(psi) ——→

T	T	R	R	T	T	R
409.9 (5820)	347.2 (4930)	348.6 (4950)	397.9 (5650)	377.5 (5360)	422.5 (6000)	378.9 (5380)

383.1 (5440)

Average of all samples = 402.8 kg/cm^2 (5720)
Average of all trimmed = 412.0 kg/cm^2 (5850)
Average of all rough = 393.0 kg/cm^2 (5580)

Average Strength Along
Horizontal Strip
10^3 psi

FIG. 4.2   ILLUSTRATION OF VARIATION OF MEASURED COMPRESSIVE
STRENGTH IN ONE PANEL (AFTER PARKER, ET AL., 1975)

Table 4.3 Summary of variations of
compressive strength in panel

	Number of specimens	Average strength kg/cm^2	(psi)	Standard deviation kg/cm^2	(psi)	Coeff. of variation %
All specimens	21	402	(5720)	46.0	(653)	11
All trimmed specimens	11	412	(5850)	48.0	(682)	12
All rough specimens	10	393	(5580)	43.9	(623)	11
All perimeter specimens	16	393	(5580)	42.6	(605)	11
All trimmed perimeter specimens	8	393	(5580)	39.2	(557)	10
All rough perimeter specimens	8	392	(5570)	48.4	(688)	12
All interior specimens	5	436	(6190)	44.8	(636)	10
All trimmed interior specimens	3	462	(6560)	31.4	(446)	7
All rough interior specimens	2	396	(5630)	--	---	-
All corner specimens	4	392	(5560)	21.6	(307)	6

Note: Refer to Fig. 4.2.

with sample location and preparation) the coefficient of variation of all the tests was 12 percent or less which can be considered good for field samples.

4.1.6 Effect of Ground Conditions on Strength

The effect of ground conditions on strength should also be appreciated. More accelerator used to seal off high groundwater flows results in lower ultimate strength. Excessive water flow also tends to reduce bond strength. Rock joint surfaces that are highly slickensided or that are coated with clay gouge also reduce bond strength. High concentrations of sulfates in the groundwater reduce the strength by affecting the durability. In fact, a number of chemicals, such as chemical wastes, in the groundwater would retard setting or could reduce ultimate strength. Bond strength can also be affected by poor curing conditions on the interface between rock and shotcrete, especially if the tunnel is too dry or if the rock tends to absorb all the moisture into it, resulting in dry curing conditions.

4.2 Typical Strength Values

The strength of shotcrete, as reported in the literature, is summarized in this section. Wide variations in mix design exist, especially in the differences between fine and coarse aggregate and between the wet- and dry-mix process shotcretes. Shotcrete is inherently a variable material. Many of the causes for variability have been discussed in the previous sections on factors affecting the in situ strength. There are no industry standards for strength testing. Methods of obtaining samples range from coring in-place shotcrete to cutting test panels into smaller specimens. In situ tests such as the Windsor Probe are also conducted. Curing conditions,

sample preparation prior to testing, and time of testing vary with each project. Consequently, the strength values reported in the literature span a wide range. The general procedure in the following sections is to tabulate test results reported in North America for all types of shotcrete and, where possible, narrow the range on the basis of experience to represent typical strength values that can be achieved in the field for conventional coarse-aggregate shotcrete. A few results from European shotcrete practice are included. The range of typical strengths can be considered representative of coarse aggregate shotcrete containing about 390 kg/m^3 (7 bags per yd^3) and 3 percent fast-set accelerator placed either by the wet- or dry-mix process under typical underground conditions.

The various reported strength values are tabulated by reference rather than by type of shotcrete. It has been found that there are too many variables involved in shotcrete to make definitive comparisons between mixes, equipment, wet or dry mix, and coarse or fine aggregate. The relative advantages of these are still uncertain. The important variables are seldom documented adequately to permit comparisons between different shotcrete types or mixes. Detailed tables are given in the subsequent sections primarily to illustrate the range of reported values, rather than to permit comparisons between different types of shotcrete.

4.2.1 Compressive Strength

As with concrete, compressive tests have been used widely as a measure of the general quality of shotcrete, and consequently there are more compressive strength data available. Values for initial (early) and ultimate (commonly taken to be 28 days) compressive strengths, as reported in the literature, are tabulated in Table 4.4. Some of the higher values in the

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Table 4.4 Summary of reported values of compressive strength

1-3 hr		3-8 hr		1 day		28 day		Mix Design	Source
kg/cm²	(psi)	kg/cm²	(psi)	kg/cm²	(psi)	kg/cm²	(psi)		
35.2	(500)	70.4	(1000)	162-176	(2300-2500)	352.1	(5000)	Dry mix, 7 bags cement, 3 percent accelerator	Blanck, 1974
-	-	-	-	70.4	(1000)	281.7	(4000)	Wet mix, 55 percent fine aggregate, 45 percent coarse aggregate, 6.7-bag mix, 2.4 percent accelerator	Chitunda, 1974
-	-	-	-	-	-	645.1	(9160)	Dry mix, fine aggregate, 11-bag mix	Tynes and McCleese, 1974
-	-	-	-	-	-	367.6	(5220)	Dry mix, coarse aggregate, 7-bag mix	
-	-	-	-	-	-	594.4	(8440)	Wet mix, fine aggregate, 8-bag mix	
-	-	-	-	-	-	589.4	(8370)	Wet mix, coarse aggregate, 7-bag mix	
								Dry mix, 13 mm (1/2 in.) coarse aggregate Type III cement, 3 percent accelerator	Bortz, et al., 1973
4.2-13	(60-190)	4.2-53	(60-750)	152	(2160)	284	(4030)	5-bag mix	
7.7-35	(110-500)	35-110	(500-1550)	207	(2940)	302	(4290)	7-bag mix	
3.5-37	(50-520)	37-92	(520-1310)	206	(2930)	311	(4420)	9-bag mix	
								Wet mix, 13 mm (1/2 in.) coarse aggregate Type III cement, 3 percent accelerator	" "
-	-	0-5.6	(0-80)	63-106	(890-1510)	264-350	(3750-4970)	5-bag mix	
0-12	(0-170)	12-57	(170-810)	193-207	(2740-2940)	340-403	(4830-5720)	7-bag mix	
0-15	(0-220)	15-51	(220-720)	246	(3490)	427	(6070)	9-bag mix	
1.4-7.0	(20-100)	2.1-9.1	(30-130)	63-176	(900-2500)	303-375	(4300-5330)	Dry mix, 13 mm (1/2 in.) coarse aggregate,	Parker, et al., 1975
1.4-7.0	(20-100)	2.1-9.1	(30-130)	63-176	(900-2500)	303-375	(4030)	7.5-bag mix, Type I cement 3 percent accelerator	
-	-	51-64	(720-910)	-	-	281-423	(4000-6000)	Dry mix, 10 mm (3/8 in.) coarse agg. 7-bag mix, Type I cement 3 percent accelerator	Fernandez, et al., 1975
								Dry mix, 19 mm (3/4 in.) coarse aggregate, 3-4 percent accelerator, Type II cement	Corps of Engineers, 1974 (New Melones Lake)
-	-	38-42	(540-590)	70-146	(1000-2700)	167-330	(2370-4690)	7-bag mix	
-	-	-	-	73-144	(1040-2040)	137-249	(1940-3530)	7.5-bag mix	
-	-	20-57	(290-810)	65-104	(920-1470)	207-249	(2920-3530)	7.75-bag mix	
-	-	51-58	(720-830)	92-161	(1300-2200)	148-265	(2100-3770)	8-8.5-bag mix	
46	(650)	-	-	-	-	366	(5200)	Dry mix, 19 mm (3/4 in.) coarse aggregate 7 bag mix, est. 3 percent accelerator	Mason, 1970
-	-	-	-	-	-	254-493	(3600-7000)	Wet mix, 19 mm (3/4 in.) coarse aggregate 7.1 bag mix	Lorman, 1968
-	-	-	-	-	-	239-451	(3400-6400)	Wet mix, 10 cm (3/8 in.) fine aggregate 8.7 bag mix	Lorman, 1968
17.6	(250)	56.3	(800)	176	(2500)	352	(4000)	Dry mix, 19 mm (3/4 in.) coarse aggregate, 7-bag mix, est. 3 percent accelerator	Klosterman, 1968

Note: 7-bag mix ~ 390 kg cement/m³

Table 4.4 continued

1-3 hr		3-8 hr		1 day		28 day		Mix design	Source
kg/cm²	(psi)	kg/cm²	(psi)	kg/cm²	(psi)	kg/cm²	(psi)		
-	-	-	-	-	-	489.4	(6950)	Dry mix, fine aggregate, 10 bag mix, 1 percent accelerator	Poad and Serbousek, 1972
-	-	3.5	(50)	77.5	(1100)	239.4	(3400)	Dry process, 3 percent powder accelerator	Sällström, 1970
-	-	7.0	(100)	77.5	(1100)	190.1	(2700)	Dry process, 6 percent powder accelerator	
49.3	(700)	147.9	(2100)	239.4	(3400)	295.8	(4200)	Dry process, 1:1 solution of agent/water (volume)	
-	-	-	-	-	-	466.1	(6618)	Wet process, 1.0 cm (3/8 in.) aggregate, Type III cement, 8-bag	Hendricks, 1969
-	-	-	-	-	-	385.2	(5470)	Dry process, 1.9 cm (3/4 in.) aggregate, Type III cement, 7-bag	
-	-	-	-	-	-	338.0-422.5	(4800-6000)	Dry mix, lightweight aggregate, 9.8 bags cement	Barnard and Tobin, 1966
-	-	-	-	-	-	281.7-352.1	(4000-5000)	Dry mix, lightweight aggregate, 8.9 bags cement	
-	-	-	-	-	-	246.5-295.8	(3500-4200)	Dry mix, lightweight aggregate, 8.0 bags cement	
-	-	-	-	-	-	466.2-557.4	(6620-7915)	Dry mix, 1 part cement to 3.5 parts sand, Type I cement, shot overhead	Fluss and Gibson, 1966
-	-	-	-	-	-	395.1-502.1	(5610-7130)	Dry mix, 1 part cement to 3.5 parts sand, Type I cement, shot vertical	
-	-	-	-	-	-	442.3-479.6	(6280-6810)	Wet process, 7 bags cement, 40 percent 1.0 cm (3/8 in.) rock, 60 percent sand, 1.9 cm (3/4 in.) slump	Fredericks, et al., 1966
-	-	-	-	-	-	443.7-514.1	(6300-7300)	Dry mix, 1 part cement to 3.5 parts aggregate, Type II cement, 7.6 cm (3 in.) out from panels, double chamber gun	Keifer, 1966
-	-	-	-	-	-	316.9-352.1	(4500-5000)	Dry process, 297.1 Kg cement per m³ (500 lb per yd³)	Kobler, 1966
14.1-17.6	(200-250)	-	-	105.6	(1500)	387.3-422.5	(5500-6000)	Dry process, 386.2 Kg cement per m³ (650 lb per yd³)	
-	-	-	-	-	-	493.0	(7000)	Dry process, with certain admixtures	
-	-	-	-	-	-	218.3-373.2	(3100-5300)	Wet mix, sand, 7.23, 8.57 bags in places	Litvin and Shideler, 1966
-	-	-	-	-	-	521.1-809.9	(7400-11,500)	Wet mix, coarse aggregate, 6.63, 8.86 bags in places	
-	-	-	-	-	-	612.7-901.4	(8700-12,800)	Dry mix sand, 8.96, 14.52 bags in place	
-	-	-	-	-	-	422.5-739.4	(6000-10,500)	Dry mix, coarse aggregate 8.3 - 12.3 bags	
-	-	-	-	-	-	211.3-669.7	(3000-9510)	Dry process, sand mix	Zynda, 1966

table were achieved with high cement contents and under laboratory curing conditions. Those in the middle of the range are more representative of field results.

There is no standard specimen for shotcrete analogous to the 15 by 30 cm (6 by 12 in.) cylinder in concrete. Hence, in shotcrete there is no standard compressive strength parameter such as f_c' although the nomenclature is often used in shotcrete also. The values that are reported in the literature include data from widely varying specimen types, ranging from 5 cm (2 in.) cubes to 15 by 30 cm (6 by 12 in.) wire-basket samples.

The high and low values from this table are listed in Table 4.5. Also included is a typical range of strengths that can be attained in the field using a conventional coarse aggregate mix, 390 kg/m^3 (7 bags per cu yd) of cement and about 3 percent accelerator (by weight of cement). This typical range is also plotted as a strength vs. log time curve in Fig. 4.3.

Table 4.5 Typical range of reported compressive strength

	1-3 hr	3-8 hr	1 day	28 days
Range of reported compressive strengths kg/cm^2 (psi)	1.4-49 (20-700)	2.1-147 (30-2100)	63-246 (890-3490)	137-901 (1940-12,800)
Range of typical compressive strengths attainable in field, kg/cm^2 (psi)	3.5-35 (50-500)	7-84 (100-1200)	106-210 (1500-3000)	280-420 (4000-6000)
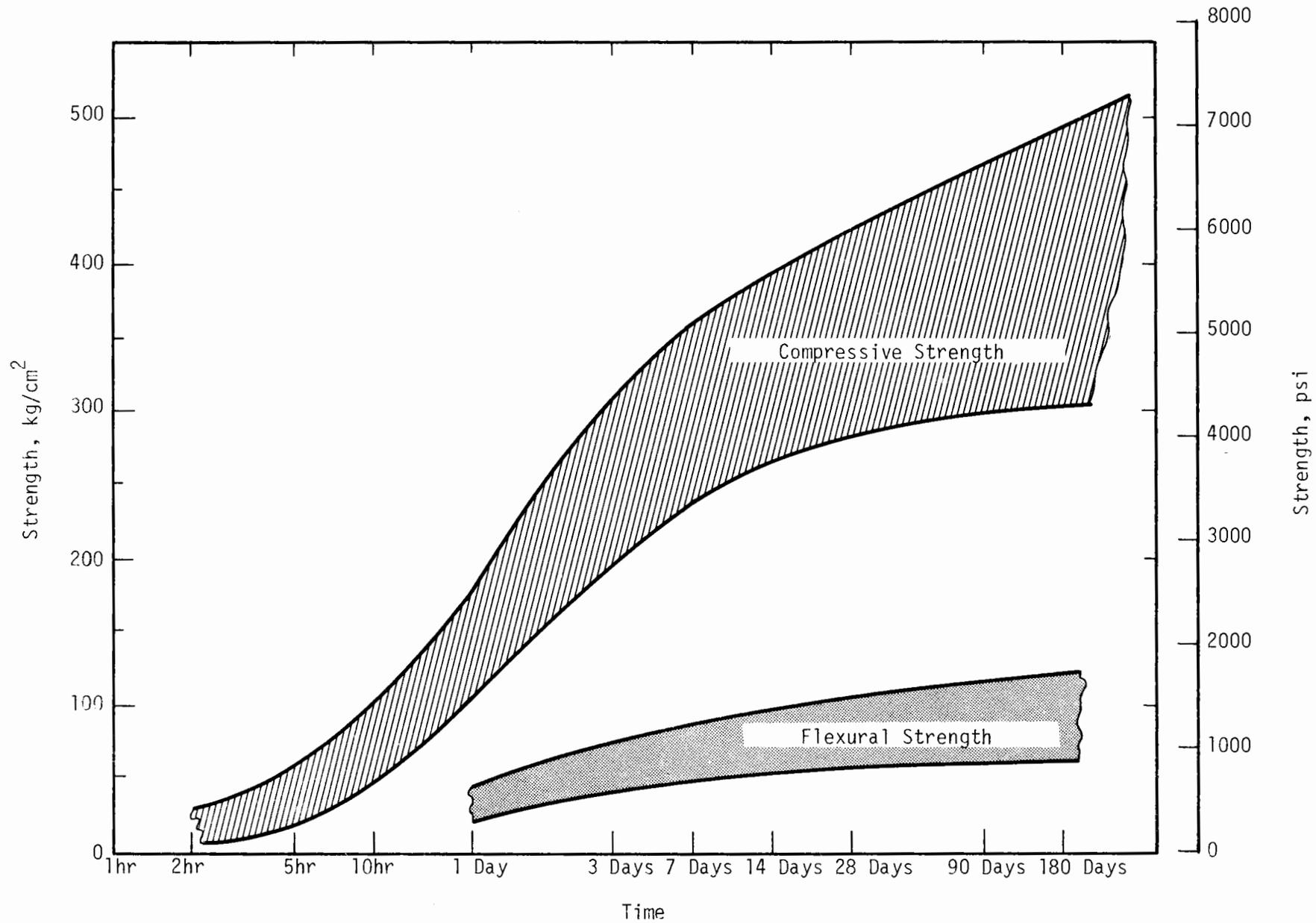
FIG. 4.3.   RANGE OF TYPICAL STRENGTHS ATTAINABLE IN THE FIELD

The potential effect of accelerator dosage is shown in Table 4.6 which summarizes some of the 28-day strengths given by Bortz, et al., 1973. The cement content increases across the table while the accelerator dosage increases down the table. The values in each box are the 28-day strengths for the combination of cement and accelerator content indicated. In most cases an increase in cement content across a line in the table results in an increase in strength. An increase in accelerator content down a column in the table results in a decrease in strength. It was reported that wet-mix did not show as strong a trend because of greater variability of the wet-mix data.

These data are shown to illustrate the potential effect accelerator can have on ultimate strength rather than a relative comparison of cement content of wet- and dry-mix processes. Initial and final set times in the Gillmore Needles test were reported to be very fast for the Type III cement and the accelerator used in these tests. Hence, it is possible that even 3 percent accelerator dosage was higher than necessary and loss in ultimate strength shown for any increase in accelerator dosage is greater than should be expected or permitted.

Most long-term results beyond 28-days indicate that the strength of shotcrete continues to increase with age provided curing conditions remain favorable (Blanck, 1974; Poad, et al., 1975 and Parker, et al., 1975). Bortz, et al., (1973) reports anomalous results and suggests additional study into long-term strength behavior.

Table 4.6 Example of effect of accelerator dosage on compressive strength
(Data from Bortz, et al., 1973)

a) Dry-Mix Process

Cement Content

Accelerator Dosage	278 kg/m^3 (5-bag mix)	390 kg/m^3 (7-bag mix)	502 kg/m^3 (9-bag mix)
0	393 (5580)	549 (7790)	476 (6760)
1	413 (5870)	461 (6540)	534 (7580)
3	284 (4030)	302 (4290)	311 (4410)
6	264 (3750)	270 (3830)	286 (4060)

b) Wet-Mix Process

Cement Content

Accelerator Dosage	278 kg/m^3 (5-bag mix)	390 kg/m^3 (7-bag mix)	502 kg/m^3 (9-bag mix)
0	279 (3960)	415 (5900)	500 (7100)
1	-	-	-
3	264 - 349 (3750-4960)	340 - 403 (4830-5720)	382 - 428 (5430-6070)
6	-	321 (4560)	-

Accelerator Dosage, percent of cement by weight

Compressive strength at 28 days, in kg/cm^2 (psi)

4.2.2 Flexural Strength

The flexural strength of shotcrete is particularly important in the design of thin shotcrete liners. The few values reported in the literature for the early and ultimate flexural strength are listed in Table 4.7.

The high and low values from Table 4.7 are summarized in Table 4.8 along with a typical range of flexural strengths that can be attained in the field using a typical conventional shotcrete mix as described in the section on compressive strength. The typical range of flexural strength is also plotted in Fig. 4.3.

The relationship of flexural strength to compressive strength is similar to that of concrete, on the order of 15 to 20 percent of the compressive strength. However, it has been reported that coarse aggregate shotcrete with large (19 mm, 3/4 in.) crushed rock aggregate has attained flexural strengths that were about 25 percent of the compressive strength (Blanck, 1974). Values reported that are greater than 30 percent of the compressive strength at 28-days have been omitted from the tables.

4.2.3 Tensile Strength

As with flexural strength, the tensile strength of shotcrete is particularly important in the design of thin shotcrete liners. In general, there are two methods for determining tensile strength: by a direct or by an indirect tension test. The direct tension test is usually performed by affixing a clamping device to each end of a shotcrete specimen and pulling. In one type of indirect test, called a splitting-tension test, a compressive load

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Table 4.7 Summary of reported values of flexural strength

7 hr		1 day		3-8 days		28 days		Mix design	Source
kg/cm^2	(psi)	kg/cm^2	(psi)	kg/cm^2	(psi)	kg/cm^2	(psi)		
-	-	-	-	-	-	70.4-106	(1000-1500)	Dry mix, 19 mm (3/4 in.) coarse aggregate, 7 bag mix, 3 percent accelerator	Blanck, 1974
-	-	-	-	-	-	81	(1150)	Dry mix, 19 mm (3/4 in.) coarse aggregate, 7 bag mix	Mason, 1970
-	-	28.8-38.0	(410-540)	28.9-61.6	(410-875)	54.6-70.8	(775-1005)	Dry mix, 13 mm (1/2 in.) coarse aggregate, 7-1/2 bag mix Type I cement, 3 percent accelerator	Parker, et al. 1975
2.7-17.6	(39-250)	-	-	9.9-52.1	(141-740)	-	-	Dry mix, coarse aggregate, 7 bags Type I cement 3 percent accelerator	Fernandez, et al., 1975
-	-	-	-	-	-	34.9-49.6	(495-705)	Wet mix, sand, Type 1 cement	Litvin and Shideler, 1966
-	-	-	-	-	-	41.9-67.3	(595-955)	Wet mix, coarse aggregate, Type 1 cement	
-	-	-	-	-	-	50.7-84.5	(720-1200)	Dry mix, sand, Type 1 cement	
-	-	-	-	-	-	41.9-59.2	(595-840)	Dry mix, coarse aggregate, Type 1 cement	
-	-	-	-	-	-	40.5-99.3	(575-1410)	Dry mix, sand, by volume 1:3 to 1:6 cement to aggregate, Type 1	
-	-	-	-	-	-	57.5-84.2	(820-1195)	Wet mix, coarse aggregate, Type 1A cement	
-	-	-	-	-	-	40.5-70.1	(575-995)	Wet mix, sand, by volume 1:3 to 1:4.5	
-	-	-	-	-	-	35.2-52.8	(500-750)	Wet mix, 19 mm (3/4 in.) coarse aggregate 7-bag mix	Lorman, 1968
-	-	-	-	-	-	28.2-52.8	(400-750	Wet mix, 10 mm (3/8 in.) fine aggregate 8.7 bag mix	Lorman, 1968
								Dry mix, 19 mm (3/4 in.) coarse aggregate, 3-4% accelerator, Type II cement	Corps of Engineers, 1974 New Melones Lake
-	-	-	-	25.3	(360)	36.3	(515)	7 bag mix	
-	-	-	-	29.9-40.8	(425-580)	35.2-52.1	(500-740)	7.75 bag mix	
-	-	-	-	38	(540)	43.3	(615)	8.5 bag mix	
-	-	-	-	-	-	67.3	(955)	Dry mix, fine aggregate	Poad, et al. 1975
17.6	(250)	42.2	(600)	70.4	(1000)	84.5	(1200)	Dry mix, 19 mm (3/4 in.) coarse aggregate, 7-bag mix, est. 3 percent accelerator	Klosterman, 1968

Note: 7-bag mix ~ 390 kg cement/m^3

Table 4.8 Typical range of reported flexural strength

	8 hr	3-8 days	28 days
Ranges of reported flexural strengths, kg/cm^2 (psi)	2.7-17.6 39-250	9.87-61.6 141-875	28.2-106 400-1500
Typical flexural strengths attainable in the field, kg/cm^2 (psi)	3.5-7 (50-100)	35-91.5 (500-1300)	56-106 (800-1500)

is applied to the sides of a cylindrical specimen along two diametrically-opposite axial lines. A transverse tensile stress is produced and the specimen fails in tension along a vertical diametral cross section. In concrete, splitting tensile strength is about 15 percent higher than direct tensile strength.

Table 4.9 contains tensile strengths reported from various sources. These values refer to the tensile strength within one layer of shotcrete. The tensile strength between shotcrete and other surfaces (rock, concrete, older shotcrete) is referred to as tensile bond strength and is discussed in a later section.

The splitting tensile strengths in the table are within the range of 8 to 12 percent of the compressive strength which agrees with the normal range for concrete. The direct tensile values are lower than would be expected from a comparison with concrete. They probably reflect the effect of laminations or other defects in the shotcrete on the tensile strength. The results of tensile tests on shotcrete are very sensitive to defects and to the anisotropy of material.

Table 4.9 Summary of reported values of tensile strength

7 day kg/cm^2	7 day (psi)	28 days kg/cm^2	28 days (psi)	Type of test	Mix design	Source
36.3	(515)	54.9	(780)	Splitting tensile	Wet/sand*	Tynes and McCleese, 1974
33.1	(470)	51.4	(730)	Splitting tensile	Dry/sand	
30.6	(435)	45.8	(650)	Splitting tensile	Wet/coarse	
29.2	(415)	41.9	(595)	Splitting tensile	Dry/coarse	
		15.8	(225)	Direct tensile	Wet/sand	
		23.2	(330)	Direct tensile	Wet/coarse	
		7.4	(105)	Direct tensile	Dry/sand	
		19.7	(280)	Direct tensile	Dry/coarse	
45.8-52.8	(650-750)	56.3	(800)	Splitting tensile	Dry mix, 10 bags cement	Poad and Serbousek, 1972

* Mix designs for abbreviated descriptions for Tynes and McCleese data:

     Wet/sand: wet mix, 8 bags cement, fine aggregate
     Dry/sand: dry mix, 11 bags cement, fine aggregate
     Wet/coarse: wet mix, 7 bags cement, coarse aggregate
     Dry/coarse: dry mix, 7 bags cement, coarse aggregate.

  Note: 7-bag mix is 390 kg cement/m^3

4.2.4 Shear Strength

A few investigators (Tynes and McCleese, 1974; and Bortz, et al., 1973) have conducted tests to determine the shear strength of intact shotcrete directly. There is no ASTM Standard Test for shear strength of concrete and there are difficulties in conducting and interpreting the tests. Furthermore, significant differences in results should be expected between shear strength measured perpendicular and parallel to the laminations.

Tynes and McCleese (1974) report 7-day shear strengths ranging from 32.4 to 44.0 kg/cm^2 (460-625 psi) for wet and dry processes of both fine and coarse aggregate with about 390 to 615 kg/m^3 (7-11 bags/yd^3) of cement. At 28 days, the shear strength ranged from 41.5 to 50.4 kg/cm^2 (590-715 psi) for the same mixes. These ranged from about 6 to 12 percent of the compressive strength. Bortz, et al., (1973) presents full strength-time curves of shear strength from 1 hour to 120 days for coarse aggregate shotcrete with various cement contents and accelerator dosages. At 7 days, wet mix and dry mix coarse aggregate shotcrete mixes with 279 to 501 kg/m^3 (5 to 9 bag/yd^3) of cement and 3 percent accelerator resulted in shear strengths ranging from 40.0 to 46.5 kg/cm^2 (440 to 660 psi); at 28 days the range was 47.2 to 64.8 kg/cm^2 (670-920 psi). Both investigators reported the results fell within the range normally obtained for structural concrete. Because of the difficulties with testing and interpreting the test, shear strength tests have limited value over more conventional tests.

4.2.5 Pull-out Strength

Pull-out test data on shotcrete are reported by Rutenbeck (1974) for a

variety of mix designs for dry mix coarse aggregate shotcrete. Shotcrete with a compressive strength of about 211 to 282 kg/cm^2 (3000-4000 psi) had a pull-out strength ranging from 49.3 to 63.3 kg/cm^2 (700-900 psi). Parker, et al., (1975) reports 76.8 to 85.9 kg/cm^2 (1090-1220 psi) at 7 days when the compressive strength of the coarse aggregate shotcrete mix was about 313 kg/cm^2 (4450 psi). At 28 days the pull-out strength was 77.5 to 98.6 kg/cm^2 (1100-1400 psi) when the compressive strength was 353 to 375 kg/cm^2 (5020-5330 psi).

The pull-out test is an indirect test usually related to compressive strength by a factor of about 4. Like other correlations to compressive strength, the magnitude of the factor varies with strength, mix design, etc. A test program is necessary to determine the proper correlation for each project.

4.2.6 Moment-Thrust Interaction

An analysis of moment-thrust interaction deals with the behavior of shotcrete when subjected to combined bending and axial loads. It is especially important in the design of thick shotcrete sections with continuous liners. Shotcrete liners are often subjected to both thrust and moment. This effect and its simulation by the beam-column test is illustrated in Fig. 4.4. Moment-thrust behavior is usually described by a failure envelope. The envelope is a graphical representation of the ultimate strength of the section at various axial and bending loads. At failure conditions, the axial load is shown on the vertical axis, and the bending load on the horizontal axis. The unconfined compressive strength of the shotcrete provides the axial load at zero moment. The result of a pure flexure test provides the moment at zero axial load.

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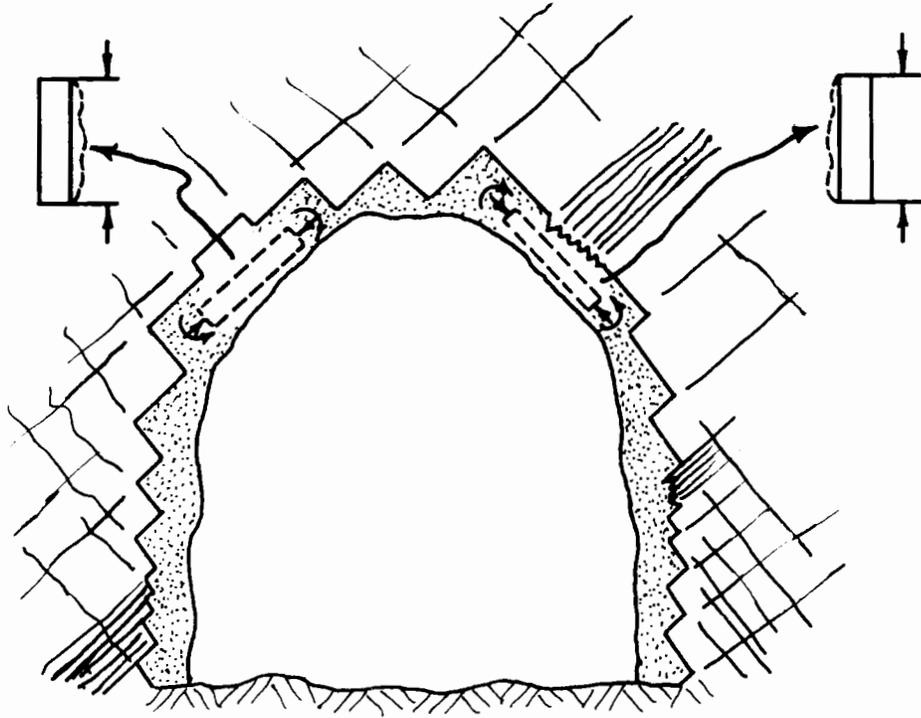
FIG. 4.4.   SIMULATION OF MOMENT-THRUST CONDITIONS
BY BEAM-COLUMN TEST

Each point on the curve represents a combination of axial thrust and moment that causes failure, as does any point that lies outside the envelope. The point of maximum moment is referred to as the balance point. At axial loads greater than the balance point, a compression failure will result, and at smaller axial loads failure will occur as a result of insufficient tension capacity.

The moment-thrust envelope shown in Fig. 4.5 is typical of those determined experimentally during a limited series of beam-column tests (Parker, et al., 1975). Samples with dimensions of approximately 61.0 x 7.6 x 7.6 cm (24 x 3 x 3 in.) were cut from test panels shot under field conditions and tested at an age of about 6 months. The shotcrete mix included 418 kg/m^3

(7.5 bags/cu yd) of cement, and about 3 percent accelerator by weight of cement. Coarse aggregate with a maximum size of 13 mm (1/2 in.) accounted for about one-half of the aggregate. Many more such tests should be conducted to evaluate the effects of different mix designs, etc., on the envelopes and to develop experimental curves. The envelope in Fig. 4.4 is given only to illustrate the curve and should not be used for design. Special tests must be run for each project.
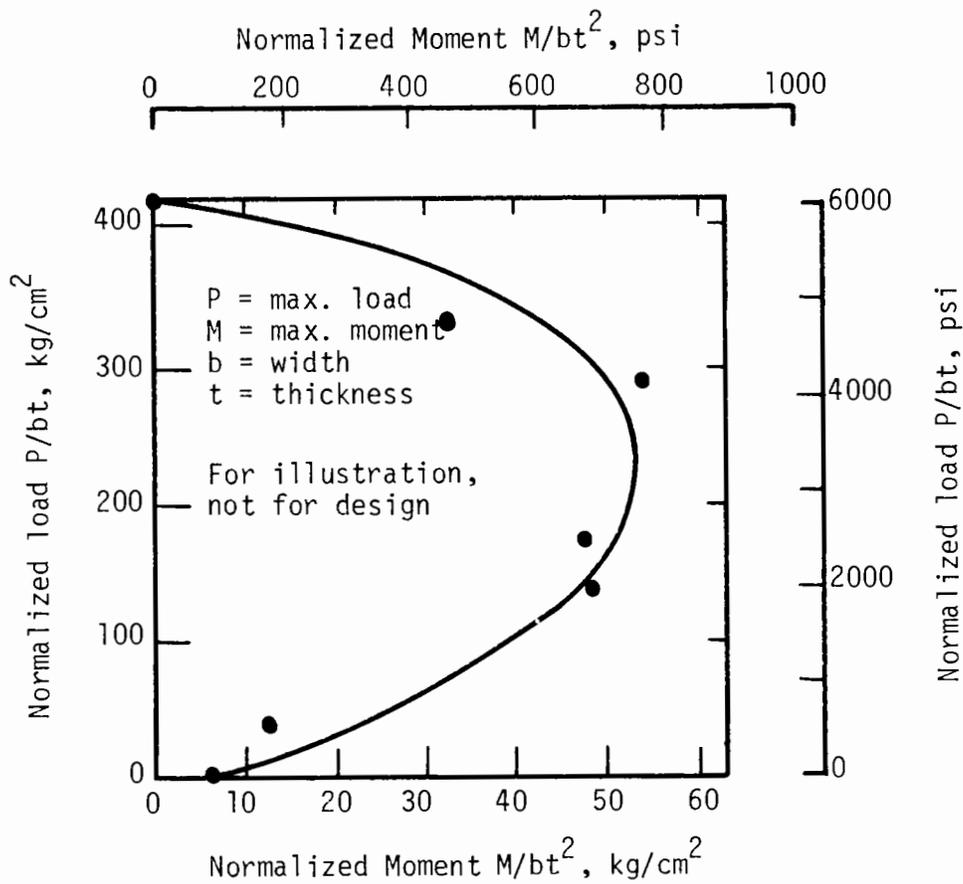
FIG. 4.5. TYPICAL MOMENT-THRUST INTERACTION DIAGRAM FOR SHOTCRETE

4.2.7 Bond Strength

Two types of bond strength must be considered for shotcrete: tensile and shear. Tensile bond strength is a measure of the ability of shotcrete to remain in contact with the rock when a tensile stress is applied normal to the rock-shotcrete interface; shear bond strength is concerned with the ability to resist stresses that act parallel to the rock-shotcrete interface. In an actual shotcrete lining there is some combination of these stresses acting on the shotcrete-rock interface.

The type of rock has a great influence on the ability of shotcrete to adhere to the surface. Factors influencing the bond strength include:

1) roughness of rock surface

2) condition of surface (cleanliness)

3) presence and nature of joint fillers such as clay gouge

4) curing conditions on the interface.

Values for tensile bond strength that have been reported in the literature are listed in Table 4.10. Although information is rather limited, tensile strengths ranging from about 7.0 to 28.5 kg/cm^2 (100 to 405 psi) have been reported between shotcrete and concrete, while somewhat higher values, ranging from 14.1 to 34.9 kg/cm^2 (200 to 495 psi), appear possible between two shotcrete surfaces. Tynes and McCleese (1974) indicate that bond strengths equal to the tensile strength of the shotcrete can be attained between two shotcrete surfaces. This is in agreement with earlier findings by Crom (1966). Tests on shotcrete-rock interfaces when subjected to tensile loading have been inconclusive to date because of difficulties in testing and because failure often occurs in the rock, not at the interface.

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Table 4.10 Summary of reported values of tensile bond strength

Interface tested	Tensile stress at failure						Mix design	Source
	7 hr		7 day		28 day			
	kg/cm^2	(psi)	kg/cm^2	(psi)	kg/cm^2	(psi)		
Shotcrete to concrete	3.2-5.4	(45-77)	13.0	(185)	-	-	Dry mix, 7 bags cement coarse aggregate 3 percent accelerator	Fernandez, et al., 1975
Shotcrete to smooth plastic surface (filament tape)	.7	(10)	1.4	(20)	-	-	Dry mix, 7 bags cement coarse aggregate 3 percent accelerator	
Shotcrete to smooth concrete	-	-	-	-	9.9	(140)	Wet/sand*	Tynes and McCleese, 1974
	-	-	-	-	2.1	(30)**	Dry/sand	
	-	-	-	-	7.0	(100)	Wet/coarse	
	-	-	-	-	16.2	(230)	Dry/coarse	
Shotcrete to rough concrete	-	-	-	-	7.4	(105)	Wet/sand	
	-	-	-	-	6.7	(95)**	Dry/sand	
	-	-	-	-	11.3	(160)	Wet/coarse	
	-	-	-	-	28.5	(405)	Dry/coarse	
Shotcrete to smooth shotcrete	-	-	-	-	23.2	(330)	Wet/sand	
	-	-	-	-	15.5	(220)	Wet/coarse	
	-	-	-	-	25.4	(360)	Dry/coarse	
Shotcrete to rough shotcrete	-	-	-	-	26.4	(375)	Wet/sand	
	-	-	-	-	34.9	(495)	Wet/coarse	
	-	-	-	-	25.0	(355)	Dry/coarse	

* Mix designs for abbreviated descriptions for Tynes and McCleese data:
        Wet/sand: Wet mix, 8 bags cement, fine aggregate
        Dry/sand: Dry mix, 11 bags cement, fine aggregate
        Wet/coarse: Wet mix, 7 bags cement, coarse aggregate
        Dry/coarse: Dry mix, 7 bags cement, coarse aggregate.

** Low value attributed to poor nozzling techniques, i.e., laminations and sand pockets.

Note: 7-bag mix is 390kg cement/m^3

Values for shear bond strength on a plane normal to the direction of shooting, as reported in the literature, are listed in Table 4.11. The data presented by Tynes and McCleese (1974) again demonstrate the high bond strength that can be attained between two layers of shotcrete, as it exceeded the average shear strength of the shotcrete. This indicates that a 100 percent effective bond can be achieved between layers of shotcrete with proper surface preparation and careful shooting. Values for shear strength between shotcrete and a rough concrete surface were somewhat less. Most of the samples tested for shear bond between shotcrete and rock (Bortz, et al., 1973) failed in the substrate and therefore do not indicate the true bond strength between the shotcrete and rock surfaces. They do represent minimum possible shear bond values.

4.2.8 Modulus of Elasticity

Values reported in the literature for modulus of elasticity are listed in Table 4.12. Much scatter can be anticipated not only from differences in mix design, age, compressive strength, different types of samples, and test errors but also from differences in the definition (initial, tangent, chord, or secant, etc.).

The high and low values of modulus of elasticity are summarized in Table 4.13 along with a typical range of values that can be used for design purposes as representative of values that can be attained in the field.

As with concrete, the modulus of elasticity increases with age and compressive strength. Generally, the relationships between compressive strength and modulus of elasticity of shotcrete are similar to those for concrete.

Table 4.11 Summary of reported values of shear bond strength

Interface tested	1 day		7 day		28 day		Mix design	Source
	kg/cm^2	(psi)	kg/cm^2	(psi)	kg/cm^2	(psi)		
Shotcrete to smooth concrete	-	-	-	-	27.5	(390)	Wet/sand*	Tynes and McCleese 1974
	-	-	-	-	41.2	(585)	Dry/sand	
	-	-	-	-	23.6	(335)	Wet/coarse	
	-	-	-	-	23.2	(330)	Dry/coarse	
Shotcrete to rough concrete	-	-	-	-	25.4	(360)	Wet/sand	
	-	-	-	-	32.0	(455)	Dry/sand	
	-	-	-	-	25.4	(360)	Wet/coarse	
	-	-	-	-	29.2	(415)	Dry/coarse	
Shotcrete to smooth concrete	-	-	-	-	66.9	(950)	Wet/sand	
	-	-	-	-	46.5	(660)	Wet/coarse	
	-	-	-	-	37.0	(525)	Dry/coarse	
Shotcrete to rough shotcrete	-	-	-	-	46.5	(660)	Wet/sand	
	-	-	-	-	61.3	(870)	Wet/coarse	
	-	-	-	-	43.0	(610)	Dry/coarse	
Shotcrete to rock	8.8	(125)	21.1	(300)	63.4	(900)	Dry mix, 19 mm (3/4 in.) coarse aggregate, 7-bag mix, est. 3 percent accelerator	Klosterman, 1968

* Mix designs for abbreviated descriptions for Tynes and McCleese data:
       Wet/sand: Wet mix, 8 bags cement, fine aggregate
       Dry/sand: Dry mix, 11 bags cement, fine aggregate
       Wet/coarse: Wet mix, 7 bags cement, coarse aggregate
       Dry/coarse: Dry mix, 7 bags cement, coarse aggregate.

** 14-day test.

Note: 7-bag mix is 390 kg cement/m^3

Table 4.12 Summary of reported values of modulus of elasticity

6-7 hr		1 day		3-8 days		28 days		Mix design	Source
10^6kg/cm²	10^6 (psi)	10^6kg/cm²	10^6 (psi)	10^6kg/cm²	10^6 (psi)	10^6kg/cm²	10^6 (psi)		
.1-.2	(0.9-2.3)	-	-	.2-.5	(3.1-7.3)	-	-	Dry mix, 7 bags Type I cement, 3 percent accelerator	Fernandez et al., 1975
-	-	-	-	.2-.3	(2.4-4.7)	.2-.4	(3.0-5.2)	Wet mix (average values)	Litvin and Shideler, 1966
-	-	-	-	-	-	.2-.3	(2.8-4.9)	Dry mix (average values)	" "
		.20-.22	(2.9-3.2)	.2-.3	(2.8-4.9)	.3-.4	(3.6-5.3)	Dry mix, 13 mm (1/2 in.) coarse aggregate, 7.5 bags Type I cement, 3 percent accelerator	Parker, et al., 1975
				.18-.24	(2.49-3.47)	.20-.28	(2.86-3.99)	Dry mix, 19 mm (3/4 in.) coarse aggregate, 7-8 bag mix, Type II cement, 3-4 percent accelerator	Corps of Engineers, 1974, New Melones Lake
.04-.07	(.58-1.03)	.14-.24	(1.97-3.39)	.19-.22	(2.72-3.09)	.18-.24	(2.58-3.35)	Dry mix, 13 mm (1/2 in.) coarse aggregate, 5-7 bag mix, Type III cement, 3 percent accelerator	Bortz, et al., 1973
		.12-.28	(1.78-4.06)	.23-.28	(3.24-3.91)	.24-.37	(3.45-5.21)	Wet mix, 13 mm. (1/2 in.) coarse aggregate, 5-7 bag mix, Type III cement, 3 percent accelerator	" "

Note: 7-bag mix ~ 390 kg cement/m³

Table 4.13 Typical range of modulus of elasticity

	1 day	3-8 days	28 days
Range of values reported in literature, kg/cm^2 x 10^6 (psi x 10^6)	0.13-0.29 (1.8-4.1)	0.18-0.34 (2.5 - 4.9)	0.18-0.37 (2.6 - 5.3)
Typical range attainable in kg/cm^2 x 10^6 (psi x 10^6)	0.11-0.21 (1.5 - 3.0)	0.14-0.25 (2.0 - 4.0)	0.18-0.32 (2.5 - 5)

4.3 Other Physical Properties

4.3.1 Volume Change

It is expected that certain aspects of volume change in shotcrete are affected at least qualitatively in the same manner as concrete. Because of the limited information available for shotcrete, some of the trends discussed are based upon knowledge of volume changes in concrete. However, in view of the fact that there are differences, at least in the water content, the method of compaction and in the uniformity between shotcrete and concrete, the validity of this assumption should be questioned in each case and should be checked experimentally in the future.

Shrinkage

Two aspects of shrinkage must be considered for shotcrete: drying shrinkage and thermal shrinkage. Drying shrinkage is primarily governed by the water-cement ratio. Litvin and Shideler (1966) determined that higher

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drying shrinkage occurs with higher water content for dry- and wet-mix shotcrete. Similarly, Studebaker (1939) reported an increase in drying shrinkage with increasing water content.

The aggregate particles reinforce the cement paste against contraction. Therefore, the expansion, contraction, and absorption characteristics of the aggregates are of concern. Any aggregate shrinking more than 800×10^{-6} cm/cm (in./in.) is undesirable (Troxell, et al., 1968). Greater particle contact reduces shrinkage. Therefore, shotcrete with large well-graded aggregate and mortar content that nearly fills the remaining voids shrinks less. Rebound influences shrinkage because it determines the aggregate gradation and paste content on the wall.

Blanck (1974) suggests there will be lower shrinkage with lower cement contents and accelerator dosages since the temperature rise will be lower. For the same reason there will be less thermal shrinkage in thin linings than thick linings that get very hot.

Drying shrinkage values for shotcrete reported in the literature range from 600 to 1500×10^{-6} cm/cm (in./in.) for dry- and wet-mix shotcrete (Litvin and Shideler, 1966) and from 650 to 1050×10^{-6} cm/cm (in./in.) for gunite (Studebaker, 1939). However, most of the values reported by Litvin and Shideler (1966) ranged from 600 to 1000×10^{-6} cm/cm (in./in.). A range of 600 to 1000×10^{-6} cm/cm (in./in.) appears reasonable for most shotcrete in free shrinkage; or about the same range as concrete. There is, however, a very important distinction between restrained and non-restrained boundary conditions for evaluation of shrinkage of shotcrete in intimate contact with rock as discussed in the next section.

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Significance of Shrinkage Cracks in Tunnel Linings

The rock surface to which shotcrete is applied as a tunnel lining usually acts as a shrinkage-restraining body. The magnitude of shrinkage that can occur can be many times less than that of non-restrained shotcrete, such as isolated shrinkage-test samples (Mahar, et al., 1972; Jones & Mahar, 1974). A comparison of shrinkage of shotcrete in a test panel (free shrinkage) and of shotcrete around the top, sides and edges of boulders to simulate a continuous lining (restrained condition) indicated that the amount of shrinkage is much smaller when shotcrete is bonded to rock (Jones, 1975). Free shrinkage values are greater and are not representative of in situ conditions.

Drying shrinkage of a thin shotcrete lining affects the rock support capability since cracks interrupt the continuity of the lining. The rock load that can be resisted by a thin shotcrete lining in tension is reduced by shrinkage. Cracking occurs at lower rock loads since shrinkage increases the initial tensile stress level in the shotcrete. Hence, the amount of stress that can be imposed by rock loads before the shotcrete cracks is reduced.

It is important to reduce the tendency for shrinkage as much as possible until the shotcrete has gained sufficient strength to withstand the combined stresses from rock loads and shrinkage. A reduction in the rate of drying will reduce the tendency to crack. Cracks may reduce the ability of the shotcrete to carry the designed load and may allow entry of water that might leach out soluble components, corrode steel reinforcement, or deteriorate the shotcrete when subjected to freezing and thawing such as at tunnel portals.

Any time a shotcrete lining cracks, the cracks should be observed carefully to determine if they are shrinkage cracks or if they are caused by rock movement. Further shotcreting or other reinforcement methods may be required.

Creep

There has been limited research on creep in shotcrete; much of the knowledge of factors affecting creep in concrete must be transferred, at least qualitatively, to shotcrete. As with shrinkage, the validity of this assumption must be checked. Creep is the deformation that occurs due to sustained loading. It is believed that the major portion of creep in concrete is caused by seepage of absorbed water into internal voids from the gel that is formed by hydration of the cement (Troxell, et al., 1968). Any factor that facilitates this movement of water tends to increase the amount of creep.

The rate and magnitude of creep should increase if the load is applied at a younger age or if the stress level in the shotcrete is higher. Mass concrete creeps less at the same stress level than thin concrete sections. Accordingly, thin shotcrete linings should creep more than a thick shotcrete final lining if the stress levels are the same. Naturally if the stress level in the thin shotcrete lining were higher, such as the case when the same magnitude of load is imposed on a thin and a thick section, the higher stress level and the thinner section both contribute to higher creep in the thin lining. Good quality aggregates produce concrete with lower creep rates than concrete with poor aggregate. There is some indication that concrete with larger size aggregate creeps less. Litvin and Shideler (1966) report higher shrinkage for dry-process sand mixes that had higher than normal water contents. They also indicate similar creep curves for dry-mix sand, dry-mix coarse aggregate, and wet-mix coarse aggregate shotcrete that had normal water contents.

The most significant variable reported by Litvin and Shideler was the water-cement ratio; high water-cement ratio coincided with higher creep in the

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shotcrete samples. A rule-of-thumb for the rate of creep in concrete is that one-fourth of the ultimate creep occurs in the first month and for practical purposes, three-fourths in the first year. Similar rates might be expected in shotcrete.

4.3.2 Durability

Of the various measures of durability, resistance to freezing and thawing is the most common concern to concrete and one of the least common to underground shotcrete except in portal areas or in large well-ventilated highway tunnels in the northern latitudes. One of the factors affecting the freeze-thaw resistance of shotcrete is the quality and character of the aggregate. Aggregates that fail the tests for soundness will have a detrimental effect on the durability of shotcrete. Another factor is the water-cement ratio. Durability increases with lower water-cement ratios, and, closely related to this, durability likewise increases with lower water contents (Troxell, et al., 1968).

One of the major factors in the durability of concrete is the air content. The presence of small air bubbles entrained in concrete greatly improves the freeze-thaw resistance by providing void spaces that tend to relieve pressure developed by freezing water. Although air-entraining agents are rarely used in wet mixes and never in dry mixes, Litvin and Shideler (1966) speculated that air voids of a size and spacing similar to those of air-entrained concrete are automatically entrapped while shooting a dry-mix shotcrete. In durability tests of shotcrete specimens subjected to accelerated cycles of freezing and thawing, they found that dry mixes generally performed better than wet mixes,

although much of the poor performance of the wet mixes could be traced to higher than usual water-cement ratios. The excellent performance of the dry-mix shotcrete (over 80 percent survived 300 freeze-thaw cycles without a significant degree of expansion, weight loss, or decrease in modulus) was partly attributed to the presence of tiny air voids, as discussed above. Measurements of actual air content in hardened samples of dry-mix shotcrete indicated air contents of 2.5 to 5.3 percent with proper bubble size and distribution. Other factors cited for the good durability were low water-cement ratio, high strength and low permeability.

Any shooting condition that leads to lower compaction, entrapment of rebound, air voids, lamination, or higher permeability will decrease the durability of the shotcrete. Poor curing conditions also reduce the degree of hydration and thus the durability.

The use of unsound, absorptive, or otherwise undesirable poor quality aggregate may result in unsatisfactory durability. The use of aggregates that are reactive to the highly alkaline cement and accelerators will result in an expansive reaction of the aggregates that could cause cracking and deterioration of shotcrete as it does in concrete.

High concentrations of soluble sulfates present in the groundwater will result in an undesirable reaction with the cement that can disintegrate the shotcrete. To the degree that good quality shotcrete is less permeable than concrete this sulfate attack may be reduced but the potential for deterioration still remains. Shotcrete is also susceptible to attack from other undesirable chemicals in the groundwater such as mine acids or chemical waste.

4.3.3 Permeability

From concrete research, the major factors affecting the permeability of shotcrete can be expected to be the water and cement contents, the aggregates, and the curing conditions. A low water-cement ratio and high cement content tend to reduce permeability. Both of these conditions exist in most shotcrete applications. A well-graded aggregate of sound quality, a high degree of compaction, and low porosity also promote water tightness. Curing conditions are important because the degree of hydration of the cement determines the extent to which the voids will be filled with the developing gel (Troxell, et al., 1968).

Tests on water permeability of shotcrete were conducted by Litvin and Shideler in 1966. For all samples that were at least several times thicker than the maximum size aggregate, essentially no flow was recorded when the shotcrete specimens were subjected to 3.5 kg/cm^2 (50 psi) water pressure for up to two weeks.

Bortz, et al., (1973) exposed 5-cm (2-in.) thick samples of coarse aggregate shotcrete to methane gas at a pressure of 4.2 kg/cm^2 (60 psi). There was no pressure loss after 5 minutes of exposure.

Both of these investigations indicate that intact shotcrete has a very low permeability for all practical purposes. However, the average permeability of a material does not necessarily govern the flow of water through it. Instead the defects or the zones of highest permeability are often more important than the average permeability. Any shooting conditions that result in sand pockets, entrapped rebound, laminations, entrapped air, etc., will make the lining more permeable even though the intact material is nearly watertight.

CHAPTER 5

PRODUCTION OF SHOTCRETE FOR UNDERGROUND CONSTRUCTION

This chapter describes the basic shotcrete operation, and how it affects both the quality and economy of the in-place material. Because of its importance, many aspects of the operation are specified in the contract documents. The type and arrangement of the equipment are usually the responsibility of the contractor, however, since he has the necessary background to choose the proper equipment and set up the operation to be compatible with tunneling. The engineer and contractor must have an appreciation for the requirements and difficulties of each other's discipline, so that the highest quality yet the most efficient work can be achieved.

The shotcrete operation involves two basic systems: 1) materials handling and 2) gunning (Fig. 5.1). The former can be further subdivided into the storing, batching, mixing, and conveying of the materials to the shotcrete machine. Gunning is done by one of two processes: wet- or dry-mix. The basic components of the shotcrete operation for these two processes are schematically shown in Fig. 5.1. Elements of the materials handling system are the same in both processes. The basic difference between these two processes lies in the water content of the materials at the shotcrete machine. In this section the four basic elements of the shotcrete operation: 1) material storage, 2) batching and mixing, 3) conveyance, and 4) gunning are described, including the requirements and methods of each element.
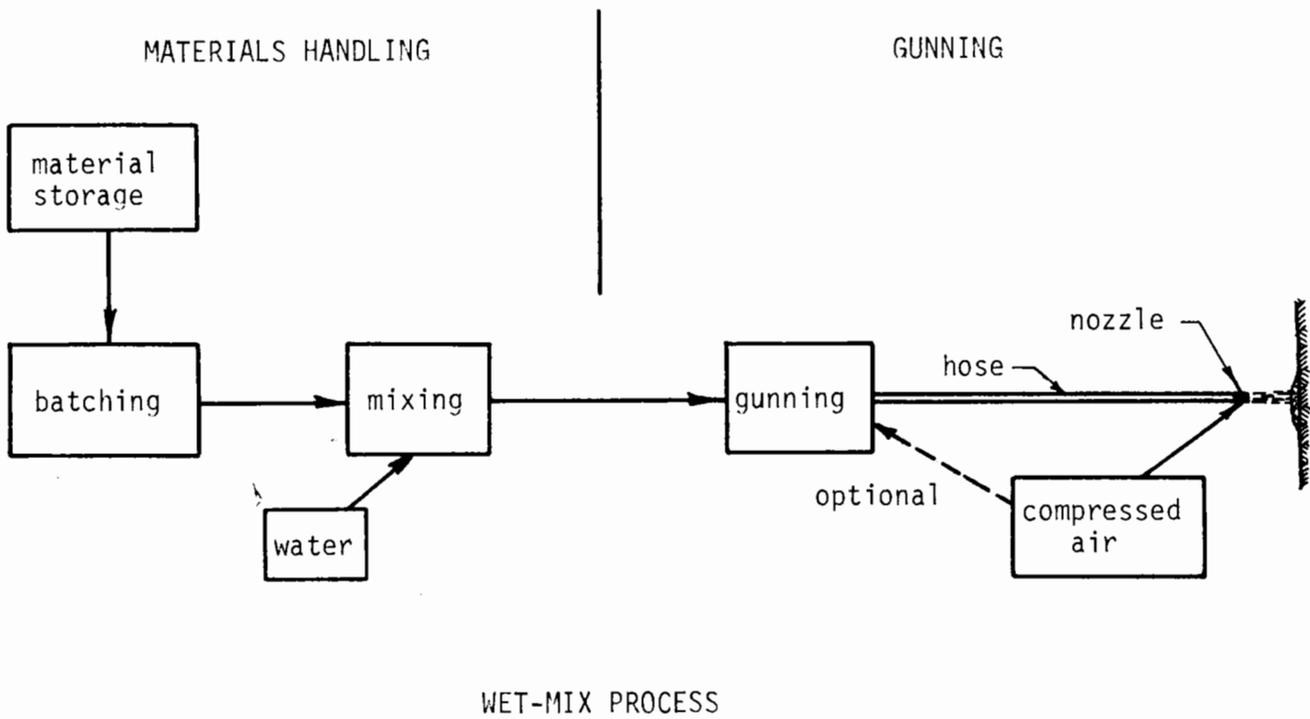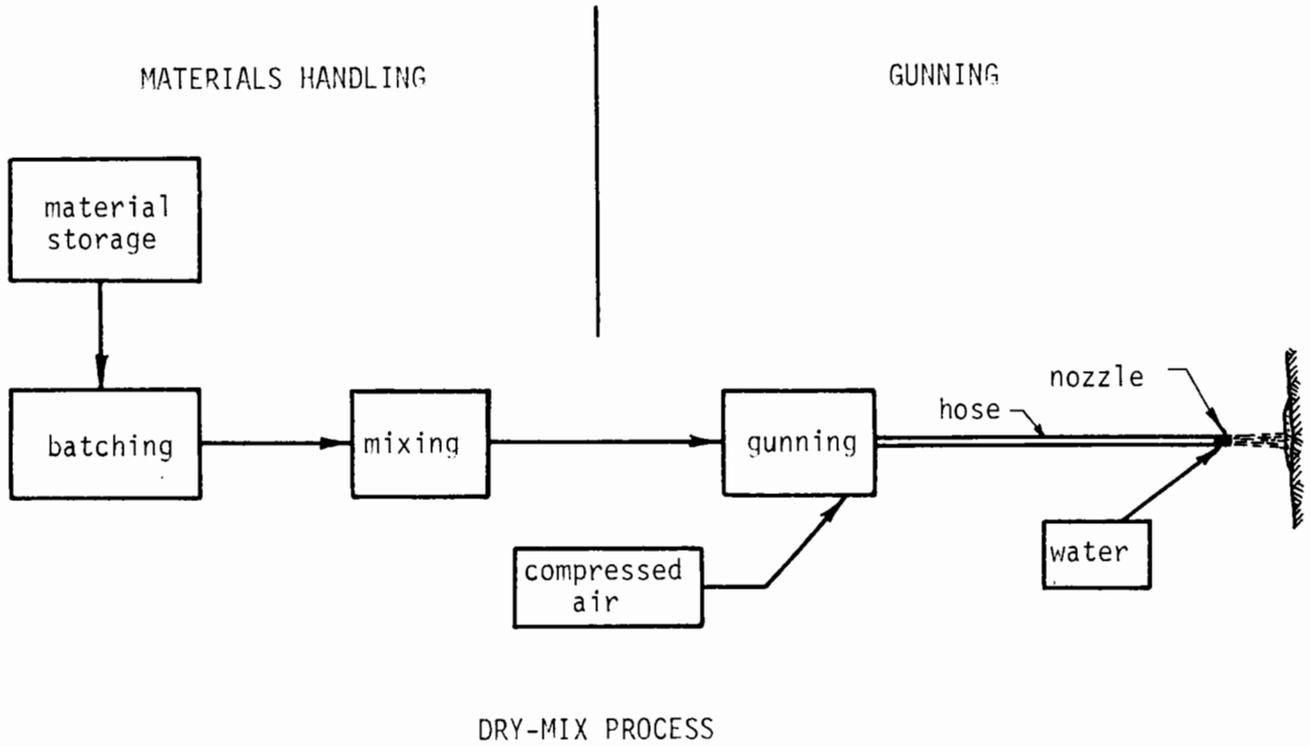
FIG. 5.1 SCHEMATIC DIAGRAMS OF THE DRY- AND WET-MIX PROCESSES.

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5.1 Material Supply and Storage

The supply and storage of materials form an integral part of the shotcrete operation. The designer must know the character of the locally available materials in order to realistically write the material specifications, while the contractor must arrange for an adequate supply of acceptable materials to meet his needs. Moisture content and contamination are the primary considerations in the storage of materials. Serious construction delays can result from either an inadequate supply or improper storage.

5.1.1 Availability

Materials meeting the design specifications must be found in sufficient quantities to meet the volume of shotcrete needed for the job. The aggregate must conform with the mix design and quality requirements. The accelerator and cement must also meet the quality specifications but, in addition, must be compatible themselves. The materials can be obtained from a supplier or, for aggregates, can be mined by the contractor. In dealing with a supplier, a contract should be set up to guarantee a sufficient supply of acceptable materials. Local suppliers should be utilized whenever possible to reduce transportation costs. If the aggregates are obtained by the contractor at a borrow area, the supply must be checked for quality and quantity. Alternate sources should be investigated to ensure a timely transition in the event that the primary supply becomes inadequate or its quality unacceptable.

5.1.2 Preparation and Delivery

The shotcrete aggregates must usually be screened and sometimes washed in

order to meet the specifications. If the material contains an appreciable percentage (above 1%) of cohesive particles it must be washed. Aggregates may also require screening and/or blending to meet the maximum size and gradation requirements. Washing and screening are usually combined into one operation if both are required. Preparation is usually done at the quarry so that the materials are delivered ready for batching. Washed materials should be allowed to drain freely for at least 12 hours before they are batched. In some cases it has been necessary to dry all or a portion of the aggregate to achieve optimum moisture content for batching or shooting.

All of the shotcrete materials must be delivered to the job site in sufficient quantities to meet the shotcrete production needs. The materials can be delivered either by the supplier, by a separate hauler, or by the contractor. Care must be taken to prevent contamination of the materials in loading and transporting them to the job site.

5.1.3 Storage of Aggregates

The aggregates should be stored so that water does not accumulate and the materials do not become contaminated. The aggregates are usually stored in bins or hoppers and in stockpiles. Bins or hoppers should have a roof or cover. The ground adjacent to bins and stockpiles should be sloped away so that the materials are able to drain. The aggregates can become contaminated with earth or foreign materials particularly when supplies are low in the bins or stockpiles. The level of supply should be kept sufficiently high to prevent foreign materials from being incorporated in the aggregate piles while

charging the batching bins. Aggregates around the perimeter of the supply should not be used since they are likely to be contaminated or segregated. Aggregates containing earth or foreign materials must be discarded. All aggregates of different gradations should be stored separately and should not be mixed before they are placed in the batching hoppers. Stockpiles and bins should be sufficiently separated to prevent mixing of the aggregates. If the aggregates become mixed they must be screened into the appropriate sizes or be discarded.

In addition to moisture and contamination control, the aggregates must not become segregated during transport or placement in storage. Segregation is most likely to be a problem with the gravel-size material; the larger particles tend to collect at the sides of the supply. To minimize segregation, the gravel should be placed into storage using a vertical, downward tapered chute whose orifice is maintained slightly above the top of the pile (Fig. 5.2). The chute should be moved back and forth across the top of the pile as the material is being discharged. The surface of the pile should be kept level to prevent the coarser aggregate from rolling down the sides of the pile and collecting at its outside edges. Segregated materials should be mixed before being placed in the batching bins, unless the pile is about the same size as one batch and the material is mixed before it is used.

5.1.4 Storage of Accelerators and Cement

Both the cement and accelerator are moisture sensitive and must be stored in an elevated and dry location. Bags of cement or accelerator should be placed on pallets not closer than 5 cm (4 in.) to the ground surface. The bags should
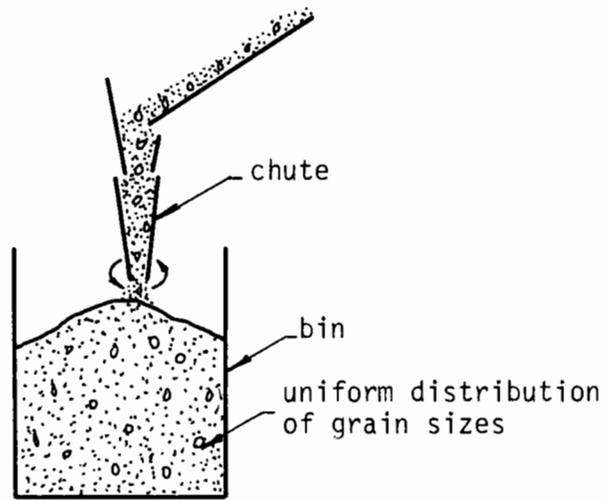
a. Correct method of charging storage unit
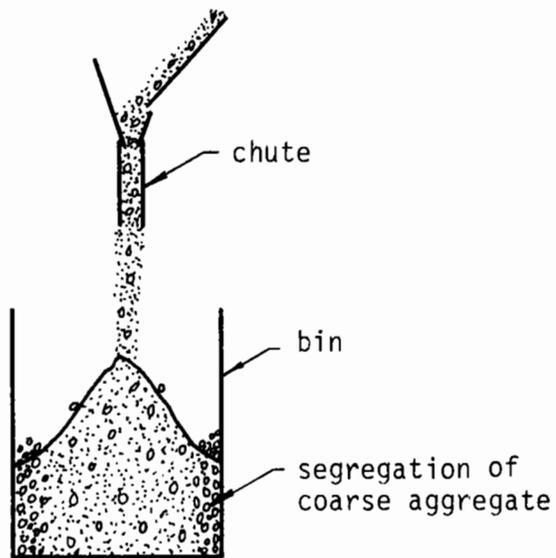
b. Incorrect method

FIG. 5.2 CORRECT AND INCORRECT METHODS OF DISCHARGING AGGREGATE (USBR, 1963).

be lined with a plastic membrane and should be covered with a tarp. The cement or accelerator in ripped bags should be used immediately after the bags are damaged or should be discarded. If the materials are supplied in bulk quantities they must be stored in moisture-proof containers and they should be protected from contamination during unloading and while in storage.

5.2   Batching and Mixing Operations

5.2.1   Batching

The fundamental requirement of the batching operation in both the wet- and dry-mix processes is that the materials be proportioned within the limits of the mix design. Weight batching is strongly recommended by the ACI Committee on Shotcrete (1966) because it provides a more accurate control of the relative proportions and total quantities of materials in comparison with the volumetric method. Materials can be batched volumetrically provided periodic weight checks are made to insure proper proportioning of constituents. Volumetric batching should be done in accordance with ASTM 685, specifications for "Concrete Made by Volumetric Batching and Continuous Mixing". If doubt exists as to the effectiveness of the volumetric batching equipment, tests can be conducted in which the mix proportions are varied over the expected range to determine the effects on shotcrete strength. Tests of this type have been performed and have demonstrated that volume control can be adequate when proper procedures are used. These tests do not eliminate the need for periodic weight checking. Aggregates and cement can be batched by either weight or volume while water (for the wet-mix materials) and accelerator are usually proportioned by volume. Volumetric batching has the advantage that the mix is

always fresh since the materials are combined just prior to shooting.

