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DESIGN OF FIBER REINFORCED CONCRETE FOR PUMPING

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FINAL REPORT

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16. Abstract

This study was undertaken to develop a positive design procedure for pumpable fibrous reinforced concrete mixes and to provide information on this method for application in tunnel liners.

The addition of fiber reinforcement to any combination of fine and coarse aggregates increases the void content of the mix. The incompressible paste content of the mix must exceed the void content so that segregation failure will not occur during pumping. Because of the inherent high void content and harshness of a fiber reinforced concrete mix compared to a plain concrete mix the gradation of the sand is more critical and the steps necessary to design a pumpable mix more detailed. The steps include selection of the aggregates, ratio of fine to coarse aggregate, volume of paste, quantity of water and the cement content. Due to the high paste requirement of pumpable fiber reinforced concrete it may be advantageous from both economical and workability considerations to include a pozzolan or other fine material in the paste.

Mixes with four different coarse aggregate maximum sizes, two water reducing admixtures and one phase thickening admixture were studied.

These mixes were evaluated in a laboratory testing apparatus designed to model actual pumping conditions.

17. Key Words

Concrete; Pumped Concrete; Tunnels; Mix Proportioning; Fiber Reinforced Concrete.

18. Distribution Statement

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PREFACE

This study was conducted in the Department of Civil Engineering of the University of Illinois at Urbana-Champaign. The research was supported by the Federal Railroad Administration, Department of Transportation, through Contract No. DOT FR 30022, under the technical direction of Mr. Russell McFarland. Project Coordinator at the University of Illinois was Dr. Stanley L. Paul.

Data and tables are presented in the English system, with International System of Units (SI) values included in parentheses. Large tables are presented with SI values in a separate table. For example, the English values may be presented in Table 3 and the SI values in Table 3-SI. Figures are presented with auxiliary scales for SI units.

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CHAPTER 1

INTRODUCTION

1.1 CONCEPT OF SLIPFORMING TUNNEL LINERS

Slipforming tunnel liners, Parker, et al., (1971), has been proposed as an efficient and safe means of lining tunnels. However, normal Portland cement concretes gain strength slowly requiring either excessively long slipforms or a rate of advancement so slow as to be impractical. The availability of quick setting cement concretes which have useable strengths within two hours after mixing overcome this difficulty and makes slipforming tunnel liners an achievable goal.

Slipforming poses no unusual problems unless the concrete liner must be reinforced. Reinforcing bars or welded wire fabric would be practically impossible to place in the slipform. In place of conventional reinforcement, steel fibers may be added to the concrete and will provide the necessary reinforcement.

The only convenient means of placing the concrete in a complete tunnel slipform is by pumping. Unfortunately, the inclusion of fibers complicates the mix design of the concrete that is to be pumped. The purpose of this report is to describe a positive mix design procedure for fiber reinforced pumpable concrete which can conveniently be used by mix design engineers.

1.2 PROBLEM

Pumping failures are usually due to either the inability of the concrete to contain the water, leaving the solid constituents to block the pipeline or an excess of fines resulting in sufficiently high friction between the concrete and the pipe such that the pressure from the pump cannot move the concrete through the pipe. The first type of failure is referred to as a segregation failure and the second as a friction failure. Field pumping trials have shown that when a fiber reinforced concrete will not pump, the cause is nearly always a segregation failure usually at a point of reduced diameter.

Segregation failures can be eliminated by reducing the size and volume of the voids in the aggregates such that the water in the paste will not pass through the mix during pumping. In most cases, this is accomplished by including appropriate proportions of the finer sizes of the fine aggregate. In fiber reinforced concrete the problem is more critical because the fibers inhibit proper compaction of the mix resulting in large void volumes. Fibers also reduce the workability of the concrete requiring higher pump pressures to move the concrete through Y's, reducers and elbows. Thus, a concrete that will pump without fibers may not pump if only a small volume of fibers are added.

1.3 OBJECTIVE

The purpose of this study was to develop a mix design procedure for pumpable fiber reinforced concrete and to demonstrate the procedure for various fiber contents, maximum aggregate sizes, and admixtures.

1.4 SCOPE

The study included concretes with and without steel fiber and with and without admixtures at four different coarse aggregate maximum sizes. Steel fiber percentages of 0.9, 1.2 and 1.5 percent by volume were used.

Two types of water reducing admixtures and one phase thickening admixture were used. Only one natural sand was used in all pumping tests. The mixes were evaluated in a laboratory testing device which has the ability to simulate pipeline pressures.

1.5 STANDARD TESTS AND SPECIFICATIONS

The following recommended practices, methods of test and specification are referred to throughout the report.

AMERICAN CONCRETE INSTITUTE

ACI 304-73 -- Recommended Practice for Measuring, Mixing, Transporting, and Placing Concrete.

AMERICAN SOCIETY FOR TESTING AND MATERIALS

C 29-71 -- Standard Method of Test for Unit Weight of Aggregate;

C 33-74 -- Standard Specifications for Concrete Aggregates;

C 127-73 -- Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate;

C 128-73 -- Standard Method of Test for Specific Gravity and Absorption of Fine Aggregates;

C 136-71 -- Standard Method of Test for Sieve or Screen Analysis of Fine and Coarse Aggregates;

C 143-71 -- Standard Method of Test for Slump of Portland Cement Concrete;

C 618-73 -- Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolans for use in Portland Cement Concrete.

CHAPTER 2

PRESENT STATE OF KNOWLEDGE

2.1 INTRODUCTION

Placing of concrete by pumping is appropriate for almost all applications and it can be the most effective means when construction conditions limit accessibility. The most troublesome phase of concrete pumping usually lies in the formulation of the mix. Designing pumpable mixes can be approached systematically if the influence of certain factors such as aggregate shape, maximum size, gradation, cement content and water content are known. In addition, knowledge of the effects of pipeline diameters and reducers, admixture quantities, entrapped air content and slump is required.

If the concrete mix is formulated properly, the concrete will move through the pipe as if it were a slug. Improperly designed mixes will pump as a viscous liquid if too wet or will not pump as a result of either a segregation failure or friction failure.

Conventional concrete pumping equipment is commercially available in three types, the piston displacement type, the pneumatic type, and the squeeze pressure type. The most common pump is the piston displacement type and a variety of manufacturers offer different models.

2.2 GENERAL REQUIREMENTS FOR A PUMPABLE MIX

2.2.1 WORKABILITY

Well proportioned, dense concrete is pumpable. Concrete mixes for pumping must be plastic (ACI-304). Concrete will pump over a wide range of slumps, but in general, if the slump values are too low, very high pump pressures will result, and if the mixes are too wet, even moderate pumping pressures will cause segregation of the particles. Most experts agree that a slump of about 4 in. (100 mm) is usually ideal although concretes with slumps ranging from 2 to 7 in. (50 to 175 mm) (Litvin, 1968) have been successfully pumped.

The concrete should be well mixed before it is fed to the pump. It must not be too harsh nor contain an inordinate amount of fine material.

Air contents should not be too high although values of 4 to 6 percent are common. If the air content is above 6 percent, compressibility of the mix may cause a problem. If the delivery line is long, the reduction in volume of air under the pump pressure may be large enough to absorb the entire stroke of the piston resulting in no net motion of the concrete (Neville, 1973).

2.2.2 PASTE CONTENT

The cement paste content of a mix is dictated by the volume of voids in the aggregate array. Denser, minimum void mixes require less paste. All of the particles should be coated with cement paste. The total volume of paste consisting of cement, pozzolan if used, and water, should generally, slightly exceed the void volume of the aggregate mixture since the paste will separate the aggregate particles which has the effect of increasing the voids. Improper amounts of paste will most likely result in a pumping failure. If too much paste is added in excess of the voids, friction failure may result. On the other hand, if the paste content is not at least equal to the void volume segregation failure may occur.

2.3 PUMPING FAILURES

The ability of a concrete mix within a pipeline to transfer applied force through the water phase to the remaining particles is an important parameter controlling pumpability. If the concrete mix is formulated properly the concrete will flow through the pipe as if it were a slug. Failure will occur if the mix is unable to contain the water or if pipeline friction is too great.

The two types of failures experienced in pumping concrete are referred to as friction and segregation failures. Although it is important that all of the particles be coated with cement paste, if too much paste is added in excess of the voids, then high pipeline friction may result, causing high pump pressures or failure to pump. Segregation failures will occur if the paste content is not at least equal to the void volume (Kempster, 1969). If it is less, the pressure exerted by the pump will force the water through the remaining voids and out of the mix, leaving an aggregate plug lodged in the conduit.

The ideal solution therefore is to produce maximum density of solids in the mix with minimum voids, and minimum frictional resistance against the pipe wall with a low surface area of the aggregate (Neville, 1973). The mix must be internally dense enough to transmit the force of the pump without segregation, but should not contain so many fines as to create high frictional resistance at the interface with the pipeline.

2.4 PUMPING EQUIPMENT

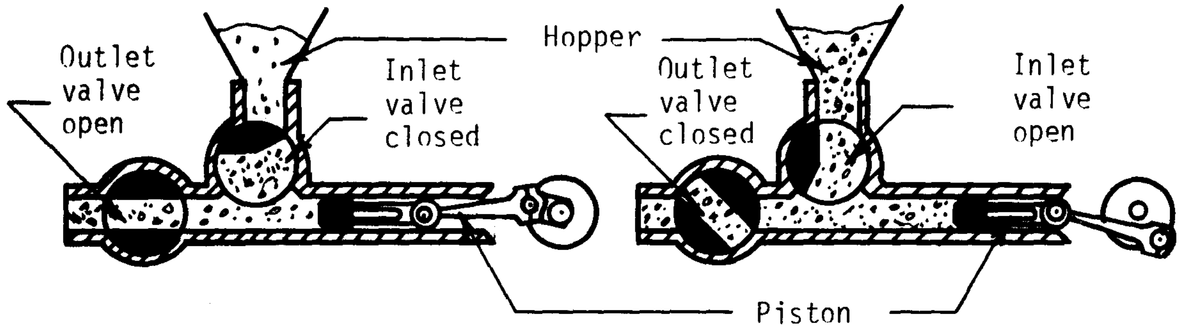
2.4.1 PUMPS

There are three basic kinds of concrete pumps: the piston displacement, the pneumatic or air-extrusion, and the squeeze pressure type. All of these pumps function to move concrete from a hopper through a delivery line to the place the concrete is to be used.