Discrepancies between the actual proportions of batched materials and mix design are likely to be caused by: 1) segregation of the aggregates in the batching bins or stockpiles, 2) improper moisture content in the aggregates, 3) faulty performance of the batching equipment, and 4) operator error. The effect of segregation is to produce a more poorly graded or gap-graded material resulting in higher rebound. To minimize segregation, aggregate should be charged in the batching bins following the placement procedures described in the previous section and illustrated in Fig. 5.2. The moisture content of the aggregates affects both volume and weight batching. Batching of sand is more sensitive to moisture than is batching of gravel, and water causes greater discrepancies in volume than in weight proportioning. For batching purposes sand is usually assumed to have a moisture content of 5% (by weight). When large fluctuations in moisture content occur, batch weights must be adjusted according to the results of actual moisture content tests.

In batching of dry-mix shotcrete the saturated surface-dry moisture content of the aggregates should range between 3 and 8% by weight. Optimum moisture content in batching and mixing for the dry-mix process appears to be roughly 5% by weight. If the moisture content is below 3%, the aggregate will not be thoroughly coated with cement; the result is higher rebound and lower compaction. The uncoated or partially coated aggregates emerging from the nozzle do not readily adhere to the in-place materials but rather tend to bounce off on impact. Effective coating does not occur at the nozzle because the cement tends to separate from the aggregate in the material hose and because insufficient time is available for proper mixing of any free

cement occurring with the aggregates. Low moisture content can also cause severe dusting in places where the material is exposed to air. If the moisture content is below 3%, water should be added prior to mixing.

Above 8% moisture content in the dry-mix process, the materials tend to lump or ball together. This inhibits their feeding into the shotcrete machine, produces an uneven flow of materials to the nozzle, and in some cases prevents operation of the machine. In addition, high moisture contents cause coating and caking of the equipment with cement and fine aggregate. These materials must be removed, usually by hand, at additional expense. When moisture contents are too high, heaters may be used for drying, or the wet aggregate may be blended with dry materials. Adding extra cement to dry the aggregates is not recommended since this is likely to cause high shrinkage and can lower the strength of the shotcrete. At high moisture contents a greater percentage of the cement will become prehydrated if the gunning operation is interrupted. To minimize prehydration when aggregates are wet, the cement can be added at the machine just prior to gunning.

In the wet-mix process, the water is batched during mixing and is proportioned to obtain the desired consistency. The procedures for adding water are the same as those used in manufacturing concrete. A small portion (5-10%) is added just before and just after the cement and aggregate are first introduced into the mixer (USBR, 1963). The remaining water is added uniformly with the rest of the material during mixing to obtain the desired consistency. When the sand has a large variation in moisture content, moisture content tests must be conducted to correct the amount of water added to the mix to obtain the desired slump.

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The temperature of the aggregates and cement in both the wet- and dry-mix processes should not be less than 3°C (38°F) during batching. Below these temperatures, the initial set is greatly retarded, rebound is increased, and possible freezing of the water in the shotcrete may occur. In addition, the high accelerator dosages (6-10% by weight cement) needed to hold the shotcrete on the tunnel surface will greatly reduce final strength. In cold weather the storage and/or batching facilities can be equipped with heaters to increase the temperature of the aggregates. The temperature of the aggregate and cement may be increased somewhat by heating the water before it is mixed with the materials.

5.2.2 Mixing

The mixing of shotcrete materials must be done so that all of the ingredients are thoroughly blended and, in the dry-mix process, so that the aggregates are thoroughly coated with cement. The materials are properly blended if there is a uniform distribution of ingredients throughout the batch. To provide proper blending and coating, the mixer must be properly designed and mixing must be carried out for a sufficient length of time. Incomplete coating of the aggregates may not necessarily be related to insufficient mixing but may also be caused by low initial moisture contents of the aggregates, as noted in the previous section.

The amount of mixing required is usually defined in terms of the mixing time and in some cases by the number of revolutions of the mixing device. In shotcrete work the minimum mixing time depends primarily on the type and size of the mixer, the amount of material batched, and on the water content of the

5-10

ingredients. For most mixers having a capacity equal to or less than 3/4 m^3 (1 yd^3), a minimum mixing time of 1 minute is required for proper blending of wet-mix materials (ACI, 1958). Fifteen seconds is added to the minimum time for each additional 3/4 m^3 (1 yd^3) or fraction thereof (Table 5.1). For the dry-mix process, the minimum mixing times given in Table 5.1 represent an increase of 50% over wet-mix times (Troxell, et al., 1968). The mixing time is defined as the interval of mixer operation starting when all of the solids have been placed in the mixer and ending when the mixing action is terminated. Mixing during discharge of the mixer is not included in meeting the minimum requirements (USBR, 1963). When mixing occurs at variable rates or when the mixing times cannot be accurately determined, the number of revolutions of the agitating device is used as a measure of proper blending.

Table 5.1 Minimum mixing times suggested for wet-mix and dry-mix shotcrete (based on ACI, 1958 and Troxell, et al., 1968).

Capacity of Mixer m^3	(yd^3)	Min. Mixing Time-Wet-Mix Materials min	Min. Mixing Time Dry-Mix Materials min
0 - 3/4	(0-1)	1	1 1/2
3/4 - 1 1/2	(1-2)	1 1/4	1 7/8
1 1/2 - 2 1/4	(2-3)	1 1/2	2 1/4
2 1/4 - 3	(3-4)	1 3/4	2 5/8
2 - 3 3/4	(4-5)	2	3
3 3/4 - 4 1/2	(5-6)	2 1/4	3 3/8

Mixer efficiency tests should be conducted to determine the actual minimum mixing requirements. These tests are described in a concrete manual published by the USBR (1963).

Overmixing of the shotcrete materials is undesirable since the grinding action can significantly increase the percentage of fines. In the dry-mix process these fines tend to clog the equipment and may increase the cement requirement whereas, in the wet-mix, more water will be needed to obtain the desired consistency. The amount of additional water required to produce the desired slump after overmixing is highly variable and is difficult to judge. To prevent overmixing, Troxell, et al. (1968) recommend that mixing not be carried out beyond 300 revolutions of the mixing device. For this reason, the mixing devices should be equipped with a counter.

The efficiency of the mixer is governed primarily by the method of charging, the amount of material mixed, and the operation and maintenance of the mixing equipment. Best results are obtained when all of the solids are simultaneously charged into the mixer since this procedure reduces chances of segregation. The mixer also operates most efficiently when it is not charged more than 10% above the rated capacity and when the mixing device is run at the manufacturer's suggested speed (Troxell, et al., 1968). The mixer must be maintained in good operating condition and kept clean so that a uniform blending action is imparted to the materials. All accumulations of materials should be removed as they build up and worn parts (such as blades) should be replaced periodically.

Several classifications of mixers are defined in concrete technology and include tilting and non-tilting, portable and stationary. In shotcrete work, tilting portable mixers are preferred to enable rapid discharge of the materials

5-12

from the mixer into the storage hopper and allow the mixing operation to remain close to the shotcrete machine. Both of these features reduce possible segregation of the materials. Non-tilting mixers may be equipped with gates at the bottom of the mix container to facilitate a rapid discharge of the prepared materials.

5.3 Conveyance of Materials

5.3.1 Compatibility With Muck Removal System

Conveyance of either raw or prepared materials to the shotcrete machine may control the production rate of the shotcrete operation and can markedly affect the rate of tunneling advance. The conveyance system must be designed so that a continuous supply of material is available to the shotcrete machine when it is needed. The system must also be compatible with the other tunneling operations to ensure that minimum interference exists. In tunnels where excavation is cyclic (drill and blast tunnels), the same equipment used for mucking can also be used to haul the shotcrete materials. A separate supply system for shotcrete is advantageous when the tunneling operation is continuous and proceeds at high rates of advance (machine-bored tunnels). Where tunneling and shotcreting are occurring simultaneously, the same conveyance equipment can conceivably be used to remove muck and supply the shotcrete materials; however, this arrangement may cause contamination of the shotcrete and delays in both operations. In this case, enough equipment must be available to accommodate both operations without causing serious interference. The equipment, in any case, must have the capacity for rapid

loading and discharging of materials. The materials handling system should
be set up to achieve an optimum rate of tunnel advance and placement of
support.

5.3.2 Methods of Conveyance

The method of conveyance used underground depends on the distance of
transport, method of handling, and available space. These methods include
vehicle, pipe, conveyor belt, auger, elevator, chute, and hand conveyance.
The distance of transport can generally be described as either short or long
haul. Short hauls involve movement of materials close to the shotcrete machine,
such as in a mobile batch plant or a shotcrete rig (Fig. 5.3). Conveyance
of materials for short distances is accomplished using any of the above methods
except vehicular transport. For long hauls, trucks, rail cars, or conveyor
belts are used depending on the method of removing muck. Pipes are also used
for long distance hauling, particularly for vertical, downward conveyance of
materials. The haulage system should be suited for the space available and
be small enough to prevent congestion.

5.3.3 Segregation

Segregation can occur during transit, or as the materials are being loaded
into or discharged from the conveyance equipment. Segregation is most critical
when the materials are not remixed before entering the shotcrete machine. Dry-
mix materials are much less sensitive to segregation during truck or rail (vehic-
ular) transport than are wet-mix materials. A mild mixing action should be im-
parted to the wet-mix near or at the end of transport to ensure proper blending.
A minimum agitation is all that is needed to obtain the desired homogeneity.

5-14

aggregate

conveyor
belt

auger or
conveyor

cement

ribbon
feed

shotcrete
machine

control
console
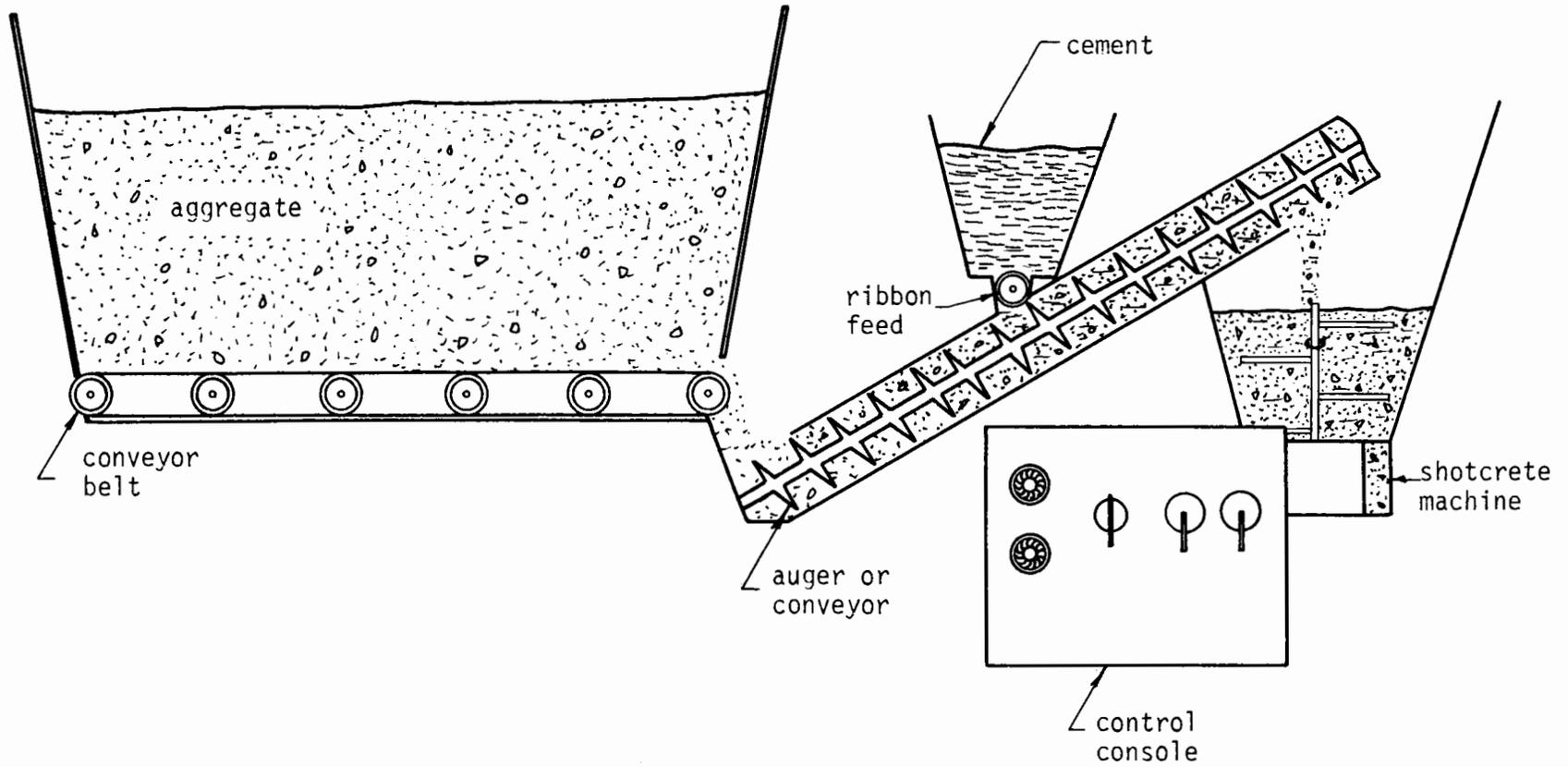
FIG. 5.3   CONVEYANCE SYSTEM IN A MOBILE, VOLUMETRIC BATCHING PLANT.

Dry-mix materials are more likely to segregate in chutes or vertical pipes than wet-mix materials. In chutes, the larger aggregates in the dry-mix tend to roll on top of a bed of fine aggregate and cement (Fig. 5.4). This causes a severe segregation and a marked difference in the gradation and cement content at the beginning and end of the batch; the first materials consist of coarse, poorly-graded aggregates containing little cement and the last consist mostly of sand and cement. To minimize segregation in a chute, the chute can be inclined at a shallow angle from the horizontal and the materials pulled by hand, or the chute can be inclined at a steep angle so that the aggregate and cement fall together. Use of long narrow chutes is not recommended because of segregation. In a vertical pipe with gravity-fed materials, the larger aggregates fall faster than the fines and cement. This velocity difference causes segregation; however, its effect can be reduced by feeding the materials into the pipe as rapidly as possible without causing a plug. This procedure allows the segregated aggregates to catch up and mix with the fines and cement of the previous charge. If the materials are pumped, the fines and cement will segregate from the coarser aggregates but with less potential separation as compared with a gravity feed. Wet-mix materials are also susceptible to segregation in chutes and pipes but are not as strongly affected as dry-mix materials.

For short conveyance distances belts, augers, or elevators are more commonly used than chutes. Belts provide a more uniform and reliable delivery of materials than augers and produce only slight segregation of the aggregates toward the top of the layer. Augers, on the other hand, provide a beneficial mixing action. Elevators are advantageous when conveyance must be nearly vertical. In small operations, materials are also conveyed over short distances by wheelbarrow or shovel.

coarse aggregates
rolling on bed of
fine aggregate
and cement

fine aggregate
and cement

chute

shotcrete
machine
hopper

coarse aggregate
charge
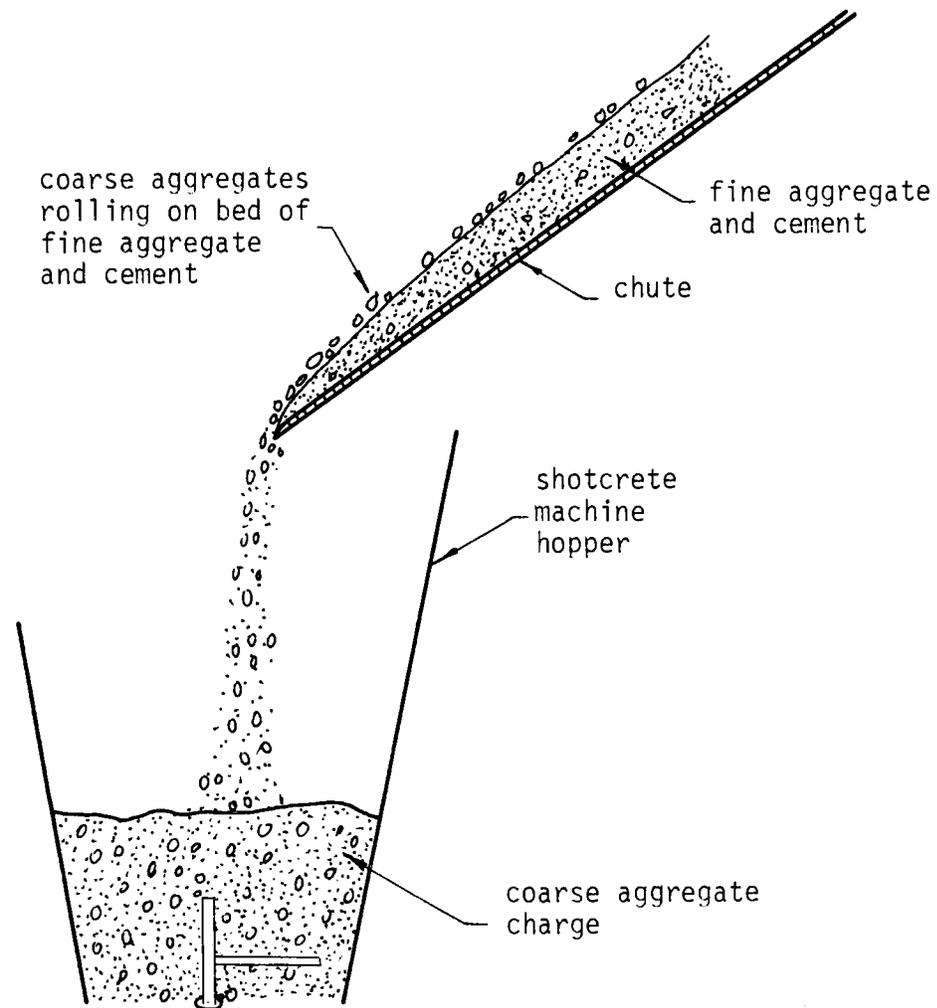
FIG. 5.4 SEGREGATION OF COARSE AGGREGATES DURING
TRANSPORT IN CHUTES.

Segregation may also be produced by improper handling of the materials during loading and discharge as previously described in the section on storage of materials (Fig. 5.2). Transfer of materials should be accomplished as rapidly as possible to minimize segregation in the conveyance equipment. Segregation causes partitioning of the batch into a coarse, poorly-graded fraction containing little cement and a fine fraction having a relatively high cement content. It affects the rebound and quality of the shotcrete. When the coarse fraction is gunned, rebound is very high and the in-place shotcrete contains laminations consisting of poorly cemented sand and gravel. These laminations can greatly reduce the strength and durability of the shotcrete. The fine fraction produces a shotcrete with a very high cement content and thus susceptible to shrinkage cracking. Where major segregation is likely to occur during transport, the entire batch should be gently but thoroughly remixed before it is placed in the shotcrete machine. Remixing of only a portion of the segregated batch, as for example in the hopper of the shotcrete machine, is inadequate since the two fractions are discharged and remixed separately and thus remain segregated.

5.3.4 Prehydration

Prehydration of the shotcrete materials causes a significant reduction (up to 50%) in the strength of the in-place shotcrete. The loss in strength results from partial setting of the cement which is later disturbed during gunning. Prehydration also increases rebound and may produce plugs or cause set-up of the materials within the equipment. Both the dry- and wet-mix

materials are susceptible to prehydration; however, the dry materials are not likely to be as severely affected because their initial moisture contents are well below the amount of water needed for complete hydration. Adding of water to prehydrated, wet-mix materials to improve pumpability should not be done because of its adverse effect on strength. Prehydration of the prepared shotcrete is most likely to occur when materials must be conveyed over long distances but may also result from interruptions in the gunning operation.

To prevent prehydrated materials from being placed underground, the prepared shotcrete should be wasted if it is not gunned within 60-90 minutes after the cement and aggregate are mixed, unless the aggregates are batched completely dry. Dry batching of the materials, however, is difficult since the aggregates must usually be dried, a source of water with a calibration device must be present near the shotcrete machine, and loss of materials from severe dusting may result. Where the conveyance distance of prepared shotcrete is long, the materials can be batched without the cement, which is later added at the shotcrete machine. The use of this procedure requires that a mixer, capable of holding the entire batch, be located near the shotcrete machine. Prehydration may also be minimized by carrying the raw materials into the tunnel and batching and mixing at the machine (Fig. 5.3).

5.4 Gunning Operation

The gunning operation is the final, yet the most critical, part of shotcreting since it involves actual placement of materials on the tunnel surface. In this operation, the prepared materials are fed into the shotcrete

machine which forces them through a hose and out of the nozzle onto the surface. The most important parts of the operation are the delivery of materials to the nozzle and the nozzling techniques. The delivery must be smooth and continuous so that little adjustment is required at the nozzle and so that the materials can be placed in the desired thickness on the surface. The delivery of materials to the nozzle is also affected by the performance of the shotcrete equipment and personnel, particularly the gunman. If the flow is uneven the material stream must be directed away from surfaces to receive shotcrete until a uniform flow is achieved.

In the dry-mix process the materials are placed in the shotcrete machine essentially dry and the water is added at the nozzle (Fig. 5.5). In the wet-mix process a low-slump material (10-75 mm [1/2 to 3 in.] slump) is pumped to the nozzle where air is injected and the materials are blown onto the surface (Fig. 5.6). On a given project, the choice of process will depend on both economic factors and on tunnel ground conditions. A comparison between the two processes is summarized in Table 5.2. The most desirable features of the wet-mix process are the lower rebound and dusting, whereas the dry-mix process is more suitable for varying ground conditions, particularly when groundwater is encountered. The dry-mix process has thus far dominated underground shotcrete construction; however, wet-mix applications are becoming popular.

The minimum equipment needs for the gunning operation in underground construction are: shotcrete machine, material hose, nozzle, compressor and air line, accelerator dispenser, and either a water hose or an air hose depending on the choice of the dry- or wet-mix process, respectively. The types of equipment and their performance requirements are described in

5-20

moistened aggregate,
cement, and accelerator

shotcrete

dry-mix shotcrete
machine

water
line

control
valve

water
ring

air

water

air

nozzle

material hose
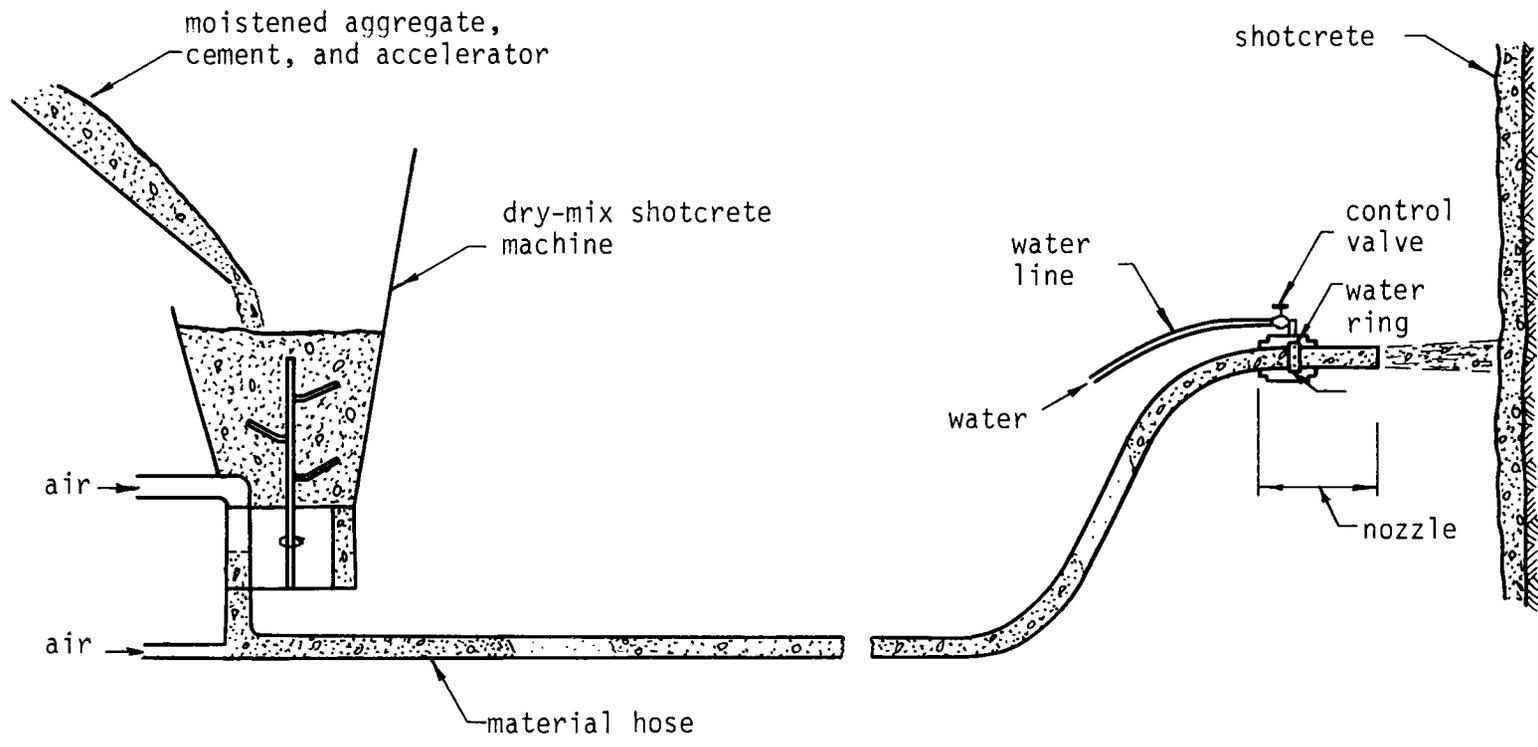
FIG. 5.5 DRY-MIX SHOTCRETE OPERATION.
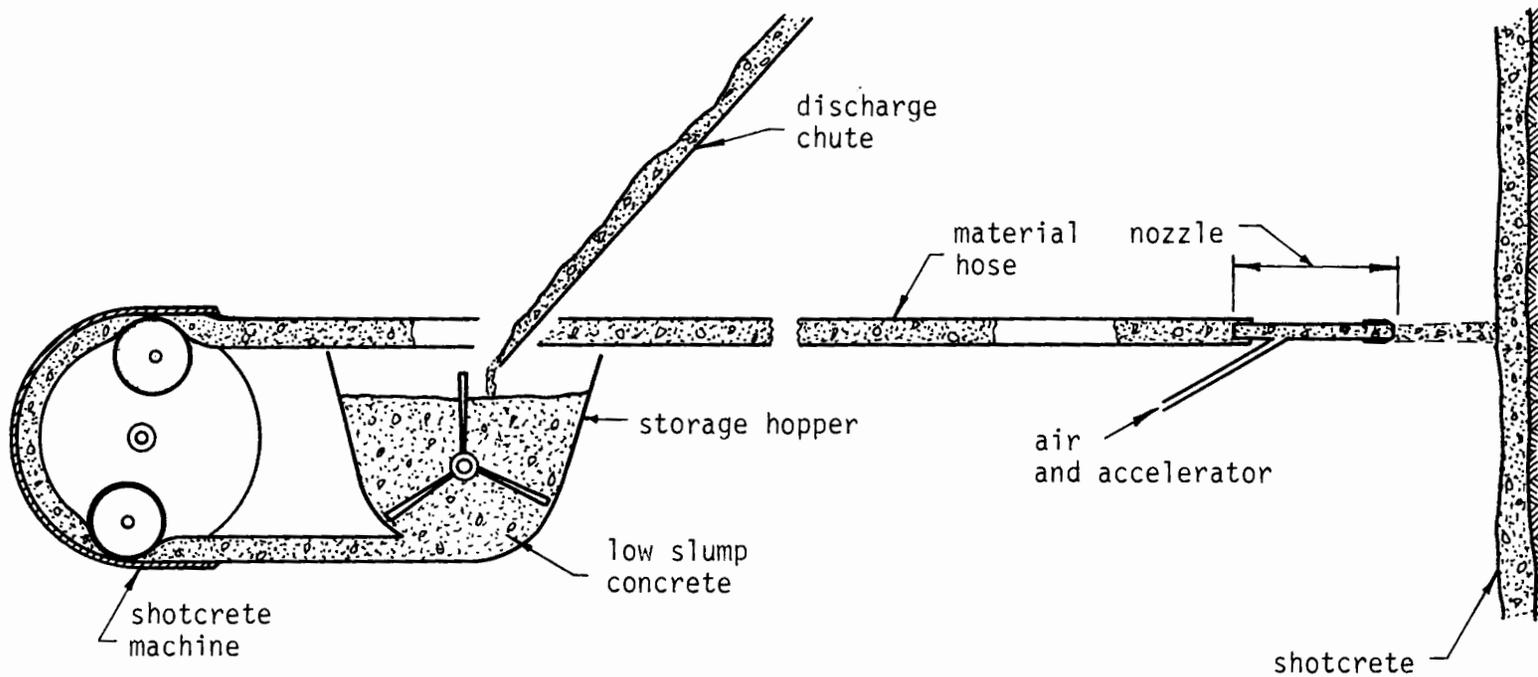
FIG. 5.6 WET-MIX SHOTCRETE OPERATION.

Table 5.2 Comparison between wet- and dry-mix processes.

Wet-Mix	Dry-Mix
•lower rebound	•more adaptable to varying ground conditions, particularly where water is involved
•lower dusting	
•control of water/cement ratio	•dry-mix equipment is typically less expensive and a larger inventory of used equipment is available
•quality control in the preparation of the materials is easier, because manufacture of materials is nearly identical to concrete.	
•quality of in-place shotcrete is not so sensitive to the performance of nozzleman since he does not adjust water	•dry-mix machines are typically smaller and thus are more adaptable to tunnels with limited space
•nozzleman directly controls the impact velocity of the particles and thus compaction by regulating air flow at the nozzle	
•easier to clean	
•lower maintenance costs	
•higher production rates	

Chapter 6. A typical arrangement of the equipment for underground applications is illustrated in Fig. 5.7 and is discussed in the remainder of this chapter. Actual placement of shotcrete including nozzling is treated in Chapter 7.

5.5 Setup of the Shotcrete Equipment

The type and arrangement of the equipment selected for a given job will depend primarily on the desired material delivery rate. This rate is governed

PLAN VIEW

compressed
air line

water line

shotcrete
nozzleman

mucker
carrying
shotcrete
materials
to storage
hopper

shotcrete
jumbo

shotcrete
machine

accelerator
dispenser

material
hose

platform

crane

face
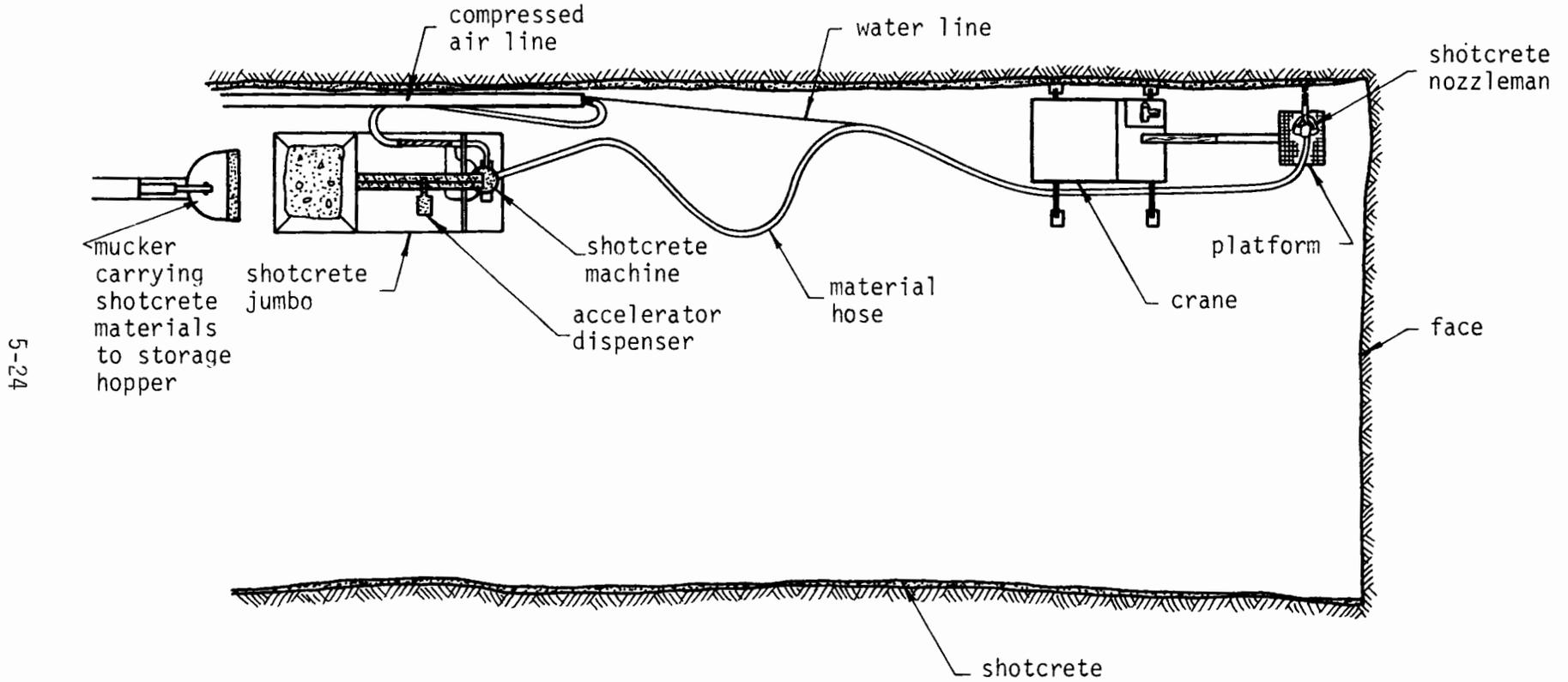
shotcrete

FIG. 5.7   SETUP OF SHOTCRETE EQUIPMENT IN
UNDERGROUND CONSTRUCTION.

by the volume and use of the shotcrete in the tunnel. High production rates are needed when the volume of shotcrete is large or if the shotcrete must be placed as part of the tunnel cycle. If the shotcrete is to be used only to seal local sections of the tunnel, then only a small operation will be needed. In some cases, the space limitations rather than the desired delivery rate may control the setup of the shotcrete equipment.

The actual delivery rate attained underground is controlled by the number of shotcrete machines, the materials handling system, the skill of the crew, and the performance of the equipment. For production rates of less than 4-1/2 m^3/hr (6 yd^3/hr) only one shotcrete machine is usually required whereas two or more machines are needed for greater production. The materials handling system must be capable of manufacturing enough shotcrete to supply the machine(s) adequately so that production will not be interrupted. The volumes prepared, however, should not be so great that excessive waste will occur if the gunning operation is shut down. The crew must be experienced in the operation of the equipment and must have incentive for rapid production of good quality shotcrete. An inexperienced crew will not only have a low production rate but will also produce shotcrete of low quality. The performance of the crew is directly related to the capability of the shotcrete foreman. The equipment must be maintained in good working order so that breakdowns will not occur during shooting. Production rates of approximately 5-1/2 m^3/hr (7 yd^3/hr) were obtained in the headings of the conventionally driven Washington Metro Tunnels and 7 to 8 m^3/hr (8-1/2 to 10 yd^3/hr) were gunned during placement of the permanent lining. These rates were obtained using two dry-mix shotcrete machines and a large batch plant. In the Tehachapi Tunnels, approximately 7 m^3 (9 yd^3) were placed in the heading within 45 min by using two machines and spraying over the muck pile.

5-25

The setup of the shotcrete equipment is controlled largely by the space limitations in the tunnel as well as its length and depth below the ground surface. The space available for the shotcrete equipment is a function of the size of the opening and of the other tunneling equipment. In small or machine-bored tunnels, only a limited amount of space may be available and the equipment must be strung out over a considerable distance along the tunnel. The length and depth of the opening also affect the materials handling system. In long tunnels an adequate conveyance system must be designed to insure that shotcrete production is not halted. Shafts or bore holes can be used to supply the shotcrete materials when the tunnel is shallow. To construct and use these shafts, the ground surface above the tunnel line must be accessible for driving the openings and storing the materials. In deep tunnels, construction of several shafts or drilling of bore holes along the tunnel line may not be economical and may be undesirable since the shotcrete material can undergo excessive segregation in transit between the ground surface and the underground opening.

Typical shotcrete operations used on actual jobs are basically of two types: small and high production. The difference between these operations lies primarily in the batching and mixing equipment and secondarily in the size of the shotcrete machine.

5.5.1 Small Production Operation

Small production operations are illustrated in Figs. 5.8 and 5.9. In both examples, batching is done by hand using either a weight or volume method. Figure 5.8 illustrates the most common small-scale operation used by
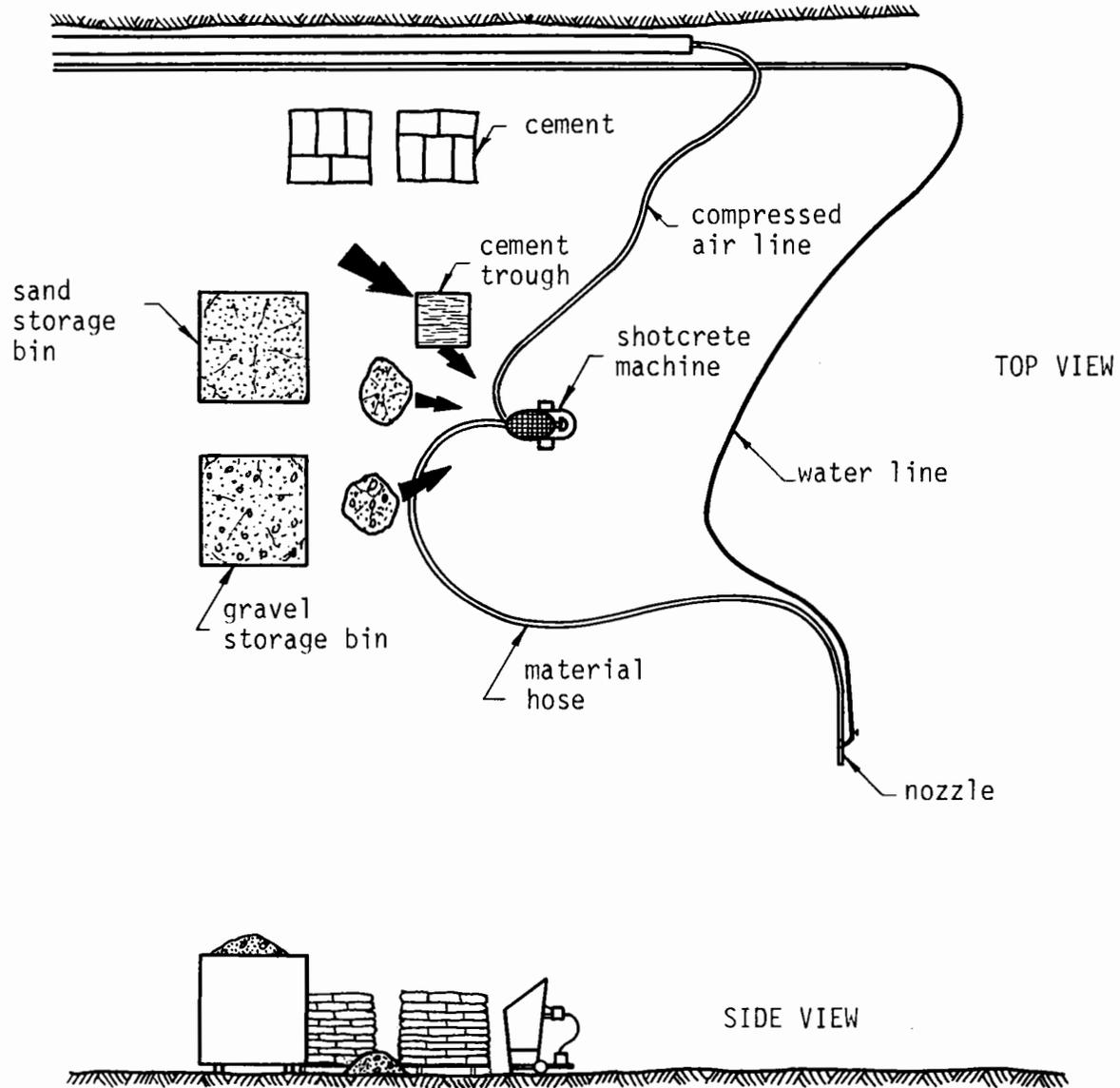
FIG. 5.8 SETUP OF SMALL PRODUCTION OPERATION IN WHICH MATERIALS ARE BATCHED
BY VOLUME AND MIXED IN THE SHOTCRETE MACHINE.

TOP VIEW

sand
storage
bin

gravel
storage bin

mixer

portable
scale

cement

compressed
air line

skid
platform

shotcrete
machine

water line

material
hose

nozzle

cement stacked
on pallets

SIDE VIEW
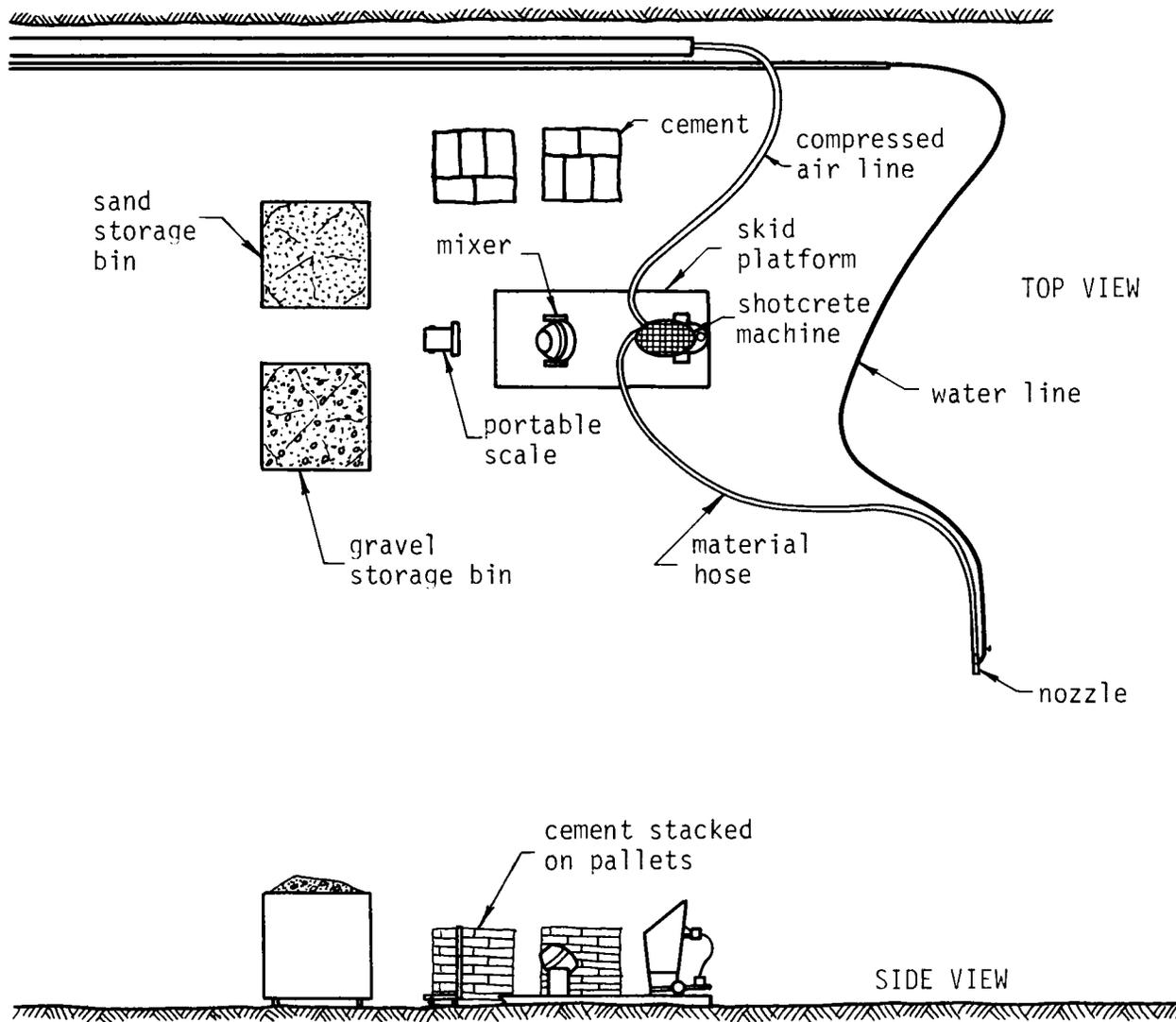
FIG. 5.9   SMALL PRODUCTION OPERATION IN WHICH MATERIALS ARE WEIGHT
BATCHED AND MIXED IN A SMALL PORTABLE MIXER.

contractors in underground construction. The materials are batched by
volume and mixed in the machine. The mix design is achieved by shoveling
the desired quantities of sand, gravel, and cement into the hopper of the
machine and allowing the agitator blades to mix the materials. Good results
can be obtained only if the materials are carefully handled and if there are
enough blades to mix the charge adequately. Large variations in the shot-
crete are likely to occur, however, because of variations in moisture con-
tent, spillage of material before it is placed in the hopper, and inadequate
mixing. The shovels used to batch the materials should be clean and hold
approximately the same volume. If a feed wheel machine is used (see Chapter 6),
the materials must be premixed before the chamber is charged. In this case,
mixing troughs or platforms should be employed.

A much more desirable small production operation from the quality control
standpoint is illustrated in Fig. 5.9. The aggregates are weighed by a por-
table scale and are mixed with the cement in a portable mixer. The mixer can
be elevated on a platform so that the prepared materials can be dumped directly
into the hopper or chamber of the shotcrete machine. If the cement and aggre-
gates are not directly charged into the machine, a mixing platform is used
to prevent contamination of the shotcrete materials. In this setup the
materials in the mixer are dumped onto the platform and then shoveled into the
machine.

In both of the operations shown in Figs. 5.8 and 5.9, the aggregates are
stored in bins and the cement and accelerator are placed on pallets. The bins
and pallets should be skid mounted or capable of being hoisted. This permits
the materials to be moved easily to other areas of the tunnel requiring

shotcrete or the bins to be transported to the storage area for recharging. The bins and pallets help to protect the materials; however, covers should be used to prevent contamination in transit and during storage.

The dry-mix process is most commonly used in the small operation, since the equipment is usually less expensive than that needed for placing wet-mix shotcrete. The shotcrete machine, whether dry- or wet-mix, should have a low output, rated by the manufacturer at approximately 3/4 to 2 m^3/hr (1 to 3 yd^3/hr). Shooting with a small machine will allow sufficient time for manufacture and delivery of materials so that smooth, continuous flow will be delivered to the nozzle. Even in shotcreting a small area, the flow of materials to the nozzle must be uniform so that a high quality shotcrete will be produced.

The materials and equipment can be placed in the tunnel or can be located above ground. If they are placed above ground, congestion in the tunnel is reduced and materials handling along the full length of the opening is eliminated. Boreholes typically 75 mm (3 in.) in diameter or larger are drilled from the ground surface to provide access for a hose or a steel pipe to convey the material underground (Fig. 5.10). The feasibility of placing the equipment at the ground surface depends on the depth of the opening and the space available along the tunnel line. The greater the depth of tunnel, the more costly the shaft or hole and the more likely an undesirable segregation of materials will occur. Ryan (1973) suggests that the material hose on the ground surface be coiled in a 6 m (20 ft) loop before it enters the vertical hole so that large pulsations will not take place in the material flow (Fig. 5.10).
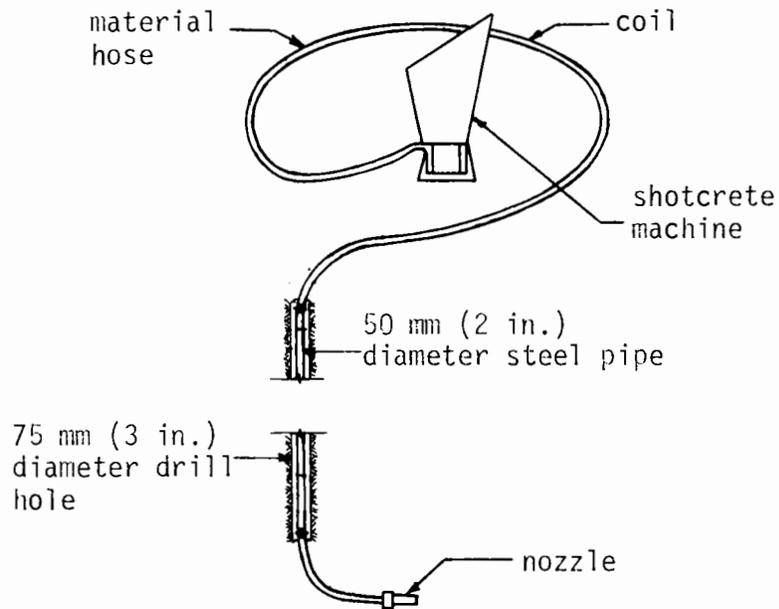
FIG. 5.10   ARRANGEMENT OF MATERIAL HOSE FOR DOWNHOLE
            SHOOTING (AFTER RYAN, 1973).

5.5.2 High Production Operation

Two basic types of operations are used for production of large volumes
of shotcrete: 1) the self-contained unit, and 2) the multiple unit. These
systems can be placed either in the tunnel or at the ground surface, de-
pending on the available space and location of the tunnel, and are used to
feed either wet- or dry-mix machines. With either the wet- or dry-mix process
the capacity of the machine should be high (>4 m^3/hr [5 yd^3/hr]). Two shot-
crete machines will be required for shotcrete output of more than 4-1/2 m^3/hr
(6 yd^3/hr) unless a double-pot machine is used. These machines have chambers
twice the length of standard models and are capable of providing approximately
twice the output.

Self-Contained Unit

In the self-contained unit the batching, mixing, and gunning equipment are at one location (Fig. 5.11). The batching, mixing, and conveyance of materials to the machine are all done automatically by means of a set of controls on the platform. Batching is usually done volumetrically with chains or belts located beneath the storage hoppers. Materials can be batched almost instantaneously and thus there is little chance for prehydration or for waste of large volumes of batched materials. The batching equipment must be checked periodically to insure that the materials are being supplied in the specified proportions.

Mixing the shotcrete materials is most commonly done with an auger that conveys the materials from the batching system to the shotcrete machine. The mixing time required for proper blending of the small volume of materials in the auger is very short, generally less than 1 minute. Powder accelerators are added and mixed with the materials as they are conveyed to the storage hopper at the machine. The prepared materials are fed directly into the hopper of the shotcrete machine or into a separate storage hopper located above the machine.

The storage capacity of the self-contained units range from 1/4 to 8 m^3 (1/4 to 10 yd^3). In some tunnels, this may be enough material to complete shotcreting in the heading. However, in many large tunnels and chambers, the volume of shotcrete required in the heading, or to complete the lining, is much higher than the storage capacity of the unit and therefore a delivery system must be set up to provide a continuous supply of material to the machine hopper. The material is usually stockpiled outside the

aggregate

cement

water and liquid
accelerator

shotcrete
machine

nozzle

conveyor

control console
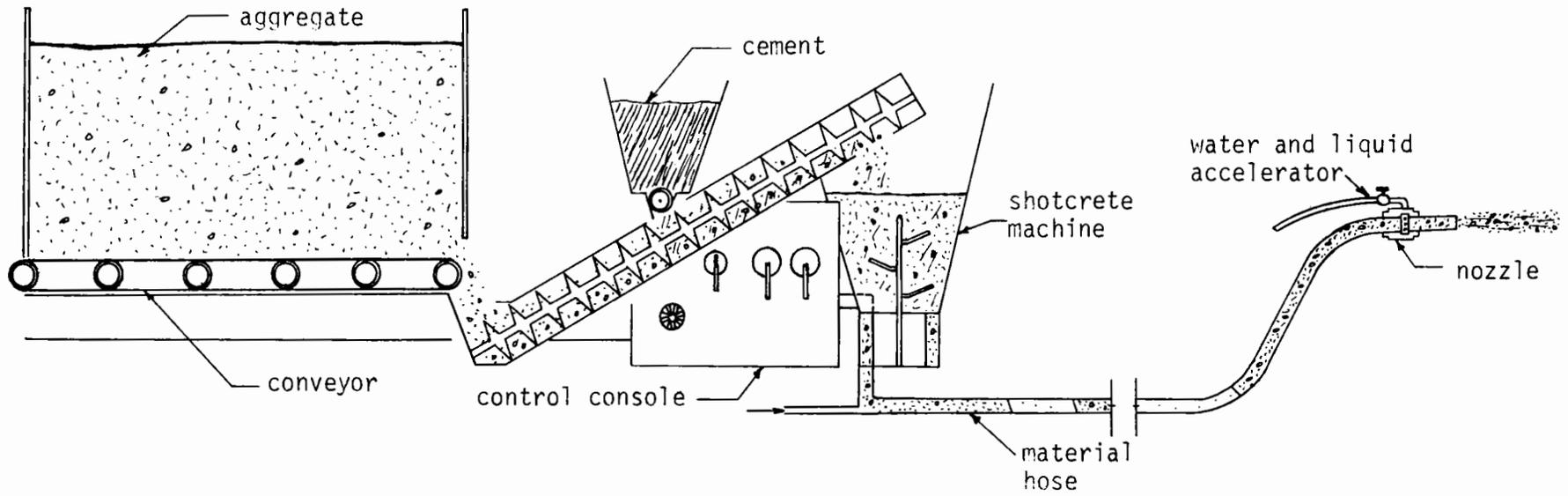
material
hose

FIG. 5.11 SELF-CONTAINED SHOTCRETE UNIT.

tunnel and conveyed to the unit by vehicle transport or through vertical shafts. If properly supplied, a large self-sufficient unit can manufacture enough material to supply two shotcrete machines up to 3/4 m^3/min (1 yd^3/min).

Multiple Unit

In the multiple unit, batching and mixing are separate from the gunning operation (Fig. 5.12). Batching of the shotcrete is done in a batch plant where the materials are usually proportioned by weight. Mixing is performed at the plant or in transit to the shotcrete machine (Figs. 5.12 and 5.13). Most batch plants used for shotcrete are capable of producing 3/4 to 11 m^3 (1 to 15 yd^3) of material per batch depending on the desired material delivery rate. The batching plant is usually placed at the ground surface; however, where a limited amount of space is available above ground the plant can be located underground. In most tunnels, this requires excavation of auxiliary shafts, adits, or chambers to house the batching facility.

Once the materials are batched, they must be conveyed as rapidly as possible to the shotcrete machine to prevent interruptions in shooting or prehydration of the shotcrete materials. The only disadvantage to manufacturing materials at a batch plant is the possible wastage of large volumes of shotcrete should prehydration occur. The materials are conveyed to the machine in trucks, railway cars, or muck removal equipment. If mucking equipment is used, care must be taken to prevent contamination of the shotcrete with tunnel muck.

The materials prepared at the batch plant are fed into the shotcrete

5-34
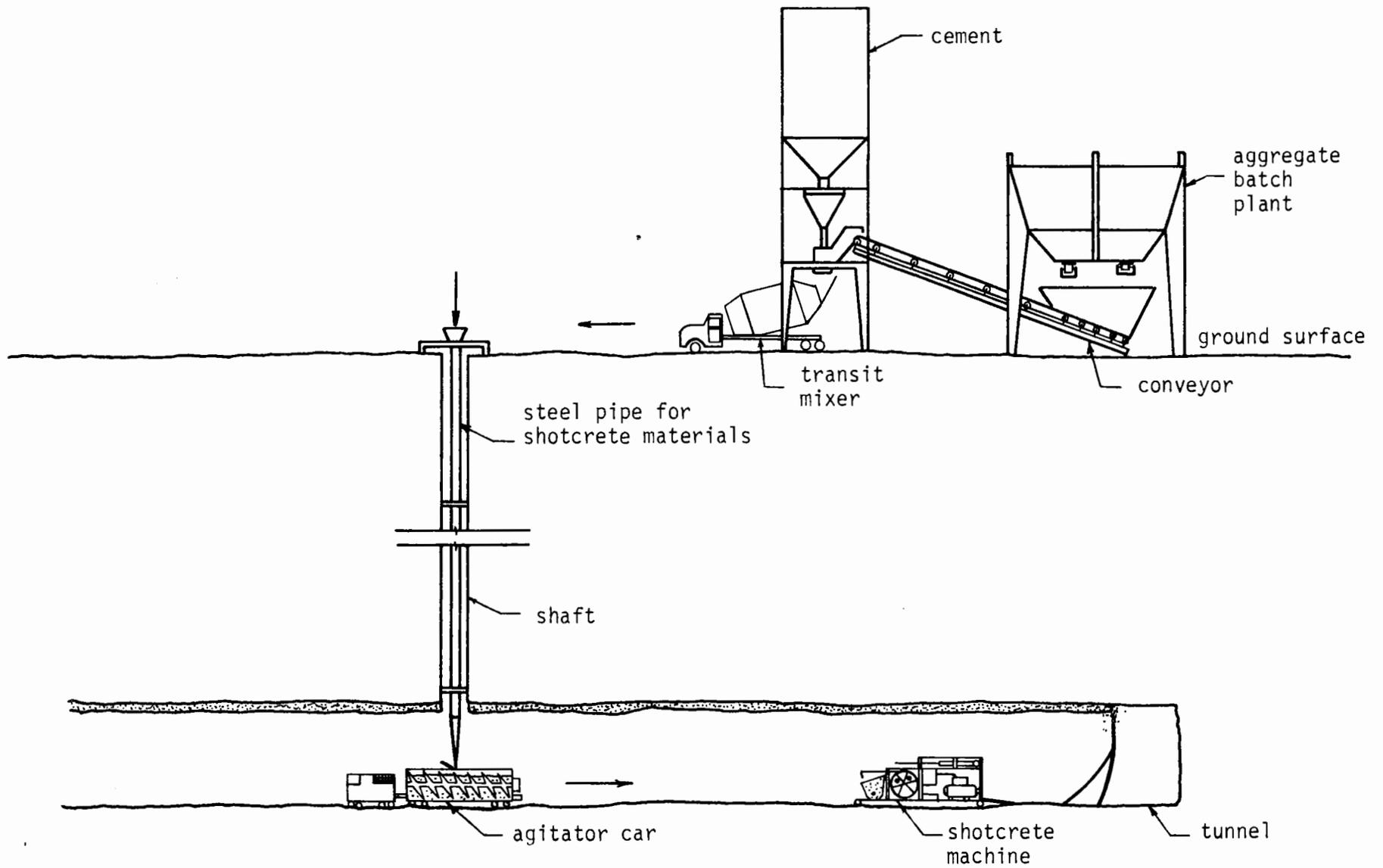
FIG. 5.12   MULTIPLE UNIT SHOTCRETE OPERATION WITH THE
BATCH PLANT LOCATED ABOVE GROUND.
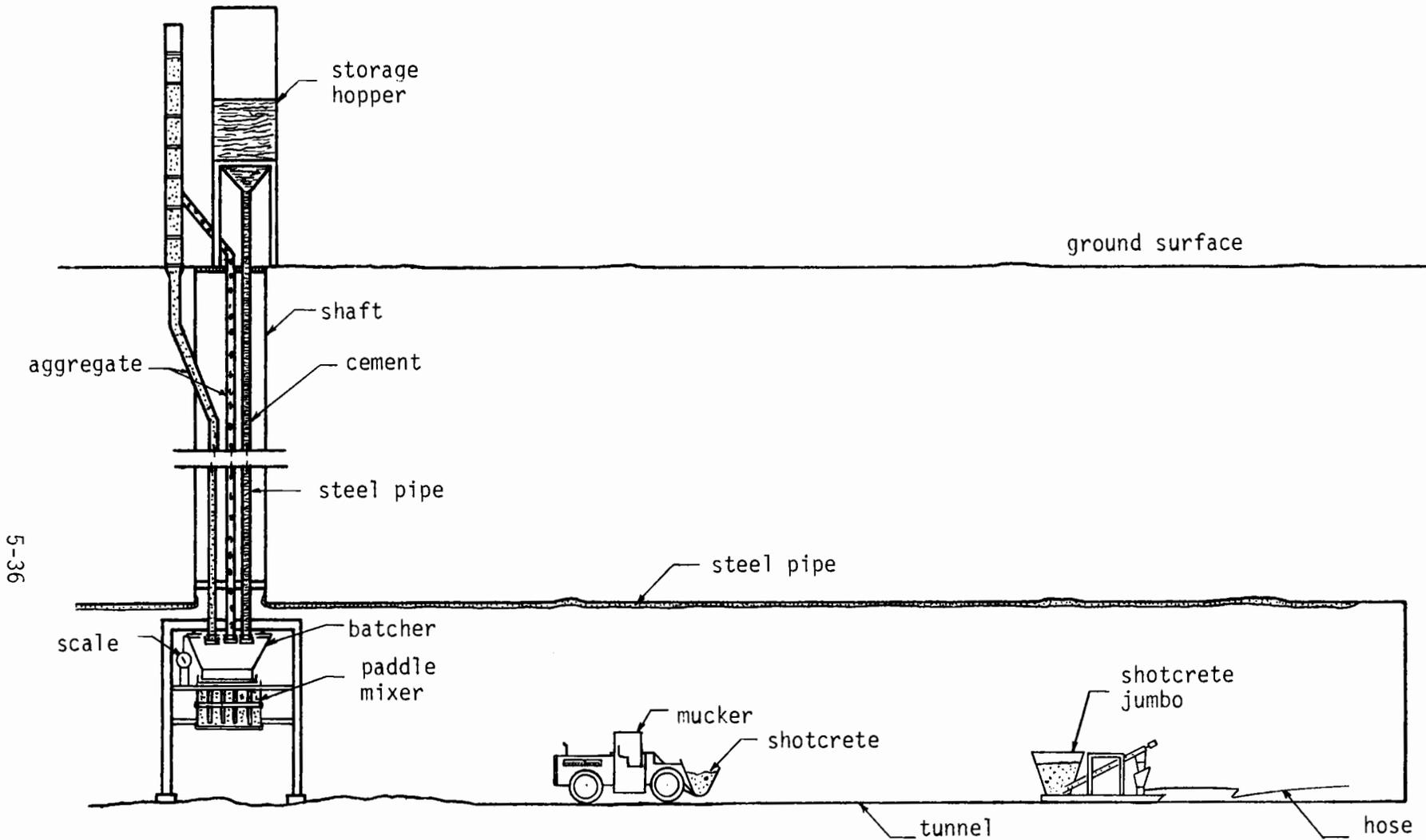
FIG. 5.13   MULTIPLE UNIT SHOTCRETE OPERATION WITH BATCH
PLANT LOCATED UNDERGROUND.

machine by means of a shotcrete rig (Fig. 5.14). The rig serves as temporary storage for the materials so that the conveyance system will not be tied up waiting for the load to be dumped and to insure that the shotcrete is quickly and continuously supplied to the machine. The prepared materials are dumped into a hopper usually having a 1-1/2 to 8 m^3 (2 to 10 yd^3) capacity. They are then conveyed to the hopper of the machine by means of an auger or belt feed. In the dry-mix process, powdered accelerators are added to the materials on the auger or belt. The dispenser should be synchronized with the drive mechanism of the belt or auger so that the accelerator will be supplied in the proper percentage. The shotcrete rig can be designed to supply one or two machines according to the desired material delivery rate.

accelerator
dispenser

chute

storage
hopper

conveyor

header

compressed
air line
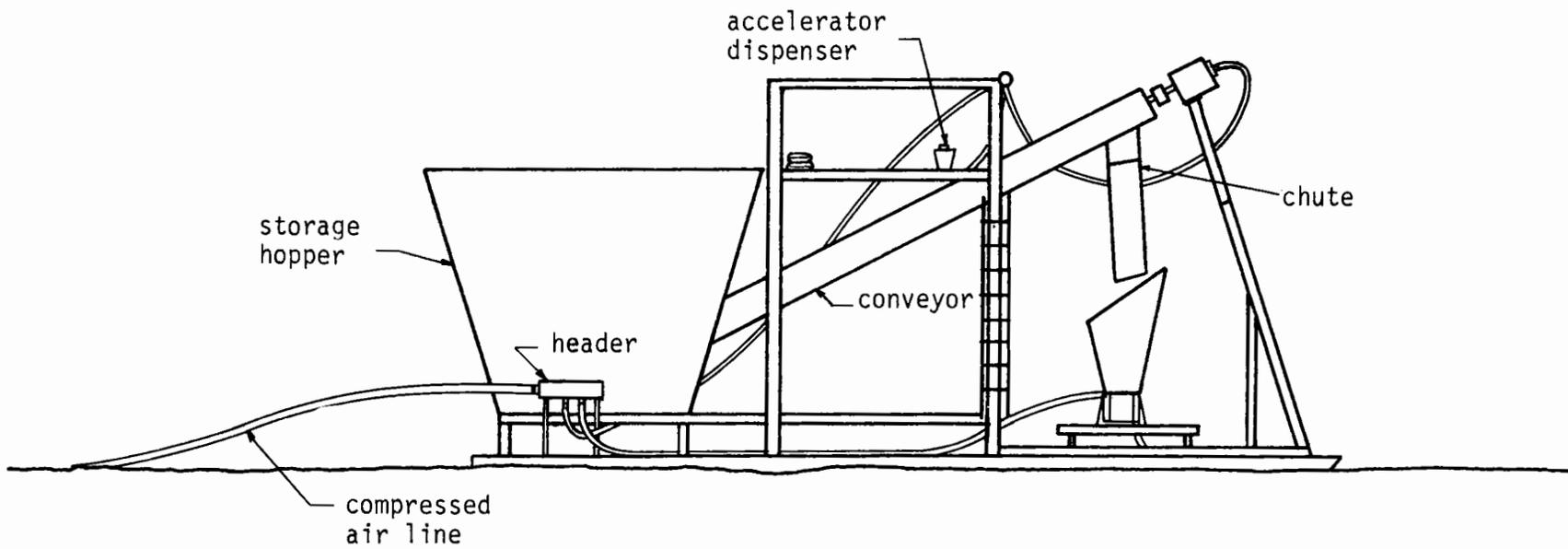
FIG. 5.14 TYPICAL HIGH PRODUCTION SHOTCRETE RIG.

CHAPTER 6

SHOTCRETE EQUIPMENT

Many different types of equipment are available for placing shotcrete
underground. The choice of equipment will depend on the process selected,
the desired material delivery rate, the initial investment, and the limita-
tions on size imposed by the dimensions of the opening and other tunneling
equipment. The placement and volume requirements for tunnel construction
govern the material delivery rate. The initial investment depends on the
equipment owned by the contractor, his capital assets, and the availability
of new, used or rental equipment. Used equipment is desirable in terms of
cost but may cause delays and additional expense if it is not in good oper-
ating condition. The shotcrete machine itself typically costs between $5,000
and $20,000.