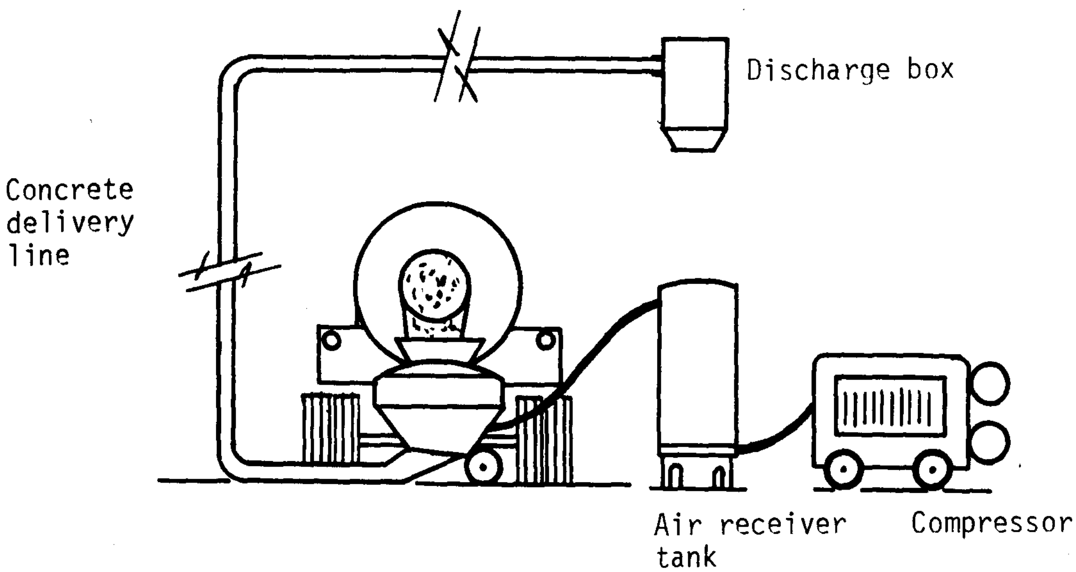
The most common type is the piston displacement pump. In this system, concrete is allowed to flow through a valve into a cylinder, Fig. 2.1a. Once the cylinder is filled, the valve is closed and the piston is advanced, pushing the concrete into the discharge line. The piston is then retracted, the valve opened, and more concrete is placed in the cylinder. Some models contain two cylinders which permit one piston to be advanced while the other is retracted, creating a continuous flow at the discharge point.

In a pneumatic concrete pump system, Fig. 2.1b, concrete is placed in a pressure vessel and the system sealed. Compressed air is charged in through the top, forcing concrete out through the bottom and into the delivery line. The concrete is pushed through the line under this air pressure to a discharge box where it is remixed before being delivered. In order to maintain a continuous flow, two or three pressure vessels may be required.

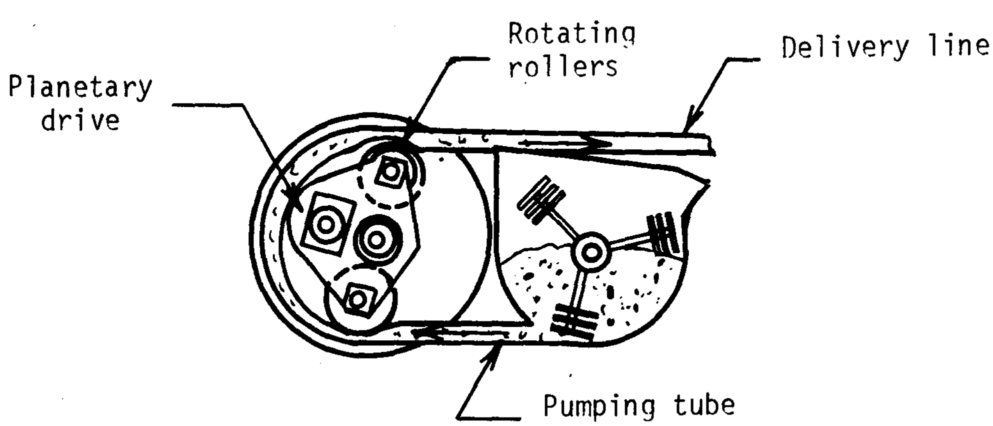
A squeeze pressure system, Fig. 2.1c, consists of a flexible pumping hose and a set of rotating rollers. Concrete is drawn into the flexible hose from the hopper and the rotating rollers squeeze the concrete through the tube to the delivery line. The squeezing action of the rollers tends to create a suction that draws a continuous flow of concrete into the tube.



a) Piston type



b) Pneumatic type



c) Squeeze pressure type

FIG. 2.1 CONCRETE PUMPS (AFTER ACI COMMITTEE 304, 1971)

2.4.2 PIPELINES, HOSES AND REDUCERS

In order to move concrete from the pump to the point of placement, steel pipe is used, sometimes with a flexible rubber hose attached at the discharge end. The minimum recommended line size for conventional concrete mixes is normally on the order of 3 to 4 times the maximum aggregate size (ACI-304).

Pipelines are available in a variety of sizes but 4-in. (100-mm) and 6-in. (150-mm) inside diameter sizes are the most common. Since the diameter of the discharge end of some pumps may be 8 to 12 in. (200 to 300 mm) in diameter, a transition, in the form of a reducer, is necessary to channel the concrete into the smaller pipeline diameter. This restriction requires the concrete to undergo a severe reworking process. Likewise, if double-action piston type pumps are used, a Y or siamese connection is required to combine the flow into one line. Both the reducer and the Y demand that the concrete be easily remolded.

Rubber hoses may be attached to the rigid pipeline at the point of discharge to facilitate the placement of the concrete. The frictional resistance of the rubber hose is much greater than that of steel pipe. Consequently, these hoses should only be used in short lengths.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION

The problems associated with pumping conventional concretes are magnified with the inclusion of steel fibers. Most fiber reinforced concrete mixes are prone to fail by segregation and require special attention. Thus, the emphasis of the study was to develop a procedure which would result in minimization of the voids in the concrete and therefore prevent segregation failures. The major steps of the study were:

1. Selection of materials.
2. Selection of an appropriate combination of fine and coarse aggregates for a given fiber content that would result in minimum voids.
3. Determination of the volume of paste required.
4. Evaluation of the pumpability of the fiber reinforced concrete in the laboratory.

3.2 MATERIALS

All tests were made with the following materials except that more than one lot of cement and aggregates was used. The source of each of these materials is the same.

Flat steel fiber, 0.010 in. by 0.022 in. by 1.0 in. (0.25 mm by 0.56 mm by 25 mm) were used.

The fly ash met all requirements for Pozzolan Class F of ASTM C 618.

Two types of water reducing admixtures and one phase thickening admixture were used in the investigation. Melment L10 and Mighty 150 super water reducers were used. Darex pumping aid was used as the phase thickener.

All of the aggregates used were from glacial outwash. Their unit weights, bulk specific gravities and absorption capacities are given in Table 3.1. Four different maximum-sized gravels were used: 3/8-in. (10-mm), 1/2-in. (13-mm), 3/4-in. (19-mm) and 1-in. (25-mm). One locally available sand was used in most of the tests. Sieve analyses of these materials appear in Table 3.2.

TABLE 3.1

PROPERTIES OF SAND AND COARSE AGGREGATE

		Coarse aggregate maximum size			
Property	Sand	3/8-in. (10-mm)	1/2-in. (13-mm)	3/4-in. (19-mm)	1-in. (25-mm)
Unit weight, lb/cu ft (kg/m^3)	107.6 (1774)	100.6 (1612)	101.8 (1631)	102.0 (1634)	104.9 (1681)
Bulk specific gravity, SSD	2.60	2.66	2.66	2.66	2.66
Absorption capacity, percent	2.2	2.2	2.2	2.2	2.2

In some of the laboratory work, regraded sand conforming to the ACI-304 gradation was formulated. Recommended amounts retained on the No. 8 and No. 16 (2.36 mm and 1.18 mm) sieves were reduced to allow for space occupied by the fibers. The ACI-304 gradation and the artificial sand formulation are shown in Fig. 3.1.

TABLE 3.2

AGGREGATE GRADATION

Sieve	Sand, percent		Coarse aggregate nominal maximum-size: 3/8-in. (10-mm), percent		1/2-in. (13-mm), percent		3/4-in. (19-mm), percent		1-in. (25-mm), percent	
	Retained	Passing	Retained	Passing	Retained	Passing	Retained	Passing	Retained	Passing
1-in. (25.0-mm)	0	100	0	100	0	100	0	100	2	98
3/4-in. (19.0-mm)	0	100	0	100	0	100	0	100	18	82
1/2-in. (12.5-mm)	0	100	0	100	12	88	25	75	45	55
3/8-in. (9.5-mm)	0	100	1	99	30	70	59	41	62	38
No. 4 (4.75-mm)	4	96	94	6	94	6	97	3	97	3
No. 8 (2.36-mm)	12	88	99	1	99	1	100	0	100	0
No. 16 (1.18-mm)	22	78	100	0	100	0	100	0	100	0
No. 30 (600-μm)	40	60	100	0	100	0	100	0	100	0
No. 50 (300-μm)	84	16	100	0	100	0	100	0	100	0
No. 100 (150-μm)	99	1	100	0	100	0	100	0	100	0
No. 200 (75-μm)	99	1	100	0	100	0	100	0	100	0
Fineness modulus	2.61		5.94		6.23		6.56		6.77	

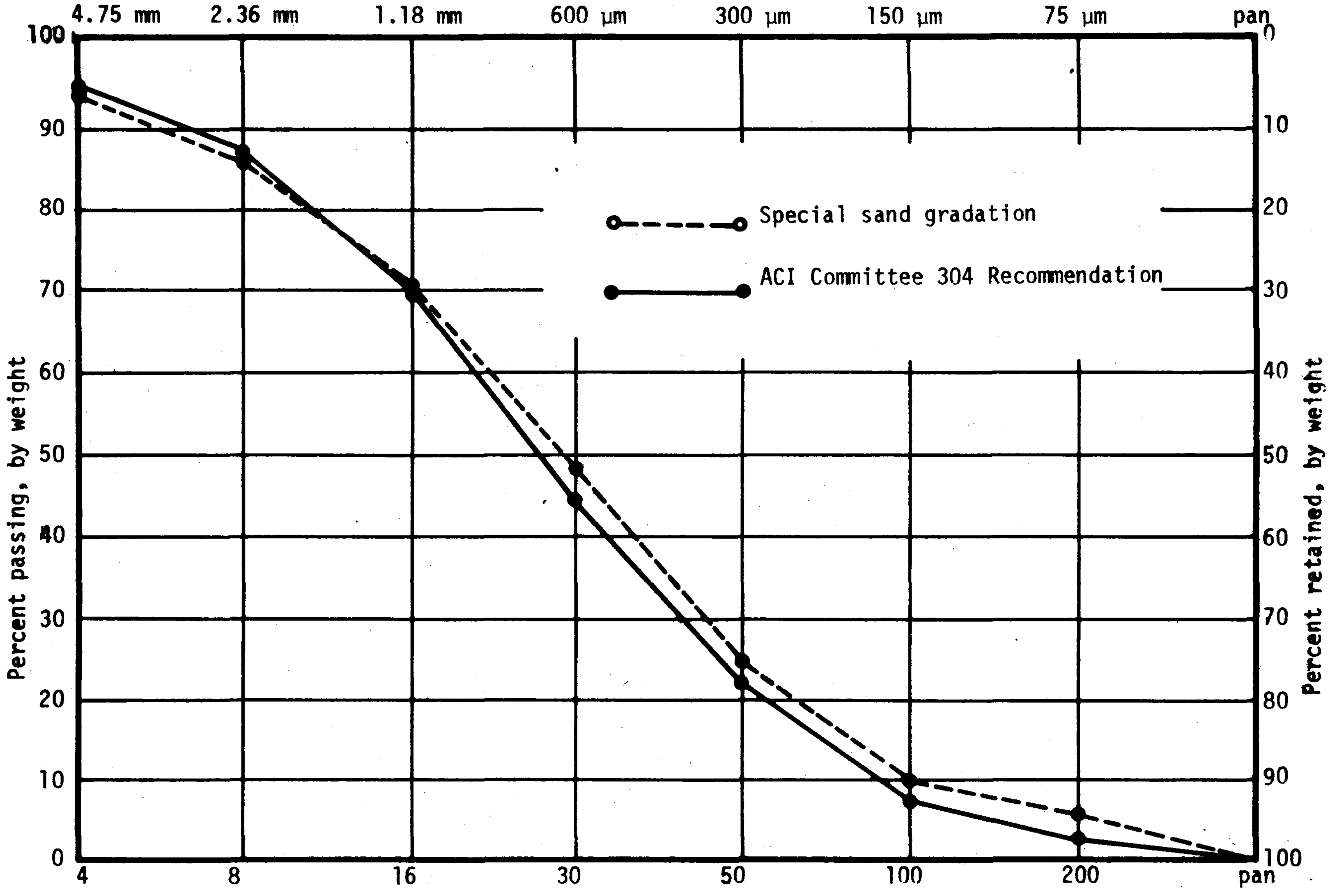


FIG. 3.1 FINE AGGREGATE GRADATION

The majority of the mixes were made with the sand graded as received at the laboratory. Since this locally available sand was deficient in fines, fly ash, in an amount of 6 percent by weight of the sand was added. Fly ash was used because it was the most readily available material.

3.3 MINIMUM VOIDS

The combination of sand and gravel for a given volume of fibers that would yield the least volume of voids was determined experimentally. Unit weight tests were conducted and the volume of voids computed, using the weights of each material and bulk specific gravities. A curve of porosity (void volume expressed as a percent of the total volume) and fine aggregate content was drawn for particular fiber percentages and coarse aggregate maximum sizes. Such curves permit the determination of the most suitable proportion of coarse and fine aggregate and indicate the volume of voids that must be filled with paste. The results of the laboratory tests appear in Chapter 4.

3.4 PASTE CONTENT

If a mix is to be pumpable, the paste, consisting of cement, water, air and fly ash if used, must at least fill the voids in the aggregate-fiber array. However, when the paste is added to the aggregates the volume of voids is increased due to separation of the constituents by the paste. For conventional concretes, paste amounts are normally proportioned to be about 3 to 5 percent in excess of the measured void volume. In fiber reinforced concrete the presence of fibers decreases the workability of the mix and because these mixes contain a large percentage of sand the volume of paste required can be expected to be somewhat greater than that for conventional concrete.

Admixtures which increase workability or increase the viscosity of the water may permit a reduction in the volume of paste required for pumpable concrete.

The minimum volume of paste can only be determined experimentally with any degree of certainty until sufficient experience is gained to make a determination otherwise.

3.5 DETERMINATION OF PUMPABILITY

The most desirable means of determining pumpability would be by conducting full-scale pumping trials with a commercially available pump. This procedure requires a large volume of concrete for a test and causes a disposal problem making it difficult to evaluate a large number of mixes. Therefore, a small pumping device, Fig. 3.2, has been developed to permit the testing of a small volume of concrete. The device consists of two cylinders, one 8-in. (200-mm) and one 4-in. (100-mm) inside diameter, joined by a reducer, 12 in. (300 mm) long. Concrete is placed in the 8-in. (200-mm) cylinder and pumped through the reducer into the 4-in. (100-mm) section. The reduction in the cross sectional area of 75 percent in 12 in. (300 mm) is believed to be much more severe than would occur in practice.

A method of applying pressure at the discharge end of the 4-in. (100-mm) cylinder of the apparatus was developed to simulate pressures that might occur in a pipeline. The device, as used in these tests, developed an average of 40 psi (275 kPa) pressure on the concrete at the discharge end of the apparatus.

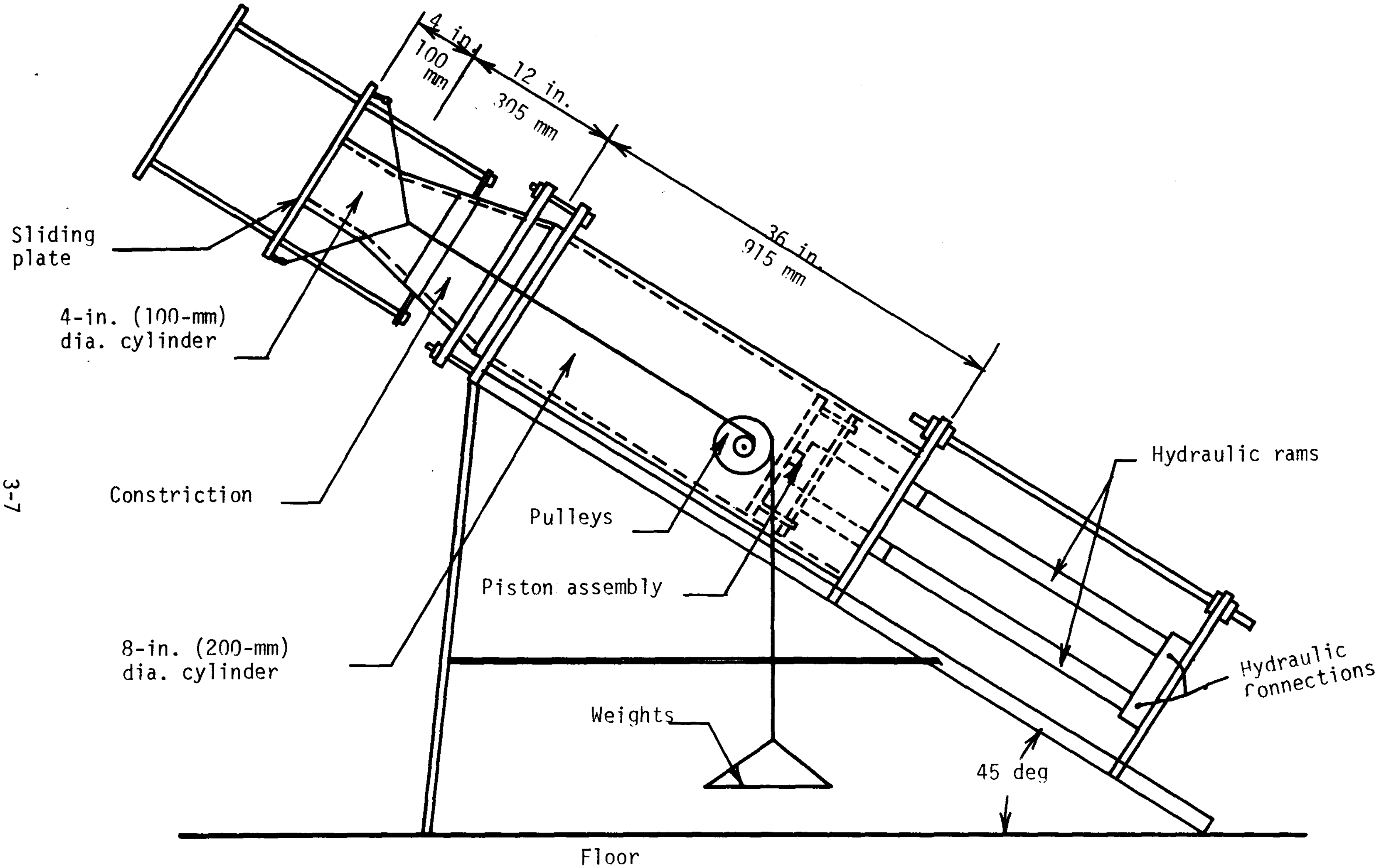


FIG. 3.2 SCHEMATIC DIAGRAM OF LABORATORY PUMPING APPARATUS

Although the total device is rather simple, it allows simulation of a piston-displacement pump under conditions that are expected to be more severe than in an actual pump and pipeline system. The device is able to readily compare the pumpability of different mixes.

3.6 SUMMARY

Briefly, the mix design procedure suggested herein consists of:

1. Selection of suitable materials, in particular, a suitably graded fine aggregate.
2. Determination of attainable minimum void content for a sand, gravel and fiber combination, and
3. Determination of a paste content in excess of the volume of voids, with an appropriate water content.

Using this procedure as a basis, a number of mixes were formulated and tested. The results are given in the next chapter.

CHAPTER 4

EVALUATION OF PUMPABILITY

4.1 INTRODUCTION

Using the concepts previously discussed, together with a workability as indicated by a 4-in. (100-mm) slump, a number of trial mixes were made. These mixes included fiber contents of 0.0, 0.9, 1.2 and 1.5 percent by volume and maximum aggregate sizes of 3/8 in. (10 mm), 1/2 in. (13 mm), 3/4 in. (19 mm), and 1 in. (25 mm). A number of the mixes contained water reducing admixtures or a phase thickening admixture.

All trial mixes were tested and evaluated for pumpability. The pumpable mixes are given in Table 4.5.

4.2 CONCRETES MADE WITH 3/8-in. (10-mm) MAXIMUM-SIZED AGGREGATE

4.2.1 DRY UNIT WEIGHT TESTS

Unit weight tests were conducted on 3/8-in. (10-mm) maximum-sized gravel and a sand graded in accordance with ACI-304 recommendations. Tests were made at fiber contents of 0.0, 0.9, 1.2 and 1.5 percent by volume. The results of these tests appear in Table 4.1 and a graph of the relationship of porosity and fine aggregate content appears in Fig. 4.1. With increasing fiber content the void volume increases and the fine aggregate content at the point of minimum voids increases.

TABLE 4.1

UNIT WEIGHT TESTS FOR 3/8-in. (10-mm)
MAXIMUM-SIZED AGGREGATE WITH STEEL FIBER

Steel fiber, percent	Fine aggregate, percent	Sand, lb (kg)	Coarse aggregate, lb (kg)	Steel fiber, lb (kg)	Unit weight, lb/cu ft (kg/m^3)	Porosity, percent
0.0	40	25.0 (11.3)	37.5 (17.0)	--	125.0 (2002)	23.0
0.0	50	25.0 (11.3)	25.0 (11.3)	--	126.1 (2020)	22.0
0.0	60	25.0 (11.3)	16.7 (7.6)	--	126.1 (2020)	22.1
0.0	70	25.0 (11.3)	10.7 (4.8)	--	125.9 (2017)	22.2
0.0	75	30.0 (13.6)	10.0 (4.5)	--	123.9 (1985)	22.9
0.0	80	30.0 (13.6)	7.5 (3.4)	--	123.1 (1972)	23.2
0.0	100	28.7 (13.0)	-- --	--	116.8 (1871)	26.9
0.9	40	25.0 (11.3)	37.5 (17.0)	2.31 (1.05)	118.9 (1905)	28.4
0.9	50	25.0 (11.3)	25.0 (11.3)	1.84 (0.83)	122.8 (1967)	25.8
0.9	60	25.0 (11.3)	16.7 (7.6)	1.55 (0.70)	123.1 (1972)	25.6
0.9	70	25.0 (11.3)	10.7 (4.8)	1.35 (0.61)	123.2 (1973)	25.6
0.9	75	30.0 (13.6)	10.0 (4.5)	1.50 (0.68)	123.8 (1983)	24.8
0.9	80	30.0 (13.6)	7.5 (3.4)	1.40 (0.64)	123.3 (1975)	24.9
0.9	85	30.0 (13.6)	5.7 (2.6)	1.30 (0.59)	122.9 (1969)	25.1
1.2	40	25.0 (11.3)	37.5 (17.0)	3.20 (1.45)	117.5 (1882)	30.1
1.2	50	25.0 (11.3)	25.0 (11.3)	2.50 (1.13)	119.4 (1912)	28.6
1.2	60	25.0 (11.3)	16.7 (7.6)	2.10 (0.95)	121.4 (1945)	27.4
1.2	70	25.0 (11.3)	10.7 (4.8)	1.80 (0.82)	122.6 (1964)	26.5
1.2	75	30.0 (13.6)	10.0 (4.5)	2.10 (0.95)	123.0 (1970)	26.0
1.2	80	30.0 (13.6)	7.5 (3.4)	1.90 (0.86)	121.8 (1951)	26.4
1.2	85	30.0 (13.6)	5.7 (2.6)	1.80 (0.82)	122.8 (1967)	26.2
1.5	40	25.0 (11.3)	37.5 (17.0)	4.00 (1.81)	114.2 (1829)	32.5
1.5	50	25.0 (11.3)	25.0 (11.3)	3.30 (1.50)	117.3 (1879)	30.4
1.5	60	25.0 (11.3)	16.7 (7.6)	2.80 (1.27)	120.4 (1929)	28.7
1.5	70	25.0 (11.3)	10.7 (4.8)	2.40 (1.09)	120.1 (1924)	28.7
1.5	75	30.0 (13.6)	10.0 (4.5)	2.60 (1.18)	122.6 (1964)	26.6
1.5	80	30.0 (13.6)	7.5 (3.4)	2.40 (1.09)	122.0 (1954)	27.1