6.1 Dry-Mix Shotcrete Equipment

6.1.1 Dry-Mix Shotcrete Machines

Two basic types of dry-mix shotcrete machines are used in the underground
work: (1) the feed wheel and (2) the rotating barrel or bowl machines. In
both machines the dry-mix material is conveyed by compartments of a wheel,
bowl, or barrel into the path of a compressed air supply that blows the material
through a material hose to a nozzle and out onto the surface. In the feed
wheel machine the chamber supplying material to the air stream is always
pressurized, whereas in the rotating barrel or bowl machines the chambers
are pressurized only when they pass through the air stream.

Feed Wheel Machine

The most commonly used feed wheel machine is the double chamber gun
(Fig. 6.1). Material in the lower chamber falls by gravity into compartments
of the feed wheel. These compartments transport the material into the path
of the compressed air supply and the material is blown into the material hose.
The upper chamber is used to recharge the lower chamber. This procedure per-
mits continuous operation of the machine. The cone valves seal the chambers
by seating against the rubber gaskets located in the tops of the chambers.
To operate the double chamber gun, both cone valves are opened and the chambers
are filled with the dry-mix material. The upper cone valve is closed and both
chambers are pressurized by opening the auxiliary air valve (Fig. 6.1).
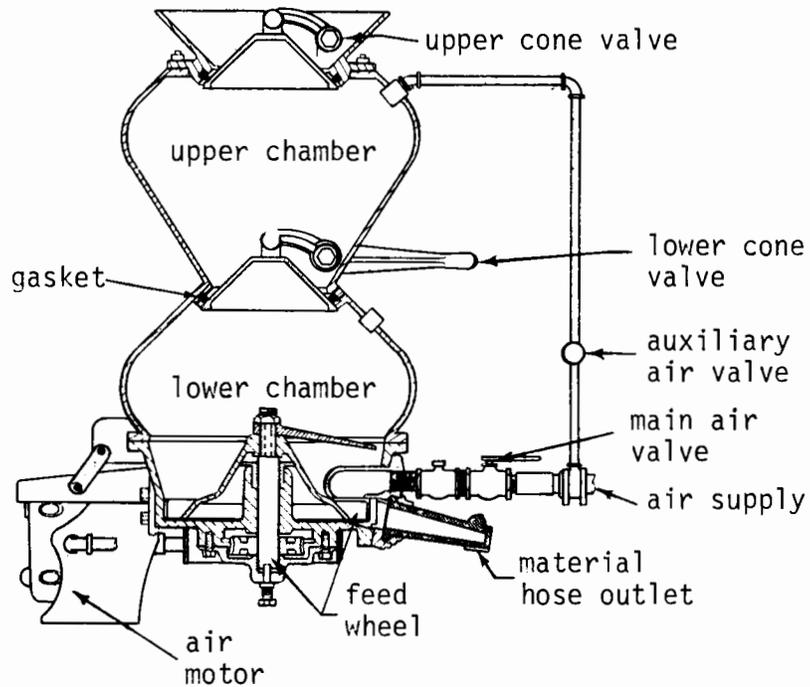
FIG. 6.1 FEED WHEEL SHOTCRETE MACHINE (CROM, 1966).

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Shotcrete is sprayed by first turning on the main air valve and then the motor driving the feed wheel. When the material level falls below the lower cone valve, this valve is closed, the auxiliary valve is closed, and the upper chamber is depressurized. The upper cone valve is opened and the upper chamber recharged with dry-mix materials. The upper cone valve is then closed and the auxiliary valve opened. When the pressure is equalized between the chambers, the lower cone valve opens and allows the material to fall from the upper to the lower chamber. These operations are repeated until shotcrete application is complete. The pressure in the chambers usually ranges between 3.5 to 7.0 kg/cm^2 (50 to 100 psi) (Crom, 1966). An experienced gunman is needed to operate the double chamber gun successfully so that a smooth, continuous flow of material is delivered to the nozzle.

Feed wheel guns having only one chamber are also available. They are nearly identical to the lower chamber of the double chamber guns. The shotcrete operation must be stopped, however, to recharge the chamber.

Rotating Barrel or Bowl Machine

The rotating barrel or bowl machines contain a number of small revolving compartments which are charged with material under atmospheric pressure and then rotated into the path of a compressed air line and the material hose. The barrel machine contains trapezoidal- or cylindrical-shaped compartments having the air line above and the outlet below the barrel (Fig. 6.2). The rotating bowl machine contains a partitioned steel bowl in which the air enters on one side of the bowl, picks up the material and blows it into the material hose through an outlet on top of the bowl (Fig. 6.3). The barrel

screen

agitator

air line

compartment

wear pad

wear plate

barrel or cylinder

compressed
air

outlet
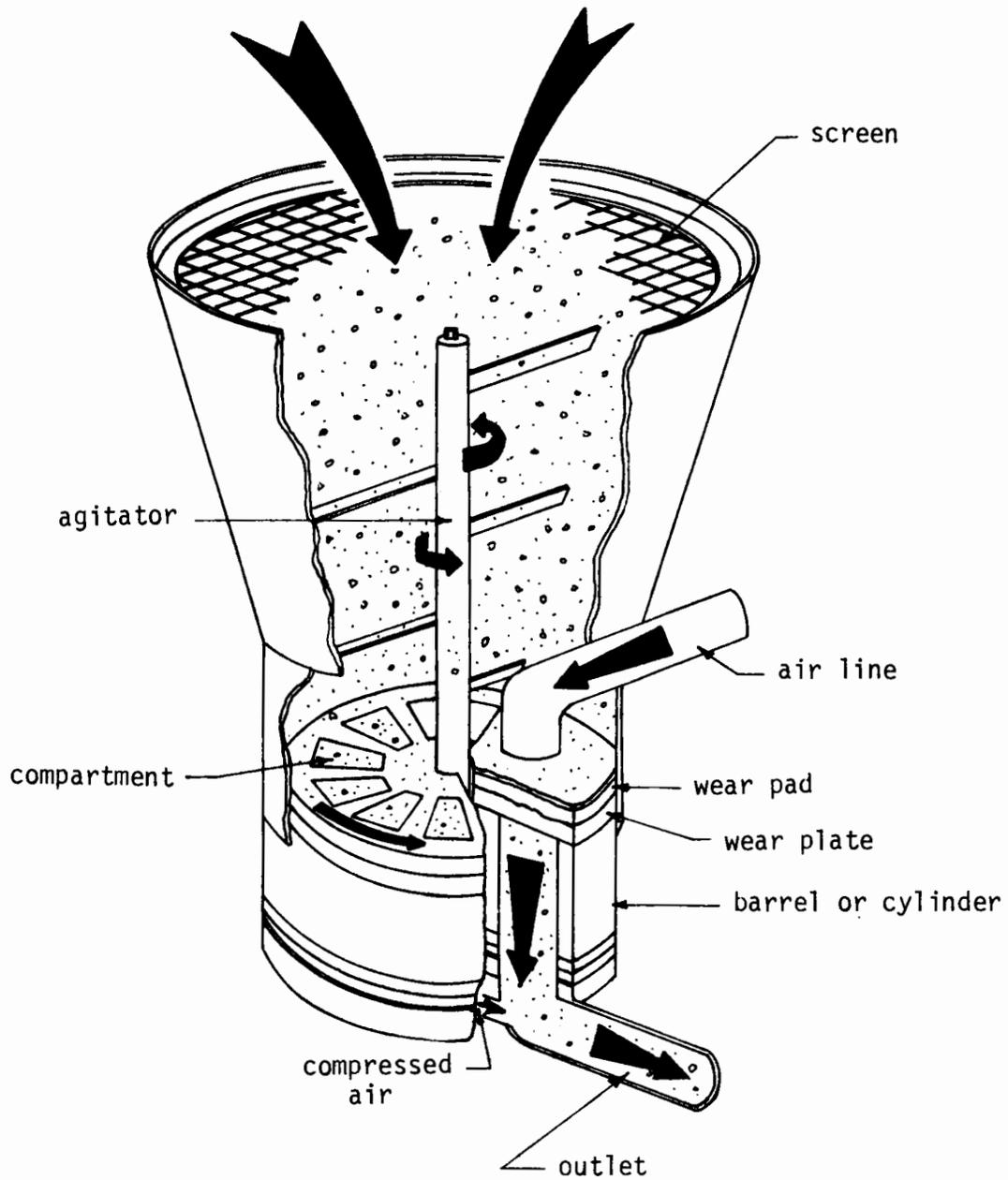
FIG. 6.2   ROTATING BARREL DRY-MIX SHOTCRETE MACHINE.
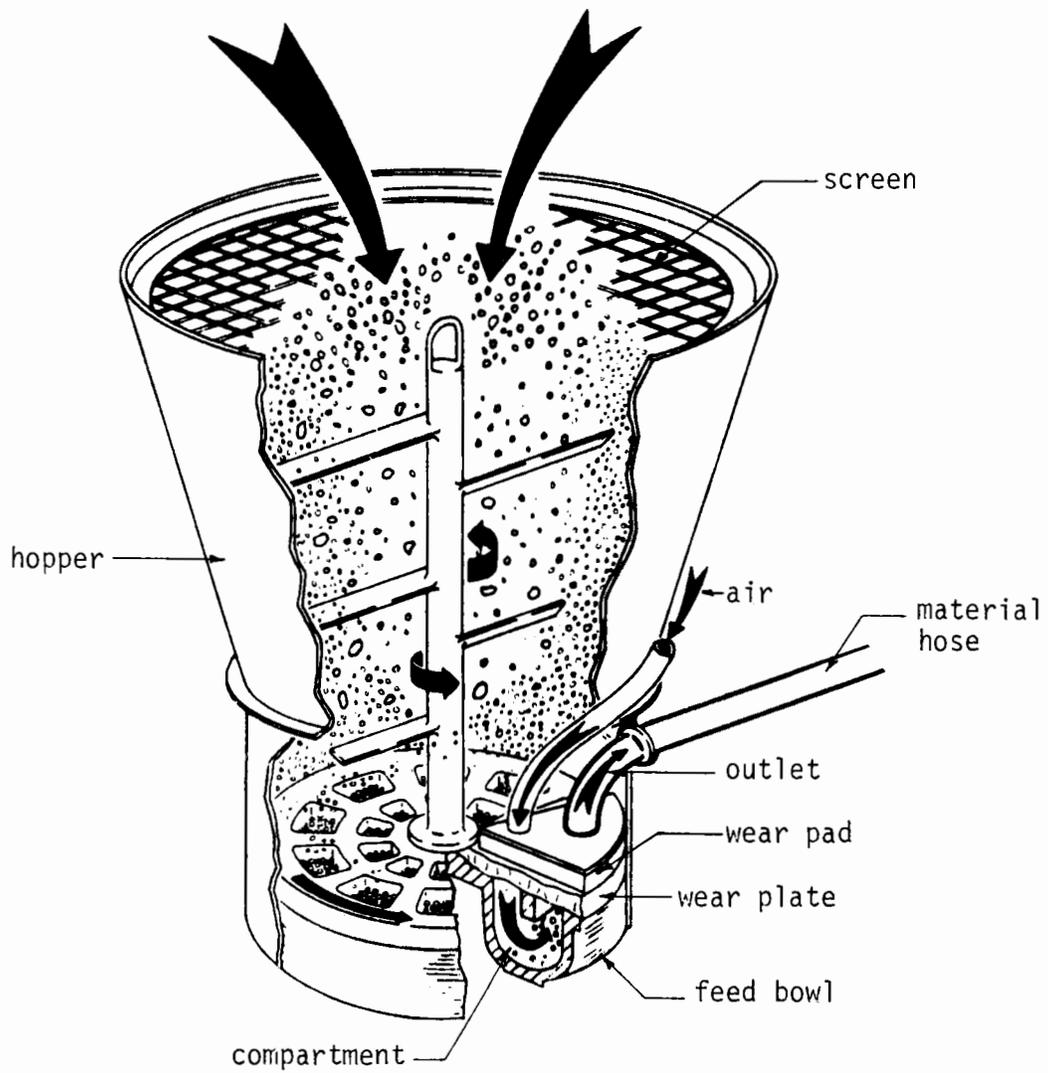
Fig. 6.3   ROTATING BOWL DRY-MIX SHOTCRETE MACHINE (COURTESY
OF REED MANUFACTURING CO., WALNUT, CA.).

or bowl is rotated at high speed so that a nearly continuous supply of material is delivered to the nozzle. On one side of the bowl or barrel the compartments are open to a hopper containing the dry-mix material. These compartments are rotated approximately 180° where they pass between the air supply line and the material hose. Gaskets seal the intake and outflow ends of the chambers. These gaskets are made of hard rubber and in some models are backed by a steel frame. Steel plated (wear plates) are located between the barrel or bowl and the gaskets. In the larger shotcrete machines, an auxiliary air supply is placed in the outlet below the chambers (Fig. 6.2). To operate the machine, the hopper is filled with material, the air supply turned on, and then the motor of the rotating barrel is started.

Drive Mechanisms of Shotcrete Machines

The feed wheel, barrel, or bowl of the dry-mix machine is driven by either an air, electric, or gasoline motor. Use of an air motor increases the consumption requirements of compressed air by approximately twice that needed to operate the machine with gasoline or electricity. If an electric motor is used, it must be properly insulated. For safety reasons, gasoline motors are never used underground but can be employed when the shotcrete machine is located above ground. Electric motors generally drive the feed mechanism of the machine at a more uniform speed than an air motor and re-quire less horsepower. Air motors are most commonly used underground because of their durability and the availability of compressed air.

Motors are connected to the feed wheel, barrel, or bowl by a chain, gear, or belt drive. Gear drive mechanisms provide the most uniform rotation speed since they are not subject to change in radius of rotation nor to slip. Belt

6-6

drives are much more susceptible to slippage than chain drives and should be checked more frequently. Slippage of the chain or belt produces an uneven delivery of material to the nozzle.

Commercial Dry-Mix Machines

Dry-mix shotcrete machines commercially available in the United States are listed in Appendix B. The range of capabilities, compressor requirements, and specifications offered by the manufacturer have been summarized in Table 6.1 for each type of machine. Statistics on feed bowl and barrel-type machines have been combined because of the similarities in their operation. Most feed bowl and barrel machines are capable of gunning aggregates up to 32 mm (1-1/4 in.) in size at delivery rates of 11 m^3/hr (15 yd^3/hr). Feed wheel shotcrete machines can shoot coarse aggregate up to 19 mm (3/4 in.) in size and are rated as delivering 1/2 to 9 m^3/hr (3/4 to 12 yd^3/hr). In actual practice, aggregate sizes are usually less than 25 mm (1 in.) and production rates are typically 4 to 5-1/2 m^3/hr (5 to 7 yd^3/hr).

Machine Maintenance

The production rates obtained underground and the quality of the in-place shotcrete are highly dependent on the operating condition of the shotcrete machine. The feed mechanism must undergo daily maintenance and the remainder of the machine must be checked periodically to insure adequate performance. All deposits of cement and fine aggregate should be removed from the material hose outlet and from the feed wheel, the compartments of the feed bowl or the chambers of the barrel. These accumulations are generally removed from

6-7

Table 6.1 Typical ranges of capabilities, requirements, and dimensions of commercially available dry-mix shotcrete machines.

Capabilities	Feed Bowl and Barrel Type	Feed Wheel
Maximum aggregate size, mm	10 - 32	19
(in.)	(3/8 - 1-1/4)	(3/4)
Delivery rate, m^3/hr	2 - 11	1/2 - 9
(yd^3/hr)	(3 - 15)	(3/4 - 12)
Maximum horizontal conveyance, m	300	300
(ft)	(1000)	(1000)
Maximum vertical conveyance, m	100	100
(ft)	(330)	(330)
Requirements		
Hose diameter I.D., mm	38 - 70	25 - 50
(in.)	(1-1/2 - 2-3/4)	(1 - 2)
Air consumption with:		
Air driven gun, m^3/min	8.5 - 17	5 - 17
(ft^3/min)	(300 - 600)	(180 - 600)
Electric or gasoline driven gun,		
m^3/min	5 - 14	N.A.
(ft^3/min)	(180 - 500)	
Dimensions		
Height, m	1.2 - 1.6	1.2 - 1.9
(ft)	(3.8 - 5.1)	(3.8 - 6.1)
Width, m	0.7 - 0.8	0.9 - 1.2
(ft)	(2.3 - 2.6)	(2.8 - 3.8)
Length, m	0.9 - 1.5	1.0 - 2.0
(ft)	(3.0 - 4.8)	(3.1 - 6.5)
Weight, kg	240 - 950	310 - 730
(lb)	(530 - 2100)	(680 - 1600)

N.A. - information not available

the metal surfaces by using a chipping hammer. The scale can also be removed by placing the part in a large oven preheated to 200°C (400°F). Differential expansion causes the cement and fine aggregate scale to spall from the surface of the metal. Care must be taken not to overheat the part since this can cause permanent deformations and ruin it. Parts undergoing friction, particularly the wear pads or plates, must be checked and repaired or replaced as needed. The motor of the shotcrete machine should be kept well lubricated and clean. Gears and chain drives must also have adequate lubrication. Preventive maintenance and cleaning of the shotcrete machine will almost eliminate costly delays from equipment malfunctions.

6.1.2 Dry-Mix Nozzles

At the dry-mix nozzle, water is injected into the materials in the air stream just before they leave the hose. These nozzles must provide a uniform wetting and mixing of the materials and must be capable of delivering the shotcrete spray onto the surface with a minimum divergence of the shotcrete stream. The design, performance, and operation of the nozzle controls in a large part the rebound and quality of the shotcrete. Laminations, incomplete hydration of the cement, and increased rebound will result if the nozzle is functioning poorly or is improperly designed. Rebound is also affected by the divergence of the material stream as it leaves the nozzle; the greater the divergence, the greater the rebound (Parker, et al., 1975).

Components of the Dry-Mix Nozzle

The basic components of the dry-mix nozzle consist of the nozzle tip,

water ring assembly, and housing (Fig. 6.4). The nozzle tip is usually made of rubber or steel with a rubber insert. Rubber is used rather than steel since it is more durable, easier to clean, cheaper to replace, provides a more uniform delivery of material and is more resistant to abrasion. The water ring assembly consists basically of the water ring, the water control valve, and the water hose. The water ring is usually made of steel or brass perforated with holes. The holes in the standard water ring are 1.5 to 4 mm (1/16 to 3/16 in.) in diameter and number 4-16 per ring. Holes are oriented normal to the curved surface of the ring and are positioned along the longitudinal centerline. These holes produce a radial flow of water into the materials (Fig. 6.4). The valve in the water ring assembly is used by the nozzleman to control the volume of water injected into the material. This valve should be easy to operate and have a quick response so that the flow rate can be readily controlled. Standard pipe fittings are used to connect the valve to the housing and the water hose. The housing, which is usually made of steel, contains the water ring assembly and connects the nozzle tip with the material hose.

Dry-mix shotcrete nozzle tips are generally 25 to 30 cm (10 to 12 in.) long; however, lengths up to 60 cm (24 in.) are not uncommon. Long nozzles (3 to 4.5 m [10 to 15 ft] which introduce the water a considerable distance before the materials are discharged at the orifice, provide a better mixing and a more uniform delivery to the surface than do the short nozzles (Parker, et al., 1975). These nozzles usually have a single water ring attached to the end of the material hose with a long section of used shotcrete hose serving

6-10
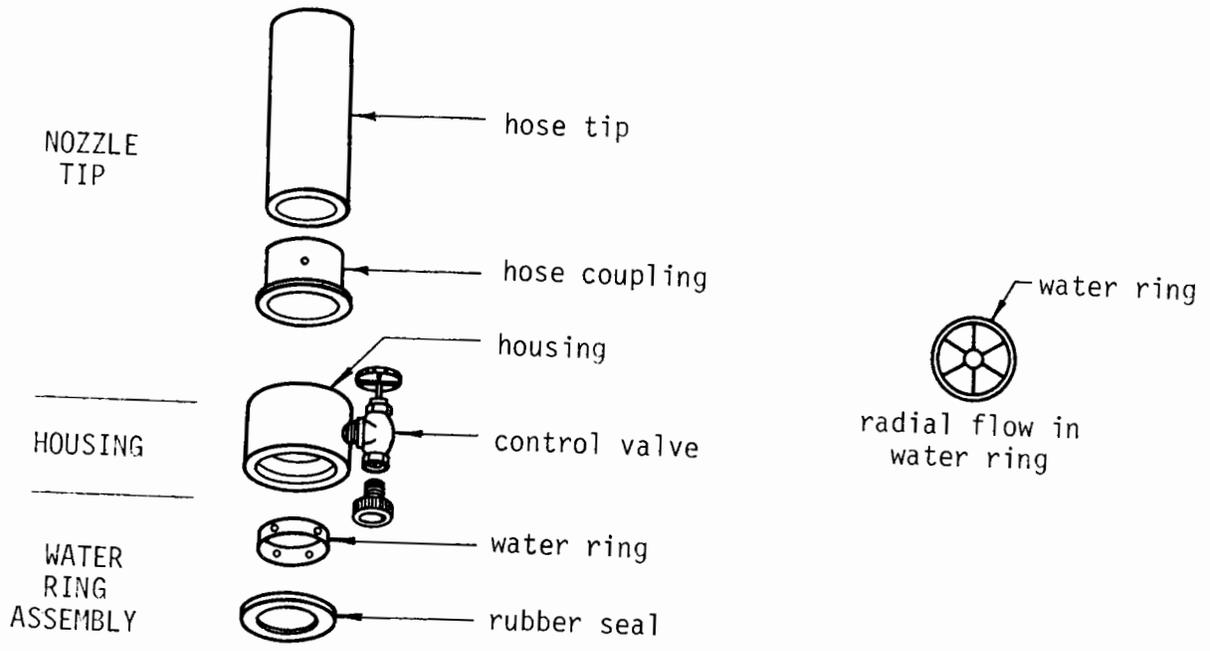
FIG. 6.4 BASIC COMPONENTS OF THE DRY-MIX NOZZLE.
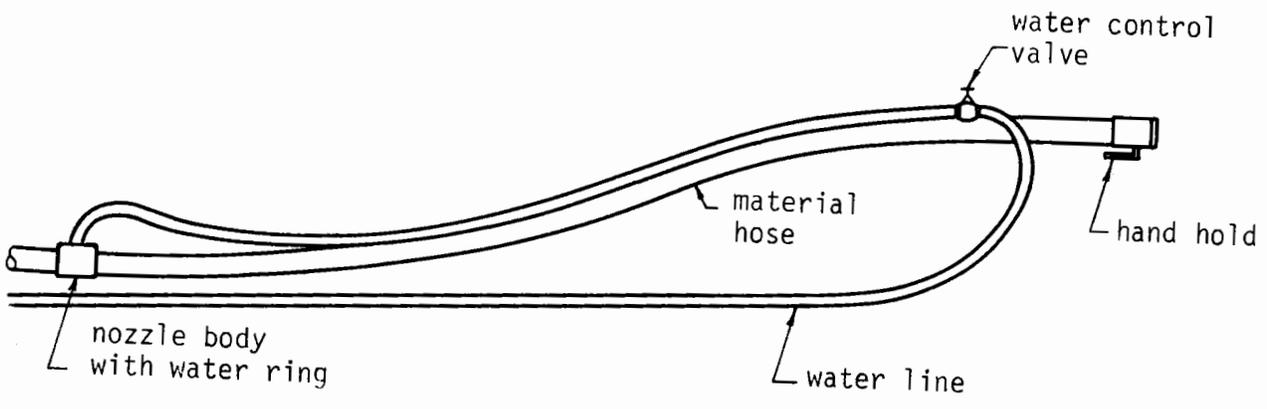
FIG. 6.5 LONG NOZZLE (AFTER PARKER, ET AL., 1975).

as the nozzle tip (Fig. 6.5). Data on rebound and strength show very little difference in results between the long and short nozzles; however, slightly higher flexural strengths were obtained in shotcrete gunned through a long nozzle (Parker, et al., 1975). The longer nozzles are more difficult to handle and regulate the water flow since the nozzleman cannot grasp the nozzle body. The long nozzles are also more susceptible to plugs.

Nozzle Tips

Four basic types of nozzles are used in shotcrete work and are classified according to nozzle tip design: 1) stepped-balloon, 2) smooth-balloon, 3) straight, and 4) tapered (Figs. 6.6, 6.7 and 6.8). Both types of balloon nozzles are designed so that the material stream is expanding at the same time water is injected into it. This is thought to allow greater penetration of the water into the incoming materials. The stepped-balloon nozzle is designed to cause a greater turbulence in the shotcrete stream than the smooth-balloon type in order to facilitate better mixing of the water and cement. Both the stepped- and smooth-balloon nozzles produce a divergence of the material stream as it leaves the orifice and thus increase rebound. The straight nozzle tip with the smooth tapered nozzle body (Fig. 6.7a) provides good wetting and a smooth delivery to the tunnel surface but is susceptible to plugs and the nozzle body wears out in a relatively short period of time. The straight nozzle provides adequate wetting of the materials with minimum divergence of the shotcrete stream and is most suitable for underground work. The tapered nozzle tip causes a convergence of the material stream as it leaves the nozzle but is more susceptible to plugs and wears out more rapidly than the other types of nozzle tips.

6-12
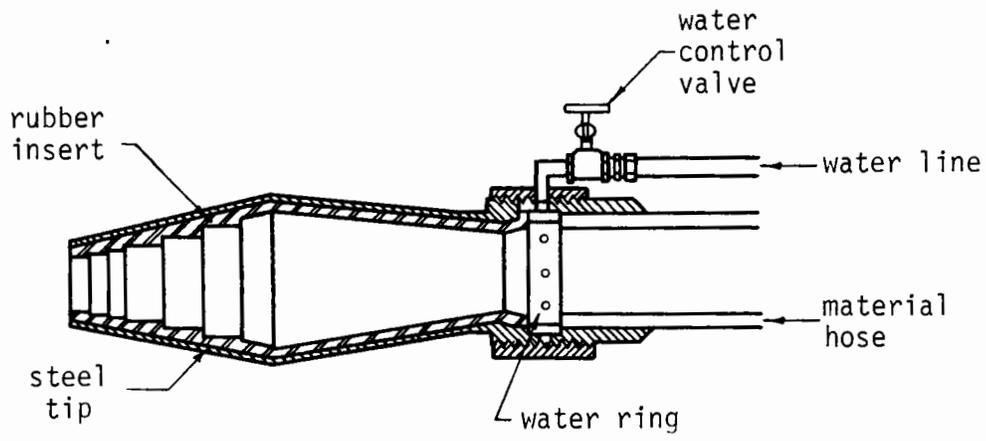
a. Stepped-balloon nozzle
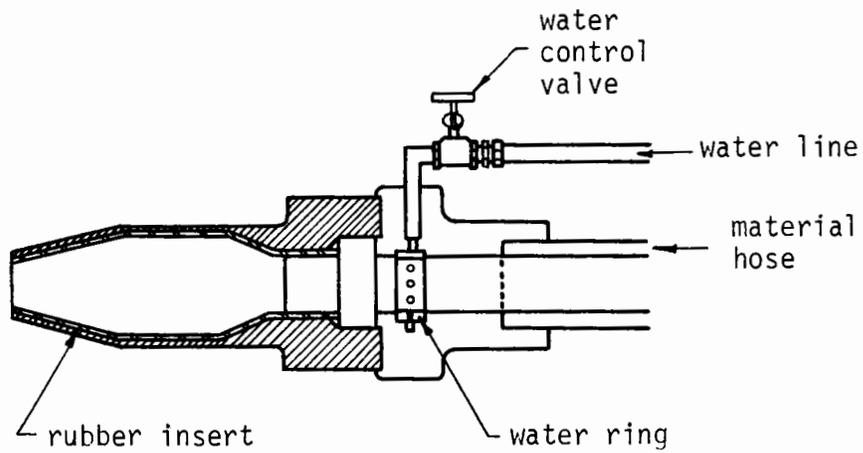
b. Smooth-balloon nozzle

FIG. 6.6 STEPPED-BALLOON AND SMOOTH-BALLOON DRY-MIX SHOTCRETE
NOZZLES (AFTER TINSLEY AND KALOUSEK, 1966 AND RYAN, 1973).
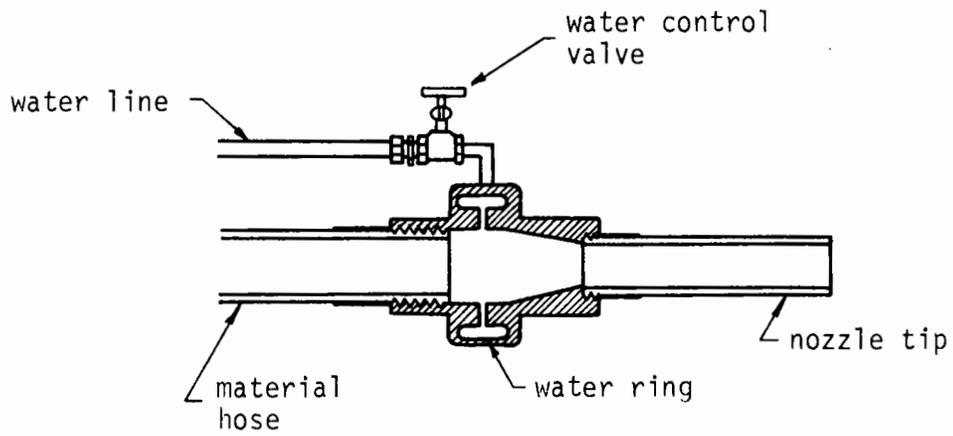
a. Smooth taper nozzle body
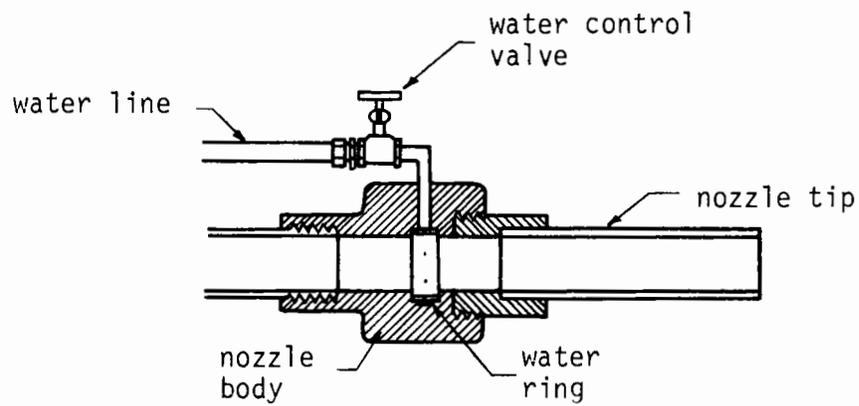
b. Straight nozzle body

FIG. 6.7 STRAIGHT TIP DRY-MIX SHOTCRETE NOZZLES.

water control valve

water line

nozzle

5 cm
(2 in.)

4 cm
(1 1/2 in.)
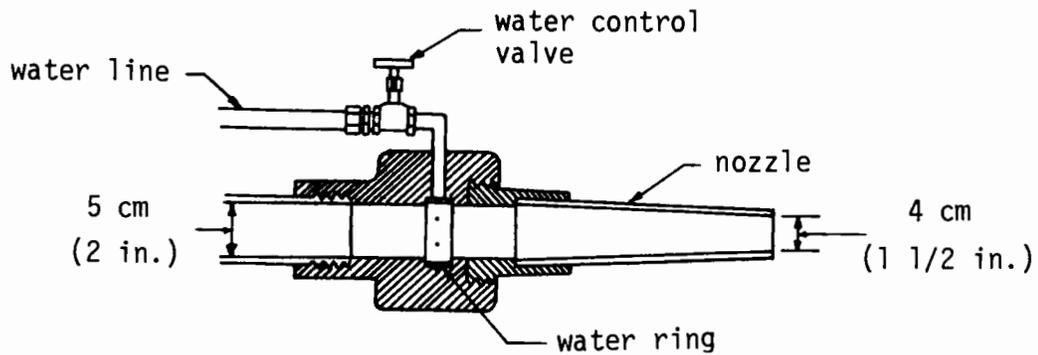
water ring

FIG. 6.8   SMOOTH TAPER NOZZLE.

Operation and Maintenance of the Nozzle

Uneven flow of water into the material stream is usually caused by plugging of holes in the water ring and leakage of water from the water ring assembly. If some of the water ports are plugged, the water will not be uniformly mixed and will tend to cause dry areas in the material stream. These dry areas produce undesirable laminations. Dry portions of the material stream can also produce excessive rebound and dusting and do not provide enough water for adequate hydration of the cement in the shotcrete. Leakage of water from the water ring assembly usually causes fluctuations in the amount of water injected into the material stream and thus produces shotcrete

that is either too wet or too dry. The holes in the ring should be checked
and cleaned if needed several times each shift. All leaks in the water
ring assembly or at connections must be sealed to prevent water loss. Parts
in the ring assembly that are subjected to excessive wear must be replaced
periodically. To minimize wear, these parts should be kept flush with the
inside of the nozzle or should be gently tapered.

The nozzle tip should be kept clean since accumulation of cement and
aggregate can cause plugs. Worn nozzle tips or inserts should be replaced
to minimize divergence of the material stream and to prevent wear of the
nozzle housing and steel tip.

6.1.3 Water Supply

The water supplied to the nozzle must be delivered under constant
pressure so that a constant flow of water is injected into the material.
Optimum water pressure depends primarily on the air pressure at the machine,
the location of the water ring, and the number and size of the holes in the
ring. Water pressure needed at the nozzle is approximately twice the pres-
sure in the material stream at the nozzle (1.5 to 3 kg/cm [20 to 40 psi]).
Improper mixing related to excessive water pressure is produced by interfer-
ence of the water jets as they approach the center of the shotcrete stream
(Fig. 6.4). In addition to the minimum pressure requirements, the pump must
be capable of supplying at least 40ℓ /min (10 gpm) to the nozzle. A line
filter should be placed in the water line to prevent dirt and other solids
from reaching the water ring and plugging its holes. The water can be sup-
plied directly from a municipal water main or if such a supply is not avail-

6-16

able, a storage tank can be substituted. If a storage tank is used, a pump is required to provide an adequate supply under proper pressure.

The most common type of pump used to supply water is the piston pump. A receiver tank must be placed in the water supply line between the pump and the nozzle to eliminate pulsations in water flow. Centrifugal pumps are also employed but are not capable of providing water under as high a pressure as the piston pump. Nevertheless, the centrifugal pump is adequate for most underground work. Since it delivers the water without surging, a receiving tank is not needed. The water pump should be kept clean and should not contaminate the water in the line.

The water is conveyed to the nozzle in a water line that connects the water supply with the control valve. Water lines are usually 19 to 25 mm (3/4 to 1 in.) in diameter and are made of high pressure, rubber tubing. The hose cover should be resistant to abrasion, cutting, and penetration by oil or water, and the connections should be adequately sealed. For many jobs, a heavy-duty garden hose will suffice as a water line.

6.1.4 Dry-Mix Accelerator Dispensers

Powder Accelerator Dispensers

Three types of dispensers are generally used for adding powder accelerators to the dry-mix materials. These are classified according to the dispensing mechanism and include 1) auger, 2) corkscrew, and 3) gear wheel. Typically these are mounted at the base of an inverted cone- or pyramid-shaped hopper containing the accelerator. The auger and corkscrew devices are nearly identical in operation and are shown in Fig. 6.9. Both the auger and corkscrew rotate

on the inside of a horizontal tube. One end of the tube is open to the accelerator at the base of the storage hopper. The powder accelerator is fed by gravity to the corkscrew helix or between the auger blades. The accelerator is then conveyed in the tube and discharged through a hole at the other end of the tube. The rate of additive feed is adjusted by increasing or decreasing the rotation speed of the corkscrew or auger. The larger corkscrew shown in Fig. 6.9b helps feed the accelerator to the metering screw and was developed by Acrison of Los Angeles, California.

The gear wheel-type dispensing mechanism is also a volumetric batcher (Fig. 6.10) but contains a small wheel with teeth on its outer edge which rotate (in a horizontal plane) at the base of the hopper. Accelerator falls through a hole in the hopper to the gear wheel where it is leveled to a uniform thickness and is conveyed between two teeth to another slot. The accelerator falls through this slot to the dry-mix materials. The accelerator is dispensed at different rates by adjusting the size of the discharge slot or by manipulating the rotation speed of the gear teeth.

A fourth type of dispenser called the vibratory feeder can also be used. This feeder consists of a tray which vibrated at a high frequency and carried the accelerator from the back to the front of the trays. At the front of the tray, a given amount of accelerator falls off its edge into the dry-mix materials. The vibratory feeders have not been used extensively underground but show promise for overcoming some of the difficulties of the other types of feeders.

Performance of Dispensers. Ideally, the amount of accelerator should be the same in all compartments of the auger, corkscrew, and gear wheel dispensers. This is rarely the case, and nearly all powder accelerator dispensers show a

6-18
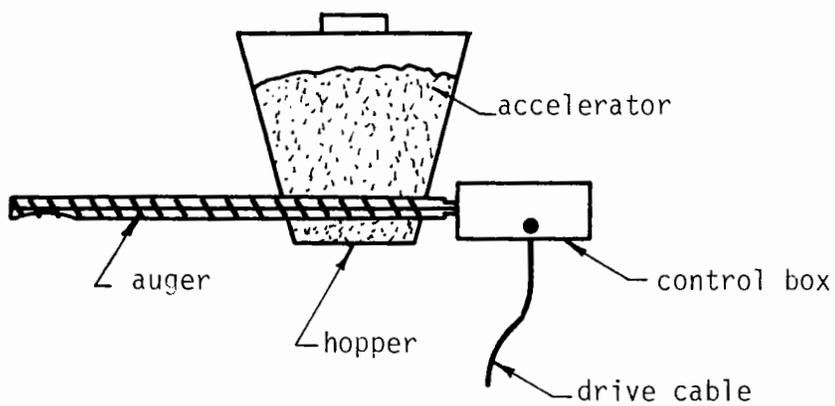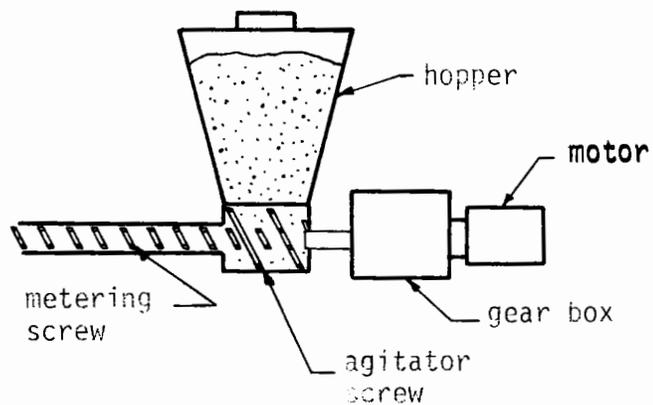
a. Auger dispenser

b. Corkscrew dispenser

FIG. 6.9 AUGER AND CORKSCREW DISPENSERS
FOR POWDER ACCELERATORS.

wide range in the amount of accelerator actually delivered to the dry-mix
materials. Most of the difficulties lie with the accelerators themselves.
The powders have a tendency to cake in the hopper above the feed mechanism
and to adhere to the sides of the compartments. In using auger-type dis-
pensers, the auger has bored holes in the accelerator without collapse of
the charge. Caking prevents a uniform deposition of accelerator in the
feed mechanism and produces errors in batching. Powder accelerators are
particularly sensitive to caking and clogging when the humidity is high
and they are exposed to air. To reduce these problems, dry powder dispensers
are generally equipped with vibrators or additional augers to agitate the
accelerator and keep it freely flowing and uniformly compacted. The results
have not always been satisfactory; variable discharge rates still occur.
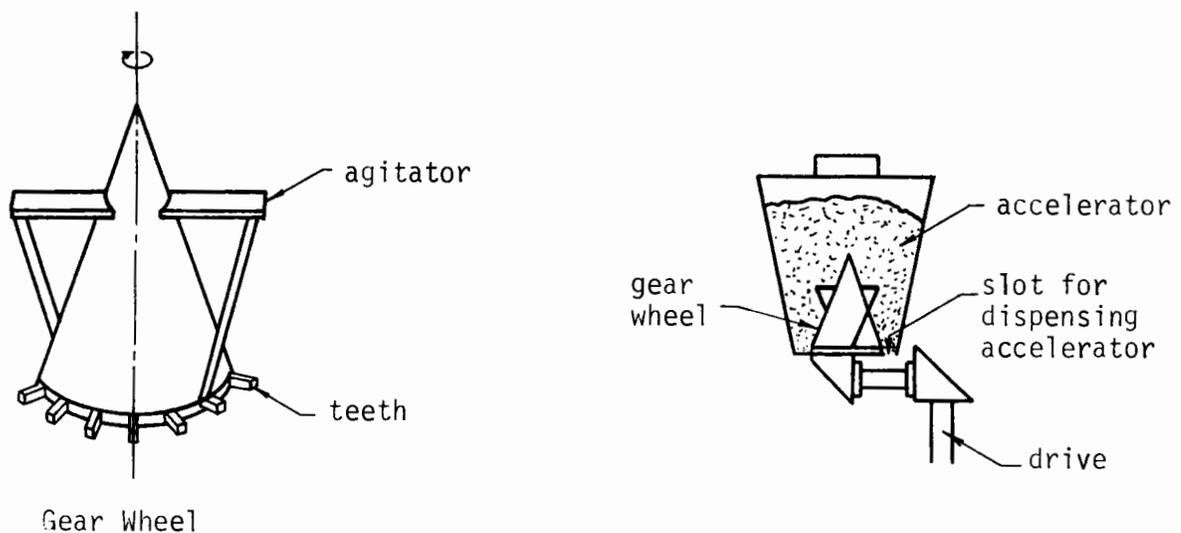
FIG. 6.10 GEAR WHEEL DISPENSER FOR DRY POWDER ACCELERATORS.

Position of Dispenser. The accelerator dispenser should be positioned above the conveyor or auger charging the shotcrete machine hopper (Fig. 6.11). This arrangement provides a relatively uniform distribution of the accelerator in the incoming shotcrete materials. The delivery rate of the accelerator must be synchronized with the rate of material delivery past the dispenser so that the desired cement/accelerator mix proportions are achieved. To do this the feed mechanism of the dispenser is driven by the motor of the auger or conveyor (Fig. 6.11). Controls on the dispenser allow the accelerator delivery rate to be adjusted independently of the speed of the auger or conveyor in order to obtain the desired cement/accelerator ratio. If an auger is used to charge the shotcrete machine, the accelerator mixes with the aggregate and cement before reaching the hopper.

In small shotcrete operations where the materials are conveyed to the machine by hand, the accelerator can be dispensed directly into the hopper (Fig. 6.12). The feed mechanism of the dispenser is driven by the motor of the shotcrete machine; thus the material delivery and accelerator feed rates are synchronized. This arrangement is not desirable because it can produce a non-uniform distribution of the accelerator, particularly at the start and finish of shooting. When the hopper is first filled, accelerator must be added by hand while at the end of shooting the feeder must be disconnected so that the last portion of the material in the hopper will not receive excessive accelerator. The material in the hopper must be kept at approximately the same level in order to obtain the desired cement/accelerator ratio since the feeder is synchronized with the outflow rather than the inflow of material. Maintaining a near-constant level in the hopper is

6-21
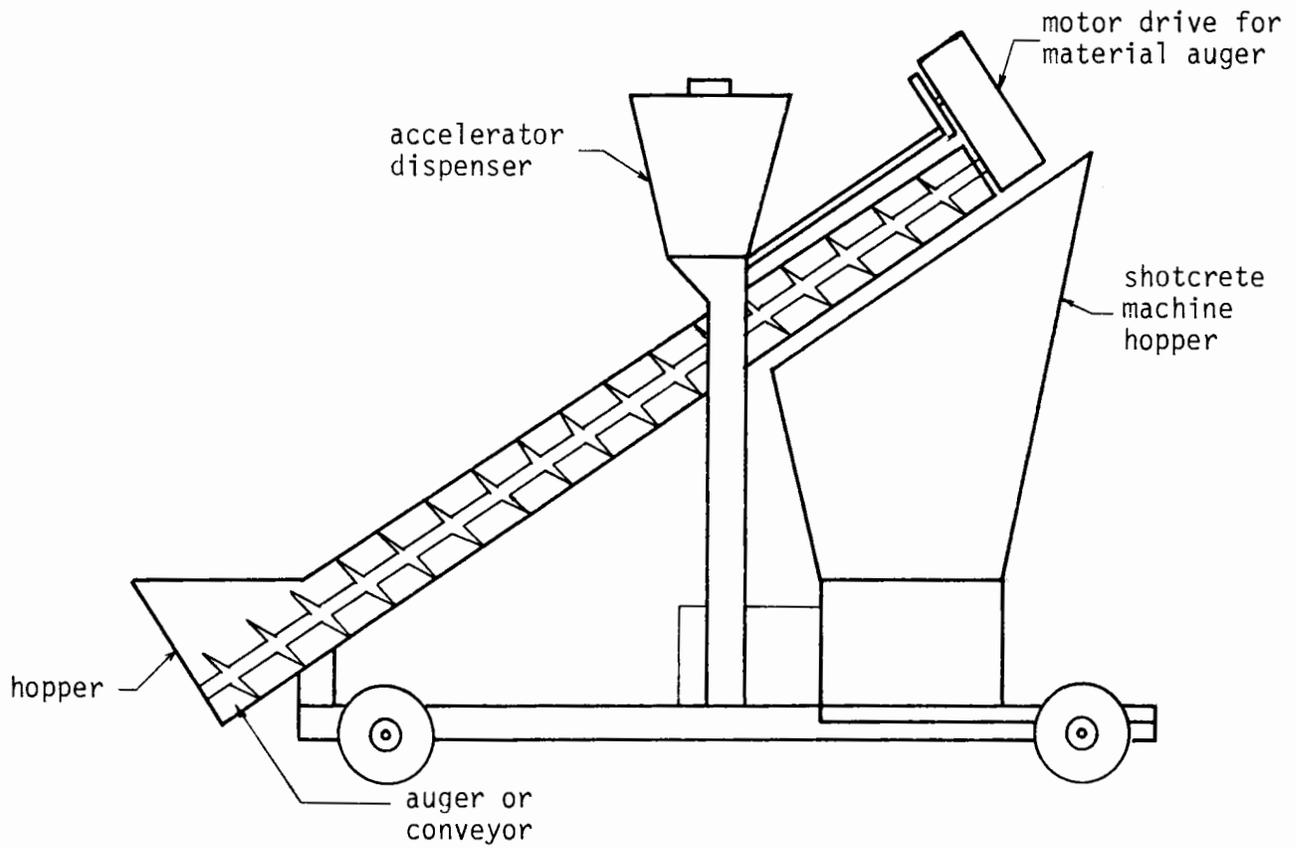
FIG. 6.11 POWDER ACCELERATOR FEED TO MATERIALS CHARGING
SHOTCRETE MACHINE HOPPER.
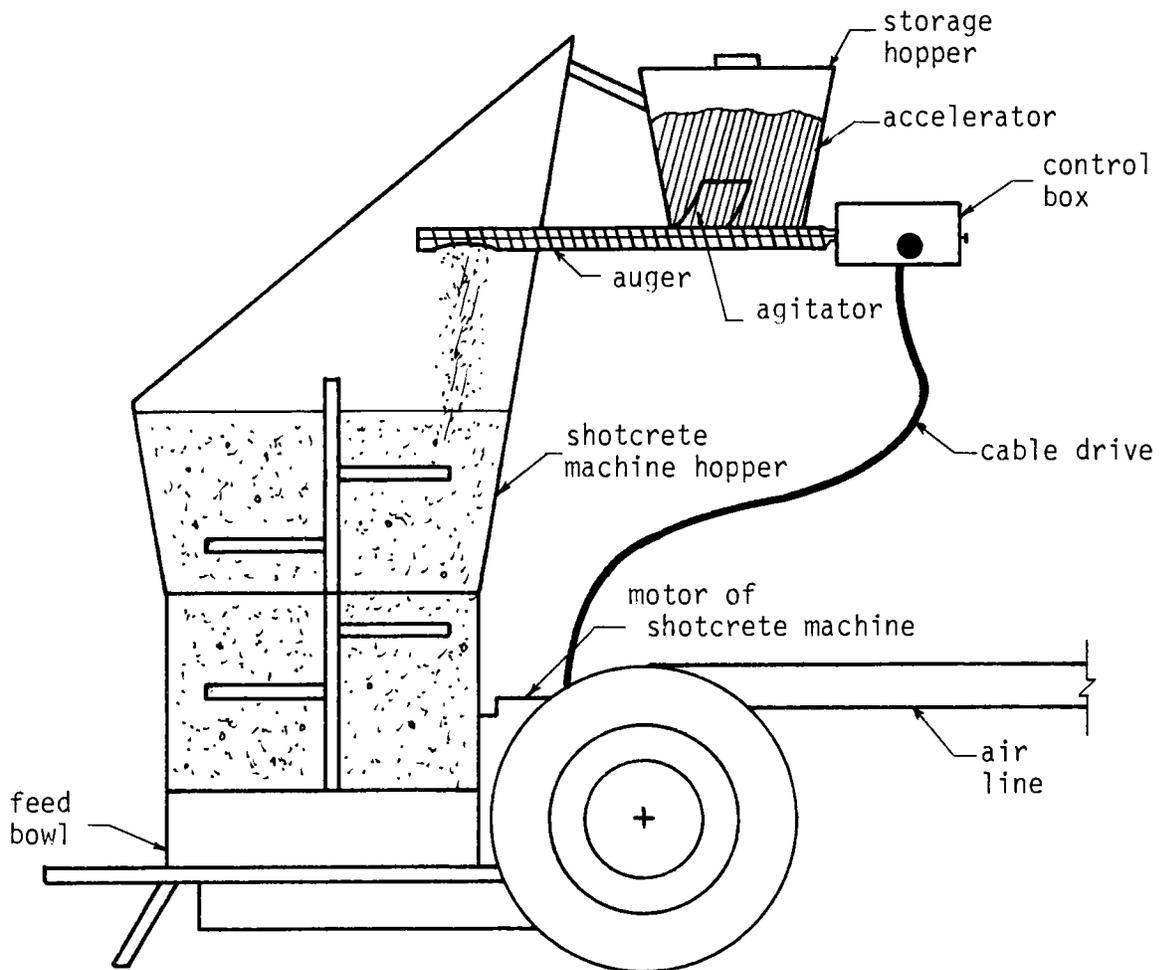
FIG. 6.12 ACCELERATOR FEED TO MATERIALS IN
SHOTCRETE MACHINE HOPPER.

difficult when it is fed by hand. In addition, the accelerator may be insufficiently mixed with the aggregate and cement when it is discharged directly into the hopper.

Calibration of Dispenser. The accelerator dispenser feed must be calibrated relative to the material feed rate to the machine or the delivery rate to the nozzle so that the desired accelerator/cement ratio can be obtained. This calibration is done by measuring the material delivery rate (kg/min [lb/min]) to the hopper or nozzle and the accelerator feed rate for a given setting of the control knob or opening of the discharge slot. The control knob regulates the rotation speed of the feed mechanism. This procedure is repeated until the full spectrum of material discharge to accelerator feed ratios is determined for each setting or width of opening. These ratios can then be used along with the cement content of the mix to adjust the control knob or opening to obtain the desired accelerator/cement ratio. The accelerator dispenser should be calibrated periodically to insure that the proper amount of accelerator is being added to the materials.

Maintenance. The following maintenance procedures should be followed to insure that the accelerator dispenser is functioning properly:

1) the entire accelerator feeder should be periodically cleaned of accumulated accelerator. It is particularly important that any caked material be removed from the dispensing mechanism (auger, corkscrew, or gear wheel) and discharge slot so that the volume dispensed will remain constant.

2) moving parts should be lubricated according to the manufacturer's recommendations. Excess oil is detrimental to shotcrete quality and should be avoided, however.

3) the drive mechanism should be periodically inspected for proper tension in the belt, cable or chain. Any slippage will upset the synchronization between the additive feed rate and shotcrete output.

The frequency at which these maintenance measures are required will depend on the tunnel conditions, the type of equipment, and the daily shotcrete output. The hopper and dispensing mechanism may require cleaning of caked material as frequently as after every shift but must be done at least once per day.

Liquid Accelerator Dispensers

If a liquid accelerator is used in the dry-mix process it is injected with the water at the nozzle. The simplest method for doing this is to add the accelerator in the desired proportion to water in a tank which supplies water to the nozzle. This practice provides good results where tunnel ground conditions do not vary and little to no water is present in the opening. It is not recommended when conditions change rapidly since the percentage of accelerator cannot be adjusted quickly enough to handle the ground conditions.

A more sophisticated system required for most shotcrete work involves adding the liquid accelerator directly into the water line with the use of a separate supply system (Fig. 6.13). The accelerator is contained in a pressurized tank and is fed into the water line at or near the nozzle. Proper proportioning by volume of water is obtained by adjustment of the additive
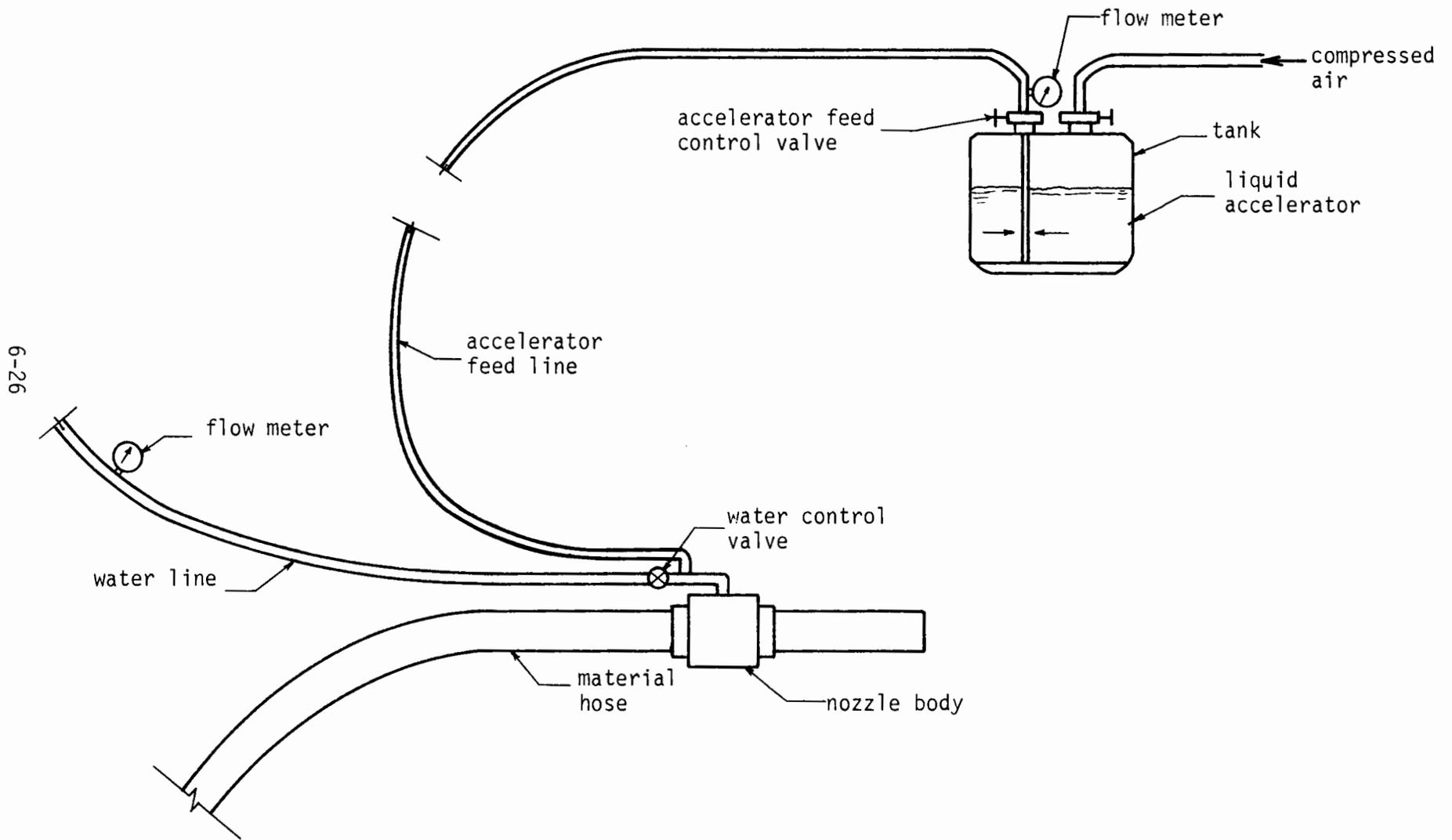
FIG. 6.13 LIQUID ACCELERATOR DISPENSER.

feed control valve. A small piston pump is sometimes used instead of an air pressure tank to convey the accelerator to the nozzle. This pump is less desirable since surging and a nonuniform flow will be produced unless a receiving tank is installed in the line. The water line at the nozzle must be adapted to accept the accelerator feed hose which is typically 6 mm (1/4 in.) in diameter. The amount of accelerator injected into the water is controlled by the gunman helper at the pump or tank. Flow rates are controlled using the outlet valve on the tank or by varying the speed of the piston pump.

As with powders, the liquid accelerator dispensers must be capable of providing the accelerator in the desired proportions. Proportioning by weight of cement is more desirable since early strength gain of the shotcrete depends highly on the accelerator/cement ratio. In present practice the accelerator dispenser and shotcrete machine are operated separately and thus there is no accurate or reliable means for controlling their feed rates simultaneously. By using the same procedures described for powder accelerators an approximate cement/accelerator ratio can be established, using the tank or pump control valve, provided the material delivery rate is relatively constant between shootings. Liquid accelerator may also be proportioned by volume of water. Flow meters placed in the lines are used to control the amount of accelerator needed to obtain the desired proportions.

The following maintenance procedures should be followed to insure proper functioning of a liquid accelerator dispenser system:

1)   the additive lines and tank should be periodically surged with
      water. All seals, fittings, valves, etc., should be checked
      for corrosion or deterioration and replaced as needed.

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2) if the additive feeder system is equipped with a pump instead
   of a pressure tank, it should be cleaned and maintained
   according to the manufacturer's recommendations.

6.2 Wet-Mix Shotcrete Equipment

6.2.1 Wet-Mix Shotcrete Machines

Wet-mix shotcrete machines are simply concrete pumps that deliver pre-
mixed, low-slump concrete to a nozzle where air is added to break up the slugs
of material and accelerate the particles toward the surface. Three types of
concrete pumps are used in wet-mix work: 1) piston, 2) squeeze, and 3) pneu-
matic. The piston and squeeze type pumps typically require a wetter consistency
than pneumatic feed machines, particularly when the concrete must be con-
veyed over long distances. Air boosters can be used along the material
line to facilitate the conveyance of low-slump shotcrete over long distances
(>30 m [100 ft]).

The components and operation of the piston pump for wet-mix shotcrete
are illustrated in Fig. 6.14. The pump basically contains two hydraulically
driven pistons and a flapper valve. The concrete is fed to the piston
chambers from a storage hopper located near the pump. On the backstroke of
the piston the flapper valve is opened to the storage hopper and concrete is
drawn into the piston chamber. On the forward stroke the valve rotates and
the concrete is forced into the material line. The pistons are synchronized
so that as one is discharging into the material hose the other is drawing
concrete from the storage hopper. The flapper valve simply directs the flow
of concrete from the receiving hopper into the piston chamber and then into

6-28
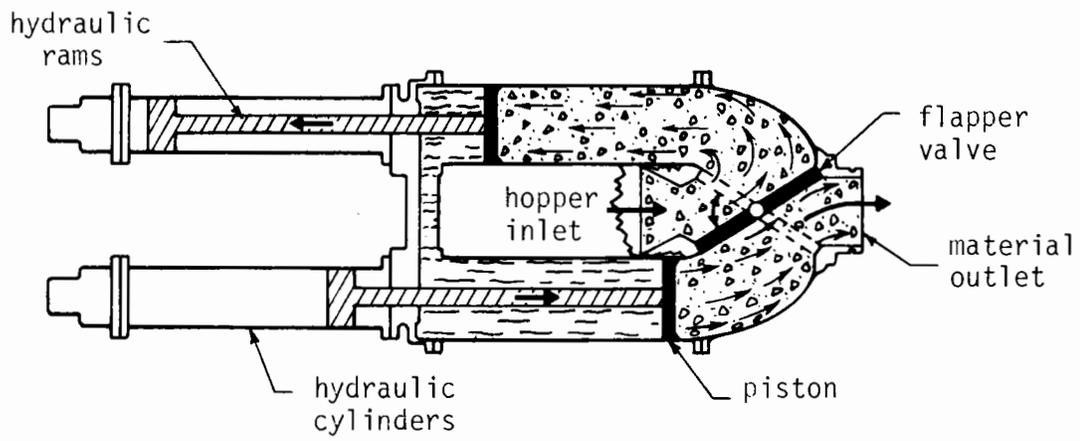
FIG. 6.14   SCHEMATIC DIAGRAM OF PISTON TYPE, WET-MIX
SHOTCRETE MACHINE (FREDERICKS, ET AL.,1966).
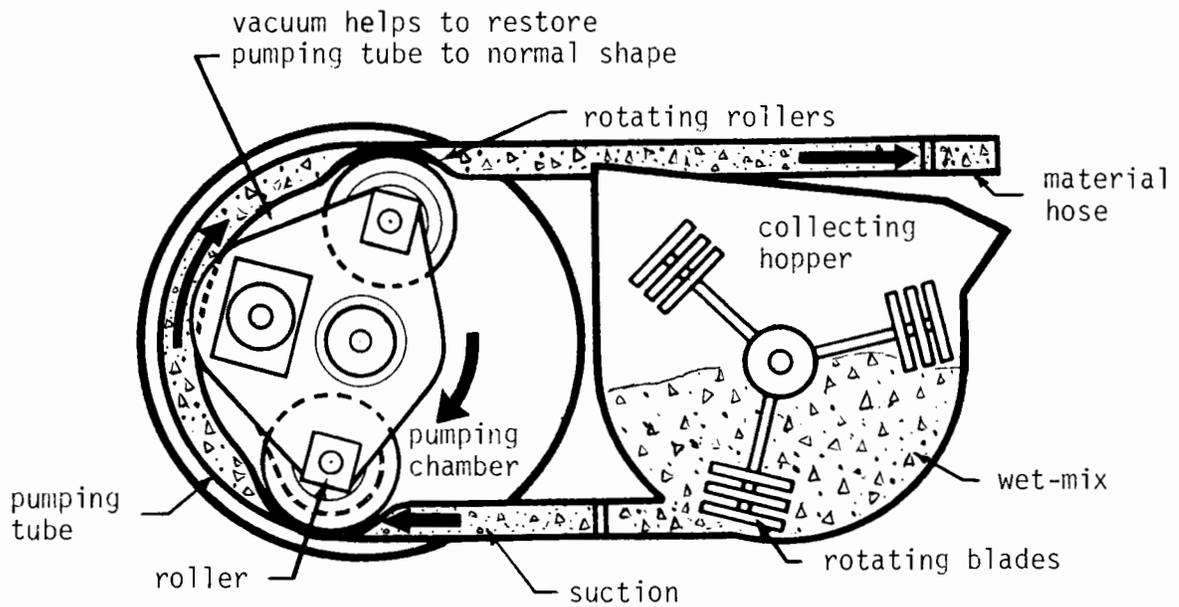
FIG. 6.15   SCHEMATIC DIAGRAM OF SQUEEZE TYPE,
WET-MIX SHOTCRETE MACHINE
(FREDERICKS, ET AL.,1966).

the material line. The pistons are driven rapidly so that a nearly con-
tinuous flow of material is supplied to the nozzle. Nevertheless, the action
of the pistons cause some surging of the material in the line.

The squeeze-type shotcrete machine consists of two rollers which squeeze
the concrete through a short section of 75 mm (3 in.) diameter flexible pumping
tube into a material line (Fig. 6.15). A collecting hopper is used to store
the prepared concrete and feed the pump. Agitator blades and suction of the
rollers force the concrete from the hopper into the pumping tube. The con-
crete is then conveyed to the material hose by the rollers, which squeeze the
pumping tube and force the concrete ahead of the constriction. The pumping
chamber is in a partial vacuum so that the shape of the pumping tube is
restored after the rollers pass. The squeeze type machine provides a very
uniform and continuous flow of material to the nozzle.

The purely pneumatic shotcrete machines operate much like the dry-mix
feed wheel guns and can actually be used to shoot dry-mix shotcrete. The
pneumatic machine consists of a pressure chamber containing a set of mixing
paddles (Fig. 6.16). Prepared concrete or raw materials are placed in the
chamber through the hatch located at the top of the tank. Batching of water
and mixing can be done in the machine. Once the materials are thoroughly
mixed, the hatch is closed and the chamber is pressurized by opening the
valve in the air line. The concrete is forced by air pressure into a dis-
charge sump located at the bottom of the tank. In the sump the concrete is
driven by an air blast into the material hose. The paddle blades strike
across the opening of the sump interrupting the flow of material into the
line. The shotcrete is conveyed to the nozzle as alternating slugs of material

6-30
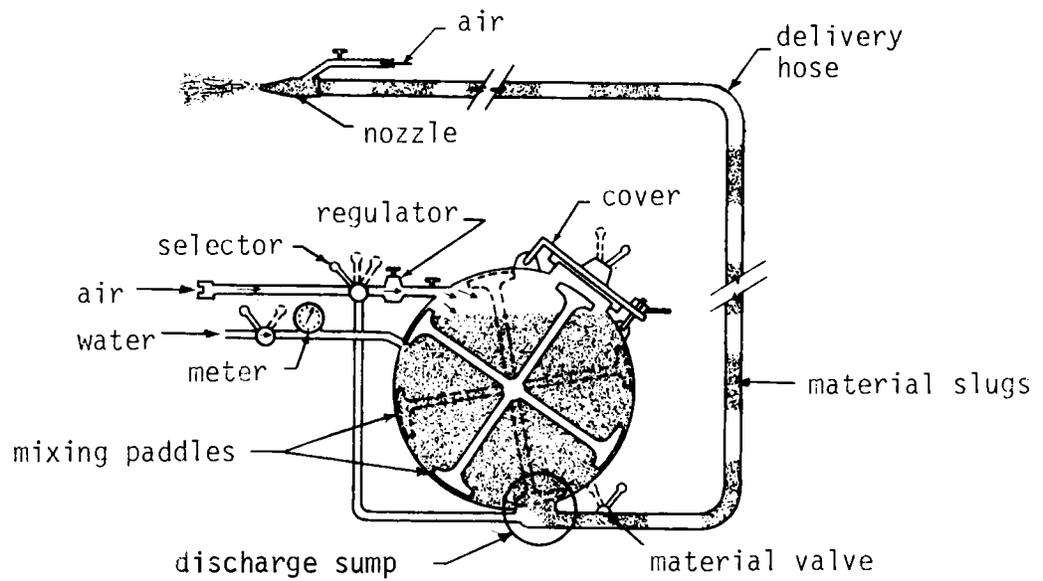
FIG. 6.16 SCHEMATIC DIAGRAM OF THE PNEUMATIC WET-MIX
SHOTCRETE MACHINE (HOFFMEYER, 1966).

and air. Flow of material to the nozzle is similar to that produced by dry-mix machines: continuous but slightly pulsating. The material delivery rate provided by the pneumatic machine is controlled by the air pressure in the sump and chambers and the rotation speed of the mixing paddles. Higher material delivery rates are obtained at higher air pressures and slower rotation speeds, provided that the feed to the sump is not so great as to cause plugs. A dual chamber machine is used for shotcrete work so that a continuous flow of material is furnished to the nozzle. While one chamber is delivering concrete to the nozzle the other is being charged with material.