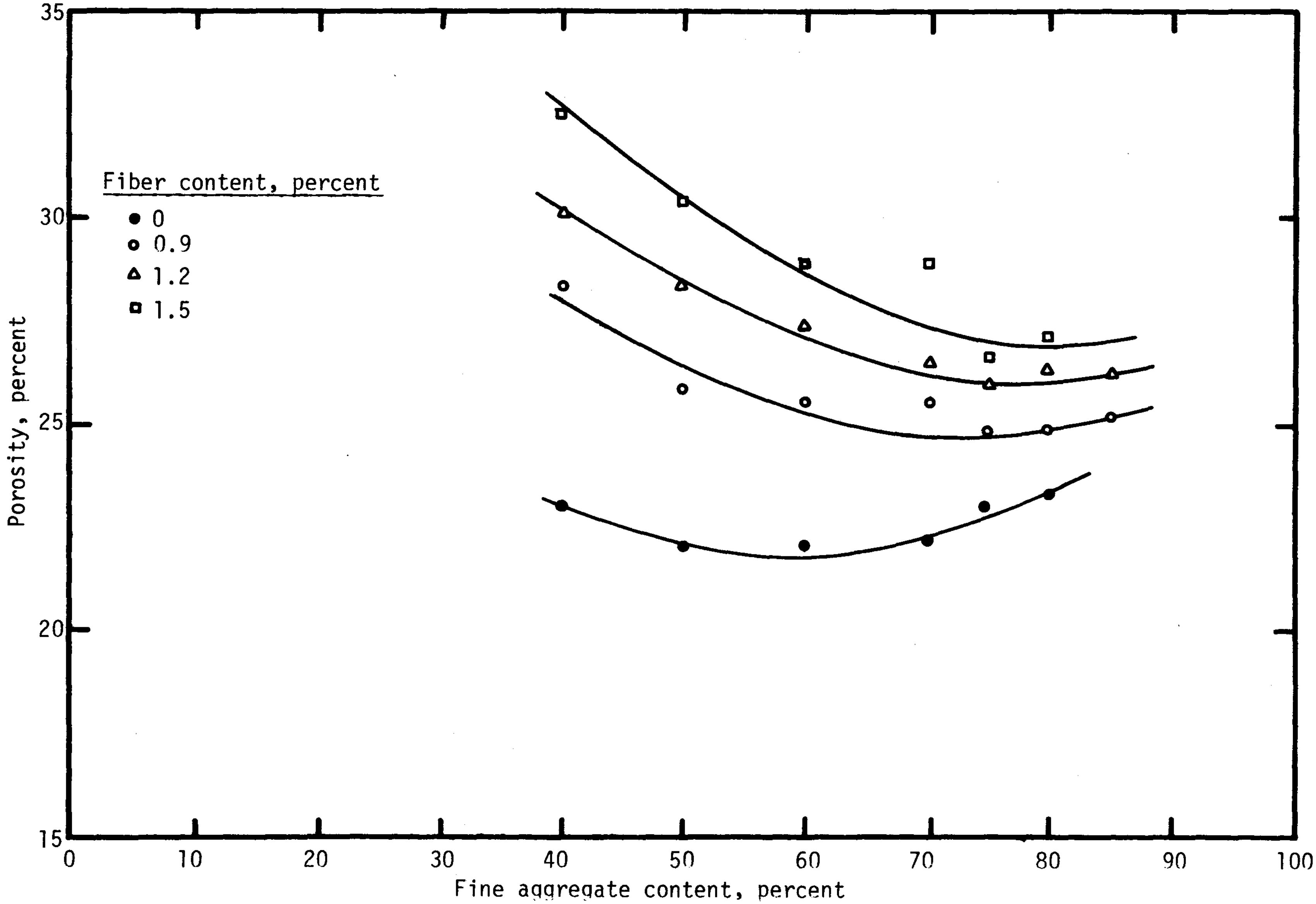


FIG. 4.1 POROSITY OF STEEL FIBER-AGGREGATE MIXTURE WITH 3/8-in. (10-mm) MAXIMUM-SIZED AGGREGATE

4.2.2 MIX DESIGN AND PUMPING TESTS

On the basis of the results of the unit weight tests, mixes were formulated for pumping trials. For each fiber content and aggregate combination yielding minimum voids an amount of paste was proportioned to be slightly in excess of the void volume. The paste consisted of water, cement and fly ash. Pumping tests were made on each trial mix. Although air is entrapped in fiber reinforced concrete mixes, it is not considered as part of the paste in filling the voids for pumpable concrete since under the pump pressure the volume of air is reduced such that it is insignificant. Initially, some mixes did not pass through the apparatus, failing by segregation at pumping pressures in excess of 250 psi (1.72 MPa). Additional increments of paste and some fines in the form of fly ash were added to help prevent segregation. With increased fiber content, pumping became more difficult. With appropriate adjustments, pumpable mixes at 0.9, 1.2 and 1.5 percent fiber were formulated.

The necessity for additional fines to prevent segregation failure is due, in part, to the deficiency of fines in the laboratory sand, the high void volume at increased fiber content and the large proportion of sand in the mix.

The amount of paste added in excess of the void volume increases with fiber content. Although plain concretes may be pumped with paste contents only slightly in excess, 3 to 5 percent, of the void volume, fibrous mixes require somewhat more paste. With this 3/8-in. (10-mm) maximum-sized aggregate a range of 8 to 10 percent excess paste is typical with higher values for increasing fiber content.

Mix designs for 3/8-in. (10-mm) maximum-sized aggregates for the three fiber contents are given in Table 4.5.

4.2.3 USE OF ADMIXTURES

Two types of water-reducing admixtures, Melment L10 and Mighty 150, were added to the pumpable mixes to reduce the amounts of free water and to improve workability.

Mixes formulated with Melment L10 effectively reduced water contents by about 12 to 15 percent for a given slump. Melment was added at the rate of about 4 percent, by weight of cement. Air contents were slightly higher than those values measured in mixes without Melment. All mixes with Melment pumped successfully.

Mighty 150 was added in an amount of about 1 percent, by weight of cement. Mixes with Mighty exhibited improved workability at slump values of 3 to 5 in. (75 to 125 mm). Water content was reduced by about 10 to 15 percent. Air contents were considerably higher than those for mixes without Mighty. These mixes pumped at lower pressures than those made with Melment or without admixtures.

Pumpable mix designs for mixes made with Melment and Mighty are given in Table 4.5.

4.3 CONCRETES MADE WITH 1/2-in. (13-mm) MAXIMUM-SIZED AGGREGATE

4.3.1 DRY UNIT WEIGHT TESTS

The coarse aggregate was graded to closely resemble the recommended gradation given in ASTM C 33 for coarse aggregate having a maximum size of 1/2 in. (13 mm). The gradation is listed in Table 3.2.

Tests were conducted to determine the fine aggregate content at lowest voids. The test results and a graph of porosity and fine aggregate content appear in Table 4.2 and Fig. 4.2, respectively. Because of the larger maximum size aggregate, the values of minimum voids were lower than those for the 3/8-in. (10-mm) maximum-sized gravel mixes. Also, the minimum void contents occurred at lower percentages of fine aggregate. Due to the reduction of both voids and surface area of the aggregates, less paste was proportioned for the concretes made with 1/2-in. (13-mm) maximum-sized aggregate than those made with 3/8-in. (10-mm) maximum-sized aggregate.

4.3.2 PUMPING TRIALS

Mixes were formulated by the method previously described. Mixes at fiber contents of 0.9, 1.2 and 1.5 percent by volume were readily pumped. It was apparent throughout the pumping trials that a paste content of about 6 to 9 percent in excess of the voids was necessary. Three mixes with a fiber content of 0.9 percent were formulated with paste contents equal to the void volume, 3 percent in excess of the void volume and 6 percent in excess of the void volume. Only the mix with a paste content of 6 percent in excess of the void volume had sufficient paste to cover all of the aggregate particles. It was also the only mix that was pumpable.

The only fly ash used in these mixes was that added to overcome the deficiency of fines in the sand.

Mix designs appear in Table 4.5.

TABLE 4.2

UNIT WEIGHT TESTS FOR 1/2-in. (13-mm) MAXIMUM-SIZED AGGREGATE WITH STEEL FIBER

Steel fiber, percent	Fine aggregate, percent	Sand, lb (kg)	Fly ash, lb (kg)	Coarse aggregate, lb (kg)	Fiber, lb (kg)	Unit weight, lb/cu ft (kg/m^3)	Porosity, percent
0.0	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	--	127.5 (2042)	20.9
0.0	40	23.64 (10.72)	1.36 (0.62)	37.4 (17.0)	--	129.2 (2070)	19.8
0.0	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	--	129.3 (2071)	19.5
0.0	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	--	127.0 (2034)	20.8
0.0	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	--	124.4 (1993)	22.2
0.0	80	28.37 (12.87)	1.63 (0.74)	7.4 (3.4)	--	121.3 (1943)	24.0
0.9	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	3.23 (1.47)	119.0 (1906)	28.0
0.9	40	23.64 (10.72)	1.36 (0.62)	37.4 (17.0)	2.40 (1.09)	123.5 (1978)	25.3
0.9	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	1.91 (0.87)	125.8 (2015)	23.7
0.9	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	1.58 (0.72)	126.6 (2028)	23.0
0.9	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	1.34 (0.61)	125.7 (2014)	23.3
0.9	80	28.37 (12.87)	1.63 (0.74)	7.4 (3.4)	1.41 (0.64)	125.0 (2002)	23.6
1.2	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	4.25 (1.93)	120.3 (1927)	27.8
1.2	40	23.64 (10.72)	1.36 (0.62)	37.4 (17.0)	3.10 (1.41)	123.9 (1985)	25.5
1.2	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	2.50 (1.13)	125.8 (2015)	24.2
1.2	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	2.05 (0.93)	126.4 (2025)	23.6
1.2	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	1.73 (0.78)	125.1 (2004)	24.2
1.2	80	28.37 (12.87)	1.63 (0.74)	7.4 (3.4)	1.81 (0.82)	123.7 (1981)	24.9
1.5	40	23.64 (10.72)	1.36 (0.62)	37.4 (17.0)	4.12 (1.87)	119.4 (1913)	29.0
1.5	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	3.15 (1.43)	122.4 (1961)	26.9
1.5	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	2.60 (1.18)	124.0 (1986)	25.7
1.5	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	2.25 (1.02)	124.3 (1991)	25.4
1.5	80	28.37 (12.87)	1.63 (0.74)	7.4 (3.4)	2.38 (1.08)	123.6 (1980)	25.6
1.5	90	33.10 (15.01)	1.90 (0.86)	3.9 (1.8)	2.50 (1.13)	122.2 (1957)	26.4

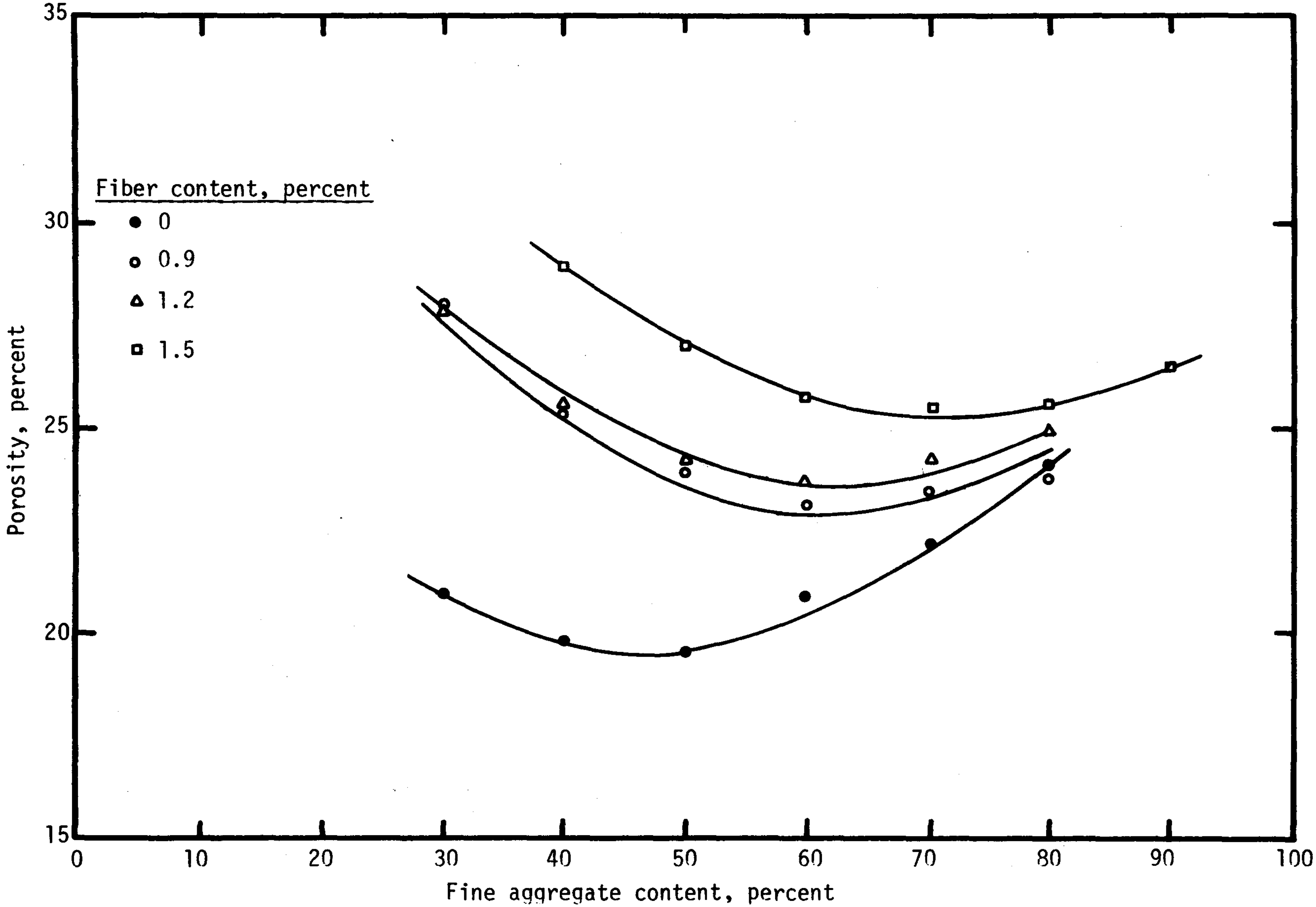


FIG. 4.2 POROSITY OF STEEL FIBER-AGGREGATE MIXTURE WITH 1/2-in. (13-mm) MAXIMUM-SIZED AGGREGATE

4.3.3 ADMIXTURES

Melment L10 was added to the mixes in amounts of 4 percent, by weight of cement. This permitted water reductions of 10 to 13 percent at slumps of 4 to 5 in. (100 to 125 mm). Entrapped air contents were 4 to 5 percent. These mixes, Table 4.5, pumped at lower pressures than the concretes without a water reducer.

4.4 CONCRETES MADE WITH 3/4-in. (19-mm) MAXIMUM-SIZED AGGREGATE

4.4.1 DRY UNIT WEIGHT TESTS

The gradation of the 3/4-in. (19-mm) maximum-sized aggregate, Table 3.2, met the ASTM C 33 specification.

The combination of sand and gravel without fibers, had a lower volume of voids than similar mixes with 3/8-in. (10-mm) and 1/2-in. (13-mm) maximum-sized aggregates. However, mixes with fiber contents of 0.9, 1.2, and 1.5 percent had minimum void contents close to those of the 1/2-in. (13-mm) maximum-sized aggregate mixes. Some balling of the fibers developed with the 3/4-in. (19-mm) maximum-sized aggregate and may have prevented proper consolidation. Test results and graphs appear in Table 4.3 and Fig. 4.3, respectively.

4.4.2 PUMPING TRIALS

Mixes were formulated using the steps previously outlined. No specific problems were encountered although some balling of the fibers did occur in the mixes with 1.5 percent fibers. Some minor adjustments to the

TABLE 4.3

UNIT WEIGHT TESTS FOR 3/4-in. (19-mm) MAXIMUM-SIZED AGGREGATE WITH STEEL FIBER

Steel fiber, percent	Fine aggregate, percent	Sand, lb (kg)	Fly ash, lb (kg)	Coarse aggregate, lb (kg)	Fiber, lb (kg)	Unit weight, lb/cu ft (kg/m^3)	Porosity, percent
0.0	20	11.82 (5.36)	0.68 (0.31)	50.0 (22.7)	--	122.7 (1966)	24.0
0.0	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	--	127.4 (2041)	20.9
0.0	40	23.64 (10.72)	1.36 (0.62)	37.4 (17.0)	--	130.7 (2093)	18.7
0.0	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	--	129.9 (2081)	19.0
0.0	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	--	127.6 (2044)	20.3
0.0	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	--	125.4 (2009)	21.5
0.0	80	28.37 (12.87)	1.63 (0.74)	7.4 (3.4)	--	122.4 (1961)	22.6
0.9	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	3.23 (1.47)	118.6 (1900)	28.2
0.9	40	23.64 (10.72)	1.36 (0.62)	37.4 (17.0)	2.40 (1.09)	123.5 (1978)	25.1
0.9	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	1.91 (0.87)	126.1 (2020)	23.3
0.9	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	1.58 (0.72)	126.0 (2018)	23.3
0.9	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	1.34 (0.61)	125.2 (2006)	23.5
0.9	80	28.37 (12.87)	1.63 (0.74)	7.4 (3.4)	1.41 (0.64)	123.5 (1978)	23.8
1.2	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	4.25 (1.93)	115.2 (1846)	30.8
1.2	40	23.64 (10.72)	1.36 (0.62)	37.4 (17.0)	3.10 (1.40)	119.1 (1908)	28.3
1.2	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	2.50 (1.13)	124.9 (2001)	24.6
1.2	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	2.05 (0.93)	126.2 (2022)	23.7
1.2	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	1.73 (0.78)	125.5 (2011)	23.9
1.2	80	28.37 (12.87)	1.63 (0.74)	7.4 (3.4)	1.81 (0.82)	123.9 (1985)	24.1
1.5	40	23.64 (10.72)	1.36 (0.62)	37.4 (17.0)	4.22 (1.91)	118.7 (1902)	29.3
1.5	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	3.33 (1.52)	122.0 (1955)	27.2
1.5	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	2.77 (1.26)	122.9 (1969)	26.5
1.5	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	2.35 (1.06)	124.0 (1987)	25.6
1.5	80	28.37 (12.87)	1.63 (0.74)	7.4 (3.4)	2.44 (1.11)	123.3 (1976)	25.3
1.5	90	33.10 (15.01)	1.90 (0.86)	3.9 (1.8)	2.56 (1.16)	121.4 (1945)	26.9