The wet-mix machines can be chain or hydraulically driven by an air, electric, or diesel motor. Gasoline motors can also be used when the machine is operating above ground. The type of motor and method of drive affect the flow of material to the nozzle from the wet-mix machine in a manner similar to the dry-mix machines. The quality of the in-place shotcrete produced by the wet-mix process, however, is not as sensitive to the uniformity of material delivery as in the dry-mix process since the water in the correct proportions is already in the mix.

Wet-mix machines commercially available in the United States are listed in Appendix B. Table 6.2 summarizes the average capabilities, requirements, and dimensions of these machines. Data given in Appendix B and Table 6.2 were taken from information provided by the manufacturers. The wet-mix machines are capable of delivering concrete at rates between 2 and 15 m^3/hr (3 and 20 yd^3/hr) with aggregates up to 25 mm (1 in.) in size. The actual production rates for placement of shotcrete in most underground construction are comparable with those obtained with dry-mix machines (4 to 5-1/2 m^3/hr [5 to 7 yd^3/hr]).

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Table 6.2 Typical capabilities, requirements, and
dimensions of wet-mix shotcrete machines.

Capabilities

Maximum aggregate size, mm	10-25
(in.)	(3/8-1)
Delivery rate, m^3/hr	2-15
(yd^3/hr)	(3-20)
Maximum horizontal conveyance, m	N.A.
(ft)	
Maximum vertical conveyance, m	N.A.
(ft)	

Requirements

Hose diameter I.D., mm	40-80
(in.)	(1 1/2-3)
Air consumption with:	
Air driven gun, m^3/min	10-17
(ft^3/min)	(370-600)
Electric/gasoline driven gun, m^3/min	3.5-11
(ft^3/min)	(125-400)

Dimensions

Height, m	1.1-2.0
(ft)	(3.5-6.5)
Width, m	1.2-2.4
(ft)	(3.8-8)
Length, m	1.5-5.2
(ft)	(5-17)
Weight, kg	950-2800
(lb)	(2100-6100)

N.A. = information not available

The wet-mix machines like their dry-mix counterparts must be cleaned and maintained on a regular basis. All components coming in contact with shotcrete must be thoroughly washed and scraped, if necessary, to remove all accumulations of cement and aggregate. Cleaning should be done on a daily basis or after each application. The motor should be maintained in good operating condition and adequately lubricated.

6.2.2 Wet-Mix Nozzles

In the wet-mix process, compressed air and accelerator are injected at the nozzle. The compressed air breaks up the slugs of wet-mix materials and accelerates the particles as they leave the nozzle. Two basic types of wet-mix nozzles are used: 1) air ring, and 2) air tube. The air ring in the air ring nozzle is similar to the water ring in its dry-mix counterpart but allows air rather than water to be added to the materials (Fig. 6.17). The air holes in the ring are slanted toward the orifice at approximately 30° from the long axis of the nozzle so that the direction of applied air is nearly parallel with the direction of movement of the materials. Air ring nozzles are generally not used when accelerators are added to the wet-mix since the holes are likely to plug.

The air tube nozzle is a later development which readily allows accelerators to be injected into the mix at the nozzle. This nozzle is usually 60 to 90 cm (24 to 36 in.) long and consists of a material and an air pipe (Fig. 6.18). The material pipe is steel and has approximately the same outside diameter as the inside diameter of the material hose. To prevent plugs the inside of the pipes should be gently tapered at its connection with the material

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air

air ring

slug of
wet mix

mix broken up and
accelerated by
injection of compressed
air
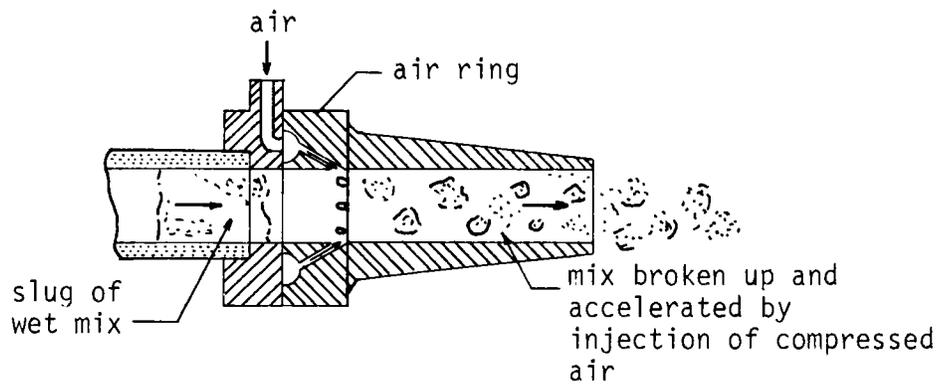
FIG. 6.17   AIR RING NOZZLE FOR WET-MIX SHOTCRETE (RYAN, 1973).

material pipe

material hose

rubber
nozzle
tip

30°

air pipe

air and dry accelerator
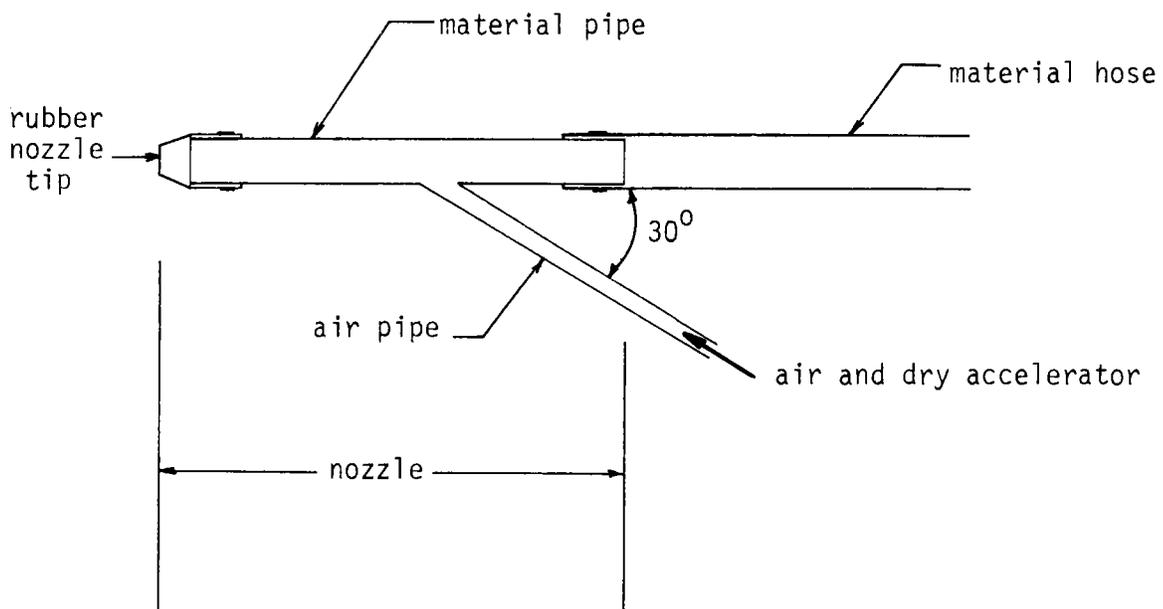
nozzle

FIG. 6.18   AIR TUBE NOZZLE FOR USE WITH POWDER
           ACCELERATORS (STEENSON, 1974).

hose. A rubber nipple is placed on the end of the material pipe to concentrate
the flow of material as it leaves the orifice. The air pipe is also steel
and has a diameter ranging between 13 and 25 mm (1/2 and 1 in.). The air
pipe is inclined at approximately 30° from the long axis of the material
pipe and is welded over a hole cut in the material pipe approximately 45 cm
(18 in.) from the nipple. Powder accelerator is added to the air stream
at the shotcrete machine; the standard air tube nozzle shown in Fig. 6.18 is
adequate for conveying both the accelerator and the air. When liquid accel-
erators are used, the air pipe must be modified so that the liquid can be
injected into the air stream just before the compressed air passes into the
material pipe (Fig. 6.19). This nozzle provides a uniform flow of liquid
accelerator into the material stream with little loss during conveyance. The
modified air pipe nozzle was developed by Mr. Jeremias Chitunda at Hecla's
Lakeshore Mine in Arizona.
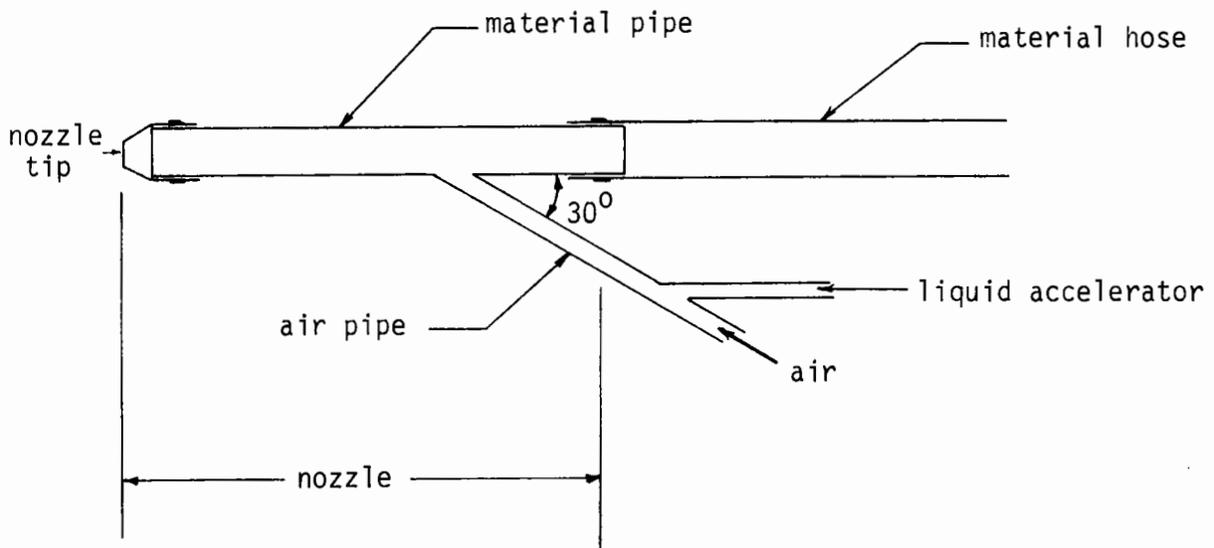
FIG. 6.19 WET-MIX SHOTCRETE NOZZLE FOR USE WITH LIQUID ACCELERATORS.

The air pressures at both the air ring and air tube nozzles are controlled by the nozzleman who adjusts a regulating valve in the air line. Air pressure at the nozzle is typically 1.5 to 3 kg/cm^2 (20 to 40 psi).

The wet-mix nozzles should be maintained in good operating condition and should be checked daily. Accumulations of cement and accelerator should be removed and worn parts repaired or replaced. The air holes in the air ring or the air pipe and, if liquids are used, the accelerator feed pipe, should be inspected to insure that they are not blocked or constricted. The quality of wet-mix shotcrete is not so sensitive to the operation of the nozzle as dry-mix shotcrete, but inadequate maintenance can cause delays in shooting, difficulties in nozzling, and large fluctuations in the amount of accelerator added to the materials.

6.2.3 Wet-Mix Accelerator Dispensers

Powder Accelerator Dispensers

At present, the only reliable method for dispensing powder accelerators directly into the wet-mix at a uniform rate at the nozzle is the log feeder system developed by Challenge-Cook Bros. The operation of this system is illustrated in Fig. 6.20. The powder accelerator is compressed into logs 15 cm (6 in.) in diameter and about 30 cm (12 in.) long, and placed into a log feeder. The log feeder consists of a long cylinder with a hydraulic ram at one end. At the other end is a chamber housing a rotating drum equipped with steel teeth and having two air ports, one on each side. The logs are placed manually in the cylinder through a hatch on the top of the feeder, the hatch is then closed, and the logs are forced against the drum by the hydraulic ram. Powder from
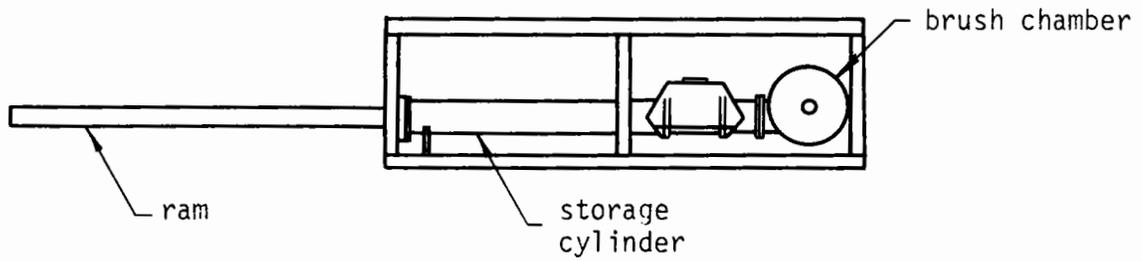
a. Log feeder assembly
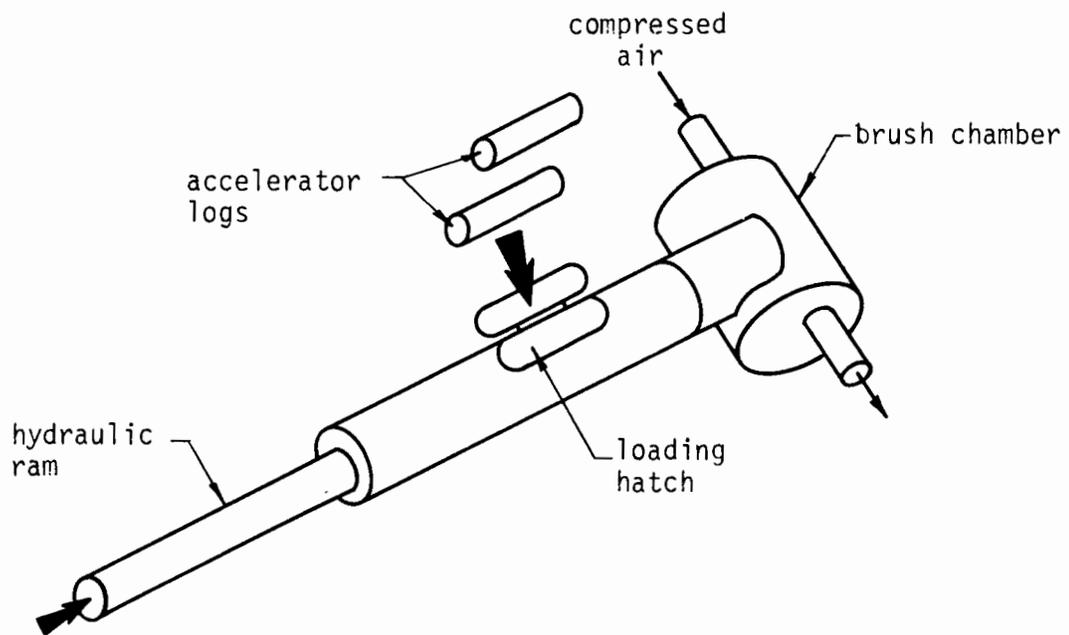
b. Log feeder

FIG. 6.20 LOG FEEDER FOR ADDING POWDER ACCELERATOR TO WET-MIX
SHOTCRETE (STEENSON, 1974).

the logs is ground off by the teeth, which are rotating at constant speed. The powder is then carried away in the air stream passing through the chamber and leading to the shotcrete nozzle. The accelerator mixes with the other materials at the nozzle and in transit to the tunnel surface. Care must be taken to prevent damaging the logs when they are placed in the storage cylinders. Broken logs can jam the hydraulic ram and result in delays in the shotcrete operation and in wasted accelerator.

The amount of accelerator fed to the air stream is controlled by varying the pressure of the hydraulic ram and thus the rate of advance of the log. This increases or decreases the amount of powder ground off the logs. The desired accelerator/cement ratio is obtained by adjusting the accelerator feed rate relative to the material delivery rate to the nozzle. Since the hydraulic ram and the wet-mix machine are operated independently, the proper accelerator feed rate must be determined by trial and error. The accelerator/cement ratio at a given ram pressure is determined and then the pressure is adjusted until the desired proportion is obtained. This ratio is estimated from a knowledge of the mix design and by determining the weight of accelerator and shotcrete delivered over a given period of time. Pressure gage readings are calibrated by comparing the accelerator feed rate at successive pressures with the material delivery rate and the cement content. Pressure readings can be used to proportion the accelerator, provided that the material delivery rate is relatively constant between shootings. The settings should be checked periodically during shotcreting to insure that the accelerator is being added in the correct proportion.

The specific details on maintenance of the log feeder system must be obtained from the manufacturer. In general, routine maintenance will include cleaning the log cylinder and brush chamber of all accumulated powder, replacement or refurbishing of the teeth on the drum, and general lubrication. A potential problem with dispensing dry powder through the air hose is condensation of water in the air stream and subsequent accumulation of accelerator. These accumulations can be removed by beating the air hose with a mallet and then blowing out the line.

Liquid Accelerators

The methods of dispensing liquid accelerator (pressure tank or piston pump) in a wet-mix operation are essentially identical to those used in a dry-mix operation, except that the accelerator is injected into the air stream instead of the water stream. These methods have been described in the previous section dealing with dry-mix accelerator dispensers.

6.3 Equipment Common to Both Processes

6.3.1 Compressed Air Supply

The entire shotcrete process (wet or dry) depends on having an adequate supply of compressed air. Not only should the compressor provide a sufficient volume of air at the correct pressure, but the pressure should not fluctuate. Fluctuations in the air supply cause nonuniform delivery of the materials to the nozzle.

In the dry-mix process, the capacity and operating air pressure of the compressor depend on: 1) the material delivery rate, 2) the diameter and

length of the material hose, 3) the height of the nozzle above the shotcrete machine, and 4) the type of motor used to drive the machine. Operating air pressures and capacities of compressors needed for dry-mix shotcrete machines as recommended by ACI (1966) are given in Table 6.3. The values given in this table are for hose lengths of 45 m (150 ft), for nozzles less than 7.5 m (25 ft) above the shotcrete machine and for air driven motors (ACI, 1966). Air compressor capacities needed to operate wet-mix shotcrete machines are typically 3.5 to 17 m^3/min(125 to 600 ft^3/min) (Table 6.2).

The air supplied to the dry-mix machine or to the wet-mix nozzle must be dry, clean, and oil-free. If oil from the compressor becomes mixed with the materials, it causes a great reduction in the intermediate and ultimate strengths of the shotcrete. Water vapor in the air supply can condense in the air line or machine and cause early hydration of the mix and clogging of the machine. Dry-mix machines are particularly sensitive to water and do not operate or operate poorly if water reaches or is condensed in the feed bowl or barrel. If appreciable water is added to the wet-mix materials at the nozzle, it can increase the slump, and cause excessive rebound and loss in ultimate strength. Air receiver units with drains are commonly installed between the air compressor and the shotcrete machine or nozzle to remove excessive moisture and impurities. Some shotcrete machines are also fitted with dryers to remove some of the moisture from the air. Dryers can also be placed along the air line and should be used in very humid conditions.

The selection of the air compressor depends on the required output (m^3/min [ft^3/min]) and on the working pressure (kg/cm^2 [psi]). In procuring a compressor both the output and the working pressure should be

Table 6.3 Air compressor requirements for dry-mix
shotcrete machines (ACI, 1966).

| Hose Diameter | | Compressor Capacity | | Operating Air Pressure | |
mm	(in.)	m^3/min	$(ft^3$/min)	kg/cm^2	(psi)
25	(1)	7	(250)	2.8	(40)
32	(1-1/4)	9	(315)	3.2	(45)
38	(1-1/2)	11	(365)	3.9	(55)
41	(1-5/8)	15	(500)	4.6	(65)
45	(1-3/4)	18	(600)	5.3	(75)
50	(2)	22	(750)	6.0	(85)

specified as closely as possible to the actual output and pressure needed

so that maximum efficiency and economy are obtained. The values specified,

however, should have an adequate margin to cover not only the shotcrete

machine but accessories (such as auxiliary pneumatic equipment) as well.

Two types of compressors are available depending on the method of drive:

diesel and electric. Diesel compressors can be either of the rotary or

piston type.

6.3.2 Compressed Air Hose

Compressed air hoses generally consist of three parts: 1) the inner

tube, 2) the reinforcement, and 3) the cover. The inner tube is in contact

with the compressed air and therefore must be oil resistant and non-flaking.

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The reinforcement provides the strength needed to withstand the air pressures and is usually either wire or rayon braid. The number of braids governs the size and working pressure of the hose. The cover should be resistant to cutting and abrasion, oil, weather, and age. Typical hose dimensions and working pressures for rayon, steel, and wire braid hoses are given in Table 6.4.

Couplings for most air hoses are either interlocking clamp-type, threaded, or Universal Quick Action. Universal Quick Action couplings should be used with a safety pin to prevent accidental disconnection. All couplings on the compressed air line should be equipped with safety chains or cables. The chains or cables reduce the chances of injury should a coupling fail during operation of the compressor. Compressed air lines used for wet-mix shotcrete have smaller diameters than those used for dry-mix because less air is required at one location.

6.3.3 Material Hose

The material hose is similar to the compressed air hose except that it has an abrasive resistant inner lining. This is a necessary feature because of the abrasive action of the aggregate as it passes through the hose. The cover of the material hose must be durable and oil resistant.

The inside diameter of the material hose is governed by the maximum size of the aggregate and the material delivery rate. Hose diameters are most sensitive to the size of the aggregate and should be at least twice the maximum nominal size (Table 6.5). For coarse aggregate shotcrete, material hoses typically have inside diameters of 50 and 64 mm (2 and 2-1/2 in.).

Static electrical charges which can severely shock the nozzleman can build up on the material hose when shooting dry-mix materials with moisture

Table 6.4 Compressed air hose dimensions and working pressures for
steel and rayon spiral air hoses and wire braid air hoses.[1]

M-16 Yellow Steel Spiral Air Hose

| Inside Diameter | | Outside Diameter | | Steel | Max. Working Pressure | |
mm	(in.)	mm	(in.)	Spirals	kg/cm^2	(psi)
19	(3/4)	33	(1.3)	2	42	(600)
25	(1)	40	(1.6)	2	42	(600)
32	(1-1/4)	50	(2.0)	4	42	(600)
38	(1-1/2)	56	(2.2)	4	42	(600)
50	(2)	70	(2.8)	4	42	(600)
64	(2-1/2)	83	(3.3)	4	35	(500)
76	(3)	95	(3.8)	4	32	(450)
101	(4)	121	(4.8)	4	25	(350)

M-11 Yellow Rayon Spiral Air Hose

| Inside Diameter | | Outside Diameter | | Steel | Max. Working Pressure | |
mm	(in.)	mm	(in.)	Spirals	kg/cm^2	(psi)
13	(1/2)	25	(1)	2	21	(300)
19	(3/4)	35	(1.4)	4	21	(300)
25	(1)	42	(1.7)	4	21	(300)
32	(1-1/4)	50	(2.0)	4	18	(250)
38	(1-1/2)	54	(2.1)	4	16	(225)
50	(2)	69	(2.7)	4	16	(225)
64	(2-1/2)	82	(3.2)	4	14	(200)
76	(3)	94	(3.7)	4	12	(175)
101	(4)	120	(4.7)	4	9	(125)

H-35 Yellow Wire Braid Air Hose

| Inside Diameter | | Outside Diameter | | Steel | Max. Working Pressure | |
mm	(in.)	mm	(in.)	Spirals	kg/cm^2	(psi)
19	(3/4)	48	(1.9)	1	56	(800)
25	(1)	38	(1.5)	1	42	(600)
32	(1-1/4)	45	(1.8)	1	42	(600)
38	(1-1/2)	55	(2.2)	2	42	(600)
50	(2)	69	(2.7)	2	42	(600)
64	(2-1/2)	82	(3.2)	2	28	(400)
76	(3)	95	(3.8)	2	28	(400)

[1]Taken from: 1975 Wholesale Catalog
The Rubber House
Montgomery, Alabama

contents below 2-3%. To prevent electrical buildup, wire should not be used for reinforcement without a static line to drain off the excess charge. Semi-conducting material hoses can also be used to prevent buildup of static electricity. Problems of buildup of excess electrical charges are most easily handled by wetting the aggregates.

6.3.4 Remote Nozzling Equipment

The remote nozzling equipment consists basically of a hydraulically operated boom (robot) and an operator's platform (Fig. 6.21). The nozzle (wet- or dry-mix) is mounted in a sleeve attached to the end of the boom. The material stream is directed by the nozzleman who uses a set of controls located on the platform. The boom and sleeve can be moved in almost any direction so that the material stream can be directed at the proper angle and distance relative to the tunnel surface and the full perimeter of the tunnel can be shotcreted. The motion of the nozzle is usually not elliptical

Table 6.5 Minimum inside diameters of material hoses
used for various maximum nominal grain sizes.

Maximum Nominal Grain Size		Inside Diameter of Material Hose	
mm	(in.)	mm	(in.)
10	3/8	45-50	1-1/2 - 2
13	1/2	50	2
19	3/4	50-65	2 - 2-1/2
25	1	50-75	2 - 3

FRONT VIEW

Motion of nozzle

SIDE VIEW

nozzle

boom

sleeve

light

material hose

platform
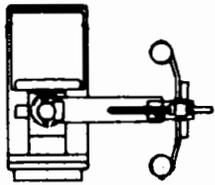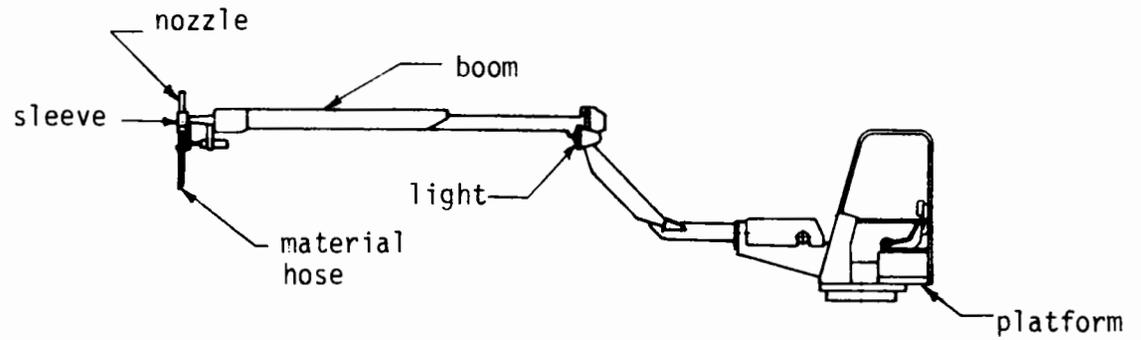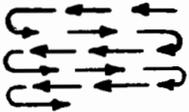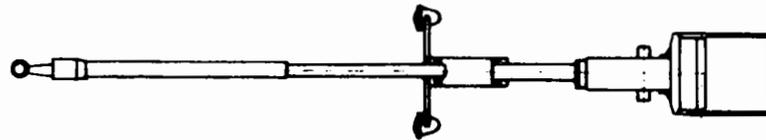
TOP VIEW

FIG. 6.21   REMOTE NOZZLING EQUIPMENT (ALBERTS, 1974).

or circular but instead is back and forth as depicted in Fig. 6.21. This back and forth motion (acceptable for both remote and hand-held nozzling) minimizes rebound entrapment and helps to control shotcrete thickness. The platform is mounted on a truck, rail car, or boom of a crane so that the remote nozzling equipment can be moved around the tunnel easily (Fig. 6.22). The remote nozzling technique and preliminary equipment were developed in a tailrace tunnel for the Holjes Hydro-Electric Project approximately 12 years ago in Sweden (Karlsson and Fryk, 1963). The patent rights are held by Stabilator AB of Bromma, Sweden.

6.3.5 Auxiliary Equipment

The auxiliary equipment needed in the shotcrete operation includes the air blowpipe, safety equipment, and tools for cleaning the shotcrete machine and nozzle. The air blowpipe is used to remove rebound during shotcreting and prevent its entrapment in the shotcrete lining. The blowpipe is made of steel pipe having an internal diameter varying between 25 to 50 mm (1 to 2 in.) and a length of approximately 1.2 m (4 ft) (Fig. 6.23). The discharge end of the blowpipe is beveled and slightly curved. The pipe is attached to an air line through a control valve that is used to regulate the air pressure and flow.

The safety equipment includes the personal safety gear used by the shotcrete crew and other accessories for reducing danger to the workmen. Safety gear that should be worn by the crew includes: 1) rubber boots, 2) rubber gloves, 3) protective clothing, 4) safety goggles, 5) respirator, and
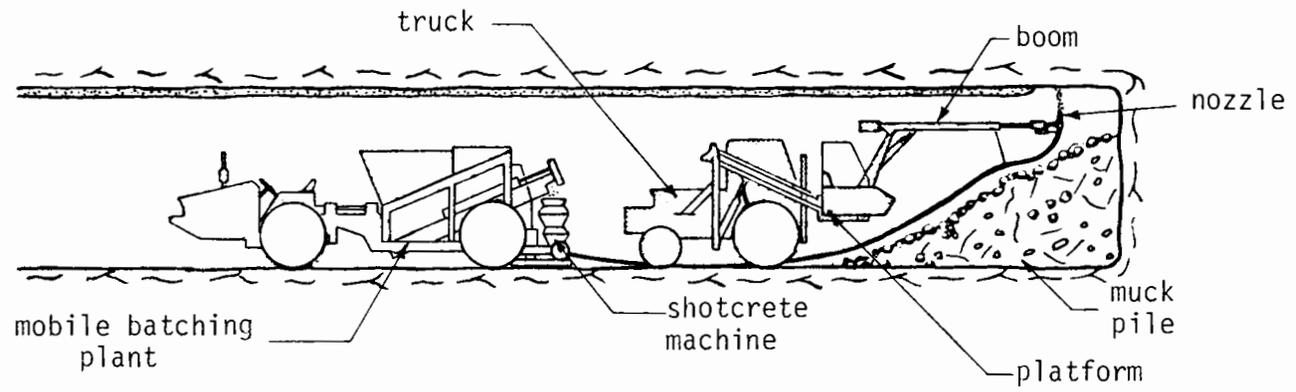
FIG. 6.22 OPERATION OF REMOTE NOZZLE UNDERGROUND (ALBERTS, 1974).
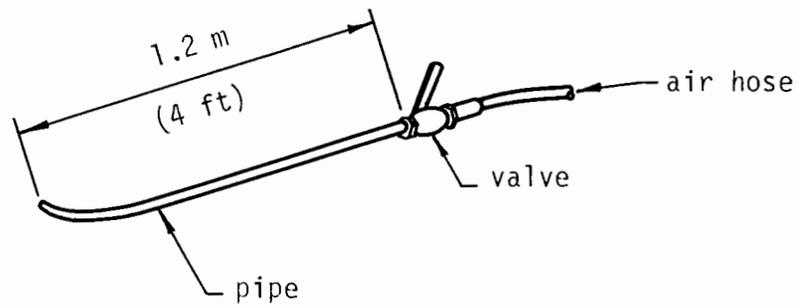
FIG. 6.23 AIR BLOWPIPE (RYAN, 1973).

6) hard hat. Accessories include safety chains and cables for air lines, and ropes or belts for use when shooting from platforms. All safety gear must meet the OSHA requirements (see Section 1926--OSHA, 1972), where applicable.

Pneumatic air hammers and compressed air jets are used to clean the dry-mix shotcrete machine and both wet- and dry-mix nozzles. The chipping hammer is equipped with a chisel and must be small enough to be operated with one hand yet have enough action to remove cement and fine aggregate scale. The air jet is used to blow out the loosened debris and to clean the shotcrete equipment.

CHAPTER 7

PLACEMENT OF SHOTCRETE UNDERGROUND

The procedures and techniques used to apply shotcrete underground dictate, to a large degree, the quality and economy of the in-place materials. The mix design and material preparation may be adequate, but if the shotcrete is improperly gunned, the final product will always be of low quality. It must be remembered, however, that poor quality shotcrete may result for reasons other than improper nozzling techniques. Surface preparation and application procedures will govern the bond, shotcrete strength, and durability of the in-place materials. Shooting techniques also control the material delivery rate and rebound, and, thus, the economy of the shotcrete operation.

This section deals primarily with the personnel requirements for a successful shotcrete operation and with proper shooting techniques. In addition, comparisons are made between remote and hand-held nozzling and a short discussion is given on curing of shotcrete underground. A training program for shotcrete nozzlemen is given in Appendix C.

7.1 Shotcrete Personnel

The shotcrete crew usually consists of 4 to 8 individuals depending on the size of the operation, the type and setup of equipment, and union requirements. A skeleton crew consists of the foreman, nozzleman, gunman and batching-mixing operator. Additional personnel such as a nozzleman helper, gunman helper and operator for haulage of materials

may also be required.

7.1.1 Foreman

The foreman of the shotcrete crew should have experience in all phases of the shotcrete operation and should have at least two years of experience as a nozzleman (ACI, 1966). This individual has the responsibility for setting up the shotcrete operation, for attaining the desired production, and for obtaining the required quality of in-place materials. He must train nozzlemen and crews in the proper techniques for rapid placement of high quality shotcrete. The foreman must assist the tunnel superintendent in coordinating the mixing and shooting operations with the mining activities so that interference is kept to a minimum. This responsibility is extremely important when placement of shotcrete is part of the tunnel cycle because of the close relation between cycle time and cost of the job. The foreman must also set up the shotcrete equipment and select the best procedure for placement of shotcrete in the opening.

7.1.2 Nozzleman

The success of the shotcrete crew depends heavily on the ability of the nozzleman since he controls the surface preparation, the material delivery rate, the impingement of the shotcrete particles on the surface, the thickness, and, in the dry-mix process, the water-cement ratio. As seen later, these parameters strongly affect the quality, rebound, and production of shotcrete.

On all underground shotcrete projects, the nozzleman should have

have at least 6 months training under the supervision of a qualified foreman (ACI, 1966). If necessary, strength and rebound tests should be conducted to verify his ability in producing the desired quality of shotcrete with minimum rebound. It is highly advantageous to have a nozzleman with shotcrete or mining experience on similar types of underground construction, since he will know the best approach in applying the shotcrete and will be able to recognize potentially dangerous rock conditions in areas where he is working. A general knowledge of and experience with concrete will also be helpful. If the nozzleman is a trainee, he should be under the direct supervision of the shotcrete foreman.

The nozzleman directs the gunning operation during placement of shotcrete. He signals the gunman to start and stop the flow of materials to the nozzle and to adjust the air pressure or feed mechanism. The nozzleman directs the gunman helper to increase or decrease the amount of accelerator as required for the tunnel ground and shooting conditions. He also motions to the hose holder which way he will be moving the nozzle.

The primary duties of the nozzleman are:

1. to adequately clean the surfaces receiving shotcrete,

2. to ensure that a smooth, continuous flow of materials leaves the nozzle at optimum velocity,

3. to use the proper nozzling techniques, and

4. to maintain in proper working order the nozzle, material hose and the air or water lines, depending on the process used.

7-3

If the material delivery is irregular, the nozzleman must direct the shotcrete stream away from the work until a continuous flow is obtained. If a steady flow cannot be maintained, he must stop the gunning operation. The nozzleman is also responsible for safety in the area where shotcrete is applied. This responsibility includes both control of the material hose and recognition of potentially dangerous rock conditions. He should be aware of other people in his immediate vicinity and take care not to direct the shotcrete stream toward them. He must always have a firm grip on the nozzle and plan his movements so that he does not lose control of the material hose.

In preparing for placement of shotcrete, the nozzleman should study the area to be sprayed, plan the sequence of coverage, and decide on the best methods for shooting the tunnel surface. This study will enable him to move efficiently and safely during the operation. Features in the rock profile should be noted and used for thickness and location control. He should inform the hose holder of his general plan for placing shotcrete if it varies from the established pattern. When placing shotcrete in unsupported tunnel headings, the nozzleman should study the ground conditions in the face and watch the scaling operation. He should take note of loose or unstable ground and generally apply shotcrete in that area first. If he recognizes potentially hazardous ground, he must avoid working directly beneath it, even if this necessitates shooting at an oblique angle to the surface with a resulting increase in rebound.

7.1.3 Gunman

A qualified gunman is as important as an experienced nozzleman for a successful shotcrete operation. The gunman must have a thorough knowledge of the components and operation of the shotcrete machine. He should be able to anticipate difficulties with the operation of the equipment and make the necessary adjustments and repairs with a minimum of down time. His ability will minimize production loss and possible waste of shotcrete materials. Ideally, the gunman should have at least 2 months experience operating a shotcrete machine or be under the direct supervision of the shotcrete foreman.

The primary responsibilities of the gunman are to supply shotcrete materials to the nozzle and to maintain the shotcrete machine in proper working order. The material supplied to the nozzle must be delivered at a uniform rate under the desired air pressures. The gunman watches the nozzleman or his helper for signals to regulate the air pressure or feed mechanism so that the material leaves the nozzle at the desired delivery rate and velocity. A good gunman will know the approximate needs of his nozzleman and can make most of the adjustments without any direction from the nozzleman. He should also be able to anticipate the requirements of the nozzleman when shooting conditions change.

The gunman must ensure that an adequate supply of material is charged to the gun. He must inform the mixing and delivery crews of the material requirements so that the operation will not be stopped by an inadequate supply. If the accelerator feeder is located near the shotcrete machine, the gunman may also be required to operate the feeder.

7-5

However, the duties and responsibilities of the gunman are so demanding that he should be restricted only to operation of the shotcrete machine. He must also prevent any deleterious substances from entering the shotcrete machine. The gunman must make sure that the materials do not segregate in the charging hopper and that they are maintained at approximately the same level. During shotcreting, the machine must be operating properly if it is to provide the desired continuity of material to the nozzle. A good gunman will know whether or not his machine is in proper working order and can often make the necessary adjustments without stopping the operation. After shooting, the material hoses and additive feed lines, for wet accelerators, must be blown out. Wet-mix machines must be thoroughly washed out, and dry-mix machines should be torn down and accumulations of sand and cement removed. The shotcrete machine must be checked for wear and the necessary repairs or replacements made.

An experienced gunman can recognize development of possible plugs in the material hose and, by reducing or stopping the material feed, can often prevent the plug from developing and minimize the whip at the nozzle. The gunman should carefully watch the nozzleman to see that he has full control of the material hose at all times, particularly when the shotcrete is applied from the muck-pile where it may be difficult to maintain stable footing. If the nozzleman loses control of the hose, the gunman should immediately shut off the air supply and the material feed. This procedure should also be followed when the material hose has ruptured, particularly if anyone is in the vicinity of the break.

After the air supply is shut off, materials in the machine and hose must be cleaned out to prevent damage caused by hardening of shotcrete in the equipment and to minimize loss of production time.

7.1.4 Batching-Mixing Operator

As with the gunman, the batching-mixer operator must be familiar with the components and operation of the equipment. He should be able to demonstrate his skill in proper batching and mixing of the shotcrete materials. The primary responsibility of the operator is to ensure that a continuous supply of material in the proper proportions and thoroughly blended is ready for delivery to the shotcrete machine. He is also responsible for the proper storage of the aggregates, cement, and accelerator and for preparing an adequate supply of shotcrete to meet production needs. The operator must ensure that the mositure content in the aggregates is within the specified range. He must check that the materials delivered to the batching facility are not contaminated and must remove any deleterious substances before they enter the mixer. The operator is responsible for performance and maintenance of the equipment and must ensure that material does not accumulate in either the batching or mixing equipment.

7.1.5 Miscellaneous Labor

On most large-scale shotcrete operations, additional laborers are employed as gunman helpers and nozzleman helpers. The duties of the gunman helper are to ensure that the charging hopper or tank is adequately supplied with accelerator and that the dispensing mechanism

is providing it in the desired quantity. If powder accelerators are used the helper must make sure that the material does not bridge over the feed mechanism.

The nozzleman helper assists the nozzleman in moving the material hose during shooting. His basic duty is to relieve the nozzleman from dragging the bulk of the hose when changing position and nozzling at the same time. To minimize plugs the helper should maintain the hose as straight as possible or in wide loops. The helper should give the nozzleman 3-5 m (10-15 ft) of hose to work with and should provide enough slack to allow the hose to touch the ground behind the nozzleman. If the shotcrete is gunned from a movable platform, the helper may signal to the platform operator the direction in which the nozzleman wants to move. The nozzleman helper may also relay directions to the gunman when the nozzling operation is not visible from the shotcrete machine.

7.2 Surface Preparation

Preparation of the tunnel surface to receive shotcrete affects the shotcrete-rock bond and the stiffness of the rock adjacent to the shotcrete layer. These are two of the most important parameters governing its performance and structural capacity. Surface and rock preparation are done by scaling, jetting and/or sandblasting; scaling and jetting are the most common methods used in present practice. The type of method and the intensity of preparation depend on the ground behavior and on the character of the tunnel surface. In some types of ground, scaling should not be done or should be confined to removal of only surficial materials.

7-8

7.2.1 Scaling

Scaling or barring down is necessary for removal of loose or marginally supported rock blocks and fragments and is carried out primarily in loosening ground. Loose blocks which may be temporarily stable at the time of shotcreting may loosen further and pose a serious safety hazard to workmen. If these blocks are supported only by a layer of fresh shotcrete, they may fail along with the shotcrete lining with little or no warning. Loose rock fragments, although they may not pose a serious hazard in themselves, may prevent a good contact from being formed between the shotcrete and the rock mass. In addition, the weight of the fresh shotcrete may be great enough to cause sagging by pulling the loose fragments away from the surrounding rock (Fig. 7.1). This sloughing effect reduces the stiffness of the medium and thus the shotcrete-rock interaction. Finally, sloughing of the shotcrete and rock increases the losses.
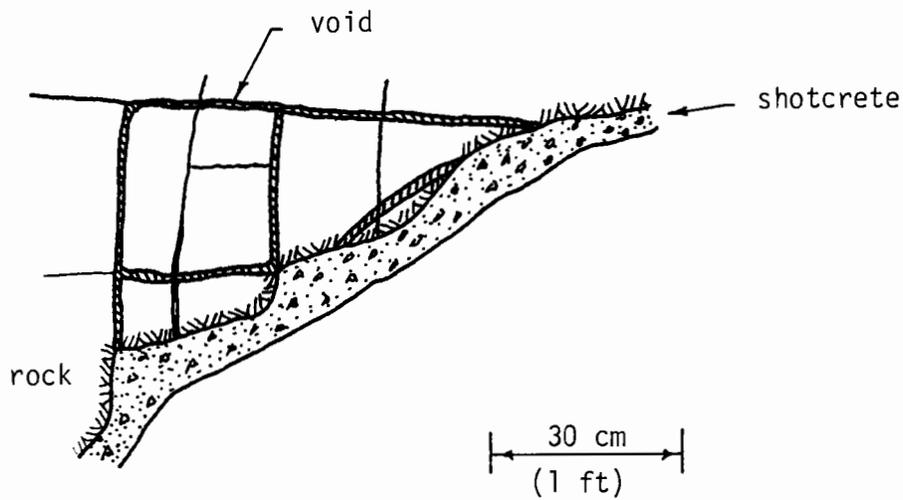
FIG. 7.1 VOID BETWEEN ROCK BLOCKS CAUSED BY IMPROPER SCALING.

7-9

In ravelling ground, scaling should be done quickly to remove only the loosest slabs and fragments. Additional barring is of little value and will only cause increased overbreak. Instead, efforts should be directed towards providing immediate initial support.

Scaling should not be done in overstressed or squeezing rock, since removal of rock in the plastic zone and placement of shotcrete against the previously confined rock will produce higher stresses in the lining than would develop if the shotcrete were placed against unscaled rock. In some cases, scaling of overstressed or squeezing rock has contributed to failure of the lining. In this ground the surfaces should only be cleaned so that the shotcrete can be applied without sloughing.

7.2.2 Cleaning With an Air-Water Jet (Jetting)

One of the most common causes of shotcrete failure is poor bond produced by inadequate cleaning of rock surfaces. Improper cleaning can also cause sloughing and sagging of the in-place materials. Sloughing increases losses while sagging produces a void between the shotcrete and the rock (Fig. 7.2). Surfaces to be shotcreted must be free of all loose or foreign material so that a proper bond can be obtained.

Use of an air-water jet is the most common method of cleaning rock or shotcrete surfaces prior to placing the initial or subsequent layers of shotcrete. Simply running compressed air through the material hose and adding water at the nozzle is sufficient for this purpose. Washing with an air-water jet is very effective in removing gouge, but can expose hard, slickensided, and polished surfaces beneath the gouge.
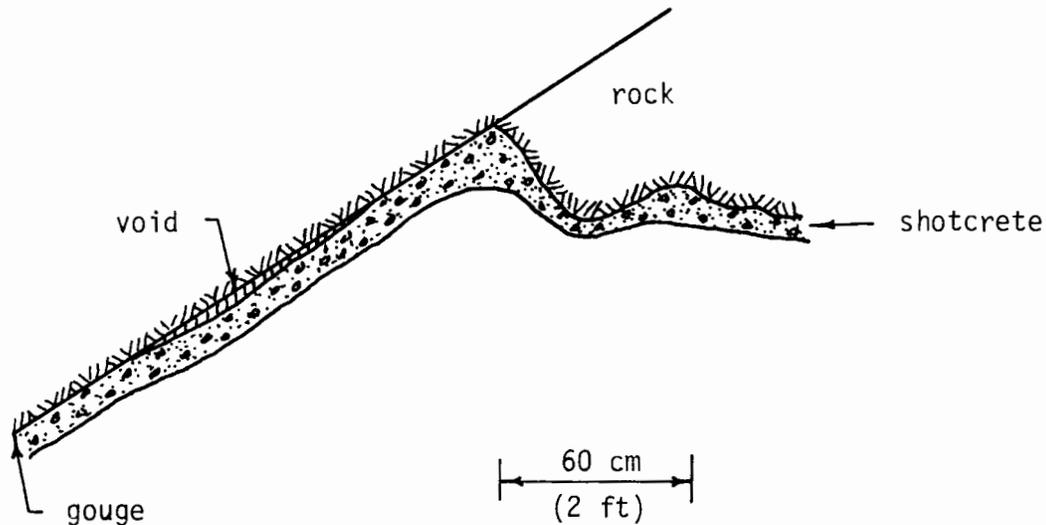
FIG. 7.2 VOID BETWEEN SHOTCRETE AND ROCK PRODUCED
BY IMPROPER CLEANING OF ROCK SURFACE.

These surfaces are not affected by the air-water jet. Removal of the
gouge is beneficial, since the shotcrete bond to a slickensided surface
is better than that to a layer of gouge. The water from the jet is also
available for hydration of the cement paste making up the first (outer)
portion of the shotcrete layer.

The jet should be applied using approximately the same pressure
as that for material delivery to the nozzle (3-4 kg/cm^2; 43-57 psi).
The volume of water should be regulated so that the surficial materials
are removed without loosening the rock blocks. The nozzle should be
held approximately 1-2 m (3-6 ft) from and normal to the surface.

7.2.3 Sandblasting

Sandblasting with the shotcrete equipment can also be used to remove
foreign material and to increase the roughness of a joint surface.

By replacing the regular shotcrete nozzle with a sandblasting nozzle, and reducing the rate of feed, a regular dry-mix shotcrete machine makes a very suitable sandblaster. A shotcrete machine will use much more material than a standard sandblaster. Sandblasting is an expensive operation in terms of time, materials, and additional equipment if a sandblaster is used, and has not gained general acceptance by the tunneling industry.

The proper procedure to be used in sandblasting is to go over the area twice. In the first pass, the nozzle is held at an angle of about 45° to the surface and in the second the jet is directed at the surface at the same angle, but in the opposite direction (Studebaker, 1939). The sand particles clean away loose material adhering to the surface. In addition to cleaning the tunnel surface, sandblasting can also be used to scour away cement and fine aggregate accumulations in the shotcrete machine and material hose.

7.3 Operation of the Shotcrete Machine

The operation of the shotcrete machine affects the rebound, the material delivery rate, the compaction, and the uniformity of material flow to the nozzle. Operation of the machine is a two part process involving selection and then matching of the air pressure or the material feed rate (Fig. 7.3). If they are improperly selected or matched, both shotcrete quality and economy will suffer. The operation of the shotcrete machine also affects wear on its moving parts.

P = Line pressure

$P_1 > P_2$ (by 1/2 - 1 kg/cm^2 [5 - 15 psi])

P_2 = Line pressure at beginning of material hose

P_1 = Gun pressure
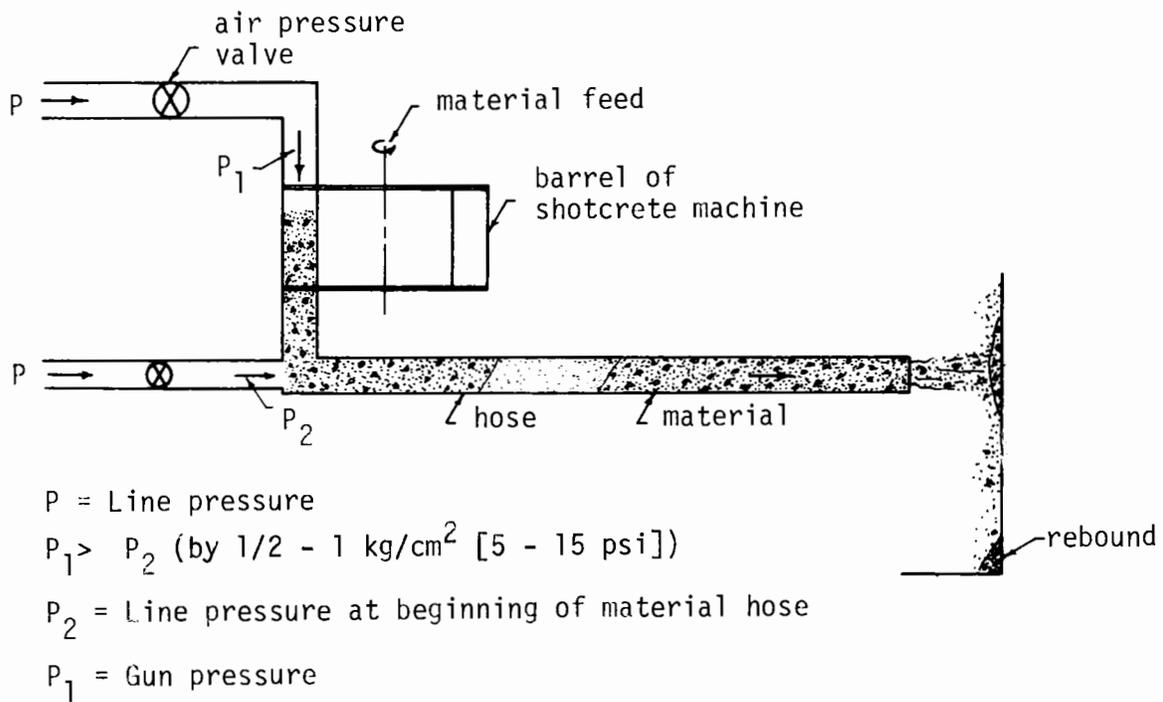
FIG. 7.3 PROPER OPERATION OF A DRY-MIX SHOTCRETE MACHINE.

7.3.1 Control of Air Pressure and Material Feed Rate

Synchronization of the air pressure at the shotcrete machine or nozzle and the rate of material feed into the air stream affect the rebound, the material delivery rate and the uniformity of material flow to the nozzle. When shooting begins, the nozzleman selects the air pressure and then the gunman adjusts the material feed to match this pressure. If the feed is too slow, the operation of the machine is inefficient and the production rate will be below maximum capacity at this air pressure. In the dry-mix machine, the compartment

7-13

discharging material will be emptied before the next cylinder can provide material to the air stream (Fig. 7.4). In addition, the delivery of materials to the nozzle will be non-uniform since large gaps will be present between the slugs of material in the hose. If the feed is too rapid, the air pressure will not be great enough to push the material through the line, causing plugs (Fig. 7.4), or in the wet-mix process, will not be great enough to drive the materials onto the rock surface. The rate of rebound also increases when the pressure and feed rate are not matched.

The actual air pressure and feed rate used for shooting govern the compaction, the rebound and the material delivery rate. Both compaction and rebound are affected by particle velocity, which is controlled by the air pressure at the shotcrete machine or at the nozzle. If air pressure and feed rate are matched, compaction is increased at higher pressures since the kinetic energy of the particles increases with the square of velocity. This same kinetic energy affects rebound; the higher the pressure and feed rate, the greater the rebound. The material delivery rate and the rebound rate control the rate of placement of shotcrete on the tunnel surface. Both rates increase with air pressure and material feed rate and thus the machine should be operated at an optimum air pressure and feed rate at which the maximum amount of material is placed on the tunnel surface over a given period of time (placement rate). The air pressure, however, must be high enough to provide adequate compaction of the in-place materials, since it affects the strength and quality of the shotcrete.

7-14
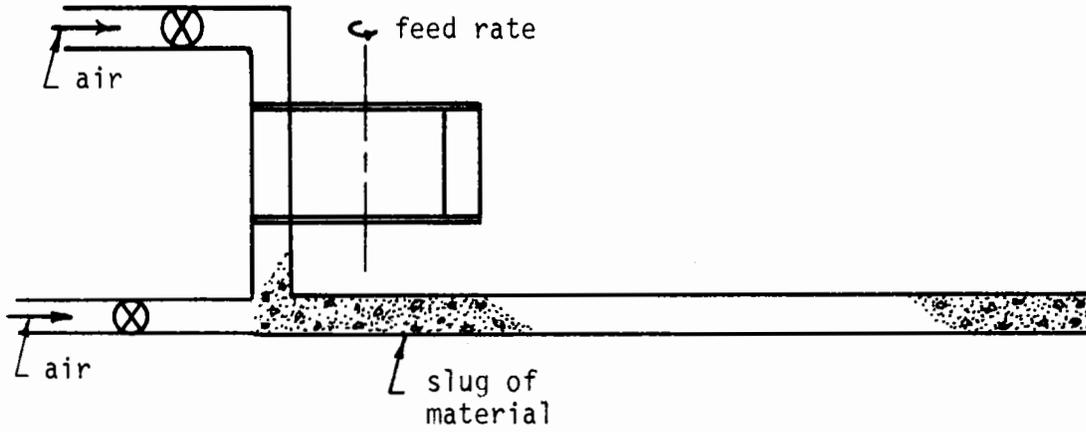
a.   Feed rate too slow
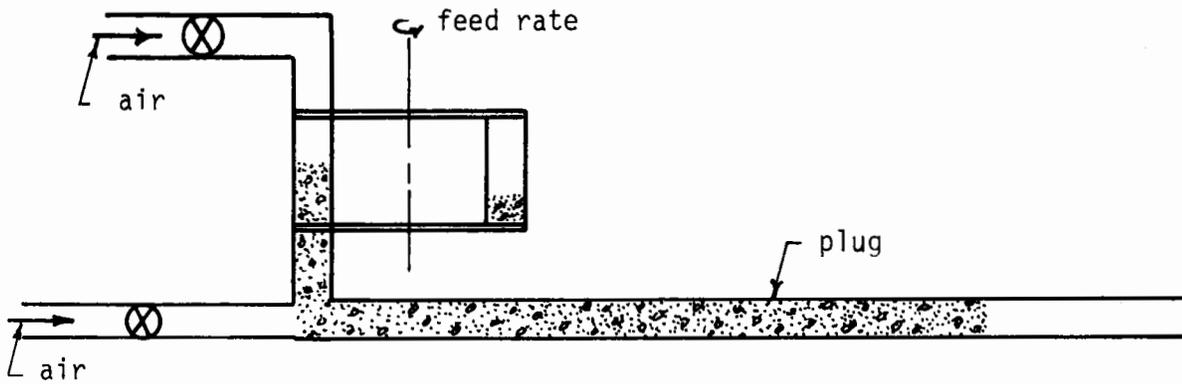
b.   Feed rate too fast

FIG. 7.4   IMPROPER OPERATION OF A SHOTCRETE MACHINE.

In the dry-mix process, the air pressure at the machine should be in the range of 3-5 kg/cm^2 (40-70 psi) for a 50 mm (2 in.) diameter hose having a length of 30 m (100 ft). These pressures would be measured in the material hose just after the air stream passes through the feed wheel or barrel (Fig. 5.4) Production rates at these pressures are typically 4-8 m^3/hr (5-10 yd^3/hr). An additional 0.35 kg/cm^2 (5 psi) air pressure should be added at the machine or at booster stations along the material line for each additional 15 m (50 ft) length of hose and/or for each 8 m (25 ft) in height above the machine (ACI, 1966). In the wet-mix process, the air pressure at the nozzle is typically 1-3 kg/cm^2 (20-40 psi).

7.3.2 Uniformity of Material Flow to the Nozzle

In both the dry and wet-mix process, the flow of material to the nozzle must be uniform. The dry-mix process is particularly sensitive to the uniformity of material flow since the water must be added in the proper proportion at the nozzle. Non-uniform flow will produce alternating wet and dry materials, the wet occurring when the flow is small and the dry resulting when the amount of material passing the water ring is high (Fig. 7.5). The wet materials usually slough or run off the surface while the dry materials contain insufficient water to hydrate the cement and produce severe laminations. These laminations reduce the strength and durability of the in-place shotcrete. The flow must be kept uniform since the nozzleman cannot react fast enough to adjust the amount of water needed to produce an evenly wetted material when the flow is non-uniform.

7-16

rock

lamination

shotcrete slough-
material too
wet

initial
layer

lamination

tunnel surface
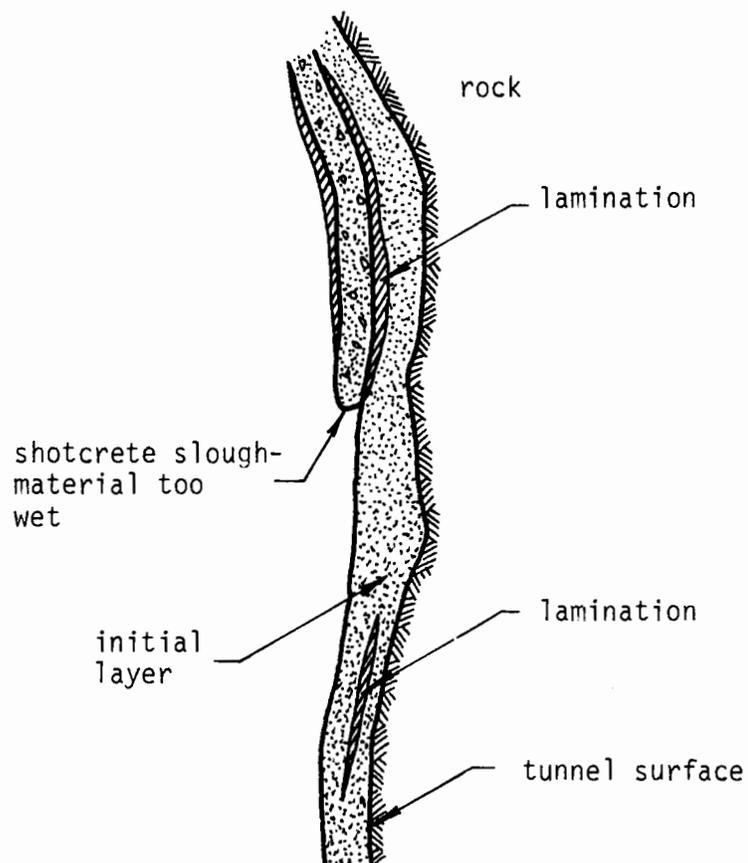
FIG. 7.5 SHOTCRETE LAMINATIONS PRODUCED BY NON-UNIFORM
DELIVERY OF MATERIAL TO THE NOZZLE.

The distribution of accelerator in the wet-mix materials is also dependent on the uniformity of flow. If the flow is non-uniform, some portions of the materials on the tunnel surface will have little accelerator whereas others will be over-accelerated. Low accelerator percentages may cause sloughing of the materials particularly if water is present on the tunnel surface or the slump is high; whereas over-acceleration can cause a large reduction in ultimate strength and also a slower set of the shotcrete.

A non-uniform flow of material is not only caused by improper matching of the air pressure and feed rate, but can also be produced as a result of inadequate supply of material in the shotcrete machine and in some cases fluctuations of the material level in the charging hopper. An inadequate supply of material to the shotcrete machine will produce a non-uniform filling of the compartment in the feed wheel or bowl or of the pumping tube. This non-uniform filling will produce a non-uniform flow to the nozzle. An adequate supply must be maintained to the shotcrete machine. Fluctuation of the material level in the charging hopper can cause non-uniform flow from dry-mix shotcrete machines having a large number of agitator blades. As the level drops the feed rate increases, and as it rises a decrease in the feed rate results. When operating these machines, the material in the charging hopper must be maintained at a constant level.

7.3.3 Equipment Wear

The wear on the shotcrete equipment depends on the velocity and delivery rate of the materials through the nozzle. Severe wear can

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develop at high velocities and production rates, not only of the parts which come in contact with the blown materials such as nozzles, material hoses, wear pads, etc. but also the drive mechanism of the shotcrete machine. Dry-mix equipment is usually more sensitive to wear than wet-mix equipment since the particle velocities and abrasion are higher in the dry process. From performance records, it appears that severe wear in dry-mix equipment occurs at air pressures in excess of 5 kg/cm^2 (70 psi) at the shotcrete machine. Wear on equipment must be considered from an economic standpoint in selecting the air pressure. In practice, the material delivery rate actually controls the economics of the shotcrete operation and component parts or machines are repaired and replaced as necessary.

Equipment wear also depends on the size and angularity of the coarse aggregate and on the equipment maintenance. Higher wear can be expected when large, crushed aggregate is used (Blanck, 1974). Regular cleaning, repair and lubrication reduces wear on the shotcrete equipment and increases its length of service.

7.4 Shotcrete Nozzling

The nozzling techniques and procedures for placing shotcrete greatly affect the quality and rebound of the in-place materials. Rebound not only causes loss of material but can become entrapped if poor nozzling techniques are used. The entrapment of cement-poor material (in laminations) produces a large decrease in the ultimate strength and durability of the shotcrete. In addition, the greater the percentage of rebound, the higher the probability for entrapment.

This section describes proper nozzling techniques including the sequence of shooting in the heading.

7.4.1 Basic Nozzling Techniques

Angle

In shotcreting planar surfaces, the nozzle should be held perpendicular to the surface. Failure to direct the shotcrete stream at 90° to the surface results in excessive rebound and decreased compaction. Inadequate control of the direction of the nozzle during application also causes large variations in the strength of the in-place shotcrete.

The only exception to aiming the nozzle normal to the surface occurs when shooting an interior corner (Fig. 7.6) or when necessary to avoid working beneath potentially hazardous rock. Interior corners should be shot holding the nozzle in the plane bisecting the angle of intersection of the two surfaces. This technique minimizes the amount of rebound entrapped in the corner (Fig. 7.6). As the corner is filled, a curved surface develops and tapers into the adjacent planar surfaces. Subsequent layers can then be applied using the recommended 90° nozzle angle to the surface by rotating the nozzle through the radius of curvature of the corner. Exterior corners (apexes) are shot by holding the nozzle perpendicular to the surface and building up the shotcrete layer on one side and then on the other side of the corner (Fig. 7.7).

Distance

The optimum distance between the shotcrete nozzle and the surface is generally accepted to be 1 m (3 ft) (Kobler, 1966). Holding the

7-20

a. Correct method   b. Incorrect method
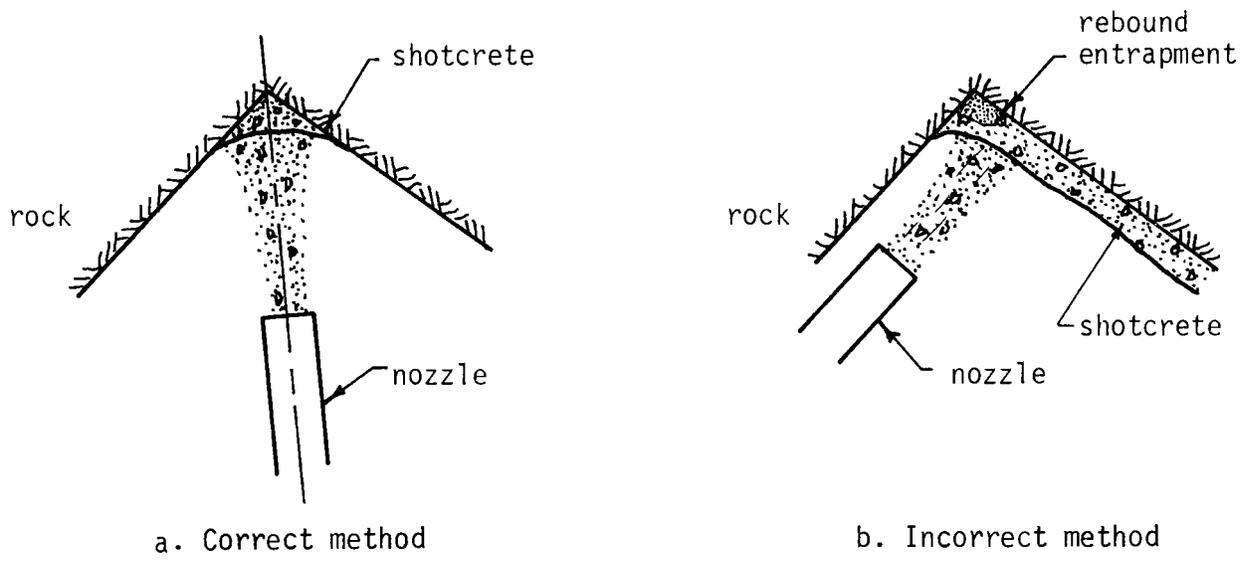
FIG. 7.6 SHOTCRETING INTERIOR CORNERS
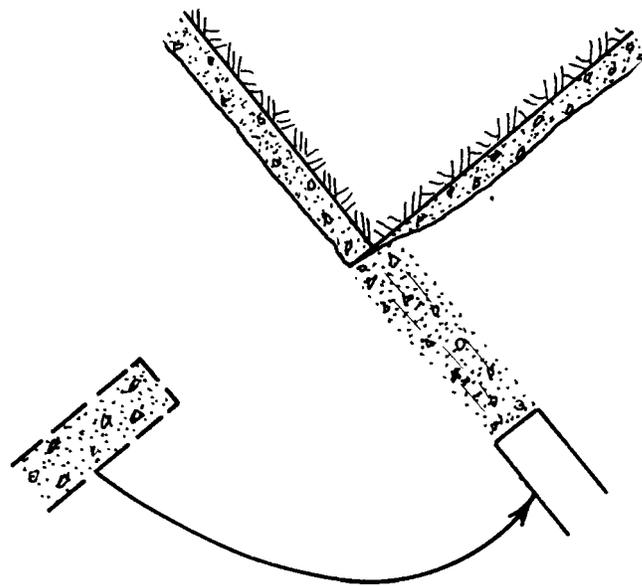
FIG. 7.7 SHOTCRETING EXTERIOR CORNERS (APEXES).

nozzle at a distance greater than 1 m (3 ft) increases rebound, decreases compaction and thus reduces strength (Fig. 7.8). If the nozzle is held closer than 1 m (3 ft), not only rebound is increased, but also the nozzleman is exposed to rebounding particles. Holding the nozzle nearer to the surface, however, does have the advantage of allowing the nozzleman to inspect the surface and the placement of the shotcrete more closely and thus can improve the overall quality of the work. This requires that the velocity and material delivery rate be reduced below those normally used in order to control rebound, to reduce danger from rebounded particles, and to reduce strain on the nozzleman from the high back pressure. In practice, the nozzle is usually held 1-2 m (3-6 ft) from the surface particularly in shotcreting headings when accessibility is limited, danger from rock falls is great, and material delivery rates are very high.