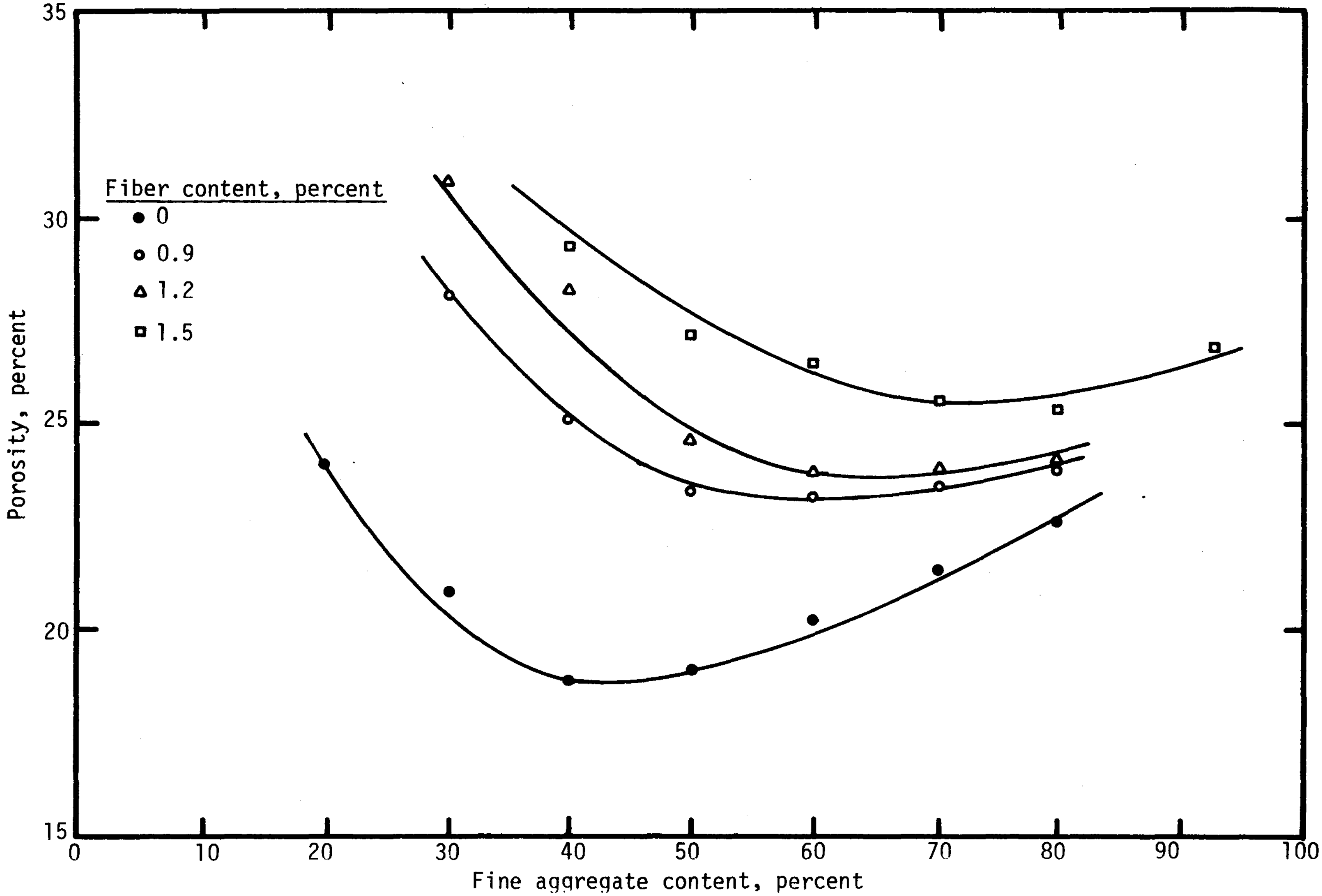


FIG. 4.3 POROSITY OF STEEL FIBER-AGGREGATE MIXTURE WITH 3/4-in. (19-mm) MAXIMUM-SIZED AGGREGATE

total aggregate gradation were made to reduce the balling tendency of the fibers. Mixes with paste contents 6 to 8 percent in excess of the void volume, Table 4.5, were successfully pumped.

4.4.3 ADMIXTURES

Both Melment L10 and Mighty 150 were added to the pumpable mixes. Melment was added to the mixes at the rate of 4 percent, by weight of cement, and permitted water reductions of 10 to 13 percent at slumps of 4 to 6 in. (100 to 150 mm). The air content of these mixes was about 4 percent.

Mixes with 1 percent, by weight of cement, of Mighty 150 permitted water reductions of 9 to 15 percent at a slump of 5 to 6 in. (125 to 150 mm). Air contents were 5 to 8 percent. Mixes at 0.9 and 1.2 percent fiber contents pumped easily but at 1.5 percent of fibers the mix required unusually higher pressures to pump.

Mix designs for these admixture concretes are listed in Table 4.5.

4.5 CONCRETES MADE WITH 1-in. (25-mm) MAXIMUM-SIZED AGGREGATE

4.5.1 DRY UNIT WEIGHT TESTS

The gradation with 1-in. (25-mm) maximum-sized aggregate was formulated, Table 2.2, in accordance with ASTM C 33 specification.

Unit weight tests were conducted with this aggregate, sand and the steel fiber. The results of these tests appear in Table 4.4 and a graph of the porosity at various fine aggregate and fiber contents is plotted in Fig. 4.4.

TABLE 4.4

UNIT WEIGHT TESTS FOR 1-in. (25-mm)
MAXIMUM-SIZED AGGREGATE WITH STEEL FIBER

Steel fiber, percent	Fine aggregate, percent	Sand, lb (kg)	Fly ash, lb (kg)	Coarse aggregate, lb (kg)	Fibers, lb (kg)	Unit weight, lb/cu ft (kg/m^3)	Porosity, percent
0.0	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	--	132.3 (2119)	18.1
0.0	40	23.64 (10.72)	1.36 (0.62)	37.5 (17.0)	--	132.3 (2119)	17.9
0.0	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	--	130.8 (2095)	18.6
0.0	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	--	128.0 (2050)	20.1
0.0	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	--	125.4 (2009)	21.6
0.0	80	28.37 (12.87)	1.63 (0.74)	7.5 (3.4)	--	122.6 (1964)	23.2
0.9	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	3.00 (1.36)	122.0 (1954)	26.2
0.9	40	23.64 (10.72)	1.36 (0.62)	37.5 (17.0)	2.30 (1.04)	126.7 (2030)	23.2
0.9	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	1.84 (0.83)	127.8 (2047)	22.4
0.9	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	1.55 (0.70)	127.1 (2036)	22.6
0.9	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	1.35 (0.61)	124.8 (1999)	23.8
0.9	80	28.37 (12.87)	1.63 (0.74)	7.5 (3.4)	1.50 (0.68)	121.8 (1951)	25.6
1.2	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	4.05 (1.84)	118.6 (1900)	28.9
1.2	40	23.64 (10.72)	1.36 (0.62)	37.5 (17.0)	2.94 (1.33)	122.7 (1965)	26.1
1.2	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	2.37 (1.08)	126.4 (2025)	23.8
1.2	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	1.98 (0.90)	125.7 (2014)	24.0
1.2	70	23.64 (10.72)	1.36 (0.62)	10.7 (4.8)	1.71 (0.78)	125.1 (2004)	24.1
1.2	80	28.37 (12.87)	1.63 (0.74)	7.5 (3.4)	1.80 (0.82)	124.0 (1986)	24.6
1.5	30	23.64 (10.72)	1.36 (0.62)	58.3 (26.4)	5.70 (2.59)	114.9 (1841)	31.9
1.5	40	23.64 (10.72)	1.36 (0.62)	37.5 (17.0)	4.20 (1.91)	118.5 (1898)	29.6
1.5	50	23.64 (10.72)	1.36 (0.62)	25.0 (11.3)	3.30 (1.50)	120.5 (1930)	28.2
1.5	60	23.64 (10.72)	1.36 (0.62)	16.7 (7.6)	2.70 (1.22)	121.6 (1948)	27.3
1.5	80	28.37 (12.87)	1.63 (0.74)	7.5 (4.8)	2.45 (1.11)	119.8 (1919)	28.1
1.5	90	33.10 (15.01)	1.90 (0.86)	3.9 (3.4)	2.55 (1.16)	118.1 (1892)	28.7

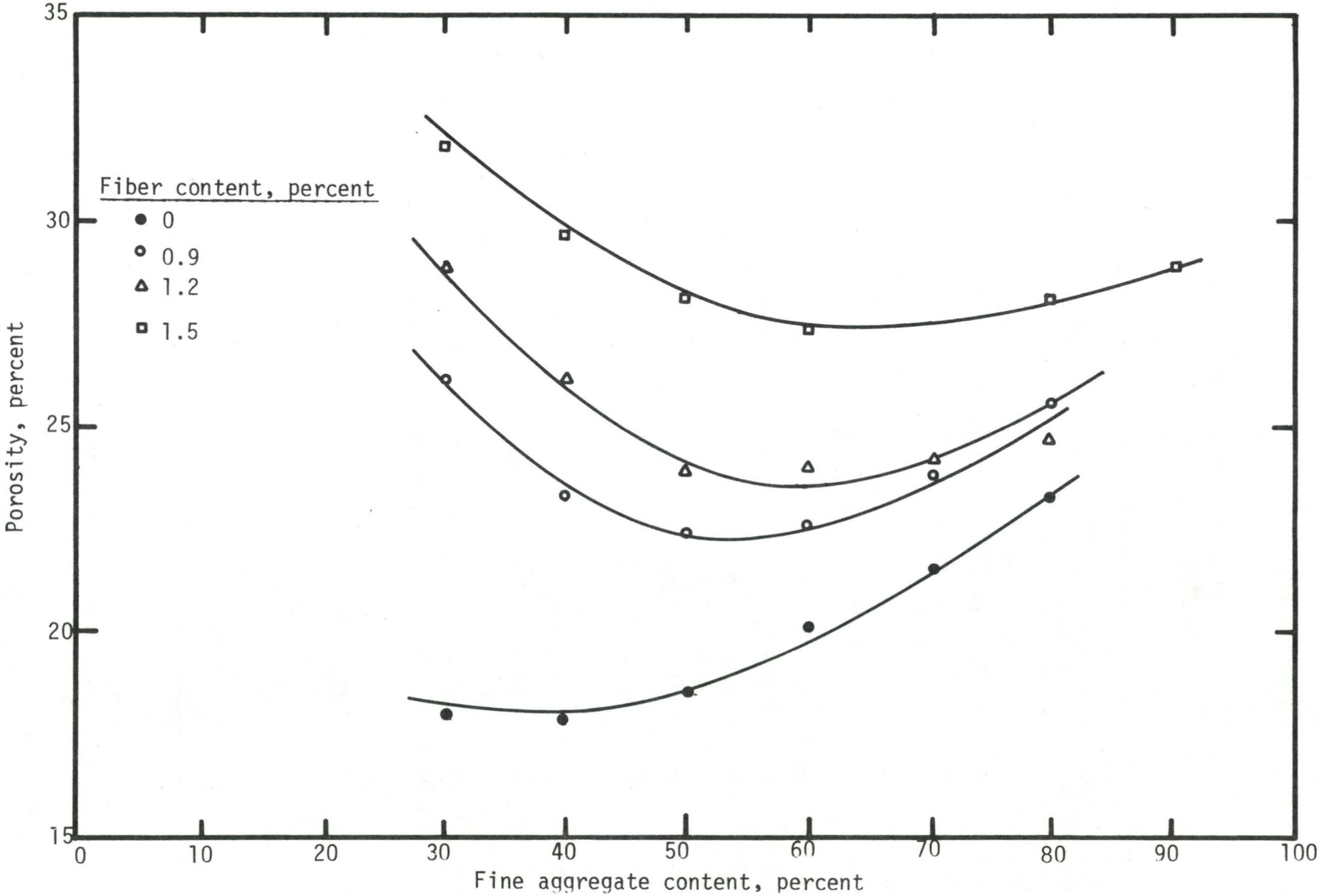


FIG. 4.4 POROSITY OF STEEL FIBER-AGGREGATE MIXTURE WITH 1-in. (25-mm) MAXIMUM-SIZED AGGREGATE

As expected, the volume of voids for mixes without fiber was the lowest of the tests. However, in mixes with fiber, the larger coarse aggregate particles caused many of the fibers to ball which made it difficult to determine the true void content of the mixes. At 1.5 percent fiber content the balling was quite extensive even though this aggregate was well graded.

4.5.2 PUMPING TRIALS

Pumping tests were conducted on mixes, Table 4.5, formulated on the same basis as previously presented. Mixes made with 0.9 percent fiber were pumped without problems but required a paste content of about 7 percent in excess of the voids. The mixes made with fiber amounts of 1.2 and 1.5 percent required larger portions of paste to coat all the particles. With appropriate paste contents in these concretes, balling was not a problem. Because of the higher paste contents and the desire to keep the slump at about 4 in. (100 mm), the water-cement ratios for these mixes are low when compared to those made with the other aggregates. However, the paste content need not be increased by cement alone, fly ash additions might well have been used.

Pumping pressures for mixes made with 1-in. (25-mm) maximum-sized aggregate averaged the highest of any of the tests.

4.5.3 ADMIXTURES

Melment L10, at the rate of 4 percent by weight of cement, was used as the water reducer for the pumpable mixes, Table 4.5. With slumps maintained at about 4 in. (100 mm), water reductions of 11 to 15 percent were achieved. Air contents averaged 4 percent.

TABLE 4.5

PUMPABLE MIXES FOR STEEL FIBER REINFORCED CONCRETE

Aggregate maximum size, in.	Volume of fibers, percent	Water-cement ratio, by wt[1]	Materials, lb/cu yd								Air content, percent	Unit weight, lb/cu ft
			Water	Cement	Fly ash	Sand	Coarse aggregate	Steel fibers	Melment L10	Mighty 150		
3/8	0.9	0.50	330	660	220	1805	775	120	---	---	3.0	144.9
3/8	1.2	0.50	340	685	225	1820	690	160	---	---	3.3	145.4
3/8	1.5	0.46	340	740	225	1790	595	200	---	---	4.1	143.9
3/8	0.9	0.42	260	655	220	1790	765	120	20	---	6.1	142.0
3/8	1.2	0.42	270	690	225	1835	695	160	21	---	4.7	144.4
3/8	1.5	0.40	285	760	225	1830	610	200	23	---	4.3	145.4
3/8	0.9	0.43	275	655	220	1785	765	120	---	8	6.0	142.0
3/8	1.2	0.42	280	675	220	1795	680	160	---	8	6.9	141.5
3/8	1.5	0.42	290	690	220	1785	595	200	---	8	8.2	140.0
1/2	0.9	0.49	300	610	90	1630	1150	120	---	---	4.2	144.4
1/2	1.2	0.49	320	660	90	1610	1140	160	---	---	3.6	147.3
1/2	1.5	0.47	350	745	100	1745	790	200	---	---	4.0	145.4
1/2	0.9	0.46	260	615	90	1655	1165	120	28	---	4.1	145.8
1/2	1.2	0.43	260	650	90	1590	1125	160	27	---	5.1	144.4
1/2	1.5	0.41	290	760	100	1780	805	200	28	---	3.9	146.8
3/4	0.9	0.48	300	620	90	1655	1165	120	---	---	3.1	146.3
3/4	1.2	0.48	310	645	95	1660	945	160	---	---	5.3	141.0
3/4	1.5	0.47	335	715	100	1760	795	200	---	---	3.3	144.4
3/4	0.9	0.42	245	625	95	1665	1175	120	26	---	4.0	146.3
3/4	1.2	0.43	265	670	100	1725	985	160	27	---	3.8	145.4
3/4	1.5	0.42	285	720	100	1775	800	200	25	---	3.3	144.4
3/4	0.9	0.43	250	590	90	1580	1115	120	---	8	8.1	138.5
3/4	1.2	0.42	275	665	95	1705	970	160	---	7	5.5	143.4
3/4	1.5	0.42	290	700	95	1720	780	200	---	8	7.3	140.0
1	0.9	0.48	300	620	80	1400	1480	120	---	---	3.6	148.3
1	1.2	0.43	310	720	90	1590	1120	160	---	---	3.3	147.9
1	1.5	0.42	360	865	95	1680	760	200	---	---	2.9	146.8
1	0.9	0.42	240	615	80	1385	1470	120	22	---	5.0	145.4
1	1.2	0.39	255	720	90	1585	1115	160	28	---	4.0	146.3
1	1.5	0.36	290	865	95	1675	760	200	30	---	4.0	144.9

[1] Water-cement ratio includes water in any admixture.

TABLE 4.5-SI

PUMPABLE MIXES FOR STEEL FIBER REINFORCED CONCRETE

Aggregate maximum size, mm	Volume of fibers, percent	Water-cement ratio, by wt[1]	Materials, kg/m^3								Air content, percent	Unit weight, kg/m^3
			Water	Cement	Fly ash	Sand	Coarse aggregate	Steel fibers	Melment L10	Mighty 150		
10	0.9	0.50	195	393	131	1072	460	71	---	---	3.0	2321
10	1.2	0.50	202	408	134	1082	410	95	---	---	3.3	2329
10	1.5	0.46	202	441	132	1062	354	119	---	---	4.1	2305
10	0.9	0.42	154	390	131	1062	455	71	12	---	6.1	2274
10	1.2	0.42	162	410	134	1088	413	95	12	---	4.7	2313
10	1.5	0.40	169	450	134	1085	362	119	14	---	4.3	2329
10	0.9	0.43	164	390	131	1060	455	71	---	5	6.0	2274
10	1.2	0.42	167	401	132	1066	404	95	---	5	6.9	2266
10	1.5	0.42	172	410	131	1060	353	119	---	5	8.2	2242
13	0.9	0.49	179	361	54	968	682	71	---	---	4.2	2313
13	1.2	0.49	191	390	53	956	676	95	---	---	3.6	2359
13	1.5	0.47	208	443	58	1036	468	119	---	---	4.0	2329
13	0.9	0.46	154	366	54	982	692	71	17	---	4.1	2335
13	1.2	0.43	154	386	53	944	667	95	16	---	5.1	2313
13	1.5	0.41	172	452	59	1056	477	119	16	---	3.9	2351
19	0.9	0.48	179	368	55	982	692	71	---	---	3.1	2343
19	1.2	0.48	184	383	55	986	560	95	---	---	5.3	2258
19	1.5	0.47	198	424	59	1045	472	119	---	---	3.3	2313
19	0.9	0.42	145	371	56	988	697	71	16	---	4.0	2343
19	1.2	0.43	156	399	58	1024	582	95	16	---	3.8	2329
19	1.5	0.42	169	428	59	1053	476	119	15	---	3.3	2313
19	0.9	0.43	147	352	53	937	661	71	---	5	8.1	2218
19	1.2	0.42	164	394	57	1012	575	95	---	4	5.5	2297
19	1.5	0.42	170	415	57	1021	462	119	---	5	7.3	2242
25	0.9	0.48	179	369	46	831	880	71	---	---	3.6	2375
25	1.2	0.43	185	428	53	945	665	95	---	---	3.3	2369
25	1.5	0.42	214	515	56	998	451	119	---	---	2.9	2351
25	0.9	0.42	141	365	46	823	873	71	13	---	5.0	2329
25	1.2	0.39	151	426	53	942	663	95	16	---	4.0	2343
25	1.5	0.36	172	513	56	993	450	119	18	---	4.0	2321

[1] Water-cement ratio includes water in any admixture.

Mixes in which the water was reduced 15 percent were difficult to pump. Possibly, regardless of the type of water reducer used, the water in a well designed mix should not be reduced by more than about 12 percent.

Since mixes at this particular coarse aggregate maximum size exhibited more difficulty in being pumped than others, the effect of a phase thickening admixture was studied. Mixes at 1.2 and 1.5 percent fiber were formulated with Darex pumping aid. These mixes exhibited improved workability and pumped at lower pressures. One mix at 1.5 percent fiber content was formulated with less paste and remained pumpable. It is apparent that the phase thickening admixtures can serve to increase the ease of pumping fiber reinforced concrete.

4.6 SUMMARY

These test results clearly show that pumpable concrete mixes for fiber contents up to 1.5 percent by volume and maximum aggregate sizes up to 1 in. (25 mm) can be designed using a rational procedure. The important steps in the procedure consist of:

1. Selecting an appropriately graded fine aggregate.
2. Determining the combination of fine and coarse aggregates that will produce the minimum voids when used with a given fiber content.
3. Selecting a paste content that is in excess of the void volume by 6 to 9 percent, depending on the fiber content.

Fiber reinforced concretes with slumps ranging from 3-1/2 to 4-1/2 in. (90 to 115 mm) pump without difficulty providing the mix is properly formulated.

Admixtures are not necessary in the formulation of fiber reinforced concrete, however, the super water reducers can permit reduction in water contents to a maximum of about 12 percent with improved pumpability. Phase thickening agents improve pumpability resulting in a reduction in the volume of paste and the pump pressure required.

All the mixes not modified with admixtures contained 3 to 5 percent air although no air entraining agents were used.

CHAPTER 5

RECOMMENDATIONS AND SUMMARY

5.1 MIX DESIGN CONCEPTS

5.1.1 AGGREGATES, GRADATION AND QUANTITITES

The gradations and proportions of the fine and coarse aggregate are important factors in pumpable concrete mixes.

The fine aggregate should conform to ASTM C 33 and have a smooth gradation curve without a deficiency or surplus of any particular size (ACI Committee 304, 1973). The most important factor is appropriate amounts of the finer sizes, material retained on the No. 100 (150 μm) and No. 200 (75 μm) sieves.

Coarse aggregate gradation is not as crucial as that of the fine aggregate but a smooth gradation curve leads to denser mixes and the increased likelihood of pumpability. The coarse aggregates should be of rounded or cubical shape.

In order to minimize voids in a concrete mix, proper combinations of various particle sizes are required. The ratio of fine to coarse aggregates that will yield minimum voids varies with maximum aggregate size even though the aggregates are well graded. The ratio of fine to coarse aggregates for minimum voids also varies with the volume of fibers used.

5.1.2 VOLUMES OF VOIDS AND PASTE

The combination of aggregates and fibers that produces the minimum void volume can be obtained experimentally. The volume of the paste, consisting of cement, water and pozzolan or other fine material if used, must exceed the volume of the voids by a slight amount. An excess amount of paste is required because of the separation of the constituents by the paste and for adequate coating of all the particles. The amount of paste in excess of the voids will be 6 to 9 percent depending on the aggregates used and the fiber content.

5.2 MIX DESIGN FORMULATION

5.2.1 PROCEDURE

A procedure which has been found to be effective for designing pumpable fiber reinforced concretes is as follows:

1. Select the aggregates.

   The aggregates should be within the gradations recommended by ACI Committee 304. Having appropriate amounts of the smaller fine aggregate sizes is most important. The coarse aggregate particles should be rounded or cubical in shape.

2. Determine the ratio of fine to coarse aggregate.

   The ratio of fine to coarse aggregate should be such that when mixed with a given volume of the fibers the combination will yield the minimum volume of voids.

   This ratio can be determined, experimentally. First select the volume of aggregates that will be used with a given volume of fibers. This selection may be made from previously determined mix proportions such as given in

Tables 4.5 and 4.5-SI. Then, various proportions of fine and coarse aggregates, retaining the proper total volume of aggregates, may be mixed with the fibers and rodded, ASTM C 29, into a known volume and weighed. The volume of voids may be computed from the unit weight, the proportions of each material and the specific gravities.

3. Determine the volume of paste required.

   The volume of paste must be somewhat greater than the volume of voids in the aggregate-fiber combination since coating these particles causes them to separate. An estimate of the volume of paste in excess of the voids can be determined from Fig. 5.1.

   For these calculations the entrapped air is not considered part of the paste since its volume is greatly reduced during the actual pumping process and it is not effective in preventing segregation failure.

4. Select the quantity of water required.

   The amount of water will be determined by the workability requirements and will depend on the maximum aggregate size and fiber content. An estimate of the water required for a 4-in. (100-mm) slump can be determined from Fig. 5.2. This relationship is based on limited laboratory results. The values presented can be used as a good first trial until sufficient data is available to allow a more exact determination.