Motion

The nozzle should not be directed at one spot for lengthy periods since this causes increased rebound and difficulty in obtaining a uniform thickness. A steady systematic circular or elliptical movement of the nozzle across the surface is a good spraying technique (Fig. 7.9). Moving the nozzle rhythmically in a series of loops will produce a uniform product with minimum rebound (Ryan, 1973). Failure to consistently move the nozzle results in areas that are well compacted adjacent to areas that are poorly compacted. The loop which the nozzleman makes should be from 45-60 cm (18-24 in.) across and 15-20 cm (6-9 in.) high (Ryan, 1973).

Distance of nozzle from application surface
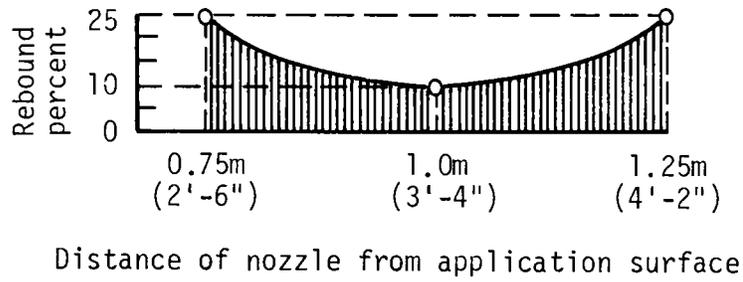
FIG. 7.8 THE EFFECT OF NOZZLE DISTANCE ON REBOUND (KOBLER, 1966).
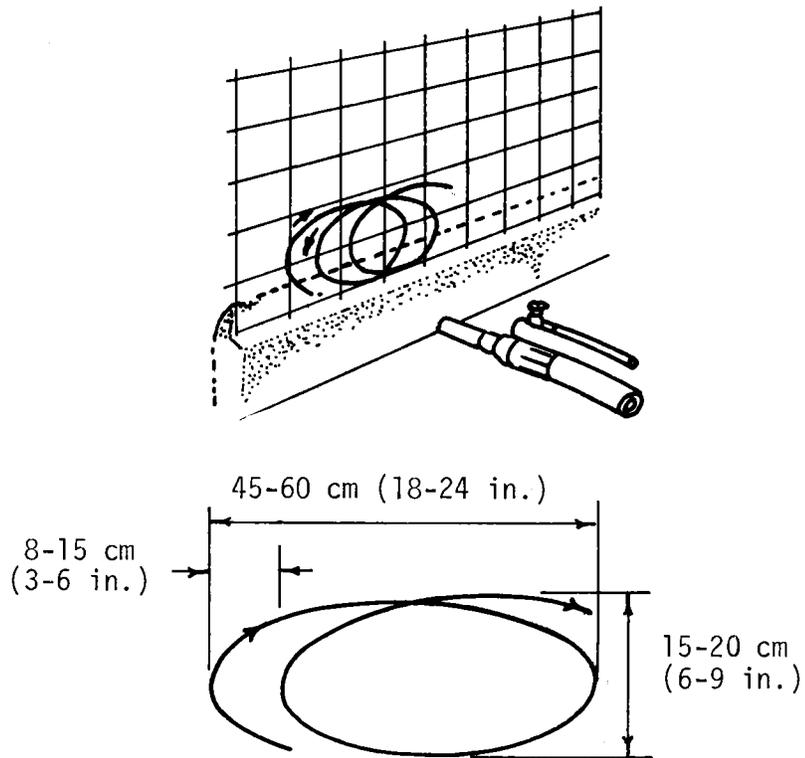
FIG. 7.9 SHOTCRETE NOZZLE MOTION (RYAN, 1973).

Control of Water

In the dry-mix process, the nozzleman must add the correct amount of water to the materials in the air stream as they pass through the nozzle. To do this, he continually watches the freshly impacted shotcrete and adjusts the water to produce a silky, glistening surface. If too much water is added, the surface will look wet and ripply and the shotcrete will sag. If too little water is added, the surface will appear granular, the material stream will be dusty, and there will be excessive rebound. Shooting too dry will also reduce the compressive strength up to 40%. An experienced nozzleman can judge the correct amount of water by observing the uniformity of color. The most important aspect in controlling water at the nozzle is to prevent large variations in the water content of the materials. These variations, particularly if they involve very low water contents, will produce undesirable laminations in the shotcrete layer. The nozzleman must set the water to obtain the desired consistency and must make sure that this consistency is maintained by making slight adjustments in the water inflow valve and by placing shotcrete only when the flow of material to the nozzle is uniform and smooth.

For a given mix design, the percent rebound is inversely proportional to the water-cement ratio. As the water content increases, the shotcrete becomes more plastic and receptive to the oncoming particles in the material stream. Dry-mix shotcrete gunned at high water contents reduces material and production costs. Nevertheless, the amount of water must be controlled to prevent sloughing of the shotcrete. The higher water contents can increase shrinkage in the shotcrete (Studebaker, 1939;

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Litvin and Shideler, 1966). This consideration is extremely important when shotcrete is used in thin linings since its capacity and performance are greatly reduced by shrinkage cracks.

7.4.2 Shotcreting in the Tunnel Perimeter

Arch and Crown

Sagging and sloughing of shotcrete and excessive rebound are the two biggest problems related to shotcreting in the arch and crown. Sagging is generally caused by applying too thick or too wet a shotcrete layer. While the shotcrete is still fresh, it has very low bond and tensile strength and the weight of the shotcrete alone may be sufficient to pull it away from the rock surface or to cause it to fail internally (Fig. 7.10). Sloughing and sagging are most likely to occur when the shotcrete is placed in layers more than 7-8 cm (3 in.) thick on slick, planar, low-lying surfaces. If sloughing or sagging occurs the liner should be built up in multiple layers rather than in one thick layer. A 4 to 6 hour interval should lapse between successive applications in order to prevent any disturbance to the initial setting process. Shotcrete placed in the arch or crown should not be thicker than 20 cm (8 in.) in one application. The thickness of the initial layer in an arch and crown containing seamy rock or shear zones should not be more than 7-8 cm (3 in.) because of the difficulty in hanging the shotcrete on the tunnel surface. In addition to thickness, sagging and sloughing can also be caused by the presence of soft materials and slickensides on the tunnel surface or water in the rock and on the joint planes. Shotcrete placed in the crown and arch should be gunned

gouge-coated,
slickensided

rock

slough

slough

shotcrete

30 cm

(1 ft)
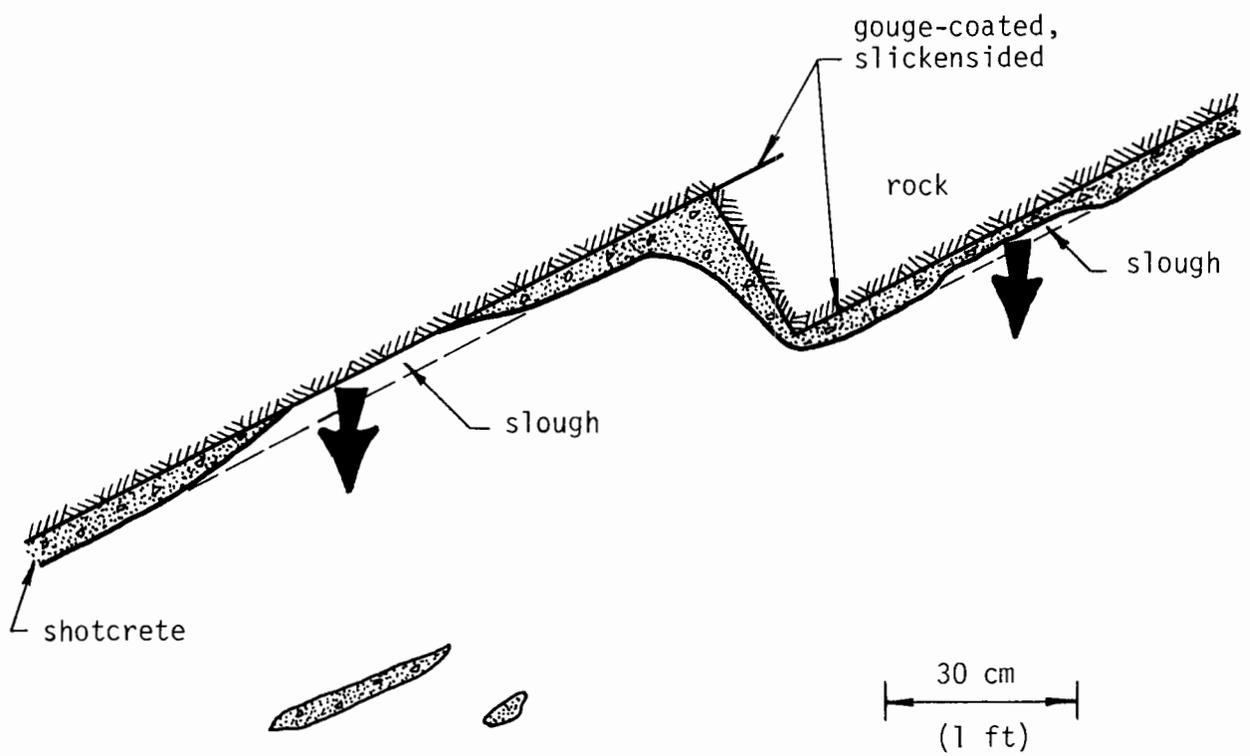
FIG. 7.10   SLOUGHING OF SHOTCRETE.

slightly drier than normal and should contain accelerator particularly in wet conditions. This reduces the setting time and provides rapid gain in early strength thus allowing the shotcrete to achieve early self-support. Rebound is always higher when shooting overhead and is likely to be twice as great as on vertical sidewalls (Fig. 7.11).

Sidewalls

Shotcreting in sidewalls should begin from the base of the wall and proceed upward so that rebound will not be incorporated in the final product. Near the invert, the nozzle should be held low to shoot the base of the wall, but should not be so low as to pick up and incorporate rebound or other debris lying on the floor. One way to avoid picking up debris is to shoot at a slight angle down toward the base of the wall.

Overshooting, or shooting too far above the advancing edge of the shotcrete layer being applied can cause the formation of rebound pockets (Fig. 7.12). This occurs when the rebound does not fall clear of the previously shotcreted surfaces but collects on an intermediate ledge and is covered with a fresh layer of shotcrete. The resulting "rebound pocket" consists of an uncompacted, uncemented, and insufficiently hydrated shotcrete having low strength and durability and susceptible to formation of shrinkage cracks. Entrapment of rebound on sidewall surfaces can be prevented by advancing the layer upward without overshooting, by maintaining a steep sloping edge, and/or by removing accumulated rebound with an air blowpipe (a steel pipe and hose attached to a compressed air line).

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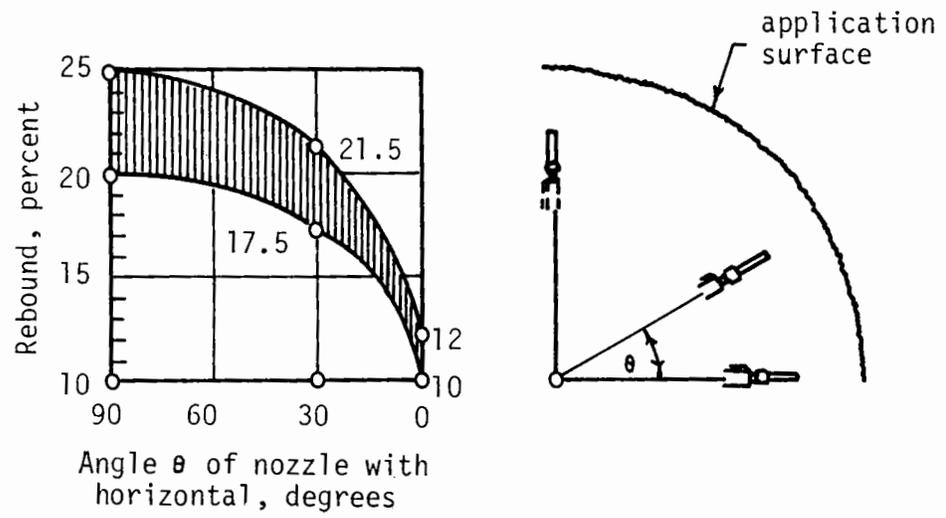
FIG. 7.11   THE EFFECT OF SHOOTING ANGLE ON REBOUND (KOBLER, 1966).
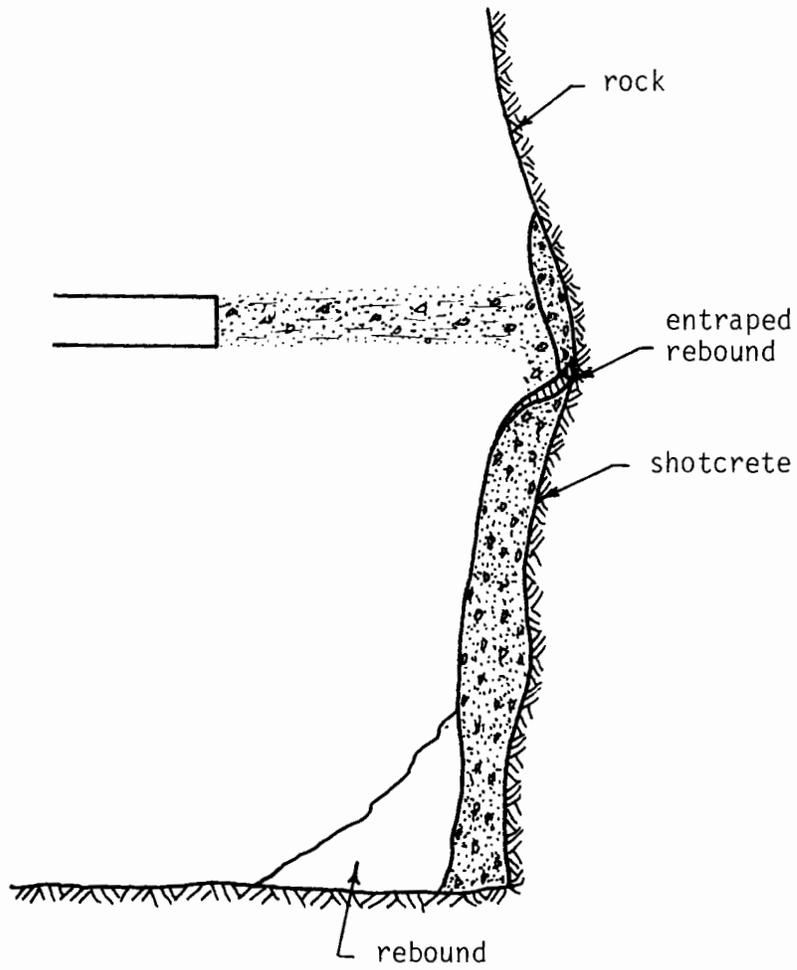
FIG. 7.12   REBOUND ENTRAPMENT CAUSED BY OVERSHOOTING (AFTER RYAN, 1973).

7.4.3 Sequence of Shooting

The initial layer of shotcrete should be started at springline and worked upward toward the crown. The recesses are filled first to help support the rock blocks and then the faces of the blocks are shotcreted. The shotcrete should be started at the edge of the previously supported section and sprayed toward the face. Once the arch and crown are completed, the shotcrete is then sprayed on the sidewalls. The layer should be started just above the rebound or muck pile and worked upward.

7.4.4 Encasement

Encasement of steel reinforcing bars with shotcrete must be carefully done to prevent pockets of uncemented aggregates from forming behind the bars (Fig. 7.13). To prevent formation of these pockets, the nozzle should be held close enough to the reinforcing bar to force material around and behind the bar. The front of the bar should remain essentially clean and free from material buildup until the entire bar is encased. If the nozzle is held too far back, the material will accumulate on the front side of the bar, effectively increasing the bar diameter, and thus causing pockets of uncemented aggregates to develop in the shielded zone behind the bar. Many users recommend that the reinforcing bar should be shot from two directions. This is a simple and effective procedure, but again no accumulation can be allowed to form on the front side of the bar. These accumulations are best removed by using a blowpipe (Fig. 7.14). The blowpipe can also be used to blow entrapped rebound from behind the bars. When using the dry-mix process, the shotcrete should be gunned at a high water content. This

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material stream

a. Shotcrete forced behind bar

b. Back of bar fully encased

c. Face of bar still free of build-up

d. Perfect encasement

a. Correct
(nozzle close)

shotcrete
build-up

a. Soft unidirectional impact
causes build-up on bar

b. Heavy build-up on face of bar

c. Aggregate pocket forming

pocket of cement-
poor aggregate

d. Shrinkage crack forms
at weakened section
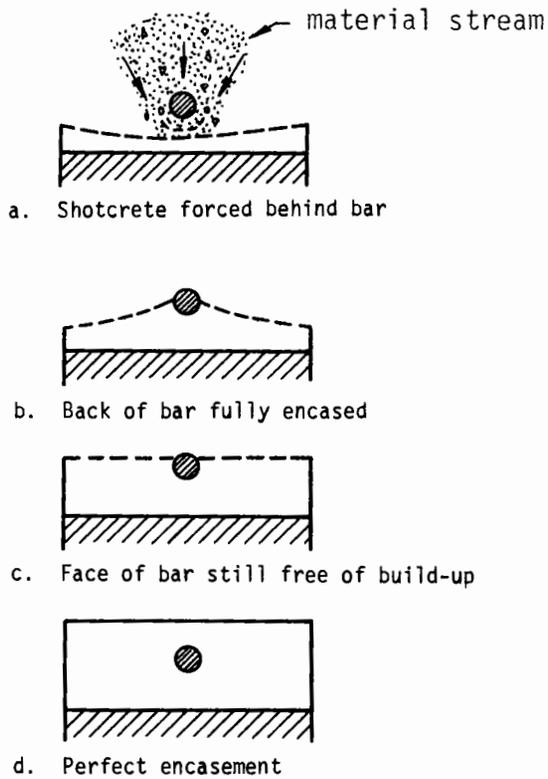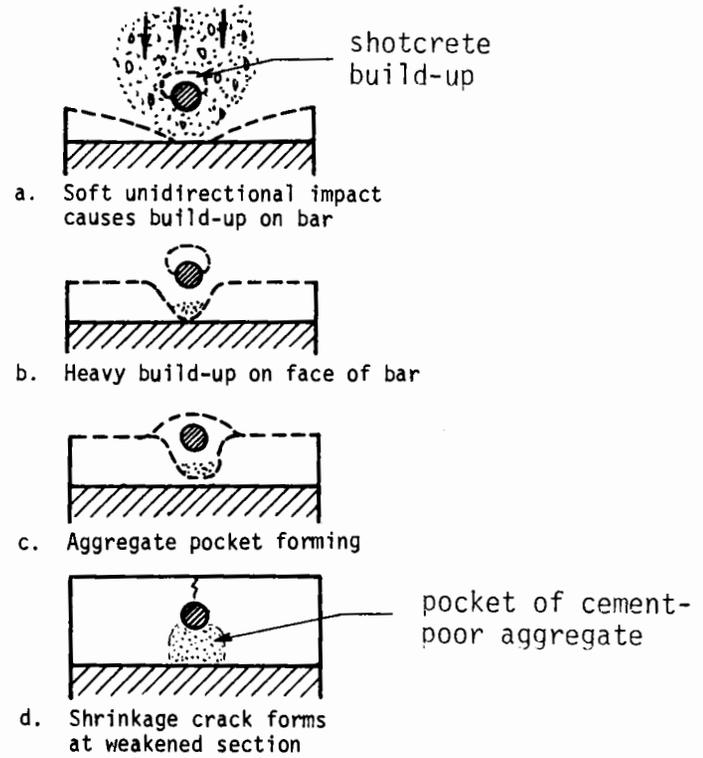
b. Incorrect
(nozzle too distant)

FIG. 7.13 ENCASEMENT OF REINFORCING BARS (ACI, 1966 AND RYAN, 1973).
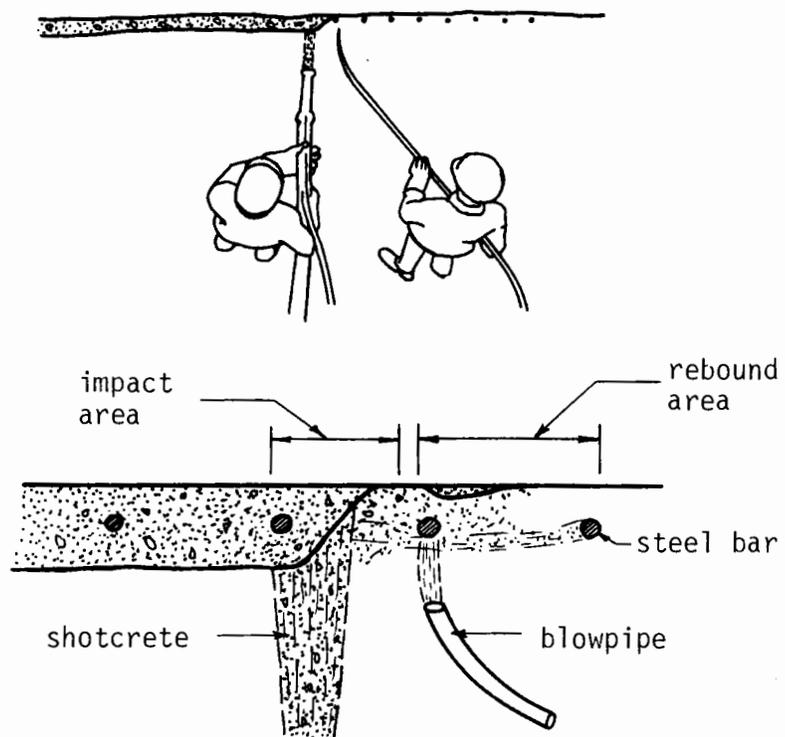
FIG. 7.14 USE OF A BLOW PIPE IN REMOVING REBOUND FOR
          PROPER ENCASEMENT OF REINFORCING BARS
          (RYAN, 1973).

allows the shotcrete to flow behind bars and prevents entrapment of rebound.

Shotcrete should never be gunned through two layers of reinforcement. Instead, separate shootings should be required for each layer. Steel bars in a given layer must not be placed closer than 50 mm (2 in.) apart and for coarse aggregate shotcrete should not be located within 50 mm (2 in.) of rock or previously shotcreted surfaces (Ryan, 1973). The bars must be covered by at least 50 mm (2 in.) of shotcrete when the lining is complete. When spacers or ties are used, they should not be placed directly beneath the bars but should be offset to one side.

7.5 Control of Shotcrete Thickness

The thickness of the shotcrete on the tunnel surface should be known at least approximately in order to check that the design requirements are being met by the shotcrete crew. The average thickness of a shotcrete layer is usually estimated from the volume of materials sprayed through the nozzle, the approximate percentage rebound, and the approximate area of the tunnel covered by the layer. This method is adequate for most underground work; however, large discrepancies can exist because of variations in the volume of batched materials and inaccurate estimates of rebound. In addition, an average thickness value may have little meaning for thin shotcrete layers sprayed over an irregular tunnel configuration, since the variations in thickness are likely to be large. Steel pins anchored in the rock surface or initial layer of shotcrete are often recommended by designers but are rarely used during construction. Placement of these pins is time-

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consuming, difficult, and, in unsupported headings, can be dangerous because of rock falls. In addition, the pins could also be dangerous to workmen who may be seriously injured if they fall against them. The best method for checking thickness is by coring or drilling of probe holes. Cores taken for testing strength can be extended to the shotcrete-rock contact to determine the thickness of the lining. In probe holes, reflectors and lights are used to determine shotcrete thickness. Drilling of core and probe holes has the disadvantage that the holes must be patched. When shotcrete is used with steel ribs, the inside flanges of the ribs serve as an excellent guide for thickness control and ensure that a continuous liner is formed.

7.6 Finishing Techniques

In some tunnels, such as those for water conveyance, a smooth surface and uniform cross section are desired. When shotcrete is used, the lining must be finished in order to obtain the desired configuration and smoothness. Finishing of shotcrete linings involves control of the thickness of the final layer, and smoothing of the surface by scraping and rubbing. Flashing of the tunnel surface with a thin coat of gunite should not be done, since this layer is likely to peel off from the underlying shotcrete shortly after the tunnel is in use (Studebaker, 1939).

7.6.1 Rodding or Screening

These terms are used interchangeably and refer to the process of smoothing the shotcrete surface by rubbing or scraping it with the edge

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of a board, either plain or metal-edged. Bulges or protrusions in the shotcrete should be removed prior to applying successive layers since such imperfections are usually carried through and exaggerated with each additional layer. A good method for removing small bumps is to slice them off by using a steel finishing trowel. The shotcrete should be stiff enough at the time of screeding to prevent grooves from being cut in the surface yet plastic enough to resist cracking. The optimum time for screeding appears to be shortly after the shotcrete has obtained an initial set (approximately 15 to 30 min after shooting). The surface of the shotcrete can be made relatively smooth by rubbing it with cloth or burlap.

7.6.2 Guide Wires, Guide Boards and Shotcrete Strips

Guide wires and guide boards are often used to assist the nozzle-man in shooting the final layer of shotcrete to produce a uniform cross-section. Guide wires are fine wires which are temporarily placed to outline the finished surface. Guide boards are usually employed to assist in placing shotcrete on vertical surfaces, but can cause undesirable entrapment of rebound if improper nozzling techniques are used.

Another technique for controlling the configuration of the tunnel is first to shoot shotcrete strips and then finish the area between them to the proper thickness. These first strips are allowed to harden and the area between them is filled in later with fresh shotcrete; the hardened shotcrete strips are used as screed rails. The technique would be most useful in machine-bored tunnels. Like the use of guide boards, this technique can lead to the entrapment of rebound along the sides of the strips.

7.7 Remote and Hand Held Nozzling

Shotcrete is applied underground using a remote or a hand held nozzle. Hand held nozzling is most commonly used in the United States, while remote nozzling has been employed for many years in Europe. Both methods have advantages and shortcomings; however, remote nozzling is preferred since it removes the nozzleman from potential dangers in unsupported headings.

7.7.1 Hand Held Nozzling

With the hand held method, the nozzleman firmly grasps the material hose or nozzle and stands approximately 1 m (3 ft) from the surface of application. Underground he stands on a mechanical platform, the invert, or the muck pile. Nozzling from the muck pile is dangerous since the unstable footing makes it easy for the nozzleman to slip or fall and lose control of the material hose.

The main advantage of hand held nozzling over remote application lies in the ability of the nozzleman to place shotcrete in tight or restricted areas such as behind steel ribs or between closely spaced blocking.

7.7.2 Remote Nozzling

The operator using remote nozzling is usually positioned on a platform 3-7 m (10-20 ft) away from the surface of application. At this distance, he is much less susceptible to injury from rebound. The nozzle is operated by using the controls located on the platform. When shotcreting in headings, the nozzleman is generally positioned beneath a previously supported section of the tunnel. Here, he is less susceptible

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to rock falls which often accompany shotcreting in the heading. With good lighting, the nozzleman has a better overall view of the working area than with a hand held nozzle. By relieving the nozzleman from holding and transporting the hose and reducing the danger from rock falls, remote nozzling allows the operator to concentrate on the final product. Remote nozzling allows shotcrete to be placed at higher material delivery rates than with hand held nozzling.

Remote nozzling shows greatest potential for use in excavations made with tunnel boring machines or smooth wall blasting techniques. The smooth surfaces formed using these methods allow the shotcrete to be sprayed with very little adjustment of the nozzle. Remote nozzling would not be advantageous when shotcrete is used only to support or seal localized trouble areas of the tunnel, or when it must be applied in tight spaces. For such applications, hand held nozzling used alone or combined with remote nozzling will provide the most efficient means of applying the shotcrete. Remote nozzling is also not practical in most small diameter or short tunnels.

7.8 Curing of Shotcrete

Shotcrete, like concrete, must be protected from drying and freezing. Drying prevents hydration of the cement, thus retarding strength gain and causing excessive shrinkage strains which may crack the shotcrete lining. Thin shotcrete layers, which are commonly used in underground construction, are very susceptible to drying (Crom, 1966). Freezing conditions not only retard strength gain but also inhibit shotcrete bonding and induce stresses which can disintegrate or spall

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the shotcrete layer. The first 7 days following application are the most critical for proper curing. After this time interval, the shotcrete has gained enough tensile strength to resist shrinkage strains and the permeability near its exposed surface is low enough to minimize loss of water from the interior of the layer (Crom, 1966). In addition, after 7 days, most of the free water has combined chemically with the cement so that little water is available to form ice lenses or crystals.

In many tunnels, the humidity is high enough to retard drying of the shotcrete and thus no special curing methods are used. The ACI committee on shotcrete recommends that natural curing be used only when the relative humidity is at or above 85% (ACI, 1975). The humidity near the portal or shafts open to the atmosphere is generally lower than that in the long sections of the tunnel. In these areas, as well as in tunnels having generally low humidities, special precautions must be taken to prevent dehydration of the shotcrete. The most common means for curing of shotcrete underground involves use of plastic sheets. These sheets are attached to the shotcrete, but are used only in local areas of the tunnel. Plastic membranes applied with mechanical sprayers have not been used underground because of the potential fire hazard, ventilation difficulties, and problems associated with the complete removal of these materials before successive layers of shotcrete can be applied. In addition, the costs for applying and removing the membrane make this technique economically prohibitive. Moist and wet curing, commonly used for concrete, are not used for shotcrete underground because of the expense and, in the case of wet curing, potential erosion of the shotcrete. If long sections of tunnel require curing, the vapor method

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is likely to be the most economical. The ACI (1975) recommends that shotcrete should be wet or naturally cured for 7 days.

Shotcrete should not be gunned at ambient air temperatures less than 3°C (38°F) unless the ingredients are preheated to at least 10°C (50°F) and sufficient heat is provided to maintain shotcrete temperatures above freezing. The aggregates and cement can be heated during batching while warm water can be used in the mix or added at the nozzle. The temperature of the water at the nozzle or in the mix should range between 10 - 20°C (50 - 70°F). Water temperatures above 20°C (70°F) may cause prehydration of the cement. Under freezing or near freezing conditions, preheating of the solids and water are necessary to offset heat losses during conveyence as well as losses to the surface receiving shotcrete. The temperature of freshly gunned shotcrete should not fall below freezing for at least 4 days after shooting. Shotcrete temperatures can be maintained above freezing using space heaters. In thick layers of shotcrete, more than 60 cm (2 ft), the heat of hydration may be great enough to prevent freezing. Loss of heat from the shotcrete layer can be reduced by placing plastic over the freshly gunned materials thus limiting air circulation at the surface. Where possible, portals and open shafts should be partially or completely blocked. The use of high concentrations of accelerator (>6% by weight of cement) to facilitate placement of shotcrete at near or below freezing temperatures is not recommended since these concentrations produce a large undesirable loss of ultimate strength.

CHAPTER 8

QUALITY CONTROL AND SAFETY

8.1 Quality Control

The purpose of quality control is to ensure that the shotcrete being applied is of acceptable quality and meets the design thickness and placement requirements. The quality of the in-place shotcrete depends on the shotcrete operation and on the curing conditions. Improper placement and curing of shotcrete must be detected and corrected while the shotcrete is being placed. Remedial measures such as removal of poor quality shotcrete are rarely taken and often times would be dangerous. The quality of the shotcrete is assessed by observing the shotcrete operation and by inspection and testing of the in-place materials. Qualified inspectors with ample experience in all aspects of shotcrete must be employed for these tasks if quality control is to be obtained. These individuals must also be familiar with the design assumptions and requirements.

8.1.1 Personnel Requirements

At least two inspectors are needed during shotcreting to ensure placement of acceptable quality shotcrete. This is particularly true if the equipment is spaced far apart and the operation cannot be observed at one location. One of the individuals (senior inspector) should have at least one year of experience as an inspector of an underground shotcrete operation. Both individuals should have a thorough knowledge of

the shotcrete process, the specifications, and the purpose for which the
shotcrete is used. The senior inspector should also have field experience
in the use of shotcrete for handling a variety of tunnel ground conditions.
The junior inspector should generally be stationed at the batching facility
and the senior inspector at the gun. The inspector of the batching oper-
ation should have at least some experience in concrete batching. The
inspectors should occasionally alternate stations so that the junior
inspector obtains experience on the gunning operation and the senior
inspector can check on the entire job. More than two inspectors may be
required when two or more guns are used simultaneously and are widely
spaced. A detailed log of the shooting should be kept by the inspectors
for use in determining causes of inadequate shotcrete quality.

8.1.2 Inspection of the Shotcrete Operation

Inspection at the Nozzle

The inspector at the nozzle must observe the application techniques,
character of the materials in the air-stream, and quality of the in-place
shotcrete. Observations of application techniques include the condition
of the surface receiving shotcrete, the distance between the nozzle and
the surface, the angle the shotcrete stream makes with the surface, and
the motion of the nozzle. Any separation or uneven delivery of materials
from the nozzle should be noted. The wetness of the shotcrete on the
surface should also be observed. Visual estimates of rebound percentage
and probable causes of excessive rebound should be logged. Areas of
sagging or sloughing shotcrete must be marked and later sounded for
drumminess. Entrapment of rebound or improper encasement of rebar should
also be reported and suspect areas checked to see if pockets of poorly

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cemented aggregates have formed. The average thickness of shotcrete should be logged as well as wet areas and seepage through the shotcrete layer. The in-place shotcrete should be examined for strength gain and excessive use of accelerator. The early strength can be assessed by comparative penetration of a pointed steel rod (screw driver) or with a calibrated penetration device. Excessive heat (causing a temperature rise of more than $17^{o}C [30^{o}F]$) in thin layers of conventional shotcrete usually indicates that too much accelerator is being added to the mix.

The duties of the inspector at the nozzle are to point out improper placement techniques and to reject poor quality shotcrete. If the shotcrete delivery becomes uneven, the nozzleman must be required to direct the shotcrete stream away from the surface until a uniform flow is obtained.

On many projects, shotcrete is rejected solely on the basis of tests or soundings made long after it is placed. The use of long term tests as a basis for ejection of shotcrete is unsatisfactory, both in terms of the stability of the opening and the possible placement of large volumes of poor quality shotcrete. Specifications must be written so that poor quality shotcrete can be detected early and adjustments made at the time of shotcrete application. Specifications dealing with early detection of poor quality shotcrete and remedial measures for rejected shotcrete are included in Chapter 9. The inspector must be allowed to sample and examine areas of suspect shotcrete even if he has to disturb small sections of the freshly gunned material. The inspector at the nozzle must also ensure that the shotcrete is sprayed to the required thickness and within the required time interval set forth in the specifications. He must check the line, grade, and finishing of the surface,when specified.

Inspection at the Shotcrete Machine

At the shotcrete machine, the inspector should watch the materials as they are fed into the hopper and observe the operation of the gunning equipment. He must make sure that foreign or deleterious materials are not allowed to pass into the machine. The inspector should also examine the aggregate to see that it is properly coated with cement and that excessive segregation does not occur while the materials are being fed into the hopper. The accelerator dispenser should be checked to ensure that the amount of accelerator is being delivered in the specified range. In the dry mix process, the inspector must check that the accelerator is properly mixed with the aggregate and cement. The operation of the shotcrete machine must be watched to ensure that a continuous supply of shotcrete is delivered at a uniform rate to the nozzle. The gun pressure should be observed and the requirements for minimum and maximum specified pressure enforced. It is the duty of the inspector at the shotcrete machine to reject either the wet- or dry-mix shotcrete which has been prepared but not gunned within 60 - 90 minutes after mixing. The batch must also be rejected if the materials have not been gunned within five minutes after the addition of the accelerator. All material wastes for each batch in excess of $0.2m^3$ (1/4 cu yd) must be reported by the inspector at the gun.

Inspection at the Batching Facilities

The inspector of the batching operations must check that the materials are of the specified gradation and percentage, that the minimum mixing requirements have been fulfilled, and that reported quantities are accurate. It is the inspector's duty to reject any unsound cement,

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poorly graded or inferior aggregate, or aggregates with moisture contents
in excess of 8 percent by weight.

8.1.3 Testing of Shotcrete

On all underground shotcrete projects, quality control tests should
be carried out by the engineer and/or contractor prior to and during
construction. The quality control tests are used to ensure that the
specifications are met and to provide control on the quality of the in-
place materials. The tests may also provide an early warning of impending
problems in shotcrete quality before they develop. The most common tests
performed prior to and during construction are summarized in Table 8.1.
The tests listed in Table 8.1 as well as supplemental tests for improving
quality control are described in the next section of this chapter (Sections
8.14 and 8.15). Many of the supplemental tests, such as for rebound,
should be made part of the usual quality control tests.

Pre-Construction Testing

At least 30 days prior to construction, tests should be performed
to check the operation of equipment, the qualifications of the crew, and
the proposed mix design for producing shotcrete of the desired quality.
The compatibility between the cement and accelerator and the gradation
of available aggregates are the initial considerations of the mix design.
Tests should also be conducted on the quality of the aggregates. The
field moisture content of the sand and gravel should be checked to
determine whether or not they will have to be wetted or dried for gunning
purposes and to evaluate possible corrections in batching weights. After
the laboratory tests are made, field trials involving application of
shotcrete must be conducted. Several trial mixes should be gunned using

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Table 8.1 Tests usually performed prior to and during construction.

Pre-construction Testing

    Aggregates

        gradation

        moisture content

        quality

    Cement-Accelerator Compatability

    Batching Operations

        weight batching - accuracy of scales

        volume batching - accuracy and repeatability of the relative
            proportions of the constitutents fed to the mix

    Strength

        compression tests on sawed and/or cored samples

Testing During Construction

    Strength

        compression tests on sawed or cored samples from panels or
        the lining

    Aggregates

        gradation

        moisture content

the most compatible cements and accelerators and aggregates having a uniform gradation and a low percentage of fines (<5% passing the No. 200 sieve). The most important variables in determining the optimum mix design from the field trials are (1) the gradation of the aggregates, (2) the amount of cement and (3) the percentage of accelerator. The trials are also used to check the proficiency of the shotcrete crew and, in particular, the nozzleman in producing uniform, high quality shotcrete. The field trials are conducted by spraying shotcrete on test panels and cutting or coring samples for unconfined compression tests. The compression tests are usually made at 8 and 24 hours, and 7 and 28 days. All samples should be carefully inspected to detect undesirable laminations or uncemented aggregate pockets in the shotcrete. The field trials must be performed with the same equipment and personnel to be employed underground in order to ensure that these tests will be representative of the shotcrete operation at the onset of construction. The trials will also establish whether or not the contractor will be able to meet the strength requirements of the shotcrete specifications. The contractor should not start his tunneling operation until he can produce shotcrete of the specified quality.

The inspection of the shotcrete operation described in Section 8.1.2 should be adhered to in the field trials. Particular attention should be given to the operation of equipment, nozzling techniques, and uniformity of the in-place shotcrete. The suitability of the batching and mixing equipment should be closely checked before construction begins.

Rebound tests should also be made as part of the pre-construction testing. These tests are useful not only in checking mix designs

and proficiency of the shotcrete crew, but also provide an estimate of
the upper limit for rebound likely to be produced in the tunnel on sur-
faces of similar orientation. These initial rebound tests are likely
to yield high rebound percentages (as much as 50%) for a 5 cm (2 in.)
layer since trial mixes are being tested and the shotcrete crew is just
starting work and may not be completely familiar with all of the equip-
ment and the set-up of the operation. Rebound losses should be reduced
significantly, however, once tunneling is in full operation and the crew
becomes more proficient, provided conditions underground do not vary
significantly from those in the tests (e.g., high groundwater flows in the
tunnel).

The pre-construction testing period allows the contractor to check
the performance of his entire shotcrete operation. The contractor, in
performing the field trials, should also conduct a series of full-scale
production tests to evaluate the amount of material he can deliver through
the nozzle (material delivery rate) and the performance of his equipment.
To determine the material delivery rate, the contractor should assess
the capability of the shotcrete machine and the capacity of his
batching and conveyance systems. The down time should be recorded to
obtain an estimate of the actual production rate. Wear and maintenance
of the equipment should also be noted during these production tests.
From these data, the contractor can estimate his production rate and cost
for applying a given quantity of shotcrete. These estimates will be only
approximate since shooting and material conveyance underground are more
difficult than shooting at the surface. However the cost difference
between placing shotcrete above and below ground is likely to be offset

by the higher production rates achieved during construction, which effectively reduce the cost of a unit quantity of shotcrete as compared with the small volumes placed during the pre-construction tests. The production tests further provide the contractor with an opportunity to change his shotcrete operation before construction begins, if it is not satisfactory in terms of delivery rates and maintenance costs. In many cases where significant changes have been implemented during construction, the modifications resulted in considerable expense and delays in the tunneling operation. Rebound tests conducted prior to construction will assist the contractor in estimating and reducing costs when payment for shotcrete is made per unit length of tunnel. Shotcrete sprayed during the pre-construction tests can serve another useful purpose if the tests can be conducted to stabilize or dress up the tunnel portal.

Testing During Construction

The owner or engineer usually reserves the right to perform quality control tests at any time during construction. On many jobs, however, very few tests, other than those for compressive strength, are performed once construction is in full operation. This procedure is inadequate for proper quality control and can lead to placement of large volumes of poor quality shotcrete, particularly if the strength tests are conducted only after 28 days of curing. Early strength and other quality control tests should be conducted periodically to check the in-place materials. They should be performed whenever changes are made in the materials or in the shotcrete operation (e.g., changes in the source of cement). The types and frequency of tests employed to control the quality

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of the shotcrete should be similar to those used in well-engineered placement of concrete. Additional specialized tests (e.g., compatibility tests) as described in the next section may also be desirable.

8.1.4 Laboratory Testing

Laboratory tests are usually performed on the individual materials making up the shotcrete. The tests are conducted primarily to evaluate the aggregate and to determine the cement-accelerator compatibility. Tests on aggregates include gradation, quality, and moisture content. The test results will be only as good as the samples which are intended to represent the overall character of the aggregates. Laboratory tests are also performed on the in-place shotcrete and rebound to determine the gradation and the cement and water contents. In a few cases, strength tests have been made on samples having the same mix design as the shotcrete but cast as concrete. Such tests, however, are not representative of shotcrete and give little information on the strength of the in-place materials.

Aggregates

Sampling. The most difficult part of the aggregate tests lies in obtaining representative samples of the materials, particularly of the fine fraction. Aggregate samples can be obtained from natural deposits, stockpiles, or directly from material on conveyors or from shotcrete after placement. In natural deposits, samples should be obtained from all strata displaying differences in physical properties. Aggregate samples may be obtained from open faces or test holes; however, open cuts are preferred since a larger exposure is available for sampling and viewing of the materials. Sampling of aggregates in stockpiles should

be avoided because they are usually segregated and representative samples are difficult to obtain. If samples must be taken from a stockpile, cuts should be made and samples collected from the interior of the pile. The most representative samples of materials to be used for shotcrete are obtained from aggregates in transit on conveyors or in chutes. Methods for sampling on a conveyor and at the end of the belt or chute are given in ASTM D 75, test for "Sampling Aggregates."

Gradation. The gradation of the aggregates is determined by conducting sieve tests on the representative samples. These tests should be performed in accordance with ASTM C 136, test for "Sieve or Screen Analysis of Fine and Coarse Aggregates." In most cases, processed aggregates used for shotcrete will not need to be washed. If appreciable fines are present in the samples and are not dislodged during the dry sieve process, however, then the aggregates should be washed. Water used in the washing must not contain chemicals such as soaps, etc. Care must also be taken not to lose the finer sand sizes during washing After washing, the aggregates should be oven-dried and sieved again. The U. S. Standard sieves used to determine the gradation of aggregate for shotcrete are given in Table 8.2. Results of the sieve analyses should be plotted on semi-log paper with the percent passing on the arithmetic scale and the grain size and U. S. Standard sieve size on the log scale (see Section 3.12).

Table 8.2   U. S. Standard sieve numbers and
             sieve openings for shotcrete aggregate
             (ASTM, 1974).

U. S. Standard sieve number	Sieve opening mm	in.
1 in.	25.0	1
3/4 in.	19.0	0.750
1/2 in.	12.5	0.500
3/8 in.	9.5	0.375
4	4.75	0.187
8	2.36	0.093
16	1.18	0.046
30	0.600	0.024
50	0.300	0.012
100	0.150	0.006
200	0.075	0.003

Aggregate Quality. Laboratory tests are often conducted to determine
the quality of the fine and coarse aggregates to be used for shotcrete.
The most common tests performed on aggregates for shotcrete work are
summarized in Table 8.3. These tests are grouped into two basic types
dealing with: (1) the intrinsic properties of the aggregate and (2) the
reactions between the aggregate and the cement. The tests for aggregate
quality should be performed in accordance with ASTM Standards. Designa-
tions of the appropriate ASTM tests are provided in Table 8.3.

The tests on the intrinsic properties of the aggregate provide infor-
mation on their strength and durability whereas tests on potential
reactivity are used to detect possible undesirable expansions in the
shotcrete caused by reactions between the cement and aggregates. The
test for alkali-carbonate reactivity is made on samples of rock to be
crushed for aggregate. ASTM recommends that this test be used not as

Table 8.3 Common laboratory tests performed on aggregates for shotcrete
(ASTM, 1974).

Intrinsic Property of Aggregate

Deleterious Substance	ASTM Designation	ASTM Test
Organic Materials	C 123	Test for lightweight pieces in aggregate
Cohesive or Poorly Cemented	C 142	Test for clay lumps and friable particles in aggregates

Aggregates

Soundness	C 88	Test for soundness of aggregates by use of sodium sulfate or magnesium sulfate
Abrasion	C 131	Test for resistance to abrasion of small size coarse aggregate by use of the Los Angeles Machine
	C 535	Test for resistance to abrasion of large size coarse aggregate by use of the Los Angeles Machine

Cement-Aggregate Reactivity

Reaction

Alkali-Silica	C 289	Test for potential reactivity of aggregates (chemical method)
Alkali-Carbonate	C 586	Test for potential alkali reactivity of carbonate rocks for concrete aggregates (rock cylinder method)

a specification but only as an index for potentially unfavorable reactions. No standard has been proposed for testing alkali-carbonate reactivity of granular materials. If the aggregate is exposed to temperatures below freezing for extended periods of time, it should also be subjected to cyclic freeze-thaw tests. The ASTM Designation C 666, test for "Resistance of Concrete to Rapid Freezing and Thawing" should be consulted for apparatus and test procedures.

Moisture Content. The moisture content of aggregate for dry-mix shotcrete must be determined periodically to ensure that it falls within the optimum range of 2-8% by weight. It must also be known for batching of wet-mix materials. The test for moisture content should be performed in accordance with ASTM C 566, test for "Total Moisture Content of Aggregates by Drying". This test essentially involves determination of weight loss in a sample by drying. The number of tests needed will depend on the size of the source and the variability of its moisture content. Enough tests should be conducted so that the average moisture content of well-defined areas, if not the entire source, is known. Test results should be given as average and extreme values.

Absorption of Aggregate. The absorption capacity of the aggregate should also be determined since it can make up a significant portion of its total moisture content. Absorbed moisture is the water contained in the aggregate which does not enter into the reaction with the cement and does not cause bulking since it is totally within the aggregate. Standard tests for determining absorption are given by ASTM C 127, test for "Specific Gravity and Absorption of Coarse Aggregate" and ASTM C 128, test for "Specific Gravity and Absorption of Fine Aggregate." Typical

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values of absorption in sand and gravel which are acceptable for shotcrete are 0-2% and 1/2-1% by weight (Troxell, et al., 1968). The moisture content of the aggregate must be adjusted for absorption when batching wet-mix shotcrete.

Cement-Accelerator Compatibility

Tests are conducted on samples of mortar to determine compatibility of cements and accelerators for use in shotcrete. The two most commonly used tests to determine compatibility are: (1) Gilmore Needles and (2) strength tests on cubes. The Gilmore Needles tests are performed to determine the initial and final set times of various combinations of cement and accelerator. Strength tests on cubes are conducted to determine the initial strength gain and the loss in 28-day strength caused by addition of the accelerator to the cement. The combinations of cements and accelerators which have the lowest percentage of accelerator and the earliest set times with minimum loss of ultimate strengths are considered compatible and will usually produce shotcrete with the lowest rebound and highest early and final strengths. Compatibility tests should be conducted both prior to and during construction. Tests during pre-construction are used to select the cement and accelerator which have the best chance for meeting the strength requirements, whereas tests during construction are conducted to ensure that the properties of the cement and accelerator have not changed.

Gilmore Needles Test. The Gilmore Needles test is the compatibility test most commonly used in the United States. This test is basically a surface-penetration resistance test that is used to determine arbitrary initial and final set times for a cement mortar. The Gilmore Needles test is based on the ASTM C 266 test for "Time of Setting of Hydraulic Cements

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by Gilmore Needles." The ASTM test, however, has been modified to account for the addition of accelerator and shorter set times in shotcrete relative to a cement mortar.

The modifications in the ASTM test include variations in the amounts of constituents, mixing requirements, and thickness of the mortar patty. In the Gilmore Needles test for compatibility in shotcrete, 100 rather than 500 g of cement are used. The amount of water added to the solid ingredients should produce a motar having approximately the same consistency as the in-place shotcrete. The amount of water needed will vary depending on the shotcrete process used and on the cements and accelerators tested. In the dry-mix process the amount of water added to the cement and powder accelerator is usually in the range of 40-45 g (w/c of 0.4-0.45). When some liquid accelerators are tested, the ratio of the weight of the water plus accelerator to the weight of the cement should be approximately 0.3. Care must be taken in compatibility testing of liquid accelerators that the amount of water contained in the accelerator is included in determining the amount of water needed to produce a given water-cement ratio. The amount of water used to determine compatibility of cements and powder accelerators for wet-mix shotcrete is typically 52-60 g (w/c of 0.52-0.60). Compatibility tests should be conducted on a series of mortar samples having 1, 2, 3, 4, 6, and 8% accelerator by weight of cement (Blanck, 1974). These percentages are within the ranges commonly found in the field. One test using 3% accelerator by weight may be conducted for a rapid check of compatibility or for quality control during construction. The full range of accelerator percentages should be tested for full compatibility determination or

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where accelerator percentages in the field exceed 3%. Dry accelerators should be thoroughly mixed with the cement; liquid accelerators should be added and mixed with the water. Mixing of the cement and water must be thorough but must not be continued beyond the initial set (Blanck, 1974). This mixing should be accomplished within 10 sec after the water is added to the cement. The thickness of the patty should be at least 20 mm (3/4-in). The temperature of the ingredients should be similar to those expected in the field. On projects where temperatures are likely to be below $16^{\circ}C$ ($60^{\circ}F$), tests should be conducted on compatible combinations of cement and accelerator at the minimum temperature at which the shotcrete may be applied. A recommended standard test for determining set times for cement and accelerators using Gilmore Needles is given in Appendix E.

The test results obtained using Gilmore Needles are affected by the quality of ingredients, test environment, test procedures, and the technician performing the test. All ingredients must be fresh and should be stored in air-tight containers. The temperature and humidity of the environment must be controlled throughout the test. This environment should be maintained with a minimum of air circulation. The cement and dry accelerator or the water and liquid accelerator should be thoroughly mixed before the water and cement are combined. If the water and cement are undermixed an incomplete and non-uniform hydration of the cement will occur. Overmixing will destroy the initial set. In both cases, set times will be much higher than for a properly prepared sample and will not provide a realistic measure of cement-accelerator compatibility. The top of the patty must be leveled without compacting the mortar sample. Compaction of the sample greatly reduces the set times. Minimum compaction is obtained by striking the top of the patty using the edge of a spatula and

moving parallel with the base of the sample. No aluminum utensils or containers should be used in the Gilmore tests. The Gilmore Needle tips must be kept clean throughout the test. Dried mortar on the side of the needle may reduce penetration while similar mortar on the tip may increase penetration. Improper release of the needles will lead to slower set times. The needle should be barely in contact with the sample and released slowly. Finally, variations in test results can be obtained between individuals not only because of subtle differences in test procedures but more importantly by judgment of set times. Thus, it is desirable that the same technician perform all of the compatibility tests for a single shotcrete project.

The results of the Gilmore Needles tests are usually summarized in tabular form and on plots of percent accelerator against setting times. Pertinent test data are shown as headings in the sample data form (Table 8.4). The percent accelerator is plotted against the log of the initial and final set times (Fig. 8.1).

Strength Tests on Mortar Cubes. Compressive strength tests on 5 cm (2 in.) mortar cubes have been used to evaluate the initial strength gain and the loss of 28-day strength caused by the presence of an accelerator. These strength tests are conducted following ASTM C 109, test for "Compressive Strength of Hydraulic Cement Mortar" (using 5 cm [2 in.] cube specimens) but modified to include the addition of accelerator. The mortar consists principally of sand and cement in a ratio of 2.75:1. Approximately 100g of cement and 275g of sand are needed for one cube. Tests are conducted on mixes having 1, 2, 3, 4, 6 and 8 percent accelerator by

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Table 8.4 Sample data form for presenting Gilmore Needles test results.

GILMORE NEEDLES TEST

PROJECT: Cement:_____

LOCATION: Accelerator:_____

                                      Water:_____

                                      Technician:_____

Date	Time	C & A Temp (^{0}C)	Water Temp (^{0}C)	Wt.Cem (g)	Wt. Water (g)	% Acc	Mixing Time (sec)	Initial Set (min/sec)	Final Set (min/sec)	Remarks
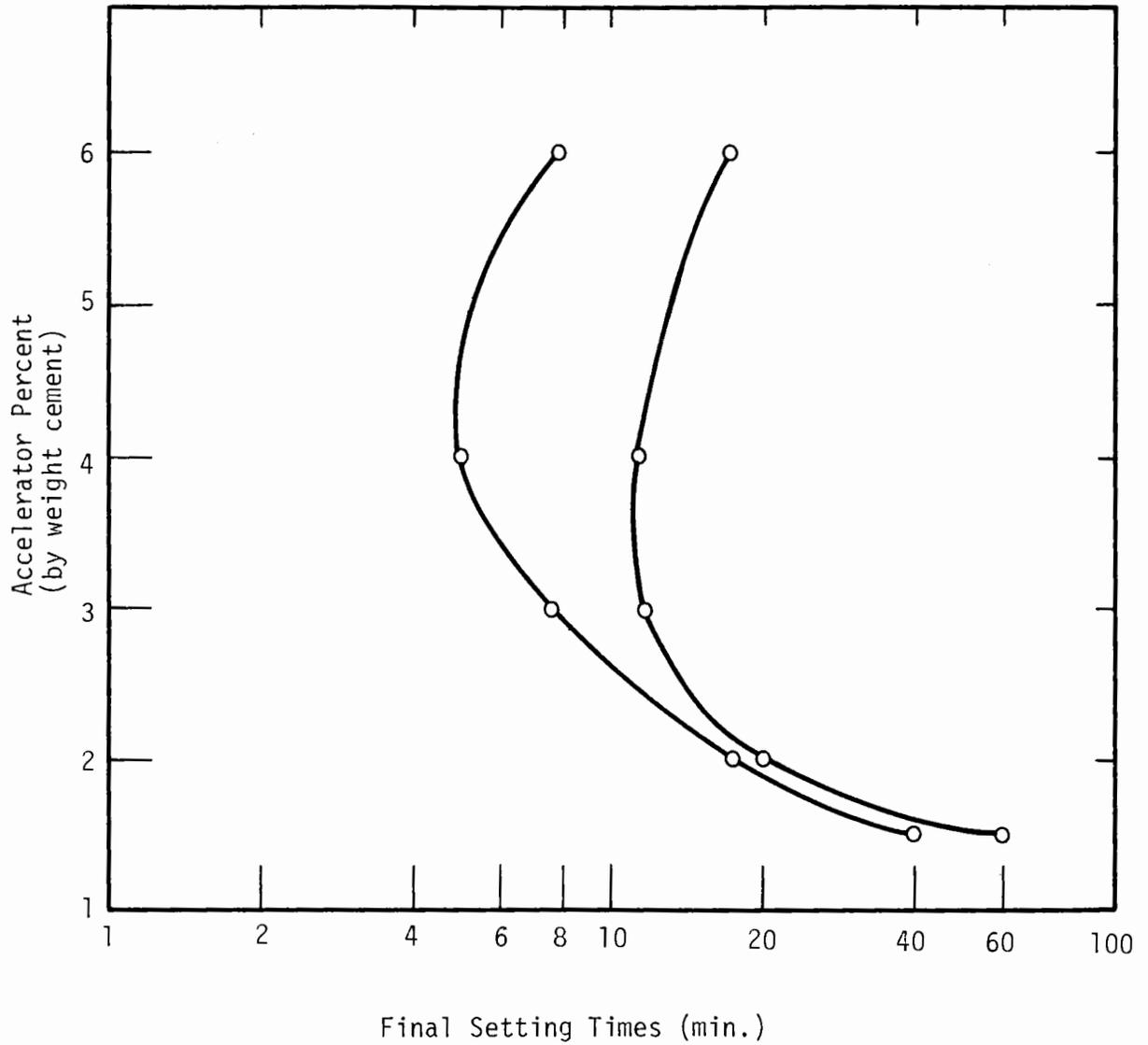
FIG. 8.1   RESULTS OF COMPATIBILITY TESTS USING
GILMORE NEEDLES (BLANCK,1974).

weight of cement. Dry accelerators are mixed with the sand and cement whereas liquid accelerators are mixed with the water. In both the dry-mix and wet-mix processes, water is added to the other ingredients to produce a mortar with approximately the same consistency as in-place shotcrete. The mortar must be mixed in the mold for a period of not more than 15 seconds. During the first 24 hours after casting, the samples are stored in a moist room having a constant temperature of $23^{o}C$ ($73^{o}F$) and a relative humidity of at least 90 percent (ASTM, 1974). After the initial 24 hours, the samples are cured under water at $23^{o}C$ ($73^{o}F$). Compression tests are run on the cubes at 8 and 24 hours and at 7 and 28 days.

8.1.5 Field Testing

Batching Operations

The equipment used to batch the shotcrete, including the additive feeder, must be checked for accuracy prior to and during operation. If weight batching is used, the scale should be checked by means of a set of standard weights. The scale should be loaded incrementally over the range of weights used in batching of the shotcrete. Scale readings are then compared with the actual weights placed on the scale. For volume batching of solids, the feed mechanism or container must be checked to ensure that the desired quantity of material is being fed to the mix. If a mechanical feeder is used to charge a mixer, e.g., batching of cement or aggregates, the feeder is checked by weighing the materials delivered in a given time interval and comparing these weights with those predicted using the setting on the feeder.

Feeders used to charge materials onto moving conveyors or into a shotcrete machine, e.g., accelerator dispensers, are checked by comparing the material delivery rates of the conveyor or shotcrete machine with the appropriate percentages indicated on the feeder. The material delivery rates of the conveyor or gun and feeder are determined by weighing the material dispensed by each during a given interval of time (Fig. 8.2). Flow meters used to regulate the amount of liquid added to the shotcrete mix are checked by filling a container of known volume with the liquid and then comparing the meter reading with the volume of the container.

In the wet-mix process, the slump test is used to check the consistency of the shotcrete materials as controlled by the amount of water added to the mix. This test serves as an index of both batching and mixing of the materials and should be performed in accordance with ASTM C 143, test for "Slump of Portland Cement Concrete."

Mixing

The mixing equipment must be checked to ensure proper blending of materials and to establish minimum mixing requirements. This check involves visual inspection during and after mixing and mixer efficiency tests. In the wet-mix process, the procedures used to check mixing are essentially the same as those used in determining the uniformity of concrete. The most common tests are the unit weight of air-free mortar and the coarse aggregate content. These tests are conducted on samples taken after 15 and before 85% of the material is discharged from the mixer (ASTM, 1974 - C 94) or from different locations in the mixer. The tests for unit weight

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gear
box

motor drive
for auger

accelerator
dispenser

wt. accelerator

accelerator feed
drive shaft

wt. cement
& aggregate

shotcrete
machine hopper

auger or conveyor
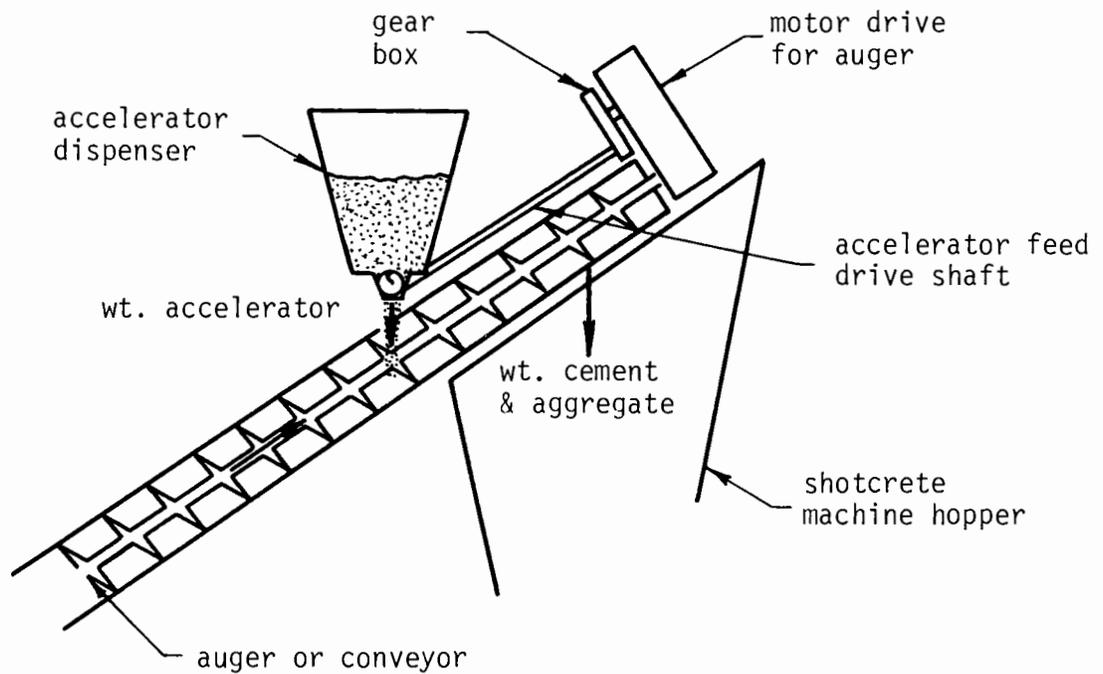
$$\% \text{ Accelerator} = \frac{\text{weight of accelerator per minute}}{\text{weight of cement per minute}}$$

$$\text{Weight of cement per minute} = \frac{\text{weight of cement in batch}}{\text{time required to convey batch (min.)}}$$

FIG. 8.2 CHECKING OF THE ACCELERATOR AND MATERIAL FEEDER.

of air-free mortar and coarse aggregate content and the implications of the test results are described in the concrete manual of the U. S. Bureau of Reclamation (1963) and in the ASTM standards (1974). In addition to these tests, air content and average compressive strength at 7 days may also be used to check the uniformity of wet-mix materials as affected by mixing (ASTM, 1974).

In the dry-mix process, the distribution of the materials in the mixer as well as the coating of aggregate particles must be checked. Uniformity of the dry mix can be determined by performing grain size analyses and determining the cement content on samples taken as the material is being discharged, or from different locations in the mixer. Samples taken during discharge from the mixer should not be obtained from the first (< 15%) nor last (> 85%) portions of the batch. The cement content of the dry-mix sample is determined using the Dunagan Test (ASTM, 1931). Care must be taken in performing this test to correct the weight of cement for the percentage of aggregate fines which pass the No. 100 (0.150 mm) sieve. The gradation and cement content obtained on two samples taken from the same batch should not differ by more than 10% if the materials are properly mixed. Coating of the aggregate with cement is checked by visual examination of the particles, preferably with an optical lens, after mixing the materials. The aggregates are properly mixed if at least 50% of their surface area is coated with cement. Improper coating of the aggregate may be caused by inadequate initial moisture content as well as insufficient mixing.

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Rebound

Measurement of rebound should be made to evaluate the shotcrete mix design and the proficiency of each shotcrete crew. If conducted properly, these tests can also be used to evaluate the optimum material delivery rate at which the maximum amount of shotcrete is placed on the tunnel surface, the optimum percentage and maximum size of coarse aggregate, and the performance of different types of equipment. The same nozzleman having a great deal of experience must be used in conducting rebound tests other than for quality control, since the nozzling techniques can overshadow all other aspects of the tests.

For purposes of quality control, rebound tests can be conducted by spraying shotcrete on a near-vertical plywood panel. This panel should be at least 1 x 2 m (3 x 6 ft) and 20 mm (3/4 in.) thick. It must be held securely to prevent sloughing and excessive rebound as a result of impact vibrations. Rebound should be collected in tarps which are placed on the ground around the front of the panel. The percentage rebound is determined by dividing the weights of the rebound material by the weight of the shotcrete delivered through the nozzle multiplied by 100. After one test is run, the shotcrete can be scooped from the surface of the panel and the panel used again for subsequent tests. The surface characteristics should be nearly the same in each test.

Overhead rebound tests as well as tests on rock surfaces are needed if estimates of rebound for the project are to be made. Rock surfaces used in the rebound tests should be representative of average and extreme conditions in the tunnel. These tests should be conducted using

essentially the same procedures described for performing rebound tests on a plywood panel.

A recommended standard test for rebound is presented in Appendix D. Rebound tests should be conducted using the same equipment, procedures, and personnel employed underground. One of the most important variables controlling rebound is the thickness of the layer. Consequently, the thickness of the shotcrete should be the same in all of the tests and should be reported with the rebound data.