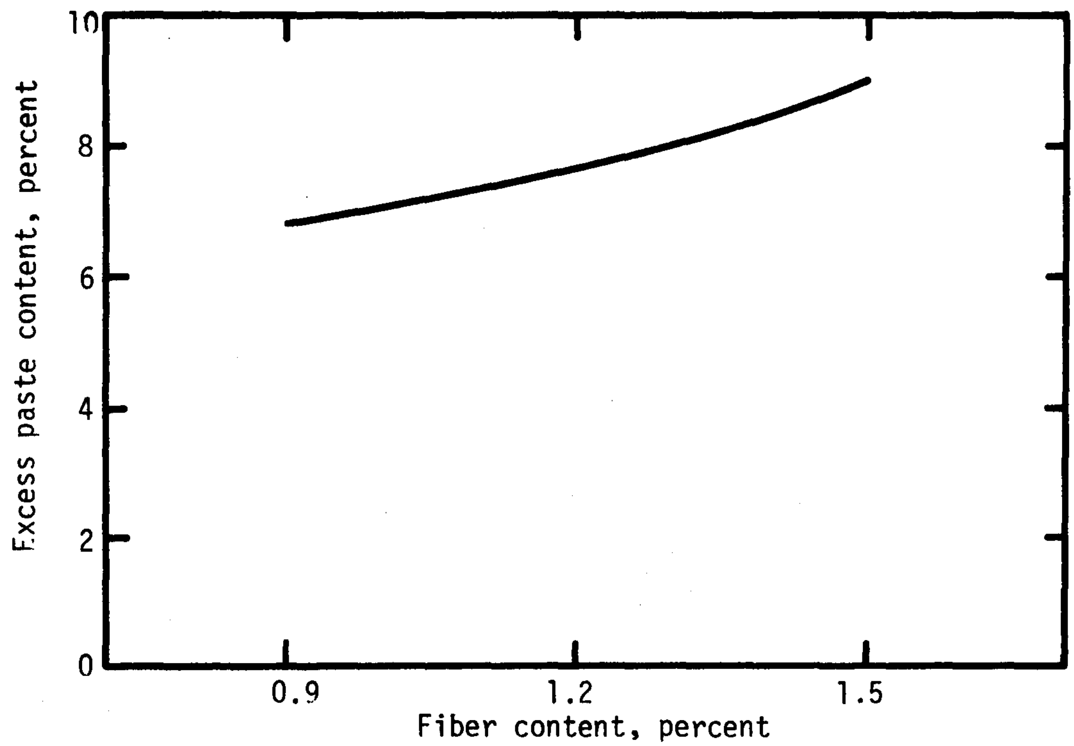


FIG. 5.1 EXCESS PASTE REQUIRED FOR DIFFERENT FIBER CONTENTS

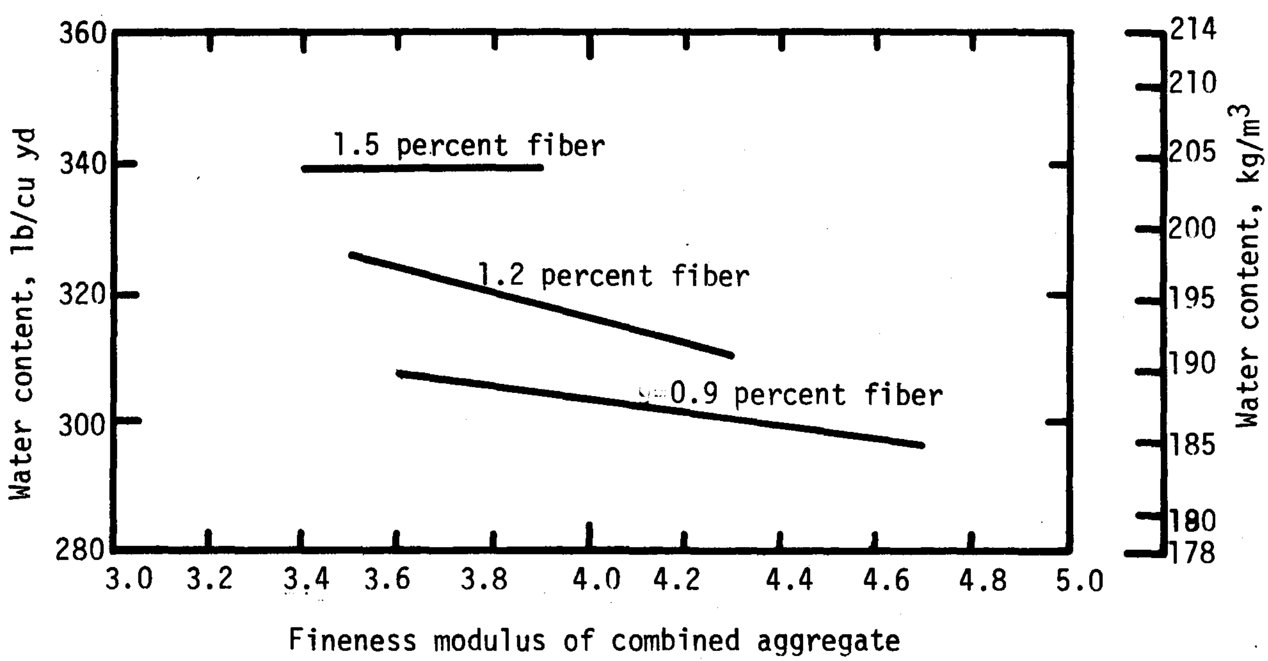


FIG. 5.2 WATER CONTENT REQUIRED FOR 4-in. (100-mm) SLUMP

5. <u>Determine the cement content</u>.

An appropriate water-cement ratio can be selected to provide the strength and durability needed. However, the quantity of cement calculated on this basis may not be adequate to provide the total paste content needed for successful pumping. There are then two methods of selecting the cement content.

The first consists of selecting the cement content which when added to the volume of water will provide the total volume of paste required.

The second method consists of selecting the volume of cement to provide the appropriate water-cement ratio and using a pozzolan or finely powdered material to provide the remaining volume of paste needed.

6. <u>Make a trial batch</u>.

Any fiber reinforced concrete mix which is to be pumped should be trial batched and tested. If the preceding steps are followed, only minor adjustments should be required in the mix proportions. If a change in aggregate content is required then the change should be made so that the fine to coarse aggregate ratio is not changed. If major changes are required, steps 2 through 5 should be repeated utilizing the information obtained in the first effort.

5.2.2 USE OF ADMIXTURES

Pumpable mixes may be modified with the addition of super water reducers or phase thickening admixtures.

Water reducers or wetting agents can effectively reduce water contents up to 12 percent with improved pumpability. Greater water reduction, however, may result in loss of pumpability.

Phase thickening admixtures can be used to improve the workability of known pumpable mixes and may increase the likelihood of pumpability of marginally pumpable mixes.

5.3 EVALUATION OF THE MIX DESIGN PROCEDURE

The results of laboratory studies indicate that the recommended mix design procedure can be used to obtain pumpable fibrous concrete.

From the results of the investigation of four coarse aggregate maximum sizes, mixes with 1/2-in. (13-mm) maximum-sized coarse aggregate appear to be the most easily pumped at nominal cement contents. This may be due, in part, to the favorable relationship of the fiber length to the maximum coarse aggregate size. No balling of the fibers was evident at this particular aggregate size and mixes exhibited the ability to be easily remolded.

Mixes formulated with the poorly graded 3/8-in. (10-mm) maximum-sized aggregate required an unusually large amount of paste to prevent segregation failure. Mixes with 3/4-in. (19-mm) maximum-sized aggregate tended to be hampered by balling of the fibers around the larger aggregate particles. With 1-in. (25-mm) maximum-sized aggregate mixes, the balling tendency was increased.

For these particular aggregates and fibers, the mixes made with 1/2-in (13-mm) maximum-sized aggregate appear to be the most suitable for pumpable fiber reinforced concrete.

5.4 PUMPING EQUIPMENT

5.4.1 INTRODUCTION

Conventional equipment can be used for pumping fiber reinforced concrete, even though well designed fiber reinforced mixes are harsh and more difficult to work with than conventional concrete. Careful selection of the elements of the pipeline, such as diameter, radius of bends, reducers, Y's and rubber hose is necessary for successful pumping.

5.4.2 PUMPS

Conventional pumps can pump fiber reinforced concrete, although some mixes may pump with more ease in one type than another. Larger diameter pumps can be expected to pump fiber reinforced concrete with less difficulty. The entrance to the pump cylinder or hose must be such that the fiber reinforced concrete can enter readily. The relatively harsh fiber reinforced concrete will not enter small openings easily.

5.4.3 PIPELINE

The pipeline is one of the most critical equipment components when pumping fiber reinforced concrete. The line should be rigid and sealed at all connections. Since the fiber reinforcement will be longer, in nearly all cases, than the diameter of the maximum size aggregate, the line must be larger than the usual 3 to 4 times the maximum aggregate size. Diameters 6 to 8 times the maximum aggregate size appear to be more appropriate. A minimum diameter of 6 in. (150 mm) is suggested. The pipeline should be no longer than necessary.

The use of Y's and reducers require the mix to undergo an extensive remolding process and thus increases the pumping pressure and the likelihood of failure. Wherever possible Y's and reducers should not be used, but when they are required they should be as long as possible so that the remolding process will be gradual. At changes in direction of the pipeline, large radii should be used.

The use of rubber or plastic hose should be avoided due to increased frictional resistance. The abrasive nature of the flowing fibrous concrete on the sides of these hoses may cause contamination of the concrete from pieces of loosened hose material.

The entire pipeline system should be chosen so that minimum remolding is required and that resistance to the flow of the concrete is as low as possible.

5.5 SPECIAL PRECAUTIONS

In a tunnel slipforming system, such as that proposed by Parker, et al., (1971), the concrete must attain adequate support strength in about two hours. Concretes which have usable strengths at such early ages generally have quick setting times. Concretes can be made that have working times of one-half hour and usable strengths in two hours. The cement used may be a fast setting cement that requires retardation or a slow setting cement that requires acceleration.

If a fast setting cement is used, the equipment must be such that it can be cleaned quickly in case of a work stoppage. If a slow setting cement is used, it may be possible to add the accelerator as the concrete enters the slipform, creating a less critical situation in case of a stoppage.

If the tunnel is in material that must be supported as soon as the tunnel boring machine passes, a redundant concrete handling system is desirable.

Since cracking of tunnel liners is to be avoided, every effort should be made in the selection of materials and the handling of the concrete to minimize shrinkage. Fiber reinforced concretes are generally high in paste content and thus have higher shrinkage potentials than conventional concretes. A cement with some expansive characteristics may be desirable.

Drying shrinkage can be minimized if a curing compound or other waterproofing material is applied to the concrete at the time it leaves the slipform. Such curing is also necessary for proper strength development.

Since concrete in a slipformed tunnel liner is loaded at an extremely early age, creep can be expected to be much higher than in normal applications. If this large creep strain can be a problem all possible means should be taken to minimize it.

The concrete in the liner must be capable of resisting any chemicals, such as sulfates, which may be present in the soil.

5.6 SUMMARY

Suitably designed fiber reinforced concrete can be pumped with properly selected equipment. The type of pumping failure most likely to occur is that of segregation. However, careful mix design and choice of equipment virtually eliminates this possibility.

Conventional pumps may be used without modification. Line diameters should be in the range of 6 to 8 times the diameter of the maximum aggregate size, with a 6-in. (150-mm) diameter as a minimum. Reducers and Y's should be eliminated, but when they must be used they should be as long as possible. Larger radii should be used for changes in direction. Rubber hoses should be avoided, if possible. The pipeline should be as short as practical.

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* Document is available to the public through the National Technical Information Service, Springfield, VA, 22151, USA.