Strength

Strength tests on shotcrete samples are the most common means for checking shotcrete quality. These tests give an indication of both the load carrying capacity and overall quality of the in-place shotcrete. Strength is a good index of the manufacture, placement, and most of the properties of the resulting shotcrete, such as durability. The results obtained from strength tests are sensitive to sampling, methods of testing, and actual test procedures; differences of more than 50% can occur. The most common test for strength is uniaxial compression; however, flexural, pullout, and penetration tests are also used for quality control. Strength tests should be made on samples which are representative of the shotcrete in the liner. In this regard, it is mandatory that samples receive the same curing as that of the in-place shotcrete. Most of the testing methods and procedures used for shotcrete are adapted from concrete quality control.

Sampling. Samples of shotcrete for testing should be obtained from wood panels or from the tunnel walls. A convenient size for the wood

panels is 75 x 75 cm (30 x 30 in.) and 20 mm (3/4 in.) thick (Fig. 8.3);
this size panel provides a sufficient number of samples yet can be moved
manually. The panel should have wing walls and is usually reinforced
with 5 x 10 cm (2 x 4 in.) wood boards which serve to stiffen the panel
and facilitate handling. If a wing wall is placed along the bottom of
the panel care must be taken not to entrap rebound, and samples from this
portion of the panel should not be used for checking the quality of the
shotcrete. The test panel should be gunned underground at a location as
close as possible to the section of the tunnel receiving shotcrete. The
thickness of shotcrete sprayed on the panels should be uniform and
approximately the same as that in the layer except that it should not be
less than 8 cm (3 in.) (ACI, 1966). The same procedures used in gunning
the lining should also be used in spraying the panel, particularly in
building up the shotcrete thickness in layers. The orientation of the
panels as shot should be marked on the surface of the shotcrete. The
panels should be allowed to cure in the tunnel and should not be moved
nor disturbed while they are curing. Samples should be taken from the
panels just prior to testing. The greatest drawback in using test panels
lies in the inevitable difference between the samples and the lining,
because of either the limited size of the panel or differences in gunning
on test panels in comparison with in-place rock (Rutenbeck, 1974).
Shotcrete panels, however, provide an easy means for obtaining samples
which can be tested in the same direction as loads are applied to the
lining, and for procuring specimens for flexure tests.

7.5 cm (3 in.)

wood board
5 x 10 cm x 1 m
(2 x 4 in. x 3 ft)

2-cm (3/4-in.)
thick plywood

85 cm (33 in.)

75 cm
(30 in.)

75 cm (30 in.)

wood board
2.5 x 5 cm x 1m
(1 x 2 in. x 3ft)

2-cm (3/4-in.)
thick plywood

15 cm (6 in.)

Front view of panel

Side view of panel

Wing walls
removed

Top

7.6cm(3in.)zone
wasted

76.2 cm
(30 in.)

8 at 7.6 cm
(3 in.)

Top

Proper testing
orientation for
7.6x7.6x15.2cm
(3x3x6in.) prisms

Alternate orientations
of flexural specimens

Panel sawed into 32 prismatic
compression samples

Rough
surface
trimmed

Panel sawed into 8 beams and
8 prismatic compression samples

FIG. 8.3.   TEST PANEL METHOD FOR OBTAINING PROPERLY-ORIENTED TEST SPECIMENS

The most representative samples of the in-place shotcrete are those obtained from sampling of the tunnel lining. However, these samples are expensive and may be difficult to obtain, particularly from shotcrete layers less than 5 cm (2 in.) thick. Samples taken from the lining should have their orientation marked so that test loads can be applied in the same direction as the loads acting on the structure. For good quality shotcrete, the orientation of the samples with respect to the loading direction will not significantly affect the test results. If the shotcrete is extensively laminated or contains pockets of uncemented aggretate, however, large differences in strength could be obtained depending on the direction of loading with respect to the direction of the defect. Where laminations are present a portion of the lining should be removed and samples obtained so that the loads can be applied in the same direction as the layering. Samples taken from the liner should be obtained just prior to testing.

Gunning into cardboard cylinders should not be used to obtain samples for strength testing. Samples procured in this manner are not representative of the in-place materials. A lesser degree of compaction, entrapment of rebound, and incomplete filling of the cylinders usually occurs. Wire baskets eliminate some of the difficulties of shooting into cardboard cylinders and can be used for processing samples for strength tests up to two hours after shooting (Blanck, 1974). This method is convenient and can be used to provide information on the early strength gain of the shotcrete. One drawback is that samples obtained after stripping the cylinders or baskets are not of uniform cross section. Moreover, making cylinders in the laboratory using fresh shotcrete mix as if it were

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identical to concrete yields samples which are less representative than those obtained by gunning into molds and should not be used for quality control purposes.

Compressive Strength. Uniaxial compressive strength tests are the most commonly used tests for indicating the strength and quality of shotcrete. This test is one of the most easily performed and most reliable tests of strength. The compression test has structural significance since structurally continuous shotcrete linings are designed primarily to act in compression. In addition, the compressive strength is also a qualitative measure of the other strength properties such as tensile or flexural capacity.

Samples for compression tests are prepared by cutting cubes or prisms or by coring. Cubes and prisms sawed from test panels are especially useful in measuring the all-important early strength of shotcrete. Samples have been successfully cut from panels and tested within 1 hour after shooting, and at compressive strengths of less than 3.5 kg/cm^2 (50 psi) (Singh and Bortz, 1974 and Parker et al., 1975). Cores, on the other hand, cannot be taken from test panels or the lining until the shotcrete has obtained a compressive strength of approximately 55 kg/cm^2 (800 psi) (Blanck, 1974). The minimum strength required for coring depends on the diameter of the core; the smaller the diameter the higher the strength required. For shotcrete containing accelerators, coring cannot usually be done until 8 hours after gunning. Thus, cores do not provide a means of obtaining samples for early strength tests but are used with cubes or prisms for determining the intermediate and long term strength of shotcrete.

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Preparation of samples by sawing or coring is done in accordance with ASTM C 42 test for "Obtaining and Testing Drilled Cores and Sawed Beams of Concrete." Samples should be taken immediately prior to testing and should be tested dry rather than wet-cured as recommended in ASTM C 42. The maximum width or diameter of the samples must be at least three times the maximum nominal size of the coarse aggregate (Kesler, 1966). Cubes 7.5 cm (3 in.) on a side and prisms 7.5 cm (3 in.) square will suffice for nearly all shotcrete mixes. Cores are usually 5 to 7.5 cm (2 to 3 in.) in diameter. Whenever possible, both the cores and prisms should have length to diameter or length to width ratios of 2. Compressive strength testing of cored and cut samples is performed according to ASTM C 39 test for "Compressive Strength of Cylindrical Concrete Specimens."

Results of the cube tests should be corrected for size relative to the standard length/diameter ratio of 2 by reducing the strength by 15% (USBR, 1963). The prisms are likely to yield lower strengths (by approximately 10%) than those obtained from cores of the same size; however, corrections should not be made in presenting results.

Samples of shotcrete are normally taken twice for each 40 m^3 (50 yd^3) gunned through the nozzle (Bawa, 1974 and Kidd, 1973). In the initial part of the project, or where difficulties are encountered in meeting strength and uniformity requirements, the frequency of testing is increased. Strength tests on samples of a given section of tunnel should be performed at 8 hr, 72 hr, and 28 days after gunning.

Flexural Strength. Tests of flexural strength are also used to assess shotcrete quality and are usually more sensitive to mix design and application than are compression tests (Blanck, 1974). These tests are also of

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structural value since, in many tunnels, flexural strength governs the support capacity of the lining (e.g., tunnels supported with a thin shotcrete lining). Samples for flexural tests are difficult to obtain from the lining and most often are cut from panels.

Cutting of samples for flexural tests is performed according to ASTM C 42. Samples should be taken just prior to testing and should be covered with a moist burlap cloth and tested wet. Drying of the sample will induce tensile stresses on the outside fibers of the beam and will greatly reduce its strength (Kesler, 1966). The minimum dimension of the sample must be at least 3 times the maximum nominal size of the coarse aggregate and the length of the beam must be at least 3 times the minimum sample dimension (Kesler, 1966). Beams of 7.5 cm (3 in.) in square cross section and 40 cm (15 in.) in length suffice for flexural tests on most shotcrete. The samples must be trimmed along the irregular face to provide a smooth surface.

The specimens are tested in accordance with ASTM C 78, test for "Flexural Strength of Concrete (Using Simple Beam with Third-point Loading)". The beam should not be tested on its sides, but rather loads should be directed normal to the surface on which the shotcrete is applied. The samples should be tested at the same temperature as the shotcrete underground.

Pull-out Tests. Results of pull-out tests involving withdrawal of steel bolts from shotcrete test panels have been correlated with results of unconfined compression tests on cubes or cores of the same materials (Rutenbeck, 1974). This test shows good promise as a means of estimating the early strength of shotcrete even though most of the experimental work

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has been done on specimens with strengths greater than 70 kg/cm^2 (1000 psi).
This test has not yet been used for quality control. The pull-out test
provides a means of assessing shotcrete strength at many different loca-
tions in a tunnel without having to extract cores or cubes. The test,
however, does require considerable preparation and testing time plus the
cooperation of the shotcrete crew. Pull-out tests can be used on shotcrete
in panels or in the tunnel lining.

The pull-out test first introduced in the United States by Mr. Owen
Richards is illustrated in Fig. 8.4. It involves extraction of a steel
bolt and washer using a center hole jack. The bolt and washer are mounted
on a frame and are embedded in the shotcrete. The bolt and washer are
then pulled through a steel ring bearing plate located against the shotcrete
surface beneath the jack. The test produces a truncated, conical-shaped
specimen which is extracted from the panel or wall. The results of the
tests are highly dependent on the cone angle and the load application
procedures. The best correlations between pull-out resistance and
compressive strength are obtained if the cone angle ranges between 60°
and 68° (Rutenbeck, 1974). This angle is governed primarily by the
embedded length of the bolt, the diameter of the embedded washer, and
the diameter of the steel ring bearing plate. The surface of the shot-
crete beneath the ring must be flat and the bolt must be pulled straight
out from the panel. If these seating and loading conditions are not met,
moments and shears will be applied to the shotcrete and will cause
erroneous results. In its present form, the pull-out test measures
strength only in the upper 5 cm (2 in.) of the shotcrete layer. In thick
liners, tests must be conducted on successive layers or modifications in
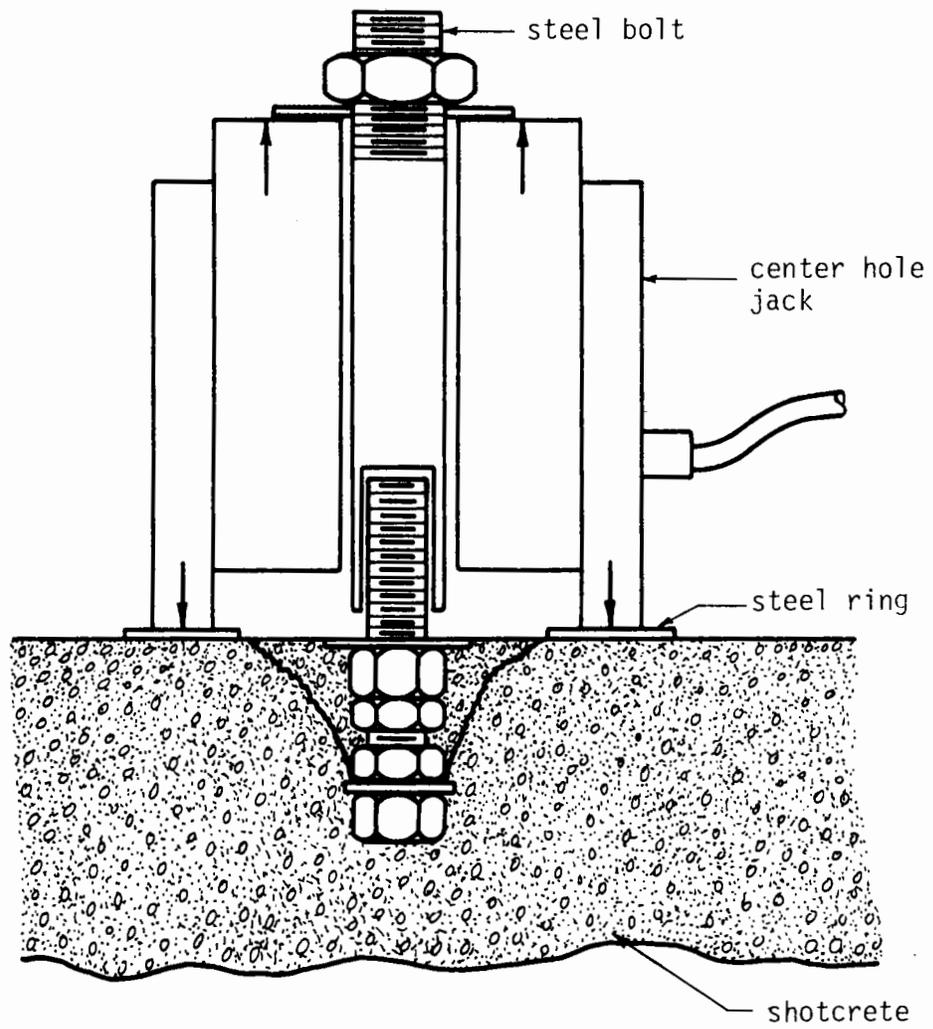
FIG. 8.4   PULL-OUT TEST ON SHOTCRETE.

the test apparatus must be made to permit testing of a thicker section of shotcrete.

The pull-out resistance is determined by measuring the pull-out force and area of the cone (P/A). This resistance, which is actually a measure of the diagonal shear strength, is then multiplied by a factor of 4 to obtain an estimate of the unconfined compressive strength of the shotcrete (Rutenbeck, 1974). If the pull-out test is to be used for quality control, a comprehensive testing program should be conducted to determine the correlation factors for the shotcrete placed on that job. These factors vary with the strength of the shotcrete and thus they must be determined for the different ages at which the shotcrete will be tested in the field. At least 20 pull-out tests should be run to determine each correlation factor. Unconfined compression tests and pull-out tests to determine each factor should be carried out on shotcrete in the same test panel. For quality control in the field at least 3 pull-out tests should be performed for each section of tunnel or volume of shotcrete tested. The results should be averaged and the difference between the individual results and the average should not be greater than 10%.

Windsor Probe. The Windsor Probe is the most common penetration test for shotcrete and concrete used in the United States. In this test, the resistance to penetration of an explosive powder-driven steel stud is used to estimate the unconfined compressive strength of the shotcrete. Good correlations have been obtained between the exposed length of probe and the compressive strength of concrete. However, the test has not been used as extensively in shotcrete since only fair correlations have been

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obtained between penetration resistance and compressive strength (Reading, 1974). The Windsor Probe test does show promise in delineating areas of poor quality shotcrete in tunnel linings. The test is inexpensive and can be easily performed anywhere in the lining. However, it cannot be used to check the early strength of shotcrete since reliable results are not obtained for strengths less than $100 kg/cm^2$ (1400 psi).

The Windsor Probe test basically involves the driving of a steel probe into the shotcrete using a calibrated powder charge (Fig. 8.5). The exposed length of probe is measured and then correlated with compressive strength. The probe should be driven into a flat surface to allow
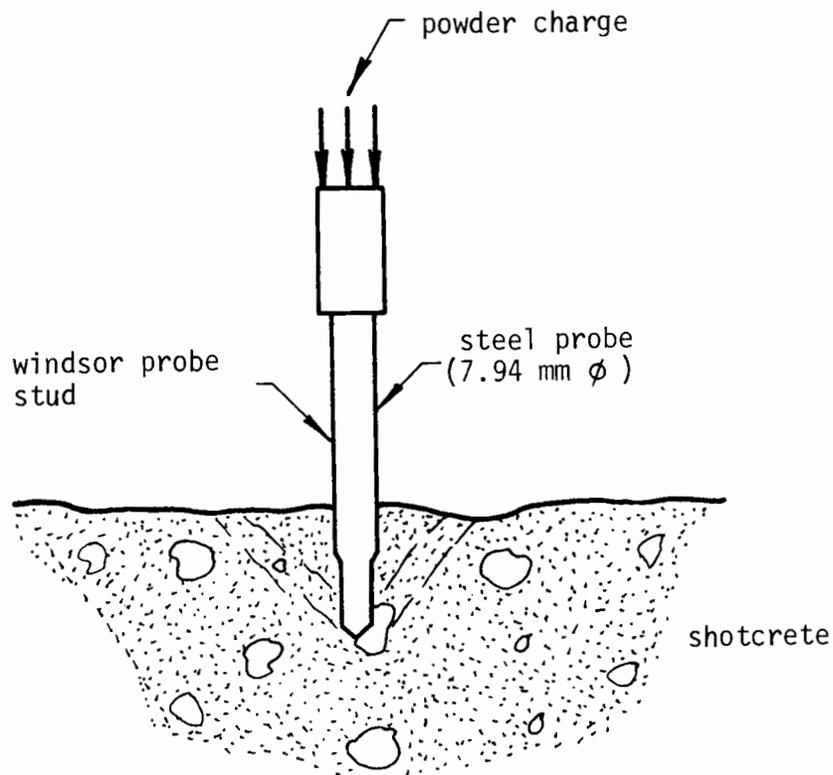
FIG. 8.5 WINDSOR PROBE TEST.

proper penetration of the probe and to facilitate measurement of the exposed length of probe. The probe must be aligned perpendicular to the test surface. At least three probe tests should be conducted at each sampling location. Probes in this test array must be spaced at least 20 cm (8 in.) apart. The results of the tests at each location are averaged and the average value is used to estimate compressive strength. The maximum length of exposed probe should not vary by more than 15%. If the variation in test results in a given location is more than 15% additional tests should be conducted. Standard calibration curves should not be used to estimate the unconfined compressive strength of shotcrete from results of the Windsor Probe tests. Rather, on each job, probe and compression tests must be conducted for each mix design and for different hardnesses of coarse aggregates in order to establish the relationship between the exposed length of probe and the unconfined compressive strength. The Windsor Probe test is used primarily to augment regular compression tests by providing a check on shotcrete quality between the compression test locations. At least 10 cm (4 in.) of shotcrete are required to perform the test. For thick shotcrete linings, penetration tests should be conducted for each successive layer of shotcrete.

Schmidt Rebound Hardness. The Schmidt rebound hardness is a non-destructive, rebound hardness test used to estimate compressive strength for concrete and shotcrete. It is not used for quality control determinations of shotcrete strength because no reliable correlations have been found between rebound hardness and unconfined compressive strength. One reason for this lack of correlation is probably related to the difficulty in properly seating the hammer on the shotcrete surface (Reading, 1974).

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Nevertheless, the Schmidt hammer can be used to locate sections of poor quality shotcrete in the lining. The test is inexpensive and can be easily performed anywhere in the opening. Rebound hardness measurements should not be made on shotcrete with strengths less than 70 kg/cm^2 (1000 psi) since the impact of the plunger will fracture the shotcrete and produce erroneous results.

The Schmidt hammer test is essentially a measure of surface hardness. A round-tip steel plunger, in contact with the shotcrete surface, is struck by an internal mass accelerated by a calibrated spring (Fig. 8.6). The rebound of the plunger is measured on an internal arbitrarily-graduated scale giving a rebound number. The test must be conducted on a flat surface of the shotcrete layer and the hammer must be held normal to the surface. The type "L" Schmidt hammer with a 750 g (1.7 lb) mass is used for shotcrete work in order to prevent damage to the specimen leading to erroneous test results.

The compressive strength is estimated from the rebound number using a set of calibration curves. These curves should be developed by performing Schmidt hardness and unconfined compression tests on samples of all of the shotcrete mixes used on the job. These tests are conducted by shooting test panels and performing (1) hardness tests on the shotcrete surface and (2) compression tests on several sawed or cored specimens taken from adjacent parts of the panel. In the field, an average of three readings is used in the calibration curves to estimate the compressive strength of the shotcrete. The results obtained from the Schmidt tests provide an index of the relative strength of the shotcrete lining but should not be used as a substitute for compression tests.

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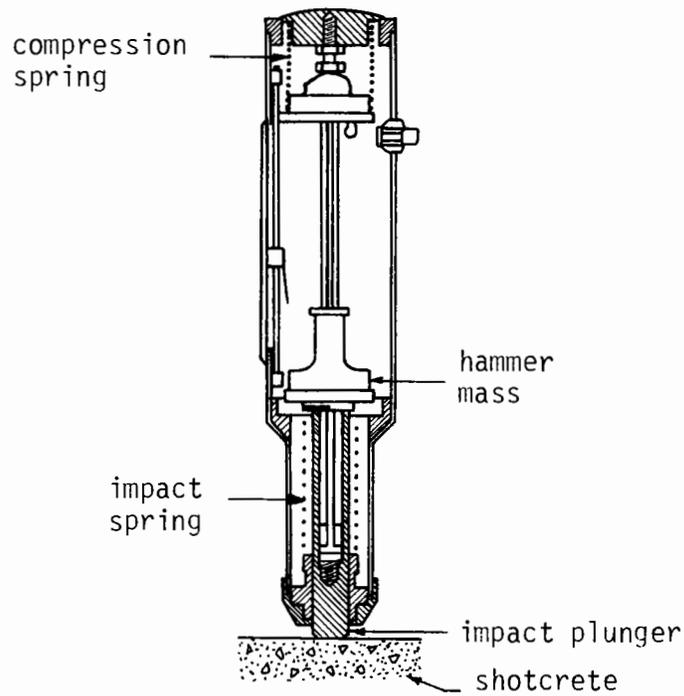
FIG. 8.6   TYPE L SCHMIDT TEST HAMMER (TAKEN
FROM DEERE AND MILLER, 1966).

The steel calibration anvil should be used periodically to check

the calibration accuracy and repeatability of the hammer.   The results

of the Schmidt tests on shotcrete depend on the orientation, curvature

and wetness of the surface.   The highest rebound numbers for a given

shotcrete are obtained for vertical, flat, and dry surfaces (Troxell,

et al., 1968).   The Schmidt hammer tests only the outer 5-7.5 cm (2-3 in.)

of the shotcrete layer.

8.2 Safety and Environmental Considerations

The safety and environmental aspects of placing shotcrete must be considered by the designer and the contractor in view of present OSHA (Occupational Safety and Health Act) requirements and probable future restrictions. Most of the present requirements and standards deal with aspects of safety underground (Bates, 1974). This emphasis is to be expected because particles in the air stream travel at high velocities, relatively high air pressures are used, and cements and accelerators are caustic. More recently, concern has been expressed on the environmental impact of the disposal of shotcrete materials and highly basic waters and the ventilation of caustic dust (Bates, 1974). Additional studies are likely to be conducted in this area as environmental restrictions are extended into mining and underground civil engineering work. Ignoring either safety or environmental aspects of shotcrete can produce serious injury and/or costly delays if the job is shut down until the conditions meet the requirements.

8.2.1 Safety Underground

Shotcrete safety underground primarily involves nozzling and the behavior of the shotcrete and rock during and after its placement. Additional care must be taken to secure compressor hoses when high air pressures are used. All employees should be thoroughly familiar with the potential hazards associated with placing shotcrete, the safety measures needed to prevent accidents and procedures and treatment required if an injury should occur.

Control of the Material Hose

The nozzleman must maintain control of the shotcrete stream at all times and prevent it from being directed toward an individual. Aggregates in the stream are traveling at velocities of 30-90 m/sec (100-300 ft/sec) which are high enough to injure an individual seriously if the material strikes at close range. Protective clothing will help to reduce the impact of the particles in the material stream but may not be thick enough to prevent bruises and broken bones. The eyes in particular are vulnerable to impact, and blindness could result where suitable goggles are not worn. The nozzleman should hold the nozzle with enough slack so that the orifice will be directed above his head if a plug develops at the nozzle. If the nozzle is held too close to the orifice, the material stream could be directed into the nozzleman's face if ne loses control.

The best means for maintaining control of the nozzle is to provide the nozzleman with a flat, rough, and secure platform to work from, or to use remote nozzling techniques. Nozzling may be done from the invert when the tunnel has been mucked out and the surface is flat and firm. If the nozzleman loses control of the stream an alert gunman can minimize injury by immediately turning off the air pressure and the material feed. Remote nozzling practically eliminates the problem of losing control of the nozzle; however, the operator must be sure that the material stream is not directed toward anyone standing near the operation.

Static Electricity

Static electricity can build up during the gunning operation causing discomfort to the nozzleman, possible loss of control of the material hose due to a severe shock or, in gaseous tunnels. production of a spark

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which could cause an explosion. Static electricity most commonly builds up when the materials are dry and the relative humidity is below 50% (Bates, 1974). It may also occur when wire-braided material hoses are used.

The buildup of static electricity is generally prevented by increasing the moisture content of the aggregates and/or the relative humidity in the tunnel. A static line or semiconductive material hoses can also be used to drain off excess electrostatic charges (Bates, 1974).

Rebounded Particles

Rebounded particles constitute the same type of hazard as the materials in the shotcrete stream, but to a lesser degree, since impact usually reduces their velocities. Bates (1974) reports that coarse aggregate particles traveling at high velocities have rebounded for distances of 9-12 m (30-40 ft). Serious injury from rebounded particles does not usually occur even at close range, except if the particles strike exposed areas of the body, particularly the face. The eyes are most vulnerable to injury and goggles must be worn in the vicinity of the nozzling operation. The nozzleman is less likely to be injured than a workman who stand close to the nozzle but at right angles to the material stream. Use of protective clothing, safety equipment, and remote nozzling techniques will help prevent serious injury from rebound.

Plugged Hose or Nozzle

Plugs in the material hose and nozzle are a potential danger because they may cause rupture and whip of the hose while gunning or blowing out of the plug. These plugs are most likely to occur at constrictions such

as hose connections, in sections of hose containing cement buildup and at locations of tight coils in the hose. When a plug forms, the pressure in the hose between the plug and the gun becomes nearly equal to the line pressure (8 kg/cm^2; 110 psi). This pressure may be great enough to rupture the hose and cause material to be ejected at the broken section if the shotcrete machine is still operating. When a plug starts to form, the machine begins to work harder. The hose will begin to buckle and whip, starting at the machine and working toward the nozzle. If the whipping action reaches the nozzle, the tip will whip upward and the nozzleman may be driven backward by the action of either the nozzle body or the material stream. An alert gunman can reduce the chances of a plug or possible injury to the nozzleman by reducing the material feed to the hose when the whipping begins at the machine. This reduction in feed will smooth out the material flow, reduce possible congestion and stop the buckling of the hose. If a plug develops in spite of this procedure the gunman should cut off the air supply and stop the feed mechanism.

With dry-mix equipment, removal of plugs is most commonly done by blowing out the material hose. In this method, the gunman alternately applies and turns off full air pressure in an effort to dislodge the plug. The material hose must be securely held to prevent whipping during application of the air. The hose should be held against the ground with the nozzleman straddling and grasping it near the end with both hands. The end of the hose should be pointed toward a wall or, if possible, placed beneath a low sturdy platform to prevent injury when the material is blown

from the hose. The particles extruded from a plug are usually traveling at higher velocities than those in the normal material stream since full air pressure is acting behind the plug and little head loss occurs between the plug and the nozzle tip. Thus, impact of the particles is greater than from a loose or misdirected hose and will cause greater damage. All individuals except the nozzleman should be kept clear of the discharge area.

Material Hose Breaks

In the dry-mix process, hose ruptures can cause serious injury by discharging shotcrete at individuals in the vicinity of the break. The velocity of the particles through the hole is nearly the same as that in the shotcrete stream. When a break occurs the gunman should immediately cut off the air supply and the material feed.

Hose breaks are usually caused by excessive wear rather than by defects in the hose. Material hoses should be periodically inspected to determine the location and extent of wear. Badly worn sections of hose can be easily indented with the fingers. These sections should be removed or replaced as soon as any indication of excessive wear is detected. Excessive wear is most likely to occur at constrictions and along the outside curves of hose loops. All constrictions and lengths of permanent loops should be closely watched for signs of possible rupture. In many cases, warning of impending rupture is given by dusting or air discharge through the outer skin of the material hose. When this occurs, the section of hose should be replaced immediately.

Coupling Breaks

Coupling breaks are caused either by improper connection or failure

of the coupling itself. These breaks produce an extreme whipping action of the hose, often with the heavy metal coupling still attached. Such breaks have caused serious and even fatal injury to many workmen. To prevent coupling breaks, connections must be made carefully and worn couplings must be replaced. Safety cables or chains must be used to prevent excessive whip of the hose in the event of a coupling break. These "whip checks" should be placed on all connections, particularly those on the compressed air line, but also including the material hose, except at the nozzle. At the nozzle, the "whip check" will be of no benefit if the nozzleman is properly holding the hose and will only impede his work.

Caustic Burns

The portland cement and accelerators used in shotcrete contain caustic materials which can cause reactions on exposed skin ranging from mild irritation to severe burns. A number of the ingredients in accelerators are highly alkaline and are classed as primary irritants. These chemicals are the most likely ingredients in shotcrete to cause burns though the lime in cement is also caustic. Both cements and accelerators cause dermatitis by direct action on the skin when they are allowed to act in sufficient concentration or quantity for a sufficient length of time (Bates, 1974). With liquid accelerators, burns can occur immediately. Powdered accelerators and dry cement require some moisture before irritating the skin; however, sufficient moisture is usually available in the form of groundwater or body fluids. The greatest danger with caustic burns is that the initial contact does not produce excessive pain but only a slight tingling or warm sensation. Since no pain is experienced, the individual

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will often continue working without treatment. Lack of immediate treatment may produce very severe burns, particularly if the area affected is rubbed by cloth or rubber. All skin coming in contact with accelerators or cements should be treated immediately. Burns can be kept to minor levels with prompt attention.

Exposure to cements and accelerators occurs throughout the shotcrete process and can linger long after shooting has ceased. The first exposure to burns occurs at the hoppers or holding tanks where the cement and accelerator are loaded into their dispensing mechanisms. Spillage of these materials can cause latent burns if the area is not kept clean. Besides the normal hazards of coming in contact with the caustic materials during loading, dry accelerators occasionally puff up in a cloud when they are dumped into a hopper (Bates, 1974). This allows the accelerator to become airborne and to be directly inahaled by the gunman or gunman helper. Safety dictates the use of dust masks around these potentially hazardous materials.

Accelerator and cement are also transmitted through the air as dust or mist and can gradually build up to unsafe concentrations as they settle out of the air onto exposed skin. A leak in any water, air, or material hose carrying accelerator or cement is a potential source of caustic particles. A major source of pollution is at the nozzle, where the accelerator and cement particles enter the free air and may drift back toward the workmen.

Shotcrete rebound is still another potential source of severe burns. Caustic burns can be produced by rebounded particles since their surfaces leave a residue of cement and accelerator when they strike the skin.

Burns caused by caustic chemicals can also be produced by coming into contact with rebound in the invert since cement and accelerators are still present in these materials. Burning can occur even through indirect contact with the shotcrete rebound such as by sitting or kneeling on the materials. If a slight amount of moisture is present either in the rebound or by condensation, the chemical will migrate through the clothing and come in contact with the skin. This usually produces severe burns in workmen not directly involved with shotcreting since these individuals are likely to be unaware that contact has been made with the caustic chemicals. Burns have been produced by contact with shotcrete rebound months and even years after it has been gunned (Bates, 1974).

Standing or running water coming in contact with shotcrete materials is one of the most common causes of burns because it is able to react quickly with the cement and some accelerators to produce caustic solutions and to transport these solutions to many parts of the excavation. Contamination of the water can occur as it flows through the shotcrete lining, comes in contact with rebound and receives dusts and mists which eventually settle out of the air. Because of the mobility of the high pH water, workmen can be burned severely in portions of the tunnel remote from the shooting area.

Because of the serious hazard to exposed skin and eyes from the accelerator and cement, personal protective equipment is required for all workers in the vicinity of the shotcrete machine and nozzle. These include long rubber gloves, rubber boots, protective goggles, respirators (discussed later), and long-sleeved shirts or coveralls. In addition, a strict program of personal hygiene is mandatory. Prior to shooting,

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protective cream or lotion should be provided and applied to skin areas likely to be exposed to the caustic chemicals. Clothing should be washed frequently and employees should bathe daily (Bates, 1974). All rubber boots, gloves, and goggles should undergo a thorough rinsing frequently and should be changed periodically.

Workmen should be instructed to report immediately all contact with caustic materials. A suggested treatment is to wash the exposed skin with water, rinse with vinegar to neutralize the alkalis, and treat with a protective cream or first-aid spray. Serious skin burns require the attention of a physician. When exposure to the eyes occurs, the chemicals should be washed from the eyes with large amounts of water followed by a prescribed eye wash. All eye exposures require the immediate attention of a physician.

Dust

The production of a considerable amount of dust and mist is an unwanted by-product of a typical shotcrete operation. In a dry-mix process, dust originates at all steps in the operation but takes place primarily at the shotcrete machine and nozzle. In a wet-mix operation, dusting is considerably less. Most dusting generally originates prior to the addition of water to the mix (i.e., in the batching and delivery operations). However, the nozzle remains a source of mists containing cement and accelerators.

The health hazard associated with high dust concentrations in the air is primarily related to inhalation of caustic and non-caustic dust. Research has shown that the amount of dust in the atmosphere can be quite high, particularly in the vicinity of the nozzleman. Consequently,

steps must be taken to reduce both the caustic and non-caustic dust concentrations to within allowable limits. This is done by elimination, ventilation, and/or filtration. The allowable limits for airborne contaminants are specified in Section 1910.93 of the Occupational Safety and Health Act (OSHA). Table 8.5 lists the threshold limit values for mineral dusts as taken from the section of the OSHA specifications.

One of the most effective methods to reduce the amount of dust generated in a dry-mix operation at the shotcrete machine is to have a sufficient initial moisture in the aggregate. Moisture contents in the range of 4 to 5 percent are effective in substantially reducing dust from the shotcrete machine. The quantity of dust can also be reduced by maintaining the machine in proper working condition (e.g., replacing or repairing worn wear pads and plates) and possibly by using a dust collector. At the nozzle dust can be controlled by shooting at a moderate air pressure, using a properly functioning nozzle and by adding a sufficient amount of water.

A ventilation system must meet all applicable standards set forth by Section 1926.800 of OSHA (1972). Consideration should also be given to dust leaving the shooting area so that other underground working locations are not contaminated (Bates, 1974).

Filtration measures include furnishing all employees exposed to dangerous levels of dust or mist with well-fitting respirators. The type of respirator chosen, whether an air-line respirator with an independent supply of pure air or simply a canister-type filter mask, will depend on the available oxygen in the atmosphere and must be determined for each tunnel condition. All respirators must have U. S. Bureau of Mines approval

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Table 8.5 Threshold limits for mineral dusts (taken from OSHA, 1972)

	Mppcf[1]	Mg/M^3[2]
Silica:		
Crystalline:		
Quartz (respirable).....................	$\dfrac{250}{\%SiO_2+5}$	$\dfrac{10}{\%SiO_2+2}$
Quartz (total dust).....................		$\dfrac{30}{\%SiO_2+2}$

Cristobalite: Use 1/2 the value
  calculated from the count or
  mass formulae for quartz.

Tridymite: Use 1/2 the value
  calculated from the formulae
  for quartz.

	Mppcf	Mg/M^3
Amorphous, including natural		
diatomaceous earth.....................	20	$\dfrac{80}{\%SiO_2}$
Silicates (less than 1% crystalline		
silica):		
Mica..................................	20	
Soapstone.............................	20	
Talc (non-asbestos form)..............	20	
Talc (fibrous). Use asbestos limit......		
Tremolite (see talc, fibrous)...........		
Portland cement.......................	50	
Graphite (natural)....................	15	
Coal dust (respirable fraction		
less than 5% SiO_2)....................		2.4
		or
For more than 5% SiO_2.................		$\dfrac{10}{\%SiO_2+2}$
Inert or Nuisance Dust:		
Respirable fraction...................	15	5
Total dust............................	50	15

[1]Millions of particles per cubic foot of air, based on impinger samples
counted by light-field techniques.

[2]Milligrams per cubic meter.

or be acceptable to the U. S. Department of Labor (OSHA 1926.103). Filter
masks used for shotcreting must be capable of removing caustic dusts
and mists in addition to non-caustic particles. Respirator equipment
must be maintained in good condition. Canisters and filters must be
replaced as often as necessary so as to provide complete protection.
Further guidelines for the proper selection and maintenance of respiratory
equipment may be found in Section 1926.103 of OSHA (1972).

Fallouts of Rock and Shotcrete

The greatest danger in shotcreting occurs during nozzling in unsupported
tunnel headings, particularly in loosening ground conditions. Rock blocks
can fall out without warning and cause serious or even fatal injury to the
nozzleman or helpers. Rock block fallouts in the heading are reduced by
proper scaling and barring down prior to shotcreting. The larger blocks,
however, are initially very difficult to dislodge from the surrounding rock
but may fall out during shotcreting as loosening progresses. With hand-
held nozzling, steel ribs and a steel canopy can be used as temporary support
above the nozzleman. This procedure is expensive since the support must
be erected before shotcreting and removed after application. The canopy
must be movable so that shotcrete can be sprayed over the entire arch. Steel
canopies above a movable platform help to protect the nozzleman from small
fallouts; however, failure of large blocks is likely to crush the cage. The
most effective and efficient means of protecting the nozzleman during applica-
tions in unsupported ground is to remove him from the heading by using remote
nozzling techniques.

Rock block fallouts involving failure of the initial shotcrete layer
are most likely to occur during and shortly after application of shotcrete

in the heading. Once the shotcrete has gained sufficient strength to reduce or eliminate rock displacements, rock block fallouts are not likely to occur. Fast-setting agents (accelerators) and quick setting cements such as regulated-set cement are used to give shotcrete a rapid gain in early strength and thus to improve safety in the heading. Most accelerators used in allowable concentrations (3-6% by weight cement) do not provide a rapid enough strength gain to significantly reduce the danger from rock fallouts in the heading within the first few hours; with time, however, shotcrete greatly improves safety in the opening. Regulated-set shotcrete exhibits a much faster strength gain and therefore provides support more quickly than conventional shotcrete (Appendix A). This shotcrete has not yet been used underground but has great potential for improving safety in the heading.

Failure of rock blocks through hardened shotcrete can also occur with very little warning; however, most impending failures show signs of distress in the shotcrete. Reinforcement is often used to improve the ductility of the shotcrete lining by allowing it to deform under rock load without causing sudden collapse. The increased ductility improves chances for early detection of unsafe areas and provides a longer time for evacuation of personnel or for placement of remedial support. The usual reinforcement is steel bars or welded wire mesh. This type of reinforcement is placed in the last layers of the lining, for structural reasons. Bars or welded wire mesh are not used in the initial layer because of installation difficulties. Steel fiber, mixed with the shotcrete materials prior to gunning, shows great promise for improving

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the ductility of the initial shotcrete layer (Appendix A). Steel fiber shotcrete has not been used extensively underground as yet, primarily because of the cost of the fibers, lack of engineering experience with the performance of fiber shotcrete, and the difficulty in preparing and gunning the materials. With additional laboratory tests and continuing success with field applications, steel fiber shotcrete will certainly be used more frequently to improve safety underground.

Spalls of hardened shotcrete can be extremely hazardous even if they are only 30 cm square by 5 cm thick (1 x 1 ft x 2 in.) and fall only 1 to 2 m (5 ft). Shotcrete spalls are produced by ground movements or shrinkage. They are most dangerous in deep shafts where even small particles, falling great distances, can kill workmen below. In tunnels, spalls are likely to take place during blasting, either in the heading or in excavations adjacent to the shotcreted opening but may also occur because of rock movements unrelated to excavations. If shrinkage is causing the spalls, or if the area of the spall is small, the shotcrete slabs can be barred down and the layer replaced with fresh shotcrete. Where large block or ground movements are responsible for spall development, additional support such as added shotcrete, rock bolts and/or steel ribs should be placed.

8.2.2 Environmental Considerations

This section deals primarily with the contamination of water and air above ground by water and dust from the shotcrete operation. Other environmental considerations such as contamination of the soil and aesthetic concerns will not be treated. The primary sources of pollution from the shotcrete operation are rebound, water, and dust. These

materials should be disposed of or treated properly so that the environment in the area of the tunnel is not damaged.

At present, most air and water pollution standards are written and enforced by local or state governments. Thus far, these standards have been applied primarily to permanent industrial and mining operations. In the near future, they probably will be expanded to include underground civil engineering work as well. The contractor should be aware of the type and nature of pollution derived from the shotcrete operations and the means of reducing its levels.

Disposal of Rebound

Disposal of rebound should be planned so that surface and sub-surface waters will not be contaminated with caustic and non-caustic materials. Rebound should never be dumped into a stream or placed above a highly permeable material. All permeable materials beneath fills containing large quantities of rebound should be sealed and drainage ditches should be dug around the fill to collect contaminated runoff. If the rainfall is great enough to overflow the ditches, water from the fill should be channeled into collecting ponds. The concentration of pollutants can be greatly reduced by dispersing the rebound in the tunnel muck.

Rebound has many uses both in tunnels and above ground. It is most commonly used above ground as a fill material for roadways or work areas. Underground, rebound is often placed in the invert and serves as an excellent base for vehicular traffic. However, when used underground, the rebound may harden and become extremely difficult to remove during cleaning of the invert. To prevent hardening, the rebound should be mixed with tunnel muck.

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Disposal of Water

Water from the area where shotcrete is being applied usually contains suspended solids and caustic chemicals. It must be treated before being discharged into streams or municipal treatment systems. The amount of treatment necessary will depend on the quality of the water as it leaves the tunnel site and/or on the local or state environmental regulations. The suspended particles derived from the shotcrete operation usually constitute only a small percentage of the suspended particles produced by the entire tunneling operation. They pose no special problems and are usually removed with the other sediments in settling ponds. Chemicals such as alum are commonly added to the water to induce flocculation and thereby reduce settling times (Bates, 1974).

The caustic chemicals produced by the shotcrete usually necessitate special treatment of the water to reduce the pH and to remove harmful compounds. The water is treated when it reaches the settling pond with acids and acid-forming materials (such as alum) to reduce the pH to acceptable levels. Chemical treatment may not be needed when subsurface water is present in sufficient quantities underground to dilute the concentration of the chemicals or when it has a pH below 7. The water can also be allowed to evaporate from the settling pond thereby eliminating the need for special treatment.

Air Ventilation During Shotcreting

The air in the vicinity of the shotcrete operation is exhausted to the atmosphere and is a source of air pollution. It usually contains dust which, in the dry-mix process, can be present in high concentrations and is likely to be caustic. The amount or concentration of the dust ventilated from the shotcrete operation may be above the minimum acceptable

pollution levels. Control measures such as filters may be required to reduce the amount of dust in order to meet air quality standards.

CHAPTER 9

SHOTCRETE SPECIFICATIONS

One of the most difficult aspects of shotcrete design is the writing
of specifications that do not place either the contractor or owner at a
disadvantage. The specifications must be carefully and clearly written
and should treat only those subjects which are the responsibility of the
engineer, namely, shotcrete quality and ground control. The documents
must be specific in areas such as contamination of the shotcrete, yet in
other areas should provide enough allowance for changes which inevitably
occur during construction (e.g., extra shotcrete applied in headings).
Considerations such as arrangement of equipment should be left to the
contractor, provided they do not affect the quality of the in-place materials.
Each word in the specification as well as the sentence content should be
analyzed for its unintended or improper implications. Improper wording
and implication, omission and over-specification have produced
disastrous results in terms of shotcrete quality or job economy.

The scope and detail of the specifications will vary with the purpose
of the shotcrete. Tight specifications will be required when the shotcrete
is used for the final lining. The specifications can be relaxed somewhat
when the shotcrete is used only as initial support (for example, reduction
in strength requirements when high accelerator dosages must be added to
the materials).

9.1 Summary of Shotcrete Specifications

The topics presently covered in most specifications have been listed
in Table 9.1. Additions have been made to make the table as comprehensive

Table 9.1 Contents of shotcrete specifications.

Topic	Contents	Section in Manual
1. Description of Work	1.1 Application of shotcrete in the tunnel as provided in specifications and shown on drawings	
	1.2 All work under application of shotcrete and clean-up	
2. Definitions	2.1 Shotcrete	1.3
3. Materials	3.1 Cement . Type . Physical and chemical properties	3.1.1

	3.2 Aggregate
	. Sampling
	. Gradation
	. Quality
	  . organic materials
	  . cohesive or poorly cemented materials
	  . soundness
	  . abrasion
	  . reactivity
		3.1.2

	3.3 Accelerator
	. Type and composition
	  . liquid or powder
	  . chemical content and corrosion
	. Compatability
	  . early
	  . long-term
	. Usage
	  . arch
	  . walls
	  . initial support
	  . permanent support
	. Maximum percentage of accelerator
		3.1.4

	3.4 Water . Quality	3.1.3
4. Mix Design (Wet-Mix Only)	4.1 Proportions . Cement/aggregate ratio . Slump	3.2

Table 9.1 Continued

Topic	Contents	Section in Manual

5. Construction	5.1 Storage of Materials
	. Moisture
	   . cement and accelerators
	   . aggregates
	. Contamination
	. Segregation
	   . aggregates
		5.1

	5.2 Batching and Mixing
	. Method
	   . weight
	   . volume
	. Moisture content of aggregates
	. Temperature of materials
	. Addition of accelerator
	. Batch tickets and records
	. Minimum and maximum mixing requirement
	. Equipment performance, maintenance and calibration requirements
	. Contamination
	. Segregation
		5.2

	5.3 Conveyance . Maximum time between mixing and shooting . Segregation . Contamination	5.3

	5.4 Shotcrete Operation
	. Equipment
	   . requirements and capabilities
	      . shotcrete machine
	      . nozzle
	      . compressed air supply
	      . water supply
	      . accelerator dispenser
	   . performance and maintenance
		6.1-6.3

6. Placement of Shotcrete	6.1 Initial Support . Time after shooting or advancing for starting and finishing application . Thickness of layer . Coverage of tunnel perimeter	2.1
	6.2 Supplementary Support (Successive Layers) . Distance from face or time after advance	2.2

9-3

Table 9.1 Continued

Topic	Contents	Section in Manual
	. Excessive wood lagging . Thickness of individual layers . Time limitations between successive applications . Coverage of tunnel perimeter	
	6.3 Final Support (Final Lining) . Distance from face or time after advance . Thickness of individual layers and lining . Time limitations between successive applications . Coverage of tunnel perimeter . Reinforcement	2.3
	6.4 Control of Groundwater	2.1.5
7. Shotcrete Application	7.1 Proficiency of Workmen . Foreman . Nozzleman . Crew	7.1
	7.2 Surface Preparation . Scaling . Cleaning . Moistening	7.2

	7.3 Application Techniques
	. Material delivery to the nozzle
	. Nozzling techniques
	  . distance
	  . angle
	  . motion
	  . encasement of steel bars, ribs, wood lagging, and wire mesh
		7.3-7.4

	7.4 Finishing . Shape of opening . Smoothness of shotcrete surface	7.5-7.6
	7.5 Curing . Temperature . Humidity . Artificial curing . Duration	7.8
8. Quality Control	8.1 Pre-Construction Testing . Time requirements relative to start of construction . Test panels and method of sampling . Curing . Test methods	8.1

Table 9.1 Continued

Topic	Contents	Section in Manual
	. Strength and quality requirements . Rebound . Inspection	
	8.2 Testing during construction . Methods of sampling . Number of samples . Depths and locations of samples taken from tunnel liner . Curing . Time of sampling . Method of testing . Strength and quality requirements . Backfilling of liner where samples taken . Rebound	8.1
9. Defective Shotcrete	9.1 Inspection . Time . Access . Lighting	9.2.3
	9.2 Nature of Defect . Laminations . Segregation . Shrinkage cracking . Sagging	9.2.3

	9.3 Remedial Work
	. Method
	  . additional shotcrete
	  . other support-rock bolts and/or steel ribs
	  . removal of defective shotcrete
	    . temporary support	

10. Safety and Environmental Considerations	10.1 Responsibility of Contractor	
	10.2 Protection from Toxic Materials	8.2.1
	10.3 Air and Water Pollution, Noise and Lighting	8.2.2
11. Measurement and Payment	11.1 Basis for Measurement . Volume through nozzle . Cement and accelerator . Weight-volume conversion . Wasted or defective shotcrete	9.2.4
	11.2 Payment . Unit price per cubic meter (yd) . Price per lineal meter (foot) of tunnel . Non-pay item	

as possible. Most of these topics have been discussed in the previous
chapters or can be found in recommended standards of the ACI Committee
on Shotcrete (1966 and 1975). Reference is made in Table 9.1 to sections
of this manual dealing with the different topics. The order of topics
in the table is nearly the same as the order of subjects treated in
actual specifications. Some of the topics, such as "field trials," have
been rearranged; field trials are usually found under mix design but have
been given herein under quality control. Topics not previously discussed
in this manual are described in the remainder of this chapter. A set of
actual specifications has been given in Appendix E. These specifications
are provided for information only and are not intended to be duplicated
for future shotcrete work.

9.2 Specification Topics Not Previously Discussed in this Manual

9.2.1 Description of Work

A general description of the shotcrete work to be completed by the
contractor is presented in the first section of the specifications. This
work would include preparation of the tunnel surface, shotcrete applica-
tion, and clean-up of rebound after application is complete. The specifi-
cation should note that all work is to be done in accordance with the
contract drawings and specifications. Specific reference is usually made
to the thickness of shotcrete, number of layers, locations in the openings,
tunnel geometry and surface finish as shown in the contract drawings or
as directed by the engineer. Work to be performed under the shotcrete
specifications also includes furnishing the materials, equipment and labor

needed for the job and assisting in quality control. Any restrictions
to or modifications of normal application should be noted.

9.2.2 Quality Control

Strength

The specified compressive strengths must be the same for pre-construction
testing as for actual application during construction. Requirements for
early strength are needed so that placement of poor quality shotcrete can
be detected early and necessary corrections can be made before large
volumes are placed. The following minimum strength requirements should
be specified for shotcrete which contains accelerator and is used for
structural support:

Table 9.2 Compressive strength requirements for shotcrete

Time	Compressive Strength f_c' [1]	
	kg/cm^2	(psi)
8 hr	50	(750)
24 hr	100	(1500)
3 day	200	(3000)
28 day	275	(4000)

[1]For specimens with length/width or length/diameter = 2

If these strengths cannot be achieved in the majority of the shotcrete
samples, the liner will not have the strength or durability needed for
long-term structural support. Strengths below these minimum values are
usually the result of inferior or incompatible materials, equipment mal-
function or contamination, and/or improper placement or curing techniques.

Every effort must be made to correct the deficiencies in the shotcrete operation so that the desired quality of shotcrete is achieved.

Shotcrete in the lining is usually accepted when a certain percentage (e.g., 80% -Blanck, 1974) of the strength tests yield values at or above those specified in the contract documents. Sections of tunnel having a lower percentage of strengths passing the specifications are considered to be defective and require remedial work (as described in the following section).

The strength limits given in Table 9.2 can also be used as guidelines for shotcrete applied for non-structural purposes (e.g., blocking of rock against steel ribs), provided allowances are made for long-term strength reductions when a rapid set must be obtained and high accelerator dosages must be used (e.g., to prevent ground water flow). The strength and quality of the shotcrete even for nonstructural purposes must be sufficient to ensure adequate performance during construction. In many cases, not enough attention is given to the application of nonstructural shotcrete, with the result that repair or replacement of the lining is required during construction. Therefore, these strength requirements must be specified for nonstructural shotcrete which is designed as a permanent part of the tunnel lining.

Compressive strength tests during construction need not be made for a given quantity of shotcrete (40 m^3[50 yd^3]- Bawa, 1974) at all of the times given in Table 9.2; however, at least one series of tests must be performed. Specification of these strength values allows the contracting officer or resident engineer to check suspected areas of defective shotcrete and to enforce the quality control requirements at a number of different times after shooting. Two of the most critical strength tests

are those at 8 hours and 3 days. The 8 hour test provides an indication of the cement-accelerator compatibility and the gain in early strength, whereas the test at 3 days serves as an index of the ultimate strength since the compressive strength at this time is sensitive to laminations and defects in the sample.

The contract specifications should also include requirements for minimum flexural strengths as a certain percentage (15-20%) of the compressive strength for the same age. The flexural strength should be specified since it is very sensitive to the quality of the shotcrete and it partially controls the capacity of thin linings used for initial ground control.

Rebound

At present maximum allowable rebound is not specified in tunnel contracts. A specification of this type, however, may help to reduce excessive rebound, thereby decreasing cost and reducing chances for rebound entrapment in the shotcrete lining. The maximum allowable rebound values specified will depend on the shotcrete process used (dry- or wet-mix) and on the location of application (sidewall or arch). Suggested maximum allowable values are given in Table 9.3. The exact values specified should be adjusted to the anticipated ground conditions; higher values would be

Table 9.3 Suggested maximum allowable rebound

	Dry-mix	Wet-mix
Arch	40%	20%
Sidewalls	30%	15%

used in wet conditions. Preliminary estimates of rebound can be obtained during the pre-construction testing; however, the first trials are likely to produce higher rebound percentages than those specified. The contractor should be able to demonstrate that he can meet the rebound requirements without sacrificing shotcrete strength before construction begins. During construction rebound should not only be estimated but should be measured periodically to ensure that the rebound is at or below the allowable limits. Guidelines for conducting rebound tests are provided in Appendix D. These tests should be conducted underground during actual shooting rather than on plywood forms.

9.2.3 Defective Shotcrete

Shotcrete defects commonly mentioned in the specifications include: laminations, sand pockets, segregation, shrinkage cracks, and sagging or loss of bond between the shotcrete and rock. Areas of the shotcrete lining not meeting the specified strength requirements may also be considered defective. The locations of defective shotcrete are reported and are marked for remedial treatment. These areas must be treated since the defects can cause failure of the shotcrete lining during or after construction and are highly susceptible to long-term deterioration.

Specifications commonly require that defective shotcrete be removed and replaced at the contractor's expense. This is rarely done in practice except for scaling of small shotcrete slabs. Removal of shotcrete is difficult and can be dangerous, particularly in areas of active rock load. Nevertheless, removal and replacement of defective areas of the final lining may occasionally be required when there are close tolerances on the thickness of the liner and the dimensions of the opening. In these cases

other supplementary support elements such as rock bolts and/or steel ribs should be used to ensure the stability of the opening (Fig. 9.1). This supplementary support should be placed in advance of the remedial work. Steel ribs used in this way should not be removed until the new shotcrete has gained sufficient strength to carry the design loads (approximately 7 days). The outer edges of the shotcrete layer outside the defective area should be gently tapered so that the fresh shotcrete will obtain a good bond with the adjacent portion of the lining and rebound will not be trapped along the shotcrete contact (Fig. 9.1).

Where possible, areas of defective shotcrete can be most safely and simply treated by applying additional shotcrete to the tunnel surface. For treatment of thin linings, the shotcrete need only be placed in the immediate area of the defect and not over extensive portions of the tunnel surface. The fresh shotcrete should have approximately the same thickness as the original layer and should overlap onto adjacent areas of good quality shotcrete (Fig. 9.2). The overlap in adjacent areas should be at least one-half the average lateral dimension of the defective area or the width of the opening, whichever is smaller, and should be gently tapered on its ends. When additional shotcrete is used to compensate for defects in the final lining, it must be sprayed in the arch and sidewalls to ensure that a continuous liner is obtained throughout the treated area.

9.2.4 Measurement and Payment

Unit Price per Cubic Meter (Yard)

The most common method for measurement and payment is based on the quantity of solid material gunned through the nozzle. This method is the

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defective
shotcrete

rock bolt

temporary
steel rib

shotcrete
removed

tapered
surface
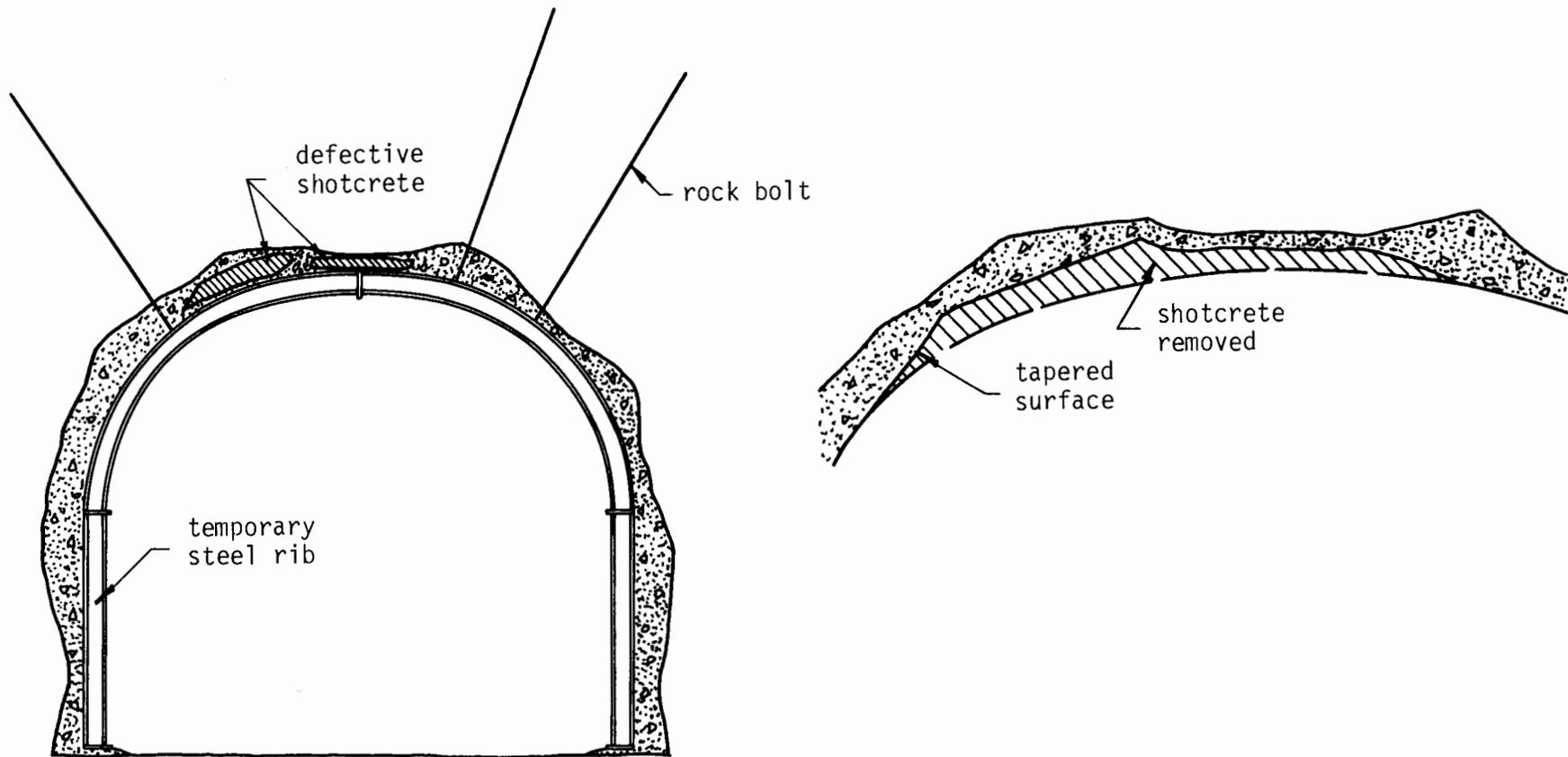
FIG. 9.1   REPAIR OF LINER CONTAINING DEFECTIVE SHOTCRETE.

defective
shotcrete

CROSS SECTION VIEW

remedial
shotcrete

rock
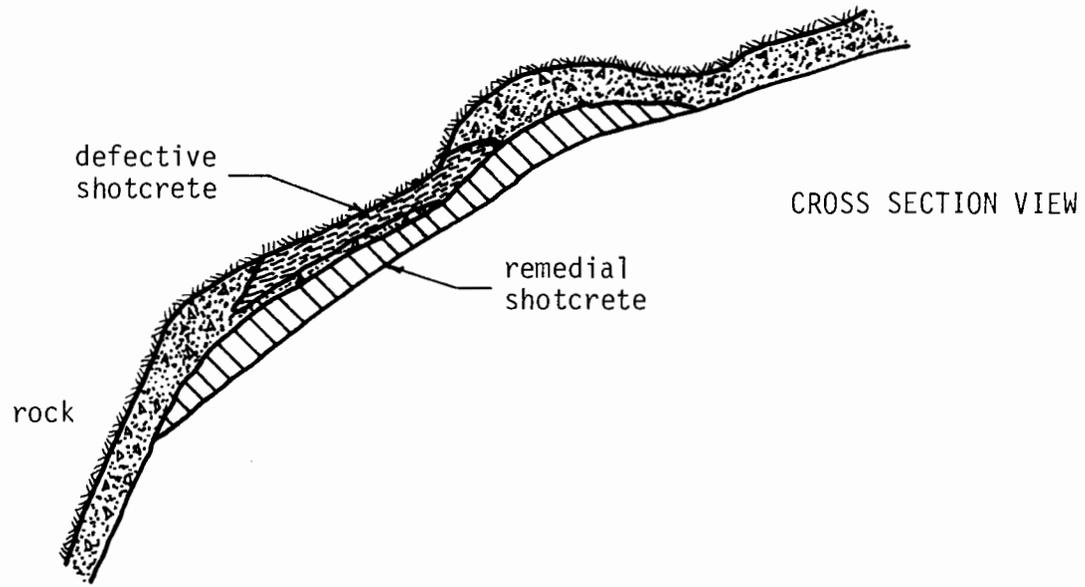
FIG. 9.2 REPAIR OF THIN SHOTCRETE LAYER.

simplest to measure since the amount of material through the nozzle can be determined from the batch weights of the cement and aggregate. Measurement of shotcrete for payment does not include shotcrete necessary to strengthen or replace defective shotcrete, shotcrete placed outside the specified excavation line, or wasted shotcrete (e.g., shotcrete which must be discarded because of prehydration).

Payment is usually by unit price per cubic meter (yard) of material gunned through the nozzle and accepted by the engineer or contracting officer. For payment purposes, the assumption that 2100-2250 kg (3500-3800 lb) equals one cubic meter (cubic yard) is made to convert the batch weights into volume. The upper range of weights per unit volume (2250 kg/m^3 [3800 lb/yd^3]) are specified to compensate for bulking of the aggregates as a result of moisture contents above saturated surface-dry, and for rebound. The actual volume shot through the nozzle is unknown. Cement and accelerator are measured and paid for as separate items. The unit price per cubic meter (yard) includes all material, equipment, and personnel costs needed to place the shotcrete.

This method of measurement and payment does not provide the contractor with an incentive for minimizing rebound but instead encourages rapid placement of as much shotcrete as possible. High air pressures associated with rapid placement of shotcrete usually increase rebound, the cost of which must be paid by the owner. For this reason, maximum allowable rebound values (e.g., 30%) should be specified when payment is made through the nozzle. No payment should be made for rebound above this limit. Payment through the nozzle is advantageous for the contractor since it provides income while the work is being performed, thereby easing cash flow problems.

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Cost per Lineal Meter (Foot) of Tunnel

A second method of payment is based on a unit length of tunnel, shotcreted to the thickness specified in the contract drawings. All costs for materials, equipment, and labor are included in the unit price per lineal meter (foot) of completed tunnel. This method of payment gives the contractor an incentive to control rebound more closely since he is paid only for the shotcrete in-place. This payment method gives the contractor an incentive to submit claims for additional shotcrete required to fill overbreak caused by natural geologic structures. In reducing rebound, the contractor may deliberately try to incorporate or "roll" rebound into the lining. Careful field inspection is needed to prevent inclusion of rebound and to ensure that the lining is completed to the required thickness. Specifying the use of an air blowpipe to remove rebound can also reduce rebound entrapment. Payment for shotcrete per lineal meter (foot) of tunnel does not provide income for the contractor until a portion of the tunnel liner is complete and thus may help cause cash flow problems.

REFERENCES

AASHTO T 26 (1972), "Quality of Water to be Used in Concrete," Highway Materials, AASHTO.

ACI Committee 614 (1958), "Recommended Practice for Measuring, Mixing, and Placing Concrete," J. ACI (November), pp. 535-565.

ACI Committee 506 (1966), "ACI Standard, Recommended Practice for Shotcreting (ACI 506-66)," ACI SP-14, pp. 196-217.

ACI Committee 304 (1971), "Placing Concrete by Pumping Methods," 18 pp.

ACI Committee 211 (1974), "Recommended Practice for Selecting Proportions for Normal and Heavy Weight Concrete," 19 pp.

ACI Committee 506 (1975), "ACI Standard, Recommended Practice for Shotcreting (ACI 506-75)" (in print)

Alberts, C. (1963), "Sprängning i doliot berg med ROBOT Sprutning," Protocol from the 1963 meeting of the Swedish Rock Blasting Committee, Stockholm.

Alberts, C. (1965), "Bergförstärkning genom Beton sprutning och Injectering," Proceedings, 1965 Rock Mechanics Symposium, The Swedish Academy of Sciences, Publication 142, Stockholm.

Alberts, C. and S. Backstrom (1971), "Instant Shotcrete Support in Rock Tunnels," Tunnels and Tunneling, Jan., pp. 29-32.

Alberts, C. (1974), "Use of Remote Controlled Spraying Nozzle," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 65-78.

Anderson, G. L. and M. E. Poad (1974), "Early Age Strength Properties of Shotcrete," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 277-296.

ASTM (1931), "A Study of the Analysis of Fresh Concrete," Proc. ASTM Vol. 31, Part I, pp. 362-381.

ASTM (1974), American Society for Testing and Materials, Part 14, Concrete and Mineral Aggregates; Manual of Concrete Testing, 612 pp.

Barnard, P. D. and R. E. Tobin (1966), "Structural Quality Lightweight Shotcrete," ACI SP-14, Shotcreting, pp. 123-137.

Bates, R. C. (1974), "Shotcrete Safety and Environmental Control," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 130-142.

Bawa, K. S. (1974), "Development of Shotcrete for Metro Construction in Washington," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 33-49.

Blanck, J. A. (1974), "Shotcrete Durability and Strength - A Practical Viewpoint," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 320-329.

Bortz, S. A., E. Aleshin, T. B. Wade and Y. P. Chugh (1973), "Evaluation of Present Shotcrete Technology for Improved Coal Mine Ground Control," IIT Research Institute, Bu. Mines Report OFR-54-73, p. 219.

Brekke, T. L. and R. Selmer-Olsen (1965), "Stability Problems in Underground Construction Caused by Montmorillonite-Carrying Joints and Faults," Engineering Geology, V. 1, No. 1, pp. 3-19.

Brekke, T. L. (1972), "Shotcrete in Hard-Rock Tunneling," Bulletin of the Association of Engineering Geologists, Vol. IX, No. 3, pp. 241-264.

Brierley, G. S. (1975), "The Performance During Construction of the Liner for a Large, Shallow Underground Opening in Rock," Ph.D. Thesis, University of Illinois, Urbana.

Case, L. A. (1974), "Quality Control and Application - New Melones Project," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 235-245.

Cecil, O. S. (1970), "Correlations of Rock Bolt-Shotcrete Support and Rock Quality Parameters in Scandinavian Tunnels," Ph.D. Thesis, University of Illinois, Urbana.

Chitunda, J. K. (1974), "Shotcrete Methods at Lakeshore Mine Aid Overall Ground Support Program," Mining Engineering, Dec., pp. 35-40.

Cording, E. J. (1967), "The Stability During Construction of Three Large Underground Openings in Rock," Ph.D. Thesis, University of Illinois, Urbana.

Cording, E. J., A. J. Hendron, Jr., D. U. Deere (1971), "Rock Engineering for Underground Caverns," Symposium on Underground Rock Chambers, ASCE, pp. 567-600.

Cording, E. J. and D. U. Deere (1972), "Rock Tunnel Supports and Field Measurements," Proceedings, North American Rapid Excavation and Tunneling Conference, AIME, 1:601-622.

Cording, E. J. (1974), "Geologic Considerations in Shotcrete Design," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 175-199.

Cording, E. J., A. J. Hendron, Jr., H. H. MacPherson, W. H. Hansmire, R. A. Jones, J. W. Mahar, T. D. O'Rourke (1975), "Methods for Geotechnical Observation and Instrumentation in Tunneling," Report for National Science Foundation, (in print).

Corps of Engineers (1974), "Shotcrete for Multipurpose Tunnel, New Melones Lake, Stanislaus River, California," Corps of Engineers, U. S. Army, Sacramento District, Sacramento, California, 87 pp.

Crom, T. R. (1966), "Dry-Mix Shotcrete Practice," ACI SP-14, Shotcreting, pp. 15-32.

Deere, D. U. and R. P. Miller (1966), "Engineering Classification and Index Properties for Intact Rock," National Technical Information Service, Springfield, Va. 22151, AD 646 10, p. 50.

Deere, D. U., R. B. Peck, J. E. Monsees and B. Schmidt (1969), "Design of Tunnel Liners and Support Systems," Report to Office of High Speed Ground Transportation, U. S. Department of Transportation, Contract No. 3-0152, NTIS No. PB 183 799, 287 pp.

Deere, D. U., A. H. Merritt, E. J. Cording (1974), "Engineering Geology and Underground Construction," 2nd International Congress of the International Association of Engineering Geology, San Paulo, Brazil, Vol. 2, 27 pp.

Fernandez-Delgado, G., J. Mahar, E. Cording (1975), "Shotcrete, Structural Testing of Thin Liners," Report for Department of Transportation, Federal Railroad Adminiskration, Washington, D. C., 219 pp.

Fluss, P. J. and G. E. Gibson (1966), "Shotcrete Repairs of Waterfront Substructures," ACI SP-14, Shotcreting, pp. 85-92.

Fredericks, J. C., N. R. Saunders and J. T. Broadfoot (1966), "Recent Developments in Positive Displacement Shotcrete Equipment," ACI SP-14, Shotcreting, pp. 75-83.

Gillespie, P. and P. J. Culliton (1924), "Gunite Protection for Steel Structures," Canadian Engineer, Vol. 47, No. 18, October 28, pp. 451-454 and Vol. 47, No. 19, November 4, pp. 473-476.

Henager, C. H. (1975), "A New Wrinkle - Shotcrete Containing Steel Fibers," Concrete Construction, August, pp. 345-347.

Hendricks, R. S. (1969), "HECLA Mining Company Case Study," Proceedings, Second Symposium on Rapid Excavation, Sacramento State College, Sacramento, California, October, pp. 7-1 to 7-38.

Heuer, R. E. (1974), "Selection/Design of Shotcrete for Temporary Support," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 160-174.

Hoffmeyer, T. A. (1966), "Wet-Mix Shotcrete Practice," ACI SP-14, Shotcreting, pp. 59-74.

Hopper, R. C., T. A. Lang and A. A. Mathews (1972), "Construction of Straight Creek Tunnel, Colorado," Proceedings, Vol. 1, North American Rapid Excavation and Tunneling Conference, Lane and Garfield, ed., American Institute of Mining, Metallurgical and Petroleum Engineers.

IITRI (1973), "Evaluation of Present Shotcrete Technology for Improved Coal Mine Ground Control," Illinois Institute of Technology Contract No. H0111881, prepared for Spokane Mining Research Center, U. S. Bureau of Mines.

Jones, R. C. (1974), "Shotcrete Practices at the Henderson Mine," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 50-57.

Kaden, R. A., (1973), "Field Placement of Fibrous Shotcrete at Ririe Dam," Lecture notes for a shot course given in July at the Joint Center for Graduate Study, Richland, Washington.

Kaden, R. A. (1974), "Slope Stabilized with Steel Fibrous Shotcrete," Western Construction, April, 3 pp.

Karlsson, L. and J. O. Fryk (1963), "Verstarkungsarbeiten im Unterwassertunnel des Wasserkraftwerkes Holjes in Schweiden/Lavori di Rinforzo Nella Galleria di Valle Dell'impianto Elettrico Holjes," Hoch-und Tiefbau/ L'Entreprise, Zurich, No. 50.

Kastner, H. (1962), "Statik des Tunnel und Stollenbaues," Springer-Verlag, Berlin, Gottingen, Heidelberg.

Keifer, Jr., O. (1966), "Multiple Layer Shotcrete Tunnel Lining," ACI SP-14, Shotcreting, pp. 93-97.

Kempster, E. (1969), "Pumpable Concrete," Current Paper No. 29/69, Building Research Station, England, August.

Kesler, C. E. (1966), "Strength," ASTM, Spec. Tech. Publication 169-A, pp. 144-159.

Kidd, B. C. (1973), "Use of Shotcrete in Tunnel Construction," Tunneling in Rock, Div. of SM and FE South African Institute of Civil Engineers, pp. 389-416.

Klosterman, R. L. (1968), "Large Aggregate Shotcreting: Look to the Future," Paper presented at 74th Annual Convention of Northwest Mining Association, Spokane, Washington, Dec. 1968.

Kobler, H. G. (1966), "Dry-Mix Coarse-Aggregate Shotcrete as Underground Support," ACI SP-14, Shotcreting, pp. 33-58.

Litvin, A. and J. J. Shideler (1966), "Laboratory Study of Shotcrete," ACI SP-14, Shotcreting, pp. 165-184.

Lorman, W. R. (1968), "Engineering Properties of Shotcrete," ACI SP-14A, 53 pp.

Mahar, J. W., F. L. Gau and E. J. Cording (1972), "Observations During
    Construction of Rock Tunnels for the Washington, D. C. Subway,"
    Proceedings, North American Rapid Excavation and Tunneling Conference,
    Lane and Garfield, ed., American Institute of Mining, Metallurgical
    and Petroleum Engineers.

Mason, E. E. (1970), "The Function of Shotcrete in Support and Lining of the
    Vancouver Railway Tunnel," Rapid Excavation - Problems and Progress,
    Soc. of Mining Engineers of AIME, pp. 334-346.

Mason, E. E. and R. E. Mason (1972), "Shotcrete Support with Special
    Reference to Mexico City Drainage Tunnels," Rock Mechanics, Vol. 4,
    No. 2, pp. 115-128.

Nussbaum, H. (1973), "Recent Development of New Austrian Tunneling Method,"
    Journal of the Construction Division, ASCE, Vol. 99, No. CO1, July,
    pp. 115-132.

OSHA (1972), Occupational Safety and Health Act as reported in "Self-
    Evaluation Checklist/Based on OSHA Standards, General Industry -
    Part 1910," National Safety Council, Vol. 1-10 (updated periodically).

Orchard, D. F. (1973), Concrete Technology, Volume 2, 3rd edition, John
    Wiley & Sons, 444 pp.

Osborne, G. J. and M. A. Smith (1974), "Exploratory Studies of Regulated-Set
    Cements," Cement Technology (London) Vol. 5 No. 3, May-June, pp. 335-
    354.

Ounanian, D. W., G. T. Halvorsen, C. E. Kesler (1975), "Concrete for Tunnel
    Liners: Pumpable Fiber Reinforced Concrete," Rept. No. FRA-OR&D-75-88
    Dept. of Transport., Fed. Railroad Admin., 45 pp.

Parker, H. W., R. M. Semple, A. Rokhsar, E. Febres-Cordero, D. U. Deere
    and R. B. Peck (1971), "Innovations in Tunnel Support Systems,"
    Report to Office of High Speed Ground Transportation, U. S. Department
    of Transportation, Contract No. DOTFR00023.

Parker, H. W. (1974), "Current Field Research Program on Shotcrete," Use of
    Shotcrete for Underground Structural Support, ASCE and ACI SP-45,
    pp. 330-350.

Parker, H. W., G. Fernandez, L. J. Lorig (1975), "Field-Oriented Investiga-
    tion of Conventional and Experimental Shotcrete," Report for Department
    of Transportation, Federal Railroad Administration, (in print).

PCA (1968), Principles of Quality Concrete, Portland Cement Association,
    John Wiley & Sons, Inc., 312 pp.

Peck, R. B. (1969), "Deep Excavations and Tunneling in Soft Ground,"
    State-of-the-Art Volume, 7th International Conference in Soil Mechanics,
    Mexico, pp. 225-290.

Poad, M. E. and M. O. Serbousek (1972), "Engineering Properties of Shotcrete," Proceedings, North American Rapid Excavation and Tunneling Conference, ed. by Lane and Garfield, American Institute of Mining, Metallurgical and Petroleum Engineers, pp. 573-591.

Poad, M. E., M. O. Serbousek and J. Goris (1975), "Engineering Properties of Fiber-Reinforced and Polymer-Impregnated Shotcrete" USBR, Report of Investigations 8001, 25 pp.

Rabcewicz, L., (1964-65), "The New Austrian Tunneling Method, Parts I, II, III," Water Power, London, Nov.-Dec. 1964, Jan. 1965.

Rabcewicz, L. (1969), "Stability of Tunnels Under Rock Load, Parts I, II, III," Water Power, June, pp. 225-234, July, pp. 266-273, Aug., pp. 297-302.

Reading, T. J. (1966), "Shotcrete as a Construction Material," ACI SP-14, Shotcreting, pp. 1-14.

Reading, T. J. (1974), "Corps of Engineers Studies of Shotcrete," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 263-276.

Romualdi, J. P. and J. A. Mandel (1964), "Tensile Strength of Concrete Affected by Uniformly Distributed and Closely Spaced Short Lengths of Wire Reinforcement," Proceedings, ACI, Vol. 61, No. 6, pp. 657-670.

Rutenbeck, T. (1974), "New Developments in In-Place Testing of Shotcrete," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 246-262.

Ryan, T. F. (1973), Gunite - A Handbook for Engineers, Cement and Concrete Association, London, England, 62 pp.

Ryan, T. (1975), "Steel Fibres in Gunite - An Appraisal," Tunnels and Tunnelling, July, pp. 74-75.

Sallstrom, S. (1970), "Improving Initial Compressive Strength of Shotcrete by Accelerating Admixtures," Large Permanent Underground Openings, ed. by Brekke and Jørstad, Universitetsforlaget, Oslo, pp. 227-232.

Sandell, B. (1968), "Erfarenheter fron Tätning av Tunnlar med Hjälp av Injektering och Sprutbetong," Norsk Besab A/S, Oslo, Norway.

Selmer-Olsen, R. (1971), "Problems with Swelling Clays in Norwegian Underground Constructions in Hard-Rocks," Stability and Strengthening of Rock Tunnels in Scandinavia, Swedish Geotechnical Institute, No. 40, pp. 1-22.

Semple, R. M. (1973), "The Effect of Time-Dependent Properties of Altered Rock on Tunnel Support Requirements," Ph.D. Thesis, University of Illinois, Urbana.

Semple, R. M., A. J. Hendron, Jr. and G. Mesri (1973), "The Effect of Time-Dependent Properties of Altered Rock on Tunnel Support Requirements," UIUC Final Report for the Federal Railroad Administration, NTIS No. PB 203 307.

Singh, M. M. and S. A. Bortz (1974), "Use of Special Cements in Shotcrete," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 200-231.

Steenson, H. N. (1974), "Using Accelerator - Wet Process," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 104-113.

Studebaker, C. H. (1939), "Report on Gunite at Arrowrock Dam," USBR Memorandum, U. S. Bureau of Reclamation, Mar.

Sutcliffe, H. and C. R. McClure (1969), "Large Aggregate Shotcrete Challenges Steel Ribs as a Tunnel Support," Civil Engineering, New York, Nov., p. 51.

Terzaghi, K., Theoretical Soil Mechanics, Wiley, New York, 1943.

Tinsley, E. C., and H. L. Kalousek (1966), "Pneumatic Gunning of Refractory Castables," ACI SP-14, Shotcreting, pp. 139-154.

Troxell, G. E., H. E. Davis, J. W. Kelly (1968), Composition and Properties of Concrete, Second Edition, McGraw-Hill, 513 pp.

Tynes, W. D. and W. F. McCleese (1974), "Investigation of Shotcrete," Technical Report C-74-5, U. S. Army Engineer Waterways Experiment Station, Concrete Laboratory, Vicksburg, Miss., 38 pp.

USBR (1963), Concrete Manual, U. S. Bureau of Reclamation, 7th ed., U. S. Government Printing Office, Washington, D. C., 642 p.

Valencia, F. E. (1974), "Practical Aspects of Shotcrete Application," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 114-129.

Vollick, C. A. (1966), "Uniformity and Workability," ASTM, Spec. Tech. Publication 169-A, pp. 73-89.

Wagner, H. (1970), "The New Austrian Tunnelling Method," The Technology and Potential of Tunnelling, Vol. 1, South African Tunnelling Conference, 1970, pp. 121-127.

Westergaard, H. M., "Plastic State of Stress Around a Deep Well," Journal, Boston Soc. CE, Vol. xxvii, Jan., 1940, pp. 387-391.

Wickham, G. E., H. R. Tiedemann and E. H. Skinner (1974), "Ground Support Prediction Model RSR Concept," Proceedings, North American Rapid Excavation and Tunneling Conference, AIME, 1:691-707.

Witte, J. (1970), "Combining Mole, Belt, Shotcrete," Western Construction, Vol. 45, No. 5, May, pp. 39-43.

Zynda, S. G. (1966), "Properties of Sand-Mix Shotcrete," ACI SP-14, Shotcreting, pp. 155-164.

APPENDIX A

DESCRIPTION OF EXPERIMENTAL SHOTCRETES

A.1 Regulated-Set Shotcrete

Regulated-set cement (reg-set) is a new portland cement containing calcium fluoroaluminate; the cement is patented by the Portland Cement Association and is now available commercially. Reg-set is an entirely new cement, not a mixture of different types of cements or accelerators; all ingredients are blended in the kiln. The calcium fluoroaluminate significantly alters the setting time and strength of the cement during the first several hours after mixing. At room temperature, regulated-set cement begins to set in about 10 minutes after mixing even without additives; set occurs almost immediately if it is mixed with hot water at about 40°C (100°F).

When reg-set cement is substituted for portland cement and accelerator, in shotcrete, the initial rate of strength gain is very rapid for the first few hours. The compressive strength of reg-set shotcrete during this period typically ranges between 70 to 140 kg/cm^2 (1000 to 2000 psi) depending upon the cement content of the mix, the percentage of calcium fluoroaluminate in the cement itself, and the temperature of the ingredients (Bortz, et al., 1973 and Parker, et al., 1975) (Fig. A.1). The rate of strength gain reduces as the hydration of the calcium fluoroaluminate subsides. After about one day the rate of strength gain and the physical properties of regulated-set shotcrete are similar to those of shotcrete containing Type 1 cement.
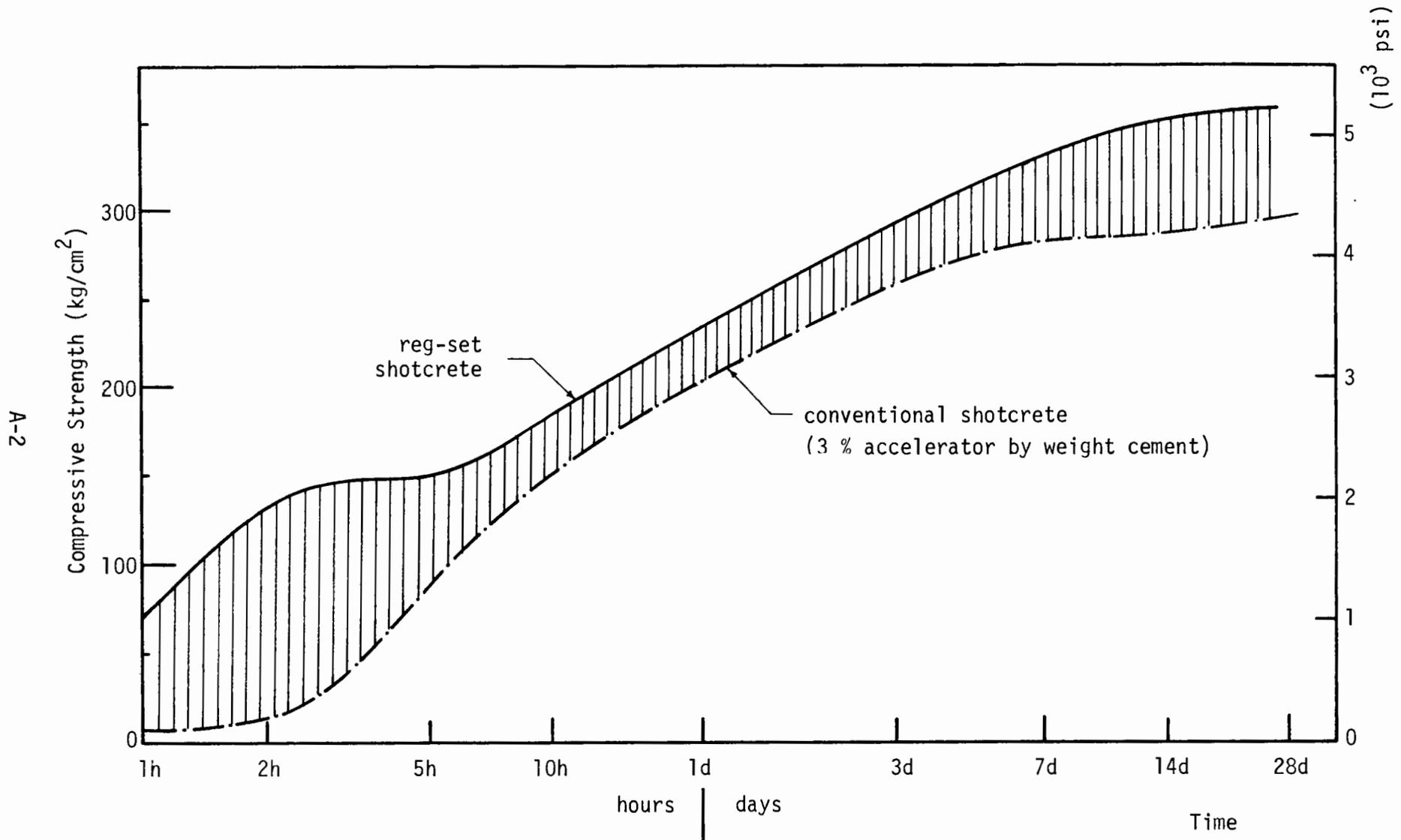
FIG. A.1   STRENGTH-TIME DATA OF CONVENTIONAL AND REG-SET SHOTCRETE
(DATA FROM BORTZ ET AL., 1973).

A-2

Reg-set cement shotcrete exhibits the greatest superiority over conventional shotcrete at early ages when it can be most beneficial in controlling loosening ground and water inflows. The strength of reg-set shotcrete is higher than that of conventional shotcrete with fast-setting accelerators at all ages; however, the difference becomes less significant with increasing age. The superiority of regulated-set shotcrete is represented by the shaded area in Fig. A.1.

Some of the advantages and disadvantages of regulated-set shotcrete are listed in Table A.1. Because regulated-set cement begins to hydrate as soon as it comes in contact with moist aggregate, the shotcrete mix should be used as soon as possible. Regulated-set shotcrete has been prepared successfully in batch-plant-mixer type operations; however,

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. costs more than regular portland cement.

	2. special handling may be required to reduce time between mixing and shooting
	3. source of hot water is required
2. strength of reg-set shotcrete during first few hours is many times that of comparable conventional shotcrete with accelerators	4. with the present technology, it should not be used with the wet-mix process
3. does not exhibit reduction in 28-day strength experienced with conventional shotcretes containing some accelerators	5. has a low sulphate resistance

A-3

a volumetric, mobile-type, batching unit having a continuous auger-type
mixing operation is recommended for regulated-set shotcrete so that
mixing can be performed immediately before shooting. Use of mobile-type
equipment will minimize chances for premature hydration of this very active
cement. Typical crews and equipment employed on tunnel projects for civil
engineering purposes have been used to shoot reg-set shotcrete underground
as part of a field research project (Parker et al., 1975). No major dif-
ficulties with equipment or performance of personnel were encountered
during these shootings. Reg-set cement sets too fast to be used in routine
wet-mix applications. Shotcrete with reg-set cement may be less hazardous
than conventional shotcrete with accelerators, because the cement is usually
shipped in bulk quantities and does not have to be handled during batching.
Reg-set cement has a low sulphate resistance because of its high aluminum
content (Osborne and Smith, 1974).

To shoot reg-set shotcrete successfully, the temperature and moisture
content of the aggregate and cement must be controlled and equipment must
be available for heating the water injected at the nozzle. The aggregate
should not contain more than 5-6% moisture by weight; higher moisture con-
tents facilitate pre-hydration during preparation and gunning of the shot-
crete. In addition, the temperature of the cement and aggregate should not
be more that 15° C (60°F). Although hydration begins as soon as the cement
comes in contact with moist aggregate, a flash set usually does not occur at
temperatures below 15° C (60°F). Best results have been obtained when the
water injected at the nozzle has heated to approximately 30-40° C (80-100°F)
(Parker, et al., 1975); however, field trials should be conducted to deter-
mine the optimum water temperature at which the strength gain of the in-place

shotcrete is most rapid and rebound is lowest. If the temperature of the water is too high, a flash set occurs in the shotcrete as it leaves the nozzle or soon after it strikes the surface. The disturbance to the initial set as the shotcrete is impacted on the surface produces a large decrease in its initial strength gain and in the intermediate and long-term strength as compared with properly gunned mixes. The optimum water temperature depends not only on the temperature of the solid ingredients and the water injected at the nozzle, but also on the temperature of the rock surface and ground water, the ambient temperature, and the thickness of the layer. Standard, high-capacity water heaters placed in the supply line can be used to heat the water injected at the nozzle.

At present the availability of regulated-set cement is limited; the only known commercial source in the United States is the Huron Cement Co., Alpena, Michigan. A list of the few sources including those outside the United States can be obtained from the Portland Cement Association. Early supplies of the cement required soda ash as an accelerator; however, the current cements have contained all the ingredients needed to achieve a very rapid set without additives. Soda ash can still be added to further reduce the set time. At the present time, quality control standards for the reg-set cement do not exist, thus the chemistry and the behavior of the cement vary significantly between the different sources and between different burns from the same source.

The cost of reg-set cement is at least twice that of ordinary Portland cement. This offsets the savings resulting from the elimination of accelerators. However, the use of this cement should not be evaluated on material cost alone since this is only a small fraction of the cost in place. The evaluation should also be made on the basis of the total cost of the support

A-5

in place which includes material costs delivered to the site, rebound losses, design thickness, safety, and its effectiveness in controlling tunnel ground conditions. It is too early to discuss these cost considerations; however, under certain conditions such as blocky ground having a short stand up time reg-set shotcrete may be competive with conventional shotcrete.

There are no known tunnels that have been supported by regulated-set shotcrete. A laboratory study on regulated-set shotcrete has been completed by the IIT Research Institute (Bortz, et al., 1973; Singh and Bortz, 1974; and Anderson and Poad, 1974). Field tests on regulated-set shotcrete are reported by Parker, 1974; and Parker, et al., 1975.

A.2 Steel Fiber Shotcrete

Steel fiber shotcrete is essentially conventional shotcrete to which steel fiber has been added. The fibers used in shotcrete work are rectangular or circular in cross section and have lengths typically ranging between 20-40 mm (3/4 - 1 1/2 in.); however, 25 mm (1 in.) is most common (Fig. A.2). The fibers are batched with the aggregate and cement and make up between 1-2% of the total volume of the mix (3-6% by weight). One percent by volume is approximately 80 kg/m^3 (132 lbs/yd^3). Fiber contents greater than 2% are difficult to prepare and shoot.

Most experimental work and field applications of steel fiber shotcrete have been made using gunite mixes having a high cement content (Table A.2) rather than coarse aggregate mixes. More recently, steel fibers have been gunned in coarse aggregate mixes with maximum nominal grain sizes up to 13 mm (1/2 in.) (Parker, 1974 and Fernandez et al., 1975). The mix design for coarse aggregate, dry-mix, fiber shotcrete is essentially the same as that used in conventional shotcrete (Table A.3). No published data are

A-6

0.55 mm
(0.022 in.) ⌐
         ⊡‡ ─── 0.25 mm
                 (0.01 in.)

0.25-0.44 mm
─ (0.01-0.016 in.)
  diameter

|← 25 mm →|
| (1 in.) |
─────────────

|← 25 mm →|
| (1 in.) |
─────────────
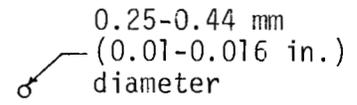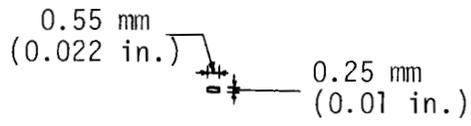
a. Typical fiber with
   rectangular cross
   section

b. Typical fiber with
   circular cross section

c. Photograph of steel fibers

FIG. A-2 TYPICAL FIBERS USED IN SHOTCRETE WORK.

Table A.2 Mix design of fine aggregate, fiber shotcrete (after
          Henager, 1975)

| Material | Weight | | Percent |
	kg/m^3	(lb/yd^3)	(by weight)
Cement	560	(940)	26
Blended Sand (passing 1/4-in. sieve)	1400	(2375)	67
Steel Fiber	140-160	(240-265)	6.7
Accelerator	5	(9)	0.3

Aggregate/Cement = 2.5/1

Accelerator/Cement = 1% (by weight)

Table A.3 Mix design of coarse aggregate, steel fiber shotcrete
          (Fernandez et al., 1975)

| Material | Weight | | Percent |
	kg/m^3	(lb/yd^3)	(by weight)
Cement	300	(660)	17.2
Sand	680	(1500)	39.6
Gravel (passing 1/2 in. sieve)	680	(1500)	39.6
Steel Fiber	80	(130)	3.0
Accelerator	10	(22)	0.6

Aggregate/Cement = 4.5/1

Accelerator/Cement = 3% (by weight)

available on mix design of wet-mix, steel fiber shotcrete; however, standard mixes can be obtained from the concrete literature (Ounanian, Halvorsen and Kesler, 1975). The main consideration in mix design of wet-mix, steel fiber shotcrete is pumpability. Slump tests should not be used to determine the workability of fiber concrete, since the fiber tends to hold the mix together and reduce the measured slump. In some cases, the mix may have a low slump yet still have good workability. On a given project, pumpable mixes should be determined by trial and error to suit field conditions and equipment at the site; however, standard mixes obtained from concrete technology can be used as initial trial mixes.

The presence of steel fiber in shotcrete increases its tensile and flexural strength but does not significantly alter compressive strength above that of conventional shotcrete. Poad and Serbousek (1972) report.that the tensile and flexural strength of fiber shotcrete at 28 days was approximately 10 and 30% higher respectively than that of comparable conventional mixes. Most of the results of compressive strength tests indicate that the ultimate strength of fiber shotcrete is typically 5-20% lower than that of non-fibrous shotcrete (Poad and Serbousek, 1972 and Parker et al., 1975). These lower strength values are probably associated with difficulties in shooting the fiber mixes. Results of on-going research at the University of Illinois suggest difficulties with shooting fiber shotcrete can be overcome using standard equipment and that compressive strength equal to or greater than non-fibrous shotcrete can be obtained.

The greatest difference in behavior of fibrous and non-fibrous shotcrete lies in the ductility or post crack resistance. This is illustrated in Fig. A.3 in which load-deflection data obtained from flexural tests are plotted.

A-9
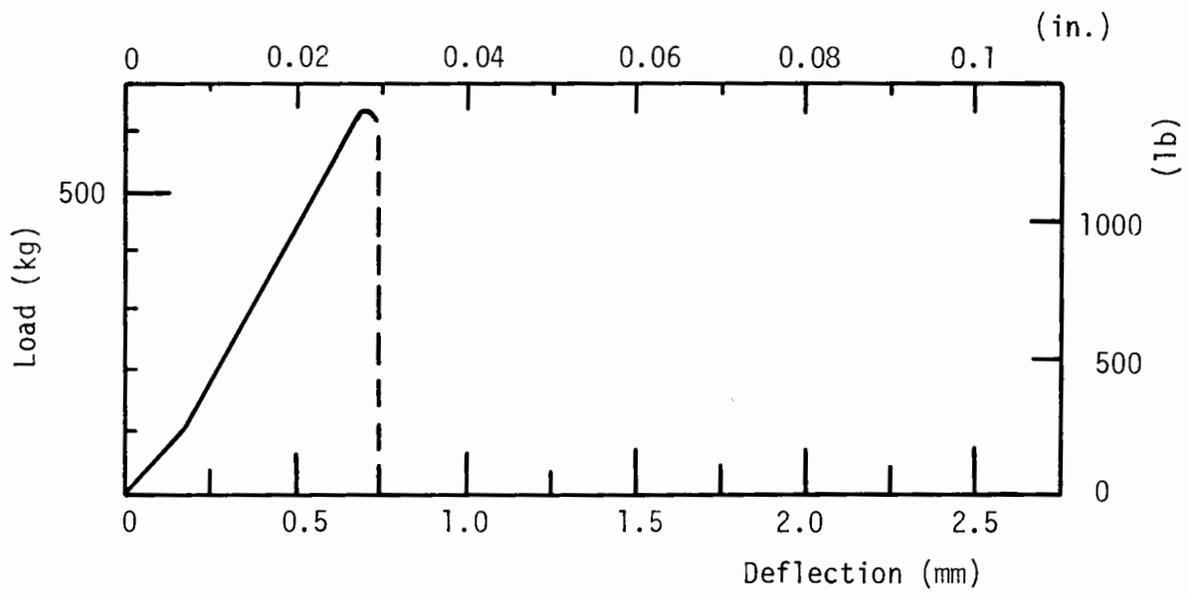
a. Conventional shotcrete
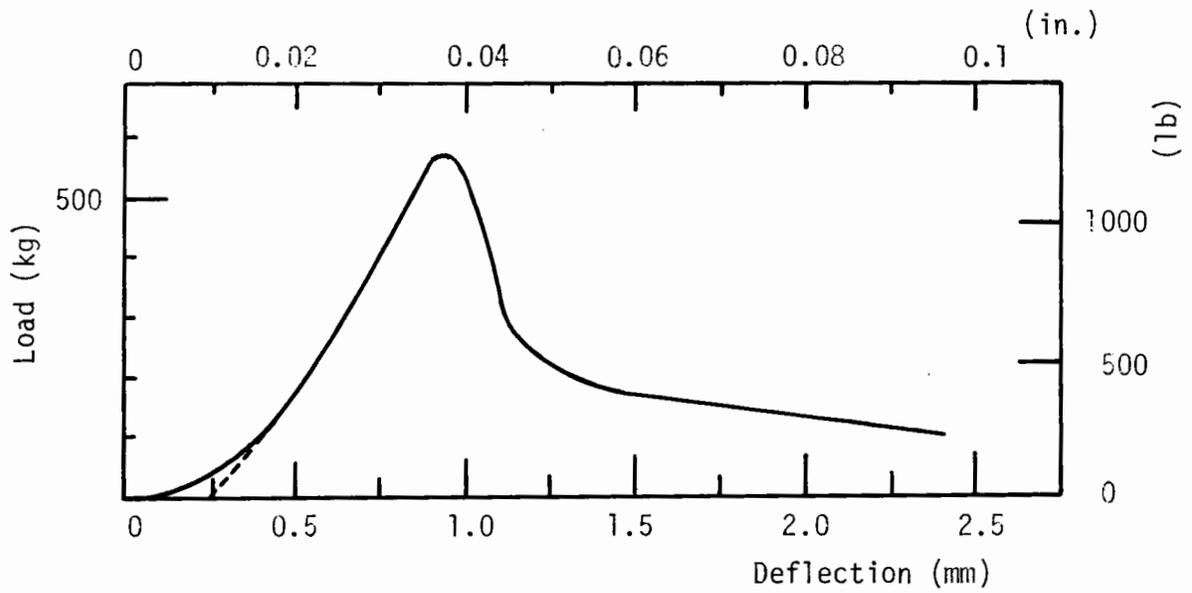
b. Steel fiber shotcrete

FIG. A.3 LOAD-DEFLECTION DATA OF CONVENTIONAL AND STEEL
FIBER SHOTCRETE TESTED IN FLEXURE.

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The specimens were cut from test panels of fibrous and non-fibrous shotcrete and were tested and prepared in the same manner. Once ultimate strength was reached, the non-fibrous specimens failed quickly as a result of the sudden release of energy stored in the testing machine. On the other hand, the steel fiber specimens failed very slowly and were able to absorb the energy of the machine. The fiber shotcrete was able to carry considerable loads (20% ultimate load) even after a large crack developed. These specimens were still carrying load when the test was arbitrarily ended; none of the fibrous specimens tested broke into separate pieces. A similar relationship was observed for fibrous and non-fibrous shotcrete tested in compression. In compression, steel fiber specimens never failed suddenly on reaching maximum load and thay always held together even though the sample was deformed to more than 10 percent strain and had broken up into many pieces. Examination at the failure surfaces reveals that all the fibers fail in adhesion with the matrix rather than in tension. Thus, the full potential of the fibers is not being achieved.

The increased ductility and post-cracked resistance imparted by the fiber improve the overall effectiveness of shotcrete in providing tunnel support and reduce some of the defiencies of conventional mixes, such as brittle behavior. Fiber shotcrete shows great promise for supporting blocky and mildly squeezing ground. Since most of the long axes of the fibers are located in planes parallel to the rock surface, the fibers are in favorable orientations for resisting tensile and flexural stresses. In addition, the presence of fibers reduces the effect of shrinkage and thermally-induced strains that cause cracking of the lining.

The addition of steel fiber to conventional mixes requires careful

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batching and mixing since the fibers tend to ball up and become kinked during preparation. Fiber balls falling into the machine can cause plugs and dangerous projectiles from the material hose and produce an uneven flow to the nozzle. Kinked fibers usually cause poor compaction, which reduces the flexural and compressive strength of the shotcrete significantly compared with that containing unbent fiber. When the fibers are batched they should be separated and dispersed throughout the mix. Separation of the fibers is accomplished by sprinkling them by hand into the materials or by using screens or vibrators. Best results are obtained when the materials are mixed at the same time the fiber is added to the aggregate and cement. In the dry-mix processes, fibers can be batched into aggregates with moisture contents of 5-7% without causing the fibers to ball during mixing. Wetter aggregates may facilitate balling of the fiber, whereas drier aggregates will not be propertly coated with cement. In field and experimental applications fibers have been successfully blended with dry-mix materials using drum-and auger-type mixers; on one project, use of a paddle (pug-mill) mixer caused severe kinking and subsequent balling of the fiber. A screen with openings approximately equal to the maximum nominal size of aggregate should be placed over the machine hopper, so that fiber balls are removed before the mix enters the shotcrete machine.

Some investigators report lower average rebound for fibrous shotcrete, whereas others contend that the presence of fibers do not significantly affect rebound losses. Ryan (1975) found that reducing the particle velocity in the material stream produced a far superior fine aggregate, fiber shotcrete than by shooting at the high pressures and feed rates

A-12

used in shooting conventional mixes. This decrease in velocity reduces the impact energy of the particles and provides a more effective wetting; both reduce rebound significantly. From our experience it appears that if shooting conditions are improved lower rebound results, but the mere presence of fiber in a mix does not affect rebound appreciably.

The rebound of the fibers themselves are extremely high; this is one of the most serious drawbacks of steel fiber shotcrete. Ryan (1975) shows that only 40 percent of the fibers in a prepared mix were present in shotcrete gunned overhead and about 65% were embedded when the shotcrete was sprayed on vertical surfaces. These correspond to rebound values of the fibers themselves of 60 and 35%, respectively. Parker et al. (1975) report fiber retentions of 44 to 88% (average 62%) of the batched fiber for a variety of coarse aggregate shotcrete mixes gunned onto vertical test panels. These measurements of fiber retention were made on samples taken from the outer 25-50 mm (1-2 in.) of a 75 mm (3 in.) layer. Thus, the average rebound of the fibers (35%) does not include the high losses that occur while the critical thickness was being established and represent a lower bound of the total losses. The actual losses for the entire layer are probably 10-20% higher (Parker et al., 1975). With the present cost of steel, such losses are unacceptable, however, several steel fiber shotcrete projects have been computed successfully and economically.

The use of steel fiber shotcrete is comparable with placing a reinforced shotcrete lining, thus the cost of materials will be greater than for conventional shotcrete by at least the cost of fiber. 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 which is located in the inner portion of the lining. 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, however, it may be economically feasible under certain conditions and fiber shotcrete is already being used on several projects.

Steel fiber shotcrete has been gunned using both the wet- and dry-mix processes. Fiber shotcrete is being used routinely in operational coal mines in England and several coal mines in the United States. Ryan (1975) summarizes studies and applications in England and Henager (1975) describes its properties and some of its uses 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, 1973 and 1974). 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); field studies have been performed by Parker, et al., 1975. Steel fiber shotcrete has recently been tested and compared to conventional shotcrete in large-scale tunnel model studies at the University of Illinois (Fernandez, et al., 1975).

APPENDIX B

COMMERCIALLY AVAILABLE SHOTCRETE MACHINES

This appendix summarizes and compares the capabilities and specifications of shotcrete machines manufactured or distributed in the United States. Information used to compile this appendix was taken from the latest available brochures supplied by manufacturers or distributors of the various shotcrete machines. It should be emphasized that all information contained herein was obtained solely from the brochures. In this rapidly changing field, it is expected that new equipment will be developed and old models improved since the publication of this report. Up to date information on the machines should be obtained from the manufacturers. In compiling the data contained in appendix B, every effort was made to obtain information on commercially available shotcrete machines used in underground work; however, it is inevitable that some brands have been unintentionally excluded.

The machines are grouped according to (1) dry-mix guns of rotating barrel or bowl design, (2) dry-mix guns of feed wheel design, and (3) wet mix guns. Performance data and specifications for each type are given in Tables B-1, B-2, and B-3, respectively. Within each of these tables, the shotcrete machines are listed by manufacturer and by model number in cases where more than one model type is made by a single manufacturer. Explanation of the subheadings is given below.

Explanation of Subheadings

Manufacturer - The machines are listed according to the manufacturer; they may be distributed by a number of firms under different names.

Type - Models can be single (s.c.) or double (d.c.) chambered.

Max. Agg. Size - Maximum nominal size of aggregate machine can shoot.

Delivery Rate - The production rate that can typically be expected.

Maximum Horizontal Conveyance - The maximum horizontal distance from the
     shotcrete machine to the nozzle.

Maximum Vertical Conveyance - The maximum vertical distance from the
     shotcrete machine to the nozzle.

Hose Diameter - Primarily dependent on the maximum aggregate size used.
     A 50 mm (2 in.) line is most common, but 75 mm (3 in.) hoses can also
     be accommodated on some models.

Air Consumption - Air driven motor - Volume of air required for a machine
     having an air motor drive for the material feed and a 50 mm (2 in.)
     diameter material hose 30 m (100 ft) in length.

Air Consumption - Gas or electric motor - Volume of air required to place
     shotcrete when the machine is equipped with a material feed powered
     by an electric or gas motor and has a 50 mm (2 in.) diameter material
     hose 30 m (100 ft) in length.

Height - Maximum height from ground to the highest point on the machine.

Width - Maximum overall width.

Length - Maximum length, including tow bar where provided.

Weight - Empty weight with no accessories.

                    *   *   *   *

Note: Specifications are subject to change at any time.

B-2

Table B.1   Performance data and specifications of rotating
barrel and bowl dry-mix shotcrete machines

Mfg.	Model	Max. Agg. Size (mm)	(in)	Delivery (m³/hr)	Rate (yd³/hr)	Maximum Horizontal Conveyence (m)	(ft)	Maximum Vertical Conveyence (m)	(ft)	Hose Diameter (mm)	(in)	Air Consumption- Air Driven Motor (m³/min)	(ft³/min)	Air Consumption- Gas or Electric Motor (m³/min)	(ft³/min)	Height (m)	(ft)	Width (m)	(ft)	Length (m)	(ft)	Weight (kg)	(lbs)
Aliva	300	10	3/8	2-4	2.5-5	200	650	100	300	40-60	1 1/2-2 1/4	12-14	400-500	6-8.5	200-300	1.8	5.9	0.8	2.6	1.5	4.8	950	2100
		30	1 1/8	4-6	5-8	300	1000	100	300	50-70	2-2 3/4	14-16	500-550	8.5-10	300-350								
	400	15	5/8	1.5-2	2-2.5	300	1000	100	300	40-60	1 1/2-2 1/4	7.5-8.5	250-300	4-5	140-180	1.2	3.8	0.6	1.8	1.1	3.6	280	620
		20	3/4	3-4	4-5	300	1000	100	300	50-70	2-2 3/4	8.5-10.5	300-370	5-7	180-230								
	600	25	1	4-5	5-6.5	300	1000	100	300	50-70	2-2 3/4	14	500	8	280	1.6	5.1	0.8	2.6	1.4	4.6	600	1330
Eimco(Cyclone)	60 & 61	10	3/8	3-4	4-5	300	1000	100	300	40	1 1/2	11-14	400-500			0.6	1.8	0.7	2.3	0.9	3.0	180	390
		13	1/2	4-4.5	5-6	300	1000	100	300	40	1 1/2	14-17	500-600	N.A.	N.A.	1.3	4.1	0.7	2.3	0.9	3.0	250	540
		20	3/4	4.5-7.5	6-10					50	2	17	600										
	70	32	1 1/4	2-15	3-20	600	2000	80-100	250-300	80	3	N.A.	N.A.	N.A.	N.A.	1.7	5.4	0.8	2.6	1.5	4.8	1030	2270
Icoma	LOVA	10	3/8	2-9	3-12					45-50	1 3/4-2	14-17	500-600	11-14	350-500	1.4	4.6	0.8	2.6	0.9	3.0	240	530
Reed	LOVA & LASC	13	1/2	3-11	4-15	300	1000	100	300	50-65	2-2 1/2	17-25	600-900	14-21	500-750	1.4	4.6	0.8	2.6	0.9	3.0	260	570
		20	3/4	3-11	4-15					50-65	2-2 1/2	17-25	600-900	14-21	500-750	1.4	4.6	0.8	2.6	0.9	3.0	270	600

N.A. = Not available

Table B.2 Performance data and specifications of feed-wheel
dry-mix shotcrete machines

Mfg	Model	Type	Max. Agg. Size (mm)	(in)	(m³/hr)	(yd³/hr)	Maximum Horizontal Conveyence (m)	(ft)	Maximum Vertical Conveyence (m)	(ft)	Hose Diameter (mm)	(in)	Air Consumption Air Driven Motor (m³/hr)	(ft³/hr)	Height (m)	(ft)	Width (m)	(ft)	Length (m)	(ft)	Weight (kg)	(lb)
Allentown	N-0	D.C.	13	1/2	0.5-1	1-1.5	N.A.		N.A.		25	1	5-7	180-230	1.2	3.8	0.9	2.8	1.0	3.3	310	680
	N-1	D.C.	13	1/2	2-3	3-4	N.A.		N.A.		30-40	1 1/4-1 1/2	10-13	350-450	1.3	4.1	1.1	3.5	1.1	3.5	330	1160
	N-2	D.C.	13	1/2	4.5-7.5	6-10	N.A.		N.A.		40-50	1 1/2-2	13-17	450-600	1,4	4.6	1.2	3.8	1.2	3.8	550	1220
	S-1	S.C.	13	1/2	N.A.	N.A.	N.A.		N.A.		30-35	1 1/4-1 3/8	N.A.		1.2	3.8	1.2	3.8	1.8	5.9	570	1260
	S-2 (10)	S.C.	13	1/2	N.A.	N.A.	N.A.		N.A.		35-40	1 3/8-1 1/2	N.A.		1.2	3.8	1.1	3.5	2.0	6.5	610	1340
	S-2 (20)	S.C.	13	1/2	N.A.	N.A.	N.A.		N.A.		40	1 1/2	N.A.		1.9	6.1	0.9	3.0	1.4	4.6	730	1600

N. A. = not available

Table B.3 Performance data and specifications of
wet-mix shotcrete machines

Mfg	Model	Type	Max. Agg. Size (mm)	(in)	Delivery Rate (m³/hr)	(yd³/hr)	Maximum Horizontal Conveyence (m)	(ft)	Maximum Vertical Conveyence (m)	(ft)	Hose Diameter (mm)	(in)	Air Consumption- Air Driven Motor (m³/min)	(ft³/min)	Air Consumption- Gas or Electric Motor (m³/min)	(ft³/min)	Height (m)	(ft)	Width (m)	(ft)	Length (m)	(ft)	Weight (kg)	(lb)
Challenge-Cook Bros.																								
	250-TG		20	3/4	9-19	12-25	N.A.		N.A.		50-80	2-3	3.5	125	N.A.	N.A.	1.5	4.8	1.2	3.8	5.2	17.0	N.A.	
																	2.4	7.7	1.2	3.8	5.7	18.6		
Conspray			25	1	15	20	N.A.		N,A.		50-80	2-3	10.5	370	N.A.	N.A.	N.A.		N.A.		6.1	20	4990	11,000
Eimco	D-2	D.C.	10	3/8	2-3	3-4	N.A.		N.A.		40	1 1/2	13	450	7.5	250	1.7	5.4	1.4	4.6	2.8	9.3	1520	3350
	F-2	D.C.	20	3/4	3-4	4-5	N.A.		N.A.		50	2	13-14	450-500	7.5-8.5	250-300	1.7	5.4	1.5	4.8	3.1	10.2	1660	3650
	GH-17	S.C.	20	3/4	4-5.5	5-7	N.A.		N.A.		50	2	14-17	500-600	10	350	1.8	5.9	1.4	4.6	2.7	8.9	2250	4950
	GH-22	S.C.	20	3/4	4.5-6	6-8	N.A.		N.A.		50	2	14-17	500-600	10	350	1.8	5.9	2.2	7.2	3.0	9.9	2490	5500
	GH-33	S.C	20	3/4	5.5-7	7-9	N.A.		N.A.		50	2	14-17	500-600	11	400	2.0	6.5	2.4	8.0	3.2	10.4	2770	6100
	CH	S.C.	20	3/4	2.5	3.5	N.A.		N.A.		50	2	13	450	3.5	125	1.5	4.8	1.2	3.8	3.2	10.4	1180	2600
	H	S.C.	10	3/8	2	3	N.A.		N.A.		40	1 1/2	13	450	3.5	125	1.1	3.5	1.2	3.8	2.9	9.6	950	2100
	G-17	S.C.	20	3/4	3-4	4-5	N.A.		N.A.		50	2	13	450	7.5-8.5	250-300	1.2	3.8	1.4	4.6	3.4	11.0	1320	2900

N. A. = not available

APPENDIX C

TRAINING OF SHOTCRETE NOZZLEMEN

On most underground projects, nozzlemen must be trained throughout the duration of the job. This training may be done at the job site or at a school for shotcrete nozzlemen. The prospective trainee should be a member of the shotcrete crew. At the beginning of a job, however, experienced personnel may not be available. The individual chosen to be the nozzleman must be articulate and have a keen awareness. Shotcrete nozzling is a difficult, dangerous, often dusty job which demands the skill of a craftsman. Much of the success of the entire operation depends on his performance.

This appendix deals with procedures for training of shotcrete nozzle-men. The program includes both a familiarity with the equipment and demonstration of basic nozzling techniques. The key to becoming a nozzle-man lies in actual nozzling experience under the supervision of the shotcrete superintendent or a competent nozzleman. The apprenticeship of a prospective nozzleman should last for a period of at least six months. To become a competent nozzleman, the individual must obtain experience in applying shotcrete under a variety of tunnel ground conditions. The training of a novice should start with a description of the entire shotcrete operation, including the batching facilities. Training of an experienced crewman can commence with basic nozzling techniques. A general training program for shotcrete nozzlemen is summarized in Table C-1.

C.1   Familiarity with Shotcrete Equipment

The first step in the training program is to familiarize the partici-
pants with the component parts, operation, and maintenance of equipment.
This instruction should cover the shotcrete machine, nozzle, and auxiliary
shotcrete equipment. General information on the parts, operation, and
maintenance of shotcrete equipment is given in Chapter 6. The instruction
is usually provided in the field using actual shotcrete equipment. One
of the best means of demonstration is to have the participants disassemble
the machine and the nozzle. The instructor can then point out the important
features of this equipment. The discussion must also include potential
difficulties with the equipment, their effects on production, and remedial
measures. Some of the difficulties encountered in operating the shotcrete
machine and the nozzle primarily for the dry-mix processes are summarized
in Table C-2. Possible causes of these problems and remedial measures
have also been included. Instruction in the field may be supplemented
by models and other visual aids such as movies. These visual aids are
extremely valuable in teaching basic nozzling techniques.

C.2   Basic Nozzling Techniques

The next step in the training program involves demonstration of
basic nozzling techniques including application, hand signals, and safety
requirements. Application procedures which should be covered are outlined
in Table C-1. Detailed procedures are described and illustrated in
Chapter 7. Hand signals used to convey shooting information between the
nozzleman and gunman are presented in Table C-1. The instructor should
also describe safety precautions since the nozzleman is directing a stream
of high velocity particles which can cause serious injury if the nozzle is

not properly controlled. The instruction on safety should include the type and use of safety equipment. The preliminary instruction should not be done while the equipment is in operation, since the noise level makes communication difficult. The best procedure for instruction is to provide a basic understanding of the shotcrete operation and then key important features during a demonstration of actual shotcrete placement.

C.3 Demonstration of Shotcrete Application

The demonstration of shotcrete application should start with operation of the shotcrete machine. This demonstration should emphasize requirements for a smooth, continuous, uniform flow of materials to the nozzle (see Chapter 7). Optimum machine pressure or material feed rate should be pointed out by the instructor for various gunning conditions. The demonstration at the shotcrete machine should include operation of the accelerator dispenser.

The instructor should finally demonstrate proper nozzling techniques. The trainee should be told of the specific features and then sequences which will be shown during gunning. In particular he should observe the wetness and color of the shotcrete, the impact, and rebound of the particles, and any sloughing or sagging of the in-place materials. The trainee should tie his observations to control of water, accelerator, and gun pressures as well as the basic techniques for nozzling. The instructor should start by wetting the surfaces to receive shotcrete and then apply shotcrete to a near-vertical surface. If possible the nozzleman should proceed up to overhead application, shooting on planar surfaces and into or at corners. Improper techniques should also be demonstrated for instructional purposes, but must not be used on any surface to receive

C-3

shotcrete as part of the underground work. The areas of poor quality shotcrete caused by improper nozzling should be examined and the undesirable qualities related to the machine performance or nozzling technique.

C.4   Applying Shotcrete

The trainee should obtain experience in handling the nozzle and material hose before he attempts to spray shotcrete. The experience is gained by holding the nozzle attached to the hose and practicing the basic nozzling techniques. After his initial contact with the nozzle, the air should be turned on without delivering material to the nozzle. The trainee should again practice the nozzling techniques. If a dry-mix machine is used, the water should be turned on and used to simulate actual placement of shotcrete. As a final preparation, sand may be fed into the dry-mix gun and nozzled by the trainee. This training aid usually requires special equipment and is expensive. The apprentice is now ready to gun the shotcrete materials.

The first attempt at shotcrete application should follow the same procedures as those used in underground construction. For the dry-mix process the first step usually involves wetting of the surface to receive shotcrete. The air which feeds the material hose is turned on at the machine and then water at the nozzle. The instructor should direct the trainee so that the water in the air stream is in approximately the correct proportion as used for normal shotcrete mixes. The material is then fed into the machine on command of the trainee. During shotcreting the trainee should periodically glance at the instructor for guidance and direction. The trainee should also experiment with air pressure and rate of material feed of the machine and the rate of water flow at the nozzle.

The sloughing, rebound, and appearance of the shotcrete should be observed each time the shooting conditions are changed. In the wet mix process, the air is turned on at the machine and the nozzle and then the material is fed into the hose at the command of the trainee. The air pressure and material feed rate should be varied to observe its effect on the quality and rebound of the in-place materials.

The initial application made by the trainee should not be made on the surfaces to receive shotcrete. A practice area may be set up using wood forms in various configurations to expose the trainee to different nozzling conditions (Fig. C-1). After his initial experience the novice must continue to nozzle under the watchful eye of the shotcrete superintendent.

Table C.1   General training program for shotcrete nozzleman

<u>Familiarity with Shotcrete Equipment</u>

     component parts

     operation

     maintenance

     trouble shooting

<u>Basic Nozzling Techniques</u>

     application procedures

         1. surface preparation

            a. scaling

            b. air-water jet

            c. sandblasting

         2. holding nozzle

            a. angle - 90^0 to surface

            b. distance - approximately 1 m (3 ft)

            c. motion - circular or elliptical

         3. control at nozzle

            a. water - surface silky, glistening (enough water to allow the coarse aggregate to be embedded in the shotcrete)

            b. accelerator - wet mix

            c. air - optimum pressure for maximum densification and minimum rebound of wet-mix

         4. shooting underground

            a. near-vertical surfaces

            b. corners

            c. overhead

Table C.1 Continued

hand signals

    1. air

        increase - 1 finger moved upward

        reduce - 1 finger moved downward

    2. material feed

        increase - 2 fingers upward

        reduce - 2 fingers downward

    3. accelerator

        increase - 3 fingers upward

        reduce - 3 fingers downward

    4. stop - hand moved horizontally

safety

    1. control of nozzle

    2. rebound

    3. hose plugs

Demonstration of Shotcrete Application

shotcrete machine

    1. continuous material and accelerator feed to machine

    2. smooth, continuous delivery to nozzle

    3. optimum gun pressure or material feed for maximum densification and minimum rebound

nozzling techniques

Applying Shotcrete - Novice

handling hose and nozzle

air or air-water jet

blowing sand through a dry-mix gun

shotcreting

Table C.2 Difficulties, possible causes, and remedies occurring in
the shotcrete machine and nozzle of the dry-mix process.

Problem	Possible Causes	Remedy
A. Non-uniform material flow to the nozzle	1) insufficient supply of materials to the shotcrete machine	1) prepare sufficient material by (a) obtaining maximum output of existing facilities, (b) by increasing batching and mixing capabilities and (c) improving conveyance
	2) aggregate in the shotcrete machine too wet or too dry	2) dry or wet aggregate as required to achieve optimum moisture (2-8% by weight)
	3) water present in the compressed air line	3) place separators or taps in the air line or use receiving tanks
	4) mismatching of outlet size, material hose diameter and/or nozzle size	4) use proper combination of outlet size, material hose diameter and nozzle size as recommended by the manufacturer
	5) shotcrete machine not functioning properly	5) maintain shotcrete machine in good working conditions by repairing or replacing worn parts and lubrication of wearing parts as specified by the manufacturer
B. Plugs or blockage	1) material feed rate too high in comparison with air pressure	1) adjust material feed rate or air pressure so that they are matched
	2) aggregate in the shotcrete machine too wet or too dry	2) dry or wet aggregate as required
	3) water present in compressed air hose	3) place separators or taps in the air line or use receiving tanks
	4) material hose kinked or tightly looped	4) place hose in straight line or wide loops
	5) water entering material hose from leaks	5) make proper hose connections and wrap with water-proof tape if necessary; keep connections out of water
	6) cement and sand buildup in the material hose	6) clean material hose line periodically

Table C.2 Continued.

Problem	Possible Causes	Remedy
C. Dusting	1) aggregate in the shotcrete machine too dry	1) add water as required before material reaches shotcrete machine
	2) insufficient water added at the nozzle	2) add water as required at the nozzle
	3) worn wear plates, pads etc.	3) repair or replace worn plates, pads, etc.
D. Non-uniform wetting of material at the nozzle	1) plugged water ring	1) clear holes in water ring
	2) water leakage from nozzle body, water valve, and/or water line	2) tighten fittings, replace washers and use sealents (when needed) to eliminate water leaks
	3) inadquate water ring or nozzle tip	3) use proper valve ring and nozzle tip to meet gunning conditions
	4) non-uniform flow of material to the nozzle	4) see A above
	5) water pressure too low	5) increase water pressure by using pumps capable of delivering water under sufficient pressure
	6) surging in water line	6) use a receiving tank or non-surging pumps

3.5 m
(12 ft)

2.5 m
(8 ft)

shotcrete

rebound

wood board
5 x 10 cm
(2 x 4 in.)

plywood
2 cm (3/4 in.)
thick

brace

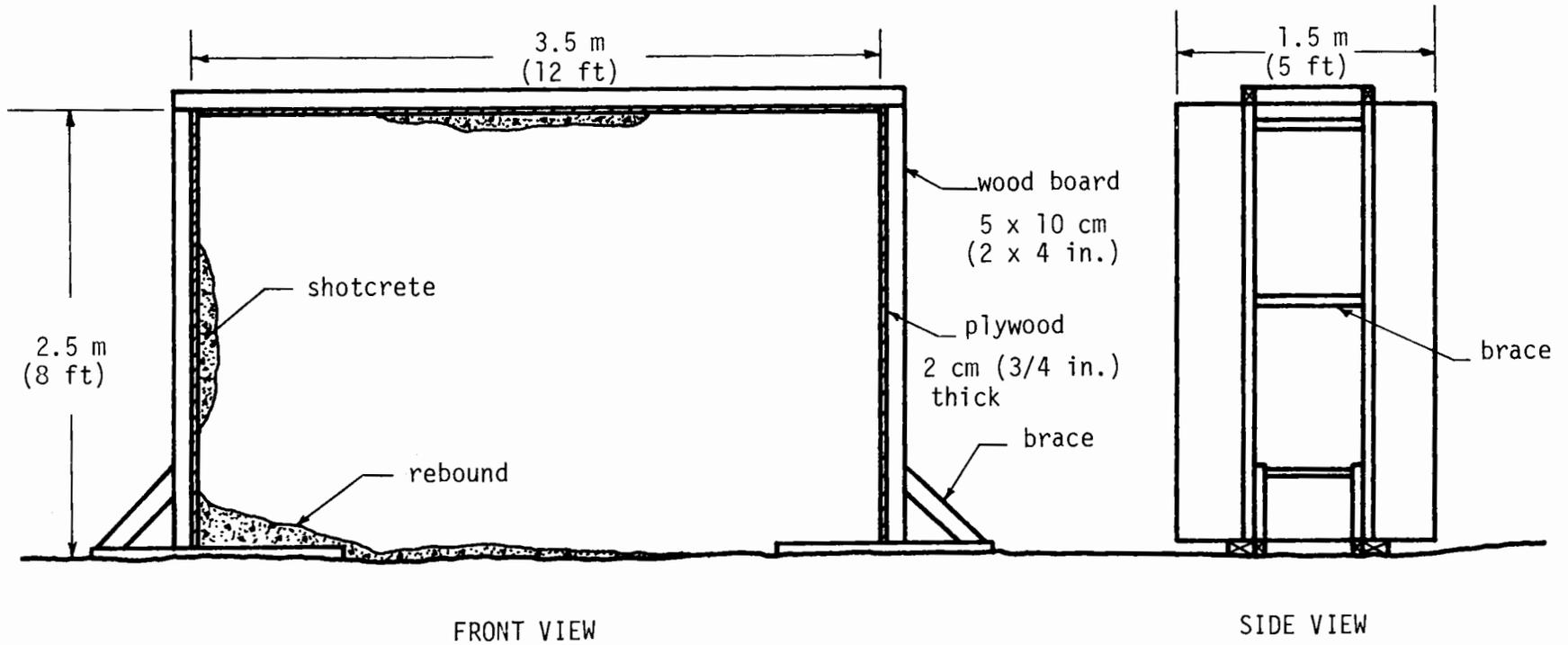FRONT VIEW

1.5 m
(5 ft)

brace

SIDE VIEW

FIG. C.1. PRACTICE PANELS FOR TRAINING OF NOZZLEMEN.

APPENDIX D

GUIDELINES FOR STANDARD TESTS OF COMPATIBILITY AND REBOUND

In 1966, the ACI Committee (506) published a standard of recommended practice for shotcreting. At present (1975), this committee is drafting a proposed "Specification for Shotcreting." The present draft was written primarily for above-ground shotcrete work. Accordingly, the proposed specification may have clauses that are not applicable and that should not be included in project specifications for underground shotcrete without modification. On the other hand, many portions of the specification will be applicable.

A supplementary specification will be prepared later by the committee to cover the use of shotcrete in underground openings. The purpose of this appendix is to suggest guidelines for some standards and tests needed for controlling the placement of shotcrete underground. Standard tests are proposed in this appendix for cement-accelerator compatibility and rebound. Special test apparatus have been developed for each test to standardize the equipment as well as the procedures. The proposed compatibility tests cover dry powder accelerators in detail. Changes in the test procedure to accommodate liquid accelerators are discussed. Much more work needs to be done on compatibility tests for liquid accelerators before standard procedures are proposed.

In addition, specifications should also be written for regulated-set and fiber shotcrete. However, this work is beyond the scope of this appendix since these shotcretes are largely experimental and insufficient field data are available.

D.1   Recommended Standard and Test for Accelerators

Accelerators as used herein are defined as chemicals in liquid or powder form which are added to shotcrete to reduce the initial setting time to a few minutes and to provide a rapid gain in early strength. The accelerator dosage is defined as the weight of accelerator divided by the weight of cement expressed as a percentage. The use of these chemicals can adversely affect long-term strength; the higher the dosage the greater the decrease in ultimate strength. Hence, there is a dual criteria for compatibility between accelerators and cement; they should have a short setting time yet should not produce an unacceptable reduction in the ultimate strength.

D.1.1   Criterion for Acceptable Long-Term Compatibility of Cement and Accelerator

To be acceptable for underground structural support, the addition of a given dosage of accelerator should not result in a compressive strength loss at 28 days of more than 30 percent of the compressive strength of unaccelerated shotcrete. To achieve these criteria with the presently available (1975) powder accelerators, the dosage of accelerator usually must be less than 6 percent (Blanck, 1974). Accelerator dosages of such magnitude that do not meet this long-term compatibility criterion may be permissible only when the shotcrete is applied for preventing water flows. Drains should be used rather than high accelerator dosages to control water flow in and immediately behind the permanent structural lining. Where possible, accelerators should not be used at all.

The test to determine this long-term compatibility should consist of

D-2

actual shooting and testing of panels of both accelerated and unaccelerated shotcrete.

D.1.2 Suggested Test for Set Time Compatibility of Cement and Accelerator

One of the best means for checking early compatibility of accelerators and cements is the Gillmore Needles Test. To date there is no standard test; however, one method has been proposed by Blanck (1974). The following is a recommended standard for determining initial and final set times of accelerator and cements for shotcrete. The standard is a modification of the standard ASTM C 266 test for "Time of Setting of Hydraulic Cements by Gillmore Needles."

Materials

Set of Gillmore needles

Laboratory scale (accurate to 0.01 g)

Thermometers (graduated from 0° C to 50° C)

Glass graduates (120 ml capacity)

Spatula (must not be aluminum or contain alluminum alloys)

Accurate timer (capable of measuring seconds)

Disposable plastic beverage cups

Accelerator(s)

Cement sample(s)

Water (same water as on project)

Standard Testing Cup

Both accelerator and cement are hygroscopic, and the supply should be stored in air-tight containers. The containers should be always tightly sealed, and opened only when samples are being taken out for tests. Tests must start as soon as possible after the samples are taken out to avoid contact with air for excessive time and absorption of moisture. If at all possible, the water used in compatibility tests should be the same water used for shotcrete on the project. If tap water is used, samples should be taken no sooner than 2 minutes after the water is turned on to avoid possible contamination from deposits in the tap. It should not be taken from a hot water tap and the water source must be reported.

Apparatus

Gillmore Needles. The Gillmore needles shall conform to the following requirements:

Initial Needle

Weight	113.4 ± 0.5 g
	(1/4 lb ± 8 grains)
Diameter	2.12 ± 0.05 mm
	(0.834 ± .002 in.)

Final Needle:

Weight	453.6 ± 0.5 g
	(1 lb ± 8 grains)
Diameter	1.06 ± 0.05 mm
	(0.416 ± 0.002 in.)

D-4

The needle tips shall be cylindrical for a distance of about 4.8 mm (3/16 in.). The needle ends shall be plane and at right angles to the axis of the rod and shall be maintained in a clean condition. The Gillmore needles should be mounted preferably as shown in Fig. D.1.
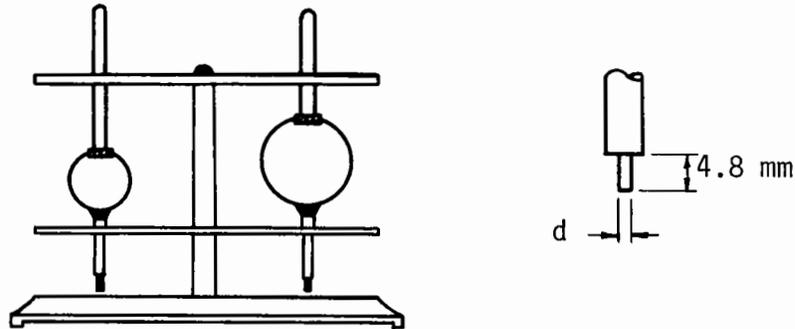
FIG. D.1.   GILLMORE NEEDLES

Standard Cup.   The standard cup is a special stainless steel cup designed specifically for testing compatibility of accelerated cements. It is used for mixing all the ingredients and its special design permits the needle tests to be conducted in the same container used for mixing. Transfer of the mix to a glass plate is not necessary so the test is faster and disturbance to the mix is minimized. Figures D.2 and D.3 are photographs of the standard cup. It consists of three parts: 1) cylinder, 2) cup, and 3) plate. They are held together in their assembled position by a quick-release mechanism for instant disassembly after mixing. The apparatus can be made by any reasonably-equipped machine shop from stainless steel stock. The dimensions for the apparatus are given in the drawings in Figs. D.4 through D.6.

D-5

FIG. D.2.   COMPATIBILITY TEST WORK AREA
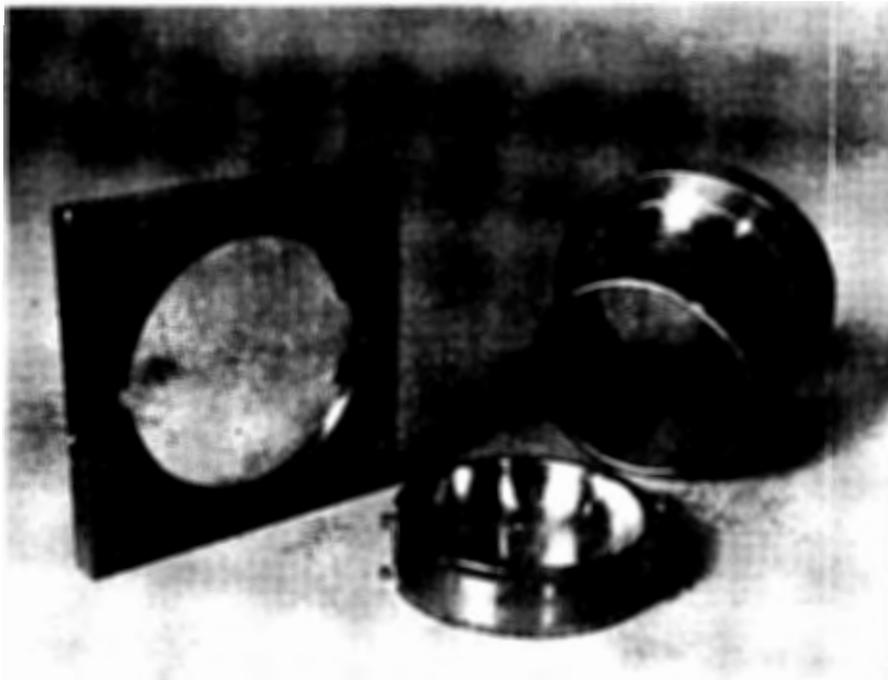
FIG. D.3.   STANDARD CUP ASSEMBLY

TOP VIEW

SECTION A-A'

FIG. D.4. CUP PORTION OF THE STANDARD CUP

stop lugs fitted
into groove

1.3 cm

0.3cm

0.6 cm

B

B'

10.2 cm

BOTTOM VIEW

0.5 cm

1.0 cm

7.3 cm

bottom of plate

top of plate

7.9 cm

10.2 cm

SECTION B-B'

FIG. D.5.   PLATE PORTION OF THE STANDARD CUP

.1.0cm
1.0cm
0.6cm

C

stop lugs fitted into groove

C'

BOTTOM VIEW

7.0 cm
6.4 cm

6.5 cm

1.1 cm
0.5cm

1.3 cm

0.5 cm
0.5 cm
0.3 cm

0.3 cm

9.2 cm

lug
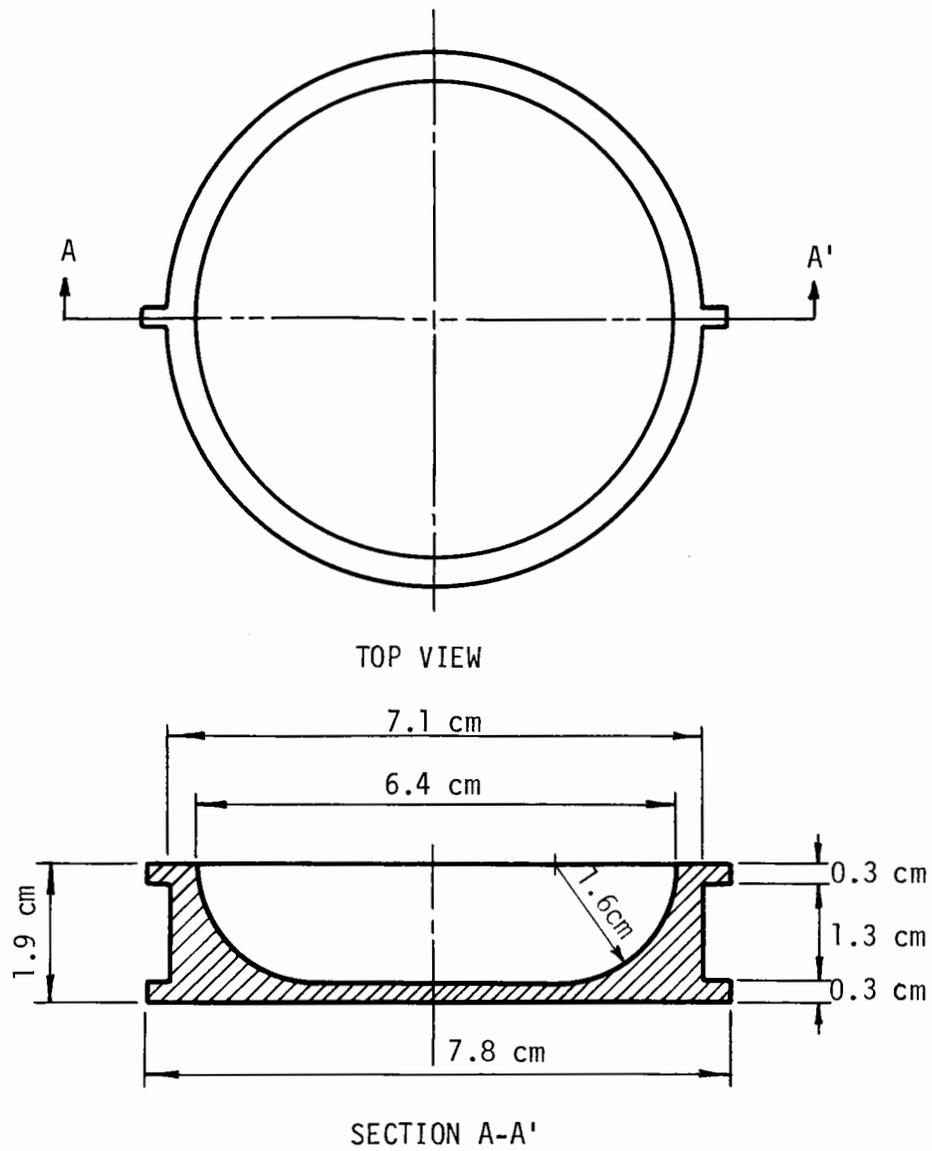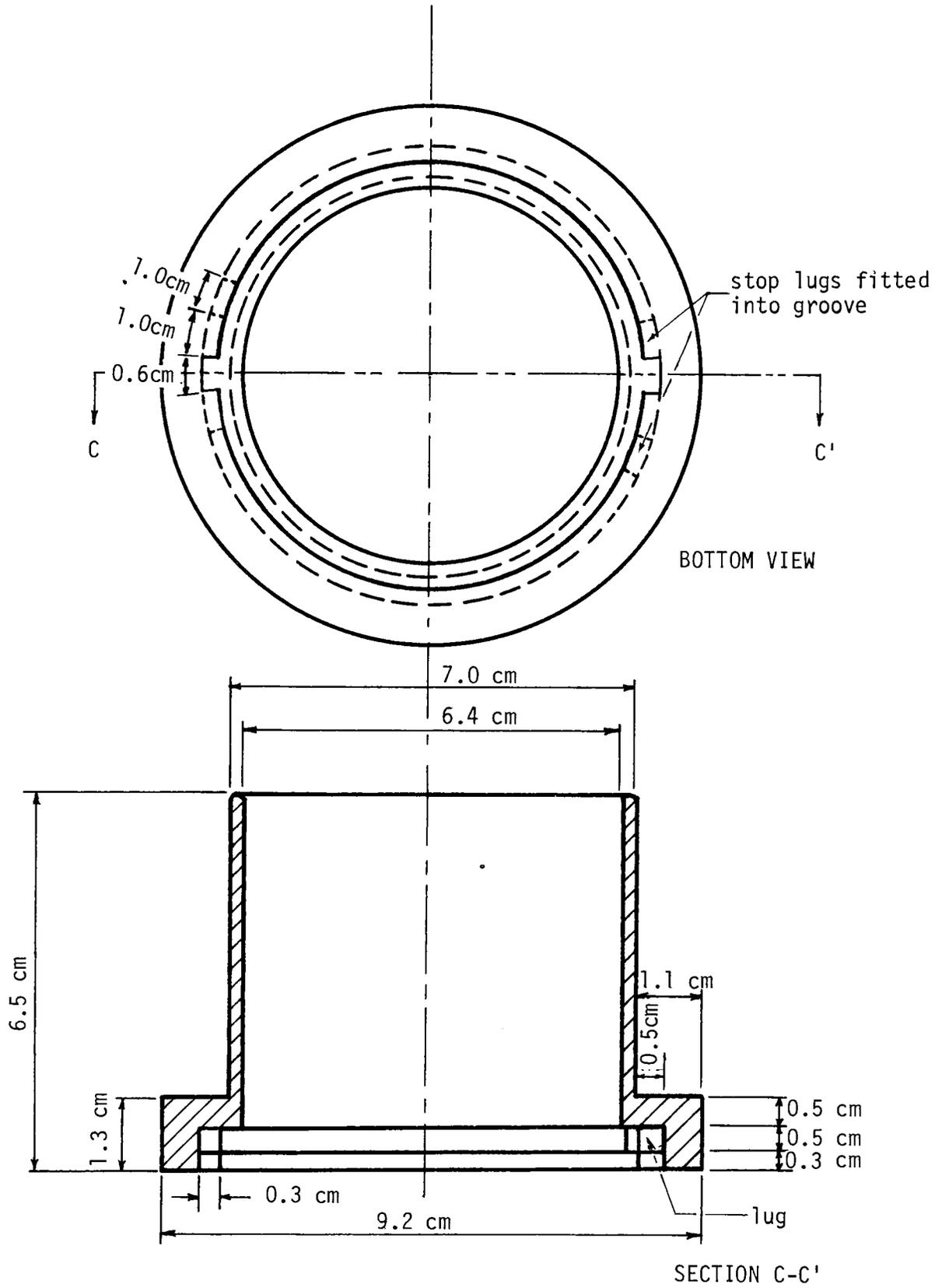
SECTION C-C'

FIG. D.6. CYLINDER PORTION OF THE STANDARD CUP

Temperature and Humidity

There shall be no air currents in the test area and the air in the vicinity of the tests shall be maintained between 20° and 28° C (68° and 82° F). The temperature of the cement, accelerator, and water shall be within $\pm 2°$ C (4° F) of the desired test temperature. Several series of Gillmore Needles Tests should be run covering the range of anticipated temperatures. One test shall be made with all materials at 20° C (68° F) and it shall be recorded as the standard. The relative humidity of the laboratory shall not be less than 50 percent.

Test Procedures for Dry Powder Accelerators for the Dry-Mix Process

Preparation of Cement Paste. Weigh 100 g of cement and place it in a disposable cup. Weigh the required percentage of powder accelerator and place it in another disposable cup. Weigh 43 g of water or carefully measure 43 cc of water in a glass graduate. Pour the water into a disposable cup. Assemble the standard cup as follows:

1) place the steel cup in the middle of the plate such that the lower knobs on the two sides of the cup are located in the notches of the plate (Figs. D.4 and D.5)

2) mount the cylinder on the cup such that the upper knobs on the two sides of the cup are resting in the two notches on the bottom of the cylinder

3) turn the cylinder clockwise so that it is locked in place.

Once the standard cup is assembled, empty the cement and accelerator into the cylinder and stir the mixture with the spatula for one minute. Form a crater in the center of the sample and pour the water into the crater; at the same

time start the timer. Mix vigorously and thoroughly with the spatula for
no more than 10 to 15 seconds, while holding the cylinder securely. Im-
mediately after mixing, turn the cylinder counterclockwise, lift it from
the cup and level the top of the cement paste with the edge of the spatula.
The edge of the spatula should be held perpendicular to the cement pat and
drawn across its top just above the upper edge of the standard cup. Care
must be taken not to press on the sample when leveling off the surface,
since this usually increases surface resistance and decreases the initial
set times. Measurements of surface resistance should be made approximately
once every 20 seconds but the time should be shortened as the initial set is
approached. Place the cup with the sample under the smaller Gillmore needle
and start the penetration tests. Both overmixing and undermixing usually
increase the setting times.

Initial Set Determination. Hold the needle in a vertical position and
place it gently on the surface of the pat. The needle should be released
slowly and then lifted, noting the indentation. Subsequent tests should be
made approximately in line with the first test so that the rate of setting
can be observed. Initial set is achieved when the needle no longer makes a
mark on the surface of the pat. As the initial set is approached, it is
recommended that impressions be tested in other areas of the pat to make sure
that the sample is achieving a uniform set. Record the time to the nearest
second when no impression is seen on the surface of the pat. Determination
of the initial set time can be facilitated by placing a steel wedge having
a 5° slope beneath the cup and performing the test as prescribed above.

Initial set is obtained when the needle makes a semi-circular impression on the sloped surface.

Final Set Determination. Using the final set weight and needle, proceed as before, but check the impressions with the needle every 1 or 2 minutes until the final set is approached. Measurements should be made at close intervals when the sample is near final set. Determination of the final set requires some judgment. It is recommended herein that final set be defined as the time at which the needle does not leave an indentation on the surface or when the needle makes a semi-circular impression on the pat when its surface is sloped.

Consistency of the Cement Paste for Dry-Mix Process. The consistency of the cement paste in the compatibility test should be approximately the same as that of shotcrete. A mortar mix having a slump of 5 - 8 cm (2 - 3 in.) can be used as a guide for the proper consistency of the cement paste in the test. For most presently available accelerators and cements, a water-cement ratio of 0.43 will produce the proper consistency and therefore was chosen as the standard. If the proper consistency cannot be obtained at a ratio of 0.43, the amount of water should be changed until the cement paste has a slump of 5 - 8 cm (2 - 3 in.) immediately after mixing. All compatibility tests conducted on that brand of cement and accelerator should be run at the new water-cement ratio. It must be remembered, however, that an improper consistency can also be caused by incomplete mixing of the water and cement and accelerator. If the sample does not exhibit a uniform consistency due to inadequate mixing, it should be discarded and the test rerun mixing more vigorously.

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Test Procedures for Dry Powder Accelerators for the Wet-Mix Process

The procedure for determining the compatibility of cements and dry powder accelerators for the wet-mix process is the same as for the dry-mix procedure described above, except for the water-cement ratio. A water-cement ratio of about 0.55 is more appropriate for wet-mix shotcrete, so 55g of water should be used in the test instead of the 43g specified for dry-mix. The paste should have a consistency equivalent to a slump of 8 - 10 cm (3 - 4 in.) immediately after mixing.

Test Procedure for Liquid Accelerators

The procedure for determining the compatibility of cements and liquid accelerators is essentially the same as for powder accelerators, however, the liquid accelerator must be mixed with the water first. The water and accelerator is then mixed with the cement. Since different manufacturers have different percentages of active ingredients (% solids), there can be no standard water-cement ratio as specified for dry powders. The amount of liquid accelerator and water to be added to the 100 g of cement must be determined by trial and error to produce the proper consistency (similar to that of a mortar mix having a slump of about 5 - 8 cm (2 - 3 in.) for the dry-mix process or 8 - 10 cm (3 - 4 in.) for the wet-mix process). Further-more, a different amount of water must be used for different accelerator dosages, so that the same water-cement ratio, and therefore similar con-sistency at the time of mixing with cement, is maintained for the entire range of accelerator dosages.

D.2   Rebound

D.2.1   Purpose

A standard test for measuring shotcrete rebound is needed to evaluate
the mix design, the performance of the crew, and for quality and economy
control both prior to and during construction. Visual estimates of rebound
are simply unsatisfactory since they are likely to be in error by 20 percent.
Implementation of a standard test would permit correlation of rebound data
between jobs. Many of the rebound values reported in the literature cannot
be compared because the parameters that affect rebound are not reported.
One such parameter commonly ignored is the thickness of the layer; the greater
the thickness the lower the rebound. For dry-mix, coarse-aggregate shotcrete,
the effect of thickness can be extremely important. This does not mean that
all previous data for coarse-aggregate, dry-mix shotcrete 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 in any comparison. Naturally, data obtained from similar rebound tests,
but with different conditions of shooting, such as those reported by Studebaker
(1939) or Kobler (1966), are less likely to be prone to bias from differences
in thickness. Average rebound, which is the value of rebound commonly re-
ported by industry, is defined as the total weight of rebound collected divid-
ed by the total weight of material shot.

D.2.2 Background

The amount of rebound is substantially higher when the nozzle is first directed toward the surface being shotcreted. Once a thin layer of paste is established, the rate of rebound is reduced significantly. A recent test program (Parker, et al., 1975) has shown that initial rebound losses are extremely important in determining the amount of rebound measured.

The mechanisms of rebound are complex, but for practical purposes and simplicity, the process of rebound of dry-mix, coarse-aggregate shotcrete might be envisioned as consisting of 2 separate phases. The first phase (Phase 1) is the establishment of the initial critical thickness during which the rate of rebound (the amount of material falling to the ground in a given period of time as expressed in kg/min [lb/min]) is between 50 and 100 percent of the rate of material being shot at the wall. The second phase (Phase 2) is the rebound that occurs after the initial critical thickness has been established. The rate of rebound in kg/min (lb/min) during this phase is probably 5 to 15 percent of the rate of material being shot at the wall for dry-mix shotcrete.

It is important to recognize that rebound losses are so high during the first few seconds of shooting (during the establishment of the initial critical thickness) that when average rebound is measured in the conventional manner for thin shotcrete layers (less than 8 cm [3 in.]) hardly any of the Phase 2 rebound appears in the results. The rebound during Phase 1 dominates the rebound data until the total amount of rebound during the Phase 2 is a substantial portion of the total collected. The relationship between average rebound,

rebound rate, and thickness, based on data from a series of field tests, is illustrated in Fig. D.7 (Parker, et al., 1975). The rate of rebound, shown by the shaded bar graph, drops as soon as the initial critical thickness is established and then is more or less constant with thickness. However, average rebound (the total weight rebounded divided by total weight shot) reduces slowly and at a rate that depends on the magnitude of the initial losses. For the test conditions, it was not until a thickness of about 10 cm (4 in.) had been shot that the change in average rebound curve was not dominated by the high losses during Phase 1. To properly evaluate rebound, both phases should be considered when conducting rebound tests.

A hypothetical average rebound curve is shown in Fig. D.8 with an assessment of the trend of the curve with different shooting conditions. It is well known that rebound varies with mix and shooting conditions and it is important that all these conditions be documented and reported.

Such a test program has not yet been conducted on fine-aggregate or wet-mix shotcrete; it is believed that both Phase 1 and Phase 2 exist to a lesser degree for both types of shotcrete.

D.2.3 Standard Test for Rebound

A simple, two-part standard rebound test as well as data to be reported with rebound values are described in this section. The test is applicable for both dry- and wet-mix shotcrete even though it was developed for the dry-mix process. The purpose of the test is to standardize the procedures, the measurement and calculations of rebound values, and the data that should be
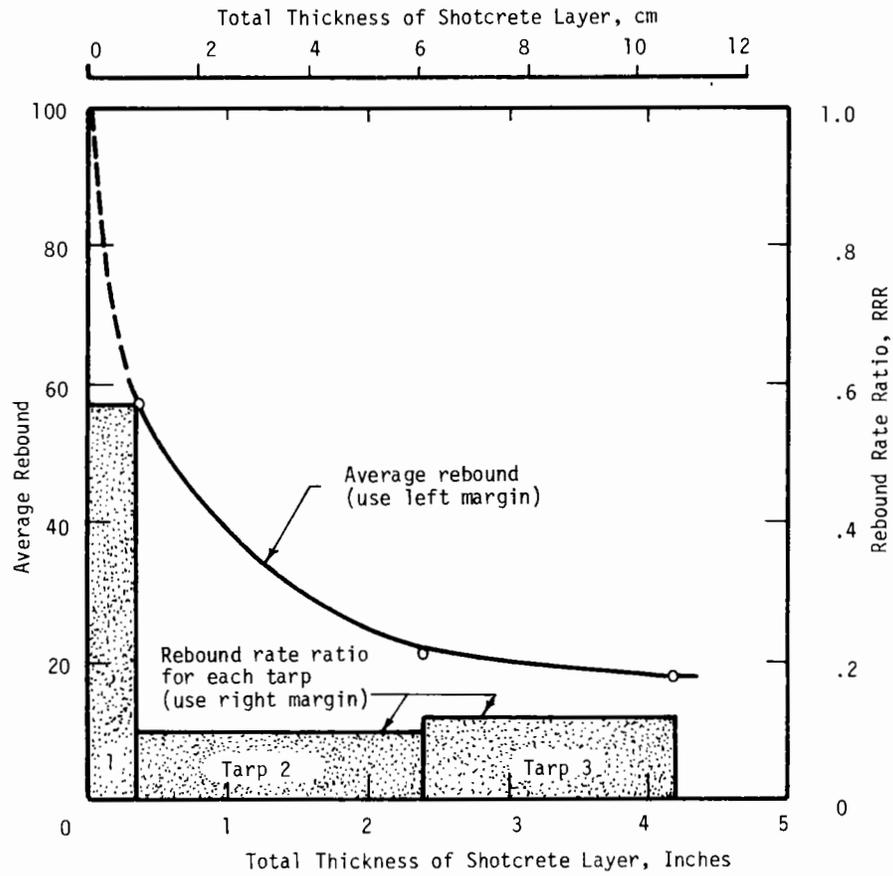
D-16

FIG. D.7.   CHANGE IN MEASURED REBOUND VALUES WITH
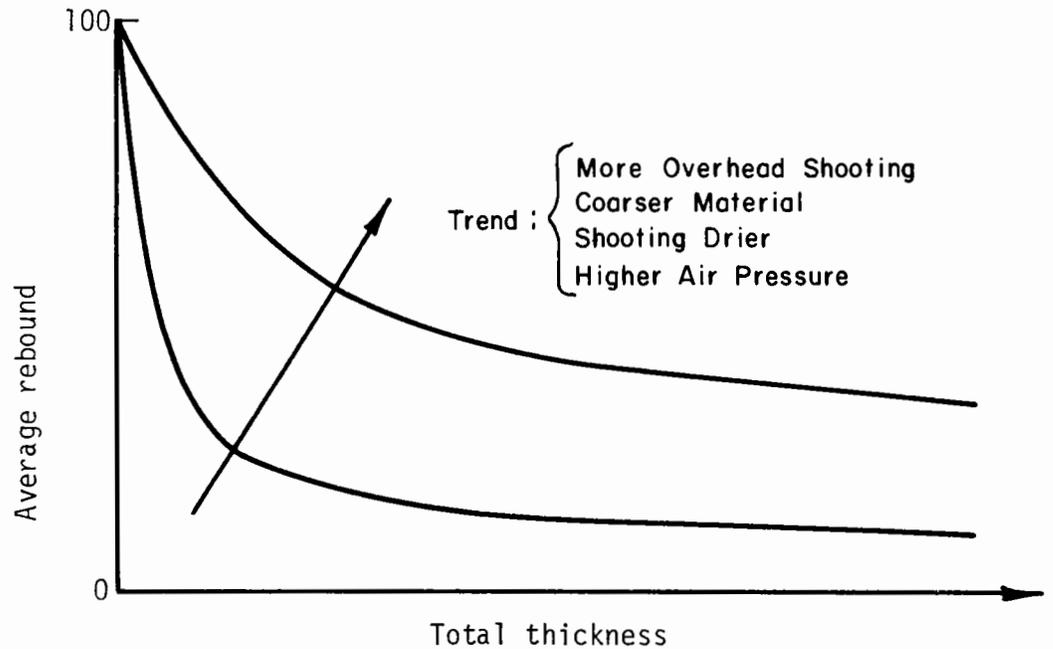THICKNESS (PARKER, ET AL., 1975)

FIG. D.8.   EFFECT OF MIX AND SHOOTING CONDITIONS
ON MEASURED REBOUND CURVES

reported to properly document the results. The standard rebound test will provide more accurate results, the interpretation of the test will be easier, and meaningful comparisons can be made not only on one project but industry-wide. Since the average rebound changes rapidly with the initial thickness, a thickness of 10 cm (4 in.) has been adopted as the standard thickness to be applied in the test. Though fine-aggregate and wet-mix shotcretes probably have flatter average rebound curves, rebound tests on these shotcretes should also be conducted to the standard thickness.

A practice panel is provided to permit adjustments of the material feed and water before beginning the actual test. The test has two parts; the standard full-thickness test and an optional test that, together with the results of the full-thickness test, can be used to determine the relative rates of rebound between Phase 1 and Phase 2. Very little extra work is required to obtain this additional information since both tests can be done in one shooting; the additional shooting for the optional test may last only a minute or two. The results of the two-part test permit a contractor or engineer to determine whether or not improvements can be made to reduce the losses during Phase 1, Phase 2, or both. To evaluate mix design and shooting conditions, the two-part test is recommended; the full-thickness test will reflect differences in mix design and shooting, but not as completely.

Materials and Equipment

Test boards (see Fig. D.9)   Practice panel

Tarps of heavy waterproof   Water meter accurate to
  canvas with grommets in   1/2 ℓ (0.1 gal)
  corners, 1 by 1 m square
  (3 x 3 ft)

Watch with second hand

Depth probe graduated in
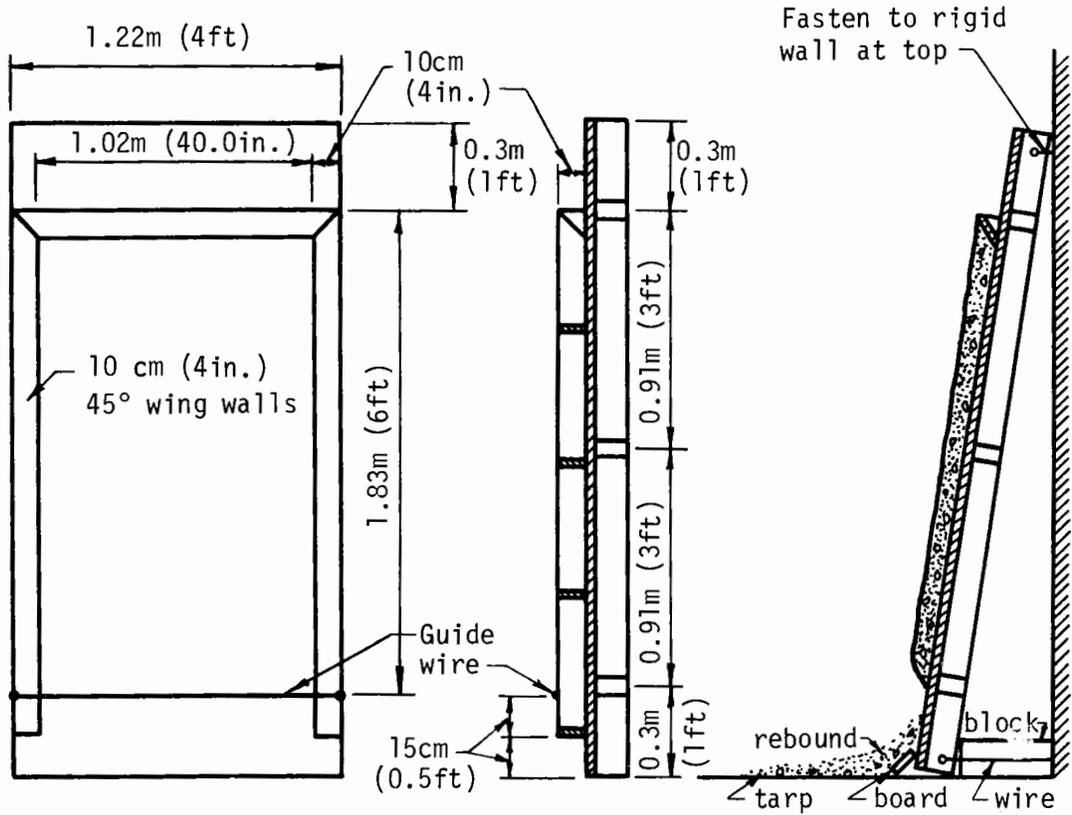 2 mm or 0.1 in.

Shotcrete materials

Scales accurate to ± 0.5 kg
  (1 lb)

Shovels and concrete trowels

Batching, mixing, and shot-
  crete equipment

Test Board

The dimensions, reinforcement, and wing walls of the test board are
shown in Fig. D.9. The wing walls give the nozzleman a gage so that he
can control the thickness of the shotcrete layer (10 cm [4 in.]) in the test.
These walls are attached to the test board 10 and 40 cm (4 in. and 16 in.)
from its side and top edges, respectively. The bottom wing wall is omitted
so that rebound will not be trapped. The wing walls are inclined at an angle
of 45° to the surface of the plywood and their edges extend 10 cm (4 in.)
which is to the edge of the board on the sides. A fine wire is strung be-
tween the lower edges of the side wing walls to assist the nozzleman in
shooting the shotcrete to the required thickness near the bottom where the
wing wall is not presented to guide him. The tarps are placed in a quilt-
like pattern in front of the test boards as shown in Fig. D.10 with an over-
lap of about 8 cm (3 in.)

Test Procedure

Full-Thickness Rebound Test. The test board is placed against a firm
backing at an angle between 80° and 90° from horizontal (Fig. D.9). The
board must be held securely in place to prevent detrimental vibrations during
shooting. The tarps are spread on the ground surface beneath and adjacent to

1.22m (4ft)

1.02m (40.0in.)

10cm
(4in.)

0.3m
(1ft)

10 cm (4in.)
45° wing walls

1.83m (6ft)

Guide
wire

15cm
(0.5ft)

Front View of Test Board
for Full-Thickness Test

Fasten to rigid
wall at top

0.3m
(1ft)

0.91m (3ft)

0.91m (3ft)

0.3m
(1ft)

Side View of
Reinforcement

rebound

tarp   board   wire

block

Side View of Boards
in Shooting Position

10cm
(4in.)

40 cm (16 in.)

9cm
(3.5in.)

1cm (0.5in.)
45° wing walls

guide wire
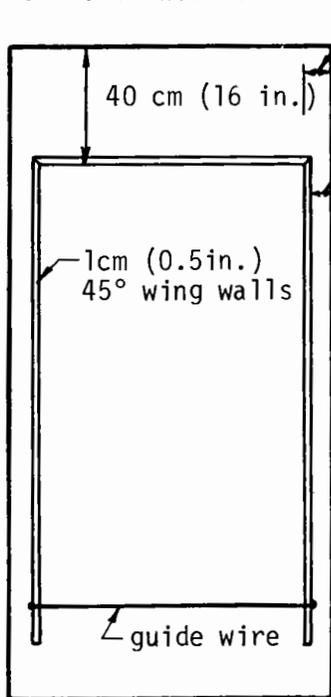
Front View of Test Board
for Optional Test

wing wall
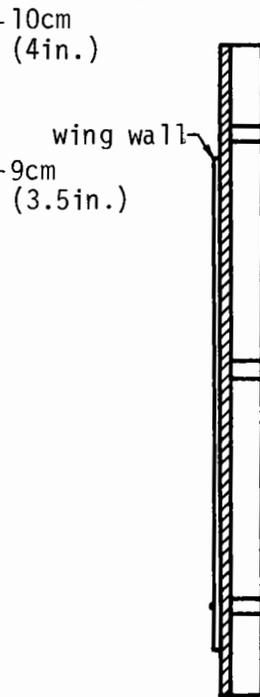
Side View
Optional Test

0.3m
(1ft)

0.6m
(2ft)

0.3m
(1ft)
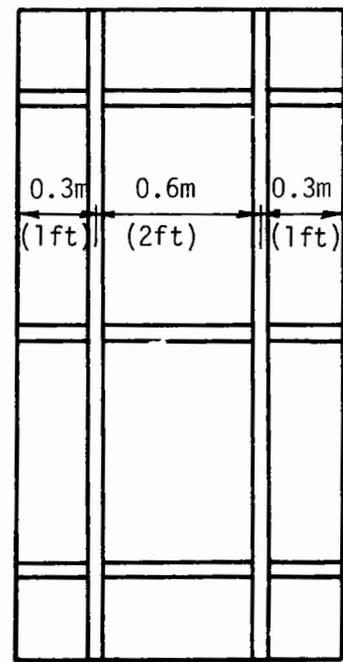
Reinforcement of Back
of Test Boards

FIG. D.9. DETAILS OF TEST BOARDS FOR STANDARD REBOUND TEST

Note: Distance between boards should be as close as practicable without contamination of tarps from adjacent tests. Use additional dividers as necessary.
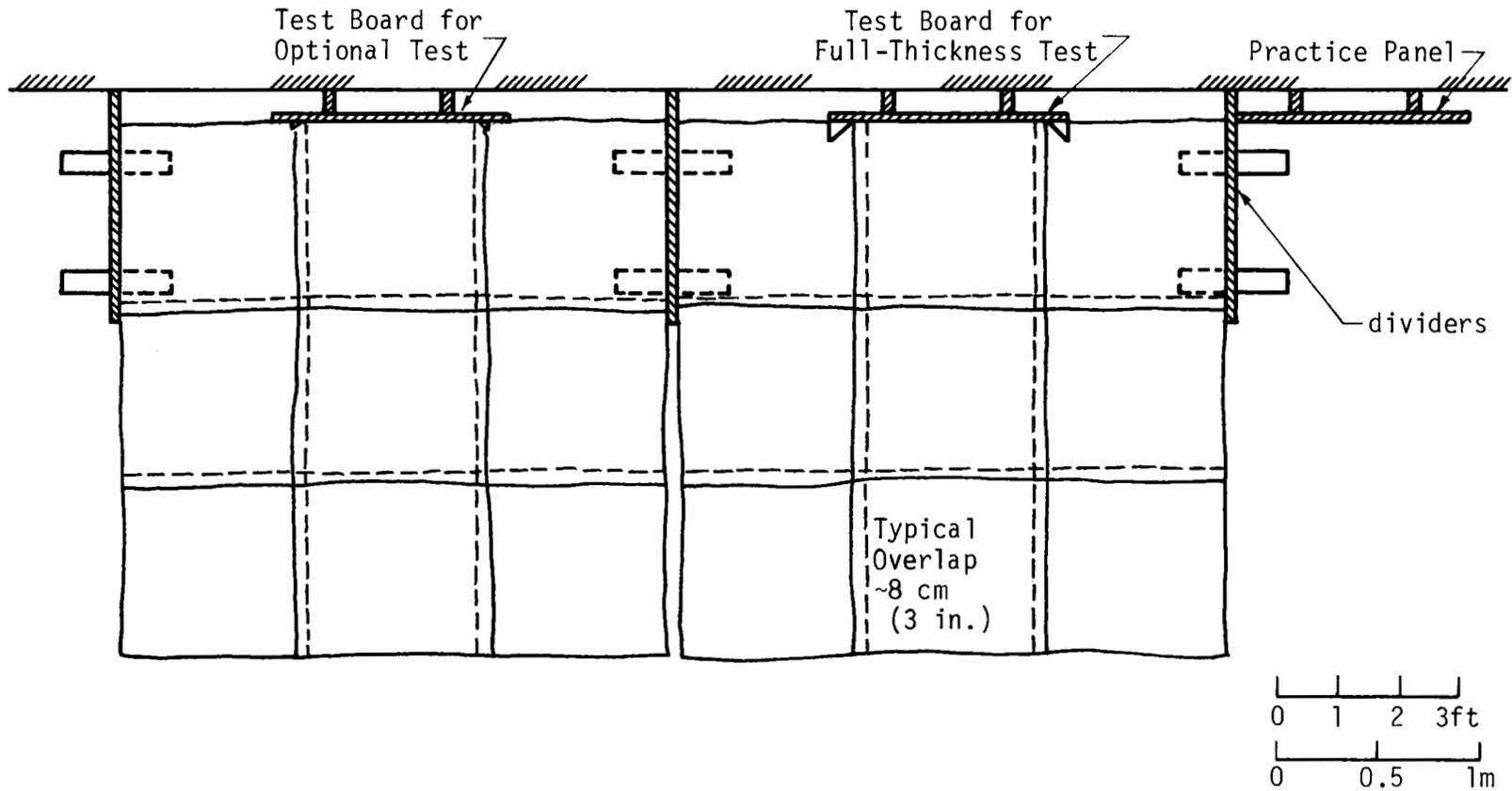
FIG. D.10. PLAN VIEW FOR SUGGESTED REBOUND TEST

Note: Distance between boards should be as close as practicable without contamination
of tarps from adjacent tests. Use additional divider panels as necessary.

divider tarp Test Board for   divider tarp Test Board for   divider Practice Panel
Optional Test   Full-Thickness
Test
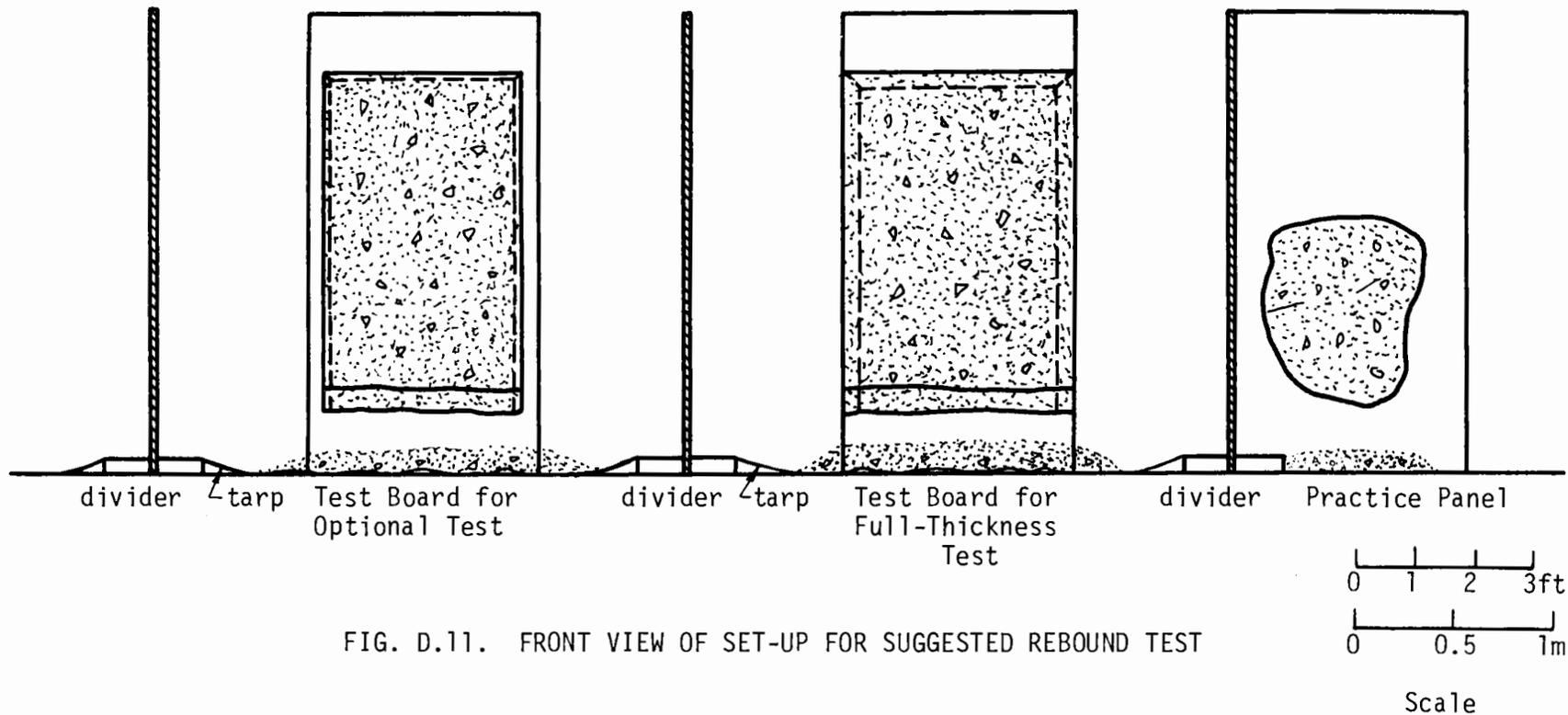
FIG. D.11. FRONT VIEW OF SET-UP FOR SUGGESTED REBOUND TEST

0   1   2   3ft

0   0.5   1m

Scale

the test board as shown in Figs. D.10 and D.11. A second plywood panel should be placed near the test board for practice shooting. A divider at least as tall as the test panel should be used between the boards to prevent rebound from the practice panel from being included in the rebound of the test. Additional tarps or dividers should be utilized as necessary to ensure collection of all material.

The same procedures, equipment, and personnel used underground should be used in the rebound test. After the water and material feed are adjusted, the shotcrete stream must be moved quickly from the practice panel to the test board without interrupting the shooting. This transfer causes some small and unimportant loss of material. Shooting on the test board should be done from the bottom upward, so that rebound will not be trapped. The lower edge of the shotcrete layer should be tapered downward but must not extend more than 15 cm (6 in.) below the guide wire. The area between the wing walls and the wire should be completely filled and the surface of the shotcrete must be flat and even with the wire and the edges of the wing walls. Shotcreting in the test area must cease as soon as the area between the walls and wire is filled; direct the nozzle back to the practice panel or, if the optional test is to be conducted, direct the nozzle to the test board for the optional test.

Immediately after shooting, each tarp is carefully picked up by the four corners and weighed. The grommets in the corners permit a simple spring scale to be used. After weighing, the tarps are cleaned and replaced beneath the test board. The shotcrete on the test board is removed with scrapers and

shovels and is collected on the tarps. The tarps are then weighed to deter-
mine the weight of shotcrete on the wall. Any easy method to remove the shot-
crete on the panel is to unfasten the top of the board and pull it over with
a cable until the shotcrete falls onto the tarps. Usually the force of impact
shakes all the shotcrete loose.

The total time to shoot the full-thickness test should be measured with
a stop watch to the nearest 5 seconds so that the average material delivery
rate can be determined.

Optional Test to Determine Phase 1 Losses. The optional test should be
done immediately following the full-thickness test by quickly directing the
nozzle to a second test board without interrupting shooting. The interior
flat surface of the second test board is to be shot to a uniform thickness
of about 1 cm (1/2 in.). This probably will require a rapid movement of the
nozzle in order to shoot the layer to a uniform thickness. The nozzleman
should practice before actually running the test. The test is completed as
soon as this thin layer is established over the entire surface of the optional
test board. The nozzle should be directed away from all test boards and tarps
and then the shooting should be stopped.

The procedures for weighing the rebound and the material on the board are
the same as for the full-thickness test. However, the thickness of shotcrete
on the board must be measured with a probe twice at the bottom, at the middle,
and at the top of the panel. This measurement must be done immediately after
shooting while the probe can still penetrate the full thickness of the layer.
The thickness to be reported is the average and maximum and minimum thicknesses
to the nearest 0.2 cm (0.1 in.).

Calculations

Calculations for Full-Thickness Test. Usually the weight of the tarps
themselves will be minor but their weight should be subtracted from the total
weight to get the net weight on the tarps, particularly if they become water-
soaked or if their weight constitutes a substantial portion of the total weight
of material on the canvas. The net weight of rebound, W_r, is the net total
weight of all the tarps containing rebound. The net total weight of shotcrete
on the wall, W_w, is the net total weight removed from the test board. The
total weight shot is the total of the rebound plus the weight on the wall,
$W_r + W_w$. Average rebound is calculated as follows:

$$\text{Average Rebound} = \frac{\text{Weight of Rebound}}{\text{Total Weight Shot}} = \frac{W_r}{W_r + W_w}$$

The time in minutes and seconds to shoot the entire full-thickness test is
$T_{(0-t)}$, where (0-t) is the thickness in cm at the end of the test (10 cm).
This time, T, should be converted to decimal form (minutes and hundredths of
minutes). The material delivery rate (MDR) is calculated as follows:

$$\text{Material Delivery Rate (MDR)} = \frac{W_r + W_w}{T_{(0-t)}}$$

Calculations for Optional Test. The total net weight of rebound collected
is the weight of rebound lost during Phase 1, W_{r_1}. The net weight scraped off
the board is W_{w_1}. The rate of rebound will be called Rebound Rate Ratio, RRR.

$$\text{Rebound Rate Ratio for Phase 1 } (RRR_{0-t_1}) = \frac{W_{r_1}}{W_{r_1} + W_{w_1}}$$

where t = average thickness in cm.

Rebound Rate Ratio for Phase 1, RRR_{0-t_1}, is the percentage of rebound lost in establishing the initial critical thickness. It should be expressed as a decimal ratio rather than as a percentage to avoid confusion with the term average rebound. The Rebound Rate Ratio for Phase 2, $RRR_{(t_1-10)}$, is calculated as follows:

$$\text{Rebound Rate Ratio for Phase 2 } (RRR_{t_1-10}) = \frac{W_r - W_{r_1}}{(W_r + W_w) - (W_{r_1} + W_{w_1})}$$

Required Documentation

The factors known to affect rebound should be measured or observed and reported. The major factors are given in Table D.1. The percentage accelerator can only be measured during the test by continuing to shoot toward a practice board after the rebound shooting is complete. To determine this percentage, the entire batch should be shot and the weight of accelerator in the dispenser before and after shooting should be measured. The accelerator dosage is then the weight of accelerator used divided by the weight of cement batched, expressed as a percentage.

Table D.1. Required documentation for rebound tests.

___

Shooting Conditions

     1.   Type of mix: dry or wet

     2.   Type of shotcrete machine, air pressures, and length of hoses

     3.   Type and internal diameter of nozzle

     4.   Temperatures of air

     5.   Material Delivery Rate, Kg per min (lb per min)

     6.   Total water shot during time T (for dry mix shotcrete only)

     7.   Distance and angle of nozzle to the test board

     8.   Measured accelerator dosage

     9.   Total time to shoot test

   10.   Maximum temperature of dry mix before shooting

Mix Conditions

     1.   Mix design - batch weights

     2.   Type of cement and accelerator - compatibility data

     3.   Initial moisture content of fine and coarse aggregate

     4.   Maximum size of aggregate, % of mix greater than No. 4 sieve (4.76 mm), gradation of fine and coarse aggregate

     5.   Temperatures of raw materials: cement, aggregate, and water

     6.   Slump and water-cement ratio of wet mix shotcrete

Rebound Data

     1.   Net weights, W_r, W_w, W_{r_1} and W_{w_1}

     2.   Thickness of shotcrete layers

___

D.2.4 Interpretation of Test Results

Standard rebound tests are primarily useful in comparisons. A contractor can compare the results of a full-thickness test with standard test results obtained on other jobs, as well as with results reported by others for similar types of shotcrete. Comparisons between different mix designs, different shooting conditions, or different crews can also be made on the basis of standard full-thickness tests. The optional test provides the information needed to reduce rebound. It is more sensitive to the details of the mix and the shooting conditions than the full-thickness test. Thus, comparative tests during pre-construction testing can show trends resulting from changes in mix and shooting conditions more quickly if the optional test is used. Data from optional tests reported by industry will eventually result in a better understanding of the mechanisms involved in rebound, of the differences in rebound when larger or a greater percentage of coarse aggregate is used, and of the differences in rebound between wet-mix and dry-mix shotcrete.

Actual rebound losses on any underground project will be different than the rebound measured in the standard test, although the test does provide an index of actual losses that may be a lower bound. Shooting overhead and shooting at wet, irregular rock surfaces tends to increase rebound over the conditions of shooting the standard test. It is expected that differences in the hardness between the plywood surface and the rock wall do not affect the amount of rebound as much as they affect how far the particles ricochet from the surface. After the initial critical thickness is established (Phase 1), the hardness of the wall no longer affects the rebound so the Rebound Rate

Ratio (RRR) for Phase 2 determined in the optional test is probably representative of the rebound against smooth walls after the initial critical thickness is established.

D.2.5 Rebound Test to Estimate Actual Project Losses

Modification of the standard tests may be made to estimate actual project losses more accurately. The test boards could be positioned overhead so that rebound losses from shooting the crown may be estimated. Similar tests could be made on actual rock surfaces, however, a specific predetermined area should be shot to some thickness representative of actual conditions.

Since the average rebound curve of dry-mix, coarse aggregate shotcrete changes with thickness (Fig. D.7), a better estimate of actual losses can be made by conducting other rebound tests and shooting to the actual thickness of shotcrete placed in an average lift. Since there are Phase 1 losses at the beginning of each lift, it is the thickness of each separate layer that determines the rebound. Thus, shooting to the total thickness of multiple layers would give erroneous rebound values that are lower than actual. If mesh or reinforcing steel is used, this condition should be simulated.

APPENDIX E

SPECIFICATIONS FOR PLACEMENT OF SHOTCRETE UNDERGROUND

A set of shotcrete specifications written and used for construc-
tion of a rock excavation are given in this appendix. These specifica-
tions were taken verbatim from the contract documents for the Dupont
Circle Station which is part of the Washington, D. C. Metro. They were
written by the DeLeuw, Cather Co., and Kaiser Engineers in cooperation
with Metro and its board of consultants. These specifications were
chosen because they are one of the most complete and well written
documents available. They have been reproduced with permission of
the Washington Metro.

SECTION 4.4

SHOTCRETE

4.4.1 DESCRIPTION OF WORK

Work under this section shall consist of the application of
shotcrete to the specified thickness at the locations indi-
cated on the contract drawings, and furnishing of materials,
equipment, tools and labor necessary to perform the preparation,
application and the clean-up pertaining thereto.

The Contractor shall apply approved shotcrete mix based on the
gradations provided herewith, except that shotcrete mix based
on gradation No. 1 shall not be used to encase structural
steel members.

In the North and South Entrance escalator shafts, shotcrete
shall be applied uniformly and built-up to a smooth surface
within the limits indicated on the contract drawings. The
shotcrete surface will serve as a base for application of
waterproof membrane to be applied in a future contract. The
shotcrete surface shall be within a tolerance of $\pm$ 1 inch of

the inside face of tunnel shown on the contract drawings.
The chord offset measured from the midpoint of a six foot
straight edge laid on the shotcrete surface parallel to
the shaft centerline shall not be greater than 1/2 inch.

4.4.2 DEFINITIONS

Shotcrete, for the purpose of this work, is defined as a
Portland Cement Concrete, containing aggregate up to 1"
in size, applied from a spray nozzle by means of compressed
air with water added at the nozzle.

Shotcrete shall contain approved additives suitable to attain
quick set and high early strengths as specified herein.

4.4.3 MATERIALS

4.4.3.1 Cement

Cement shall conform to the requirements of ASTM Designation
C 150, Type I, and shall meet the requirements of Section 3.8,
Portland Cement Concrete. Type III cement may be used, if
approved by the Engineer, at no additional cost to the
Authority.

4.4.3.2 Aggregate

Fine and coarse aggregate shall conform to the requirements of
Section 3.8, Portland Cement Concrete, except as hereinafter
specified. The gradation of the combined coarse and fine aggre-
gate mixture shall conform to the following limits:

Per Cent Passing

U. S. Standard Sieve Size	Gradation No. 1	Gradation No. 2
1 inch	100	-
3/4 inch	90 - 100	-
1/2 inch	75 - 95	100
3/8 inch	65 - 88	95 - 100
No. 4	48 - 75	72 - 85
No. 8	34 - 56	52 - 73
No. 16	22 - 43	36 - 55
No. 30	12 - 32	20 - 38
No. 50	5 - 20	7 - 20
No. 100	2 - 10	2 - 12
No. 200	0 - 5	0 - 5

All aggregates shall be uniformly well graded and shall not exhibit extremes of variation. The maximum size of the aggregate may be varied subject to the approval of the Engineer, or as directed by the Engineer.

4.4.3.3 Accelerating Admixtures

Ar. approved accelerating admixture shall be used to develop quick set and high early strength, as follows:

Time of initial setting	3 minutes maximum
Time for final setting	12 minutes maximum
Compressive strength in 8 hours	800 psi minimum

Time of setting shall be determined in accordance with ASTM Designation C 266, "Time of Setting of Hydraulic Cement by Gillmore Needles", as modified herein. The accelerator shall be added to 50 grams of cement in the preparation of the pat, together with water to produce a water-cement ratio of 0.40, in the percentage expected to be used in actual shotcrete application. The minimum possible time interval shall be used to attain the proper mixing without disturbing the initial set of the paste.

The compressive strength shall be determined in accordance with ASTM Designation C 109, "Compressive Strength of Hydraulic Cement Mortar", except that the accelerator in percentage expected to be used in the shotcrete mix design shall be added to the mortar prepared with a water-cement ratio of 0.40. In order to accomplish the molding of specimens before the initial setting of the mortar takes place, the intervals of time provided in the above specification need not be observed.

Admixtures shall conform to the applicable requirements of ASTM Designation C 494, "Chemical Admixtures for Concrete".

Admixture shall not contain chlorides or materials corrosive to steel, and shall not entail other detrimental effects such as cracking and spalling. The admixture used shall have an acceptable service history of at least five years in a similar application.

4.4.3.4 Water

Water for shotcrete shall conform to the requirements of Section 3.8, Portland Cement Concrete.

4.4.4   MIX DESIGN

The Contractor shall develop the shotcrete mix by laboratory
tests and field trials as indicated herein at least 90 days
prior to the actual application of shotcrete to any surface
forming a permanent part of the work under this contract.
Laboratory trial mixes shall be made with exactly the same
ingredients that the Contractor proposes to use in his work.
Certification that ingredients comply with the specifications
shall accompany the mix design.

The proportions of shotcrete dry mix shall be equivalent to
those of a concrete mix having between 6.5 and 7.5 bags per
cubic yard, and a water-cement ratio of 0.40. The proportion
of admixture shall not exceed 6% of the cement weight.

4.4.4.1 Laboratory Tests

Prior to making laboratory tests the Contractor shall submit
a detailed plan showing the methods and materials to be used
in such tests. The Engineer reserves the right to inspect
the tests at any time.

To ascertain the compatibility of the ingredients and their
optimum proportions, the Contractor shall develop a shotcrete
mix having the same strength and characteristics as required
for actual application. For this purpose, 3" cubes, and
3" x 3" x 12" beams of concrete shall be made using the approx-
imate cement factor and water cement ratio suggested herein
and tested for the specified compressive strength at intervals
of 8 hours, 72 hours, and 28 days. These laboratory trial
tests shall be performed at no cost to the Authority. The
Contractor shall furnish a complete report of test results to
the Engineer at the conclusion of a laboratory testing.

4.4.4.2 Field Trial

After completion of the laboratory tests and their approval,
the Contractor shall make field trial using selected mixes to
demonstrate capability of equipment, workmanship, and materials
under field conditions at least 60 days prior to actual appli-
cation of shotcrete in permanent work. The mixes selected
for field trials shall be subject to the approval of the
Engineer.

The field application of each mix selected for field trial
shall be made on one horizontal and one vertical test panel
to simulate construction conditions. Test panels shall be
cast on wood forms measuring not less than 36" x 36" x 3".
Test panels shall be cured by the Contractor in accordance
with ASTM Designation C 31, "Making and Curing Concrete

Compressive and Flexural Strength Test Specimens in the Field."
Test specimens shall be obtained by the Contractor by neatly
sawing or coring 3" cubes or 3" x 3" cores and 3" x 3" x 12"
beams from test panels. Specimens shall be cured under identi-
cal conditions used for the test panels.

The specimens shall be obtained, prepared and tested in
accordance with ASTM Designation C 42, "Obtaining and Testing
Drilled Cores and Sawed Beams of Concrete", as herein modified.

The compressive strength of specimens obtained by applying the
load normally to the direction in which the material was shot
shall meet the following minimum compressive strength requir
ments:

> 800 psi at 8 hours
> 3,000 psi at 72 hours
> 5,000 psi at 28 days

The flexural strength of beams at 28 days shall be at least
15% of the compressive strength at the same age, except that
for compressive strengths of over 5,000 psi the flexural
strength shall be at least 10%. In addition to the strength
requirement, the shotcrete specimens shall be dense, impermeable,
low shrinkage, uniform and non-laminated. The Contractor is
expected to have sufficient over-design in field trials to
allow for variations in his workmanship and to meet strength
and other requirements during actual application of shotcrete.

All costs for developing shotcrete mixes including field trials
and laboratory tests, prior to approval of mixes by the Engi-
neer, shall be at the expense of the Contractor, and shall be
considered incidental to work under this Section.

All phases of field trial work shall be performed in the
presence of a representative of the Engineer. Upon completion,
the Contractor shall submit 12 test specimens of each mix that
the Contractor proposes to use in the work together will all
relevant data which demonstrates conformance to the specifica-
tions in all respects. The specimens will be tested by the
Engineer at various stages of curing (ages) to verify con-
formance with these specifications.

The Engineer will inform the Contractor, in writing, of his
approval of mixes which meet the requirements. No shotcrete
shall be used in permanent work that has not been approved
by the Engineer.

The exact proportions of ingredients determined on the basis of trial mixes shall be used in the actual application of shotcrete and shall not be varied without the written approval of the Engineer.

4.4.5   CONSTRUCTION

4.4.5.1 Proportioning and Mixing

Proportioning of aggregate and cement shall be accomplished on a weight basis by a suitable batching plant. The batching plant and proportioning devices shall conform to the applicable provisions of Section 3.8, Portland Cement Concrete.

The moisture content of the combined aggregate at the time of mixing with cement shall be in the range of 3% to 6% of the oven-dry weight of the aggregate.

Mixed material shall be used within 60 minutes after adding cement; or waste without payment.

The accelerating additive shall be added immediately prior to depositing the materials in the placing equipment, or if in liquid form, may be accurately proportioned into the water supply at the application nozzle. Dry additive shall be accurately proportioned and thoroughly mixed with the other ingredients.

4.4.5.2 Placing Equipment

Placing equipment shall consist of a spray nozzle providing for ejection of dry materials and water in an intimate mixture, separate hoses to deliver dry materials and water to the nozzle, a suitable machine to introduce the dry materials to the delivery hose under air pressure, and air and water supply system. The water supply system shall consist of a local reservoir and a positive displacement pump capable of supplying water through a regulating valve, easily and accurately controllable by the nozzleman, in sufficient amount and at pressure slightly above the operating air pressure recommended by the manufacturer of the delivery machine.

The air supply system shall be capable of supplying the delivery machine and hose with air at the pressures and volumes recommended by the manufacturer of the machine. No air supply system shall be used that delivers air contaminated by oil or that is incapable of maintaining constant pressure.

The delivery machine shall be capable of introducing dry materials to the delivery hose at a uniform rate, with ejection from the nozzle at velocities that will afford adherence of

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material to the treated surface with a minimum rebound and maximum adherence and density

The entire system shall be so arranged that the nozzleman may use air and water in any combination to prepare surfaces on which shotcrete will be applied. In addition, a separate air hose and blow pipe shall be available to remove dust and rebound during shotcrete application.

Equipment shall be provided to allow application of shotcrete to surfaces at an approximate range of 3-1/2 feet from the nozzle.

4.4.6   CLASSIFICATION

For the purpose of this specification, shotcrete applications shall be divided into one of three classifications; namely, Class I, Class II, and Class III.

4.4.6.1 Class I Shotcrete

Class I shotcrete is defined as shotcrete applied within 50 feet of the face in accordance with the following limitations. The Contractor shall apply a layer of Class I shotcrete to the newly-exposed surface of the tunnel arch in the heading above the springline immediately after blasting. This application shall commence not later than one hour after the time the blast is fired and shall be completed within two hours after the blast is fired. The Engineer may also direct, under this paragraph, the application of Class I shotcrete to other areas in the vicinity of the heading shortly after blasting. The Contractor will not be required to apply less than two cubic yards nor more than eight cubic yards of Class I shotcrete after any single blast.

4.4.6.2 Class II Shotcrete

All shotcrete not meeting the requirements of Class I shotcrete as defined above and outside the limits of Dupont Circle Station described in paragraph 4.4.6.3, shall be considered Class II shotcrete.

4.4.6.3 Class III Shotcrete

All shotcrete not meeting the requirements of Class I shotcrete as defined above and inside the limits of Dupont Circle Station shall be considered Class III shotcrete. The limits

of Dupont Circle Station, for purposes of this Section of
these specifications, are from station 72+10 to station 64+86
and up to the face of collar closest to the centerline of Du-
pont Circle Station at entrances.

4.4.7 SHOTCRETE APPLICATION

Surfaces, whether new or previously shotcreted, which are to
receive shotcrete, shall be cleaned of all loose material,
mud and other foreign matter which is not automatically removed
by the shotcreting operation. The surface shall be moist at
the time shotcrete is applied. The nozzle shall be held at
a predetermined distance and position so that the stream of
flowing material shall impinge as nearly as possible at
right angles to the surface to be covered. Shotcrete of the
approved mix design shall be applied in a circular fashion to
build up the required thickness of layer.

Prior to application of the first layer of Class II or Class
III shotcrete, the Contractor shall furnish and install
approved measuring pins to the surfaces to be treated for
the purpose of indicating the thickness of shotcrete layers.

Pins shall be noncorrosive and so designed as not to cause
infiltration of water through the shotcrete. Pins shall be
installed at five foot centers in horizontal and transverse
directions, and at other locations as directed by the
Engineer.

4.4.7.1 Proficiency of Workmen

Nozzlemen shall have had previous experience in the applica-
tion of course aggregate shotcrete on at least two projects
of comparable nature, or shall work under the immediate
supervision of a foreman or instructor with at least five
years of such experience. Each crew shall demonstrate, to
the satisfaction of the Engineer, acceptable proficiency in
the application of shotcrete to vertical and overhead test
panels before beginning production work.

Acceptable shotcrete shall consist of a dense uniform concrete
without major rebound inclusions, and without discernable
weakness of bond between layers. The nozzleman shall shoot
shotcrete with a uniform consistency in order to maximize
binding, cohesion, and density, minimize rebound and prevent
sagging of the applied shotcrete. The inclusion of rebound

or aggregate pockets will not be permitted in the finished work. Rebound shall be removed and disposed of at the Contractor's expense.

4.4.7.2 <u>Sequence of Operations</u>

Outside the limits of Dupont Circle Station, all rock surfaces, including those which have been coated with Class I shotcrete, shall have the first layer of Class II shotcrete applied within 150 feet of the working face. Succeeding layers shall be applied within 150 feet of application of the last preceding layer. Rock bolts and steel ribs shall be installed prior to the first layer of Class II shotcrete. Surface reinforcement shall be installed prior to the last layer of Class II shotcrete.

Inside the limits of Dupont Circle Station, all rock surfaces, including those which have been coated with Class I shotcrete, shall have the total thickness of Class III shotcrete applied within 48 hours after exposure of the rock surface to be treated, except that the total time may be extended to 72 hours for Design "Y" shown on the contract drawings. Rock bolts and steel ribs shall be installed prior to the first layer of Class III shotcrete. Surface reinforcement shall be installed prior to the last layer of Class III shotcrete.

A succeeding shotcrete layer shall be applied no earlier than four hours after application of the preceding layer. All laitance, loose material and rebound shall be removed and the surface layer sounded with a hammer for voids, rebound or aggregate pockets, and unbonded areas. Defective areas shall be removed and replaced. Where the contract drawings indicate shotcrete thickness per layer in excess of two inches, the shotcrete shall be built up in individual layers not more than four inches thick.

Steel ribs, rock bolts and welded wire fabric shall be installed as shown on the contract drawings.

The final shotcrete layer shall be cured for seven days in accordance with the applicable paragraphs of Section 3.10, Concrete Structures, except as approved or directed by the Engineer.

4.4.7.3 <u>Control of Water</u>

Water flows and seepage shall be controlled in such a manner that detrimental effects are completely and permanently

eliminated. The Contractor may drain such water by pipes, chases or other appropriate methods approved by the Engineer. No separate payment shall be made for this work, and it shall be considered incidental to the work under this section.

4.4.8   TESTING DURING CONSTRUCTION

The Contractor shall provide 3-inch diameter standard core test specimens at the rate of two for each 50 cubic yards of material or each 25 linear feet of lining, whichever may be less. These specimens shall have a minimum length equal to the diameter and shall expose the bond between shotcrete and rock. They shall be cored from completed work at locations specified by the Engineer. The test cores will be tested by the Engineer in accordance with ASTM Designation C 42, "Obtaining and Testing Drilled Cores and Sawed Beams of Concrete", as herein modified. Curing shall be in accordance with ASTM Designation C 31, "Making and Curing Concrete Compressive and Flexural Test Specimens in the Field". These routine specimens shall be furnished by the Contractor without extra cost to the Authority.

At the discretion of the Engineer, the Contractor shall furnish test specimens at the reduced rate of two for each 100 cubic yards of material, or each 50 linear feet of lining, whichever may be the least, after application of the first 500 cubic yards of shotcrete.

The compressive strength of cores shall not be less than 5,000 psi at 28 days.

Additional specimens may be required at any time by the Engineer. Should additional specimens show acceptable strength, the Contractor will be reimbursed for the cost of obtaining such additional cores. Should these specimens fail, the cost of additional specimens shall be deemed incidental to the work.

The Contractor shall plug the voids caused by the coring operation by the use of material equal to the shotcrete in-place and workmanship to insure continuity of the lining as to water-tightness, strength, and appearance.

4.4.9   SAFETY MEASURES

Alkali hydroxides and other chemicals contained in shotcrete admixtures are moderately toxic, and can cause skin and respiratory irritation unless adequate safety measures are

undertaken. In applying shotcrete containing toxic admixtures, the nozzlemen and helpers shall wear appropriate hoods supplied with filtered air free of toxic or objectionable material. Gloves and necessary protective clothing shall be worn to protect against dermatitis.

4.4.10   DEFECTIVE SHOTCRETE

Shotcrete which lacks uniformity, exhibits segregation, honey-combing, lamination, shows cracking, or lacking water-tightness shall be regarded defective shotcrete. The Engineer reserves the right to order removal of defective shotcrete and its replacement with acceptable shotcrete without additional cost to the Authority. Any remedial measure ordered by the Engineer to correct defective shotcrete shall also be at the expense of the Contractor.

4.4.11   MEASUREMENT AND PAYMENT

Measurement of shotcrete will be made on the basis of volume in cubic yards actually discharged through the nozzle and accepted by the Engineer. Cement and accelerating additive used in shotcrete will be measured separately. Cement will be measured by the sack of 94 pounds. Accelerating additive will be measured either by the pound, for powder, or fluid pint for liquid.

The shotcrete volume in cubic yards shall be computed from the weight of the material batched at the batch plant by assuming that 3,800 pounds, of mixed materials in bulk, cement and saturated surface-dry aggregate, equals one cubic yard. Any shotcrete which is wasted or placed in violation of these specifications will not be measured for payment. The weight-volume relationship assumed here is based on aggregates in saturated surface-dry condition having an average bulk specific gravity of 2.60.

The accepted shotcrete will be paid for at the respective contract unit prices for "Shotcrete", Class I, Class II, and Class III, per cubic yard; for "Shotcrete Cement", per sack; and for "Shotcrete Additive" per pound, avoirdupois or fluid pint as applicable, as shown on the Unit Price Schedule.

Such prices shall include the furnishing of labor, materials, including water, tools, equipment, transportation and all other incidentals. Payment for the aforementioned work shall

also include compensation for the development and testing of trial mixes, and the furnishing of all test specimens of shotcrete as required by these specifications.

No separate payment will be made for drainage and seepage control, and all necessary materials and labor shall be considered incidental to work under this section of these specifications.