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Performance of Grouts for Post-Tensioned Bridge Structures

Research and Development
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6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report documents a study to evaluate the performance of several grout mixes that may be used for filling the ducts of post-tensioned bridge structural elements. These mixes include pozzolanic materials and commercially available grouting admixtures.

The study included laboratory investigations to determine mechanical properties as well as the protection capability against corrosion of the grout mixes evaluated. This report will be of interest to bridge engineers and designers of post-tensioned concrete structures. The study will also be of interest to owners, inspectors, design firms, and construction contractors of post-tensioned concrete structures.

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Acting Director, Office of Engineering and
Highway Operations Research and
Development

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16. Abstract

Selection of an appropriate grout mix for filling the ducts of post-tensioned bridge structural elements is an important task that could provide long-term protection of post-tensioning steel against corrosion. Important properties of a suitable grout mix include its workability, protection against corrosion of steel, low permeability, ability to expand, high compressive strength, ability to bond to the steel and duct, and overall durability.

To identify the most appropriate grout mix for the post-tensioning application, a test program was carried out in this study to evaluate 15 different grout mixes that had shown promise based on an evaluation of existing literature and data. These mixes included pozzolanic materials, i.e., portland cement and commercially available grouting admixtures. For each grout, several properties were determined. The findings included results on the expansion and shrinkage, bleeding characteristics, compressive strength, flow time, permeability, pH of bleed water, setting time, and surface corrosion observations of the post-tensioning steel surrounded by each mix. As a result of the study, it was determined that the most appropriate mix for the post-tensioning application consisted of type I portland cement, 20 to 25 percent silicafume by the weight of cement, potable water, and a superplasticizer. Other than a slight shrinkage of this mix, the grout showed a superior performance with regard to the properties that were determined through this laboratory testing. If a small dosage of an expansive agent can be added to the mix without adverse effect, the slight shrinkage of the mix may be overcome readily.

Most grouts that are used for grouting of post-tensioning ducts exhibit thixotropic property and therefore, the present ASTM Standard Flow Cone Test cannot be used to determine the flowability of the mixes. New test apparatus and procedures were designed and developed during this study that permit quantitative measurement of the flowability of all mixes, including those with thixotropic characteristics. The test procedure includes measuring time of flow, or discharge, for a mix that is placed in a pressure chamber and is forced to pass through a special orifice.

17. Key Words
Concrete, grout, admixtures, grout testing, bridges, post-tensioning ducts.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**	**Symbol**	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	square meters	1.195	square yards	ac
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	mi^2
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.386	square miles	
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	l	l	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	cubic meters	35.71	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION					**ILLUMINATION**		
fc	foot-candles	10.76	lux	l	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**		
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
psi	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

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CHAPTER 1. INTRODUCTION

INTRODUCTION

Post-tensioned prestressed concrete construction was first introduced in the 1930's.(1) The majority of post-tensioned structures have been completed during the past 40 years. Prestressed/post-tensioned concrete elements are widely used mainly because they permit longer spans with more slender and economical cross sections than are otherwise possible using reinforced concrete. In post-tensioned structures, hollow ducts are placed in the formwork prior to placement of the concrete. Once the concrete hardens and gains strength, seven-wire prestressing steel strands are passed through the ducts and the strands are tensioned and anchored at the ends of each member. The ducts are then normally filled with a grout mix to provide corrosion protection to the steel. Figure 1 shows a typical cross section of a duct in a post-tensioned structure. Due to a characteristic property of many grout mixes, the available water in the mix sometimes separates from the cement particles. As shown in the figure, a void filled with the separated water, called the bleed water, is formed at the upper region in the duct. A longitudinal profile of a concrete element with post-tensioning tendons is illustrated in figure 2.

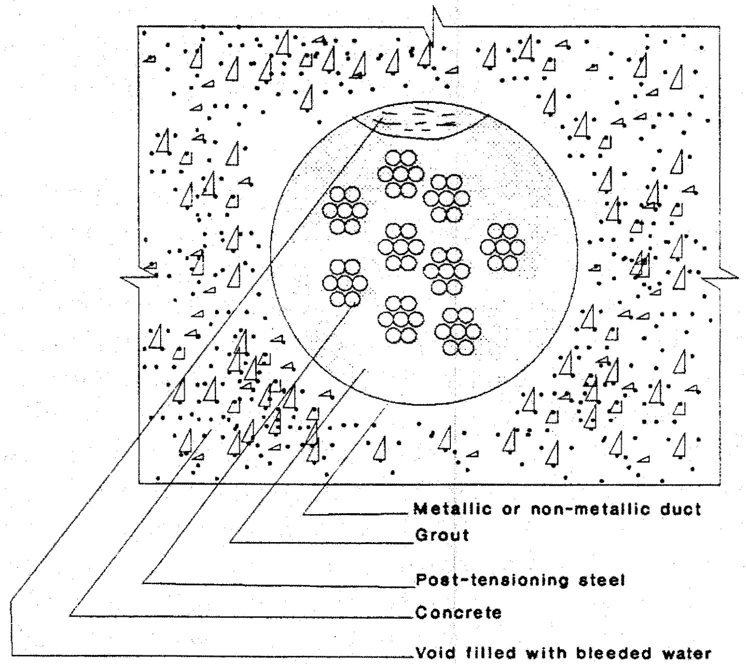


Figure 1. Cross section of a concrete element with post-tensioning tendon.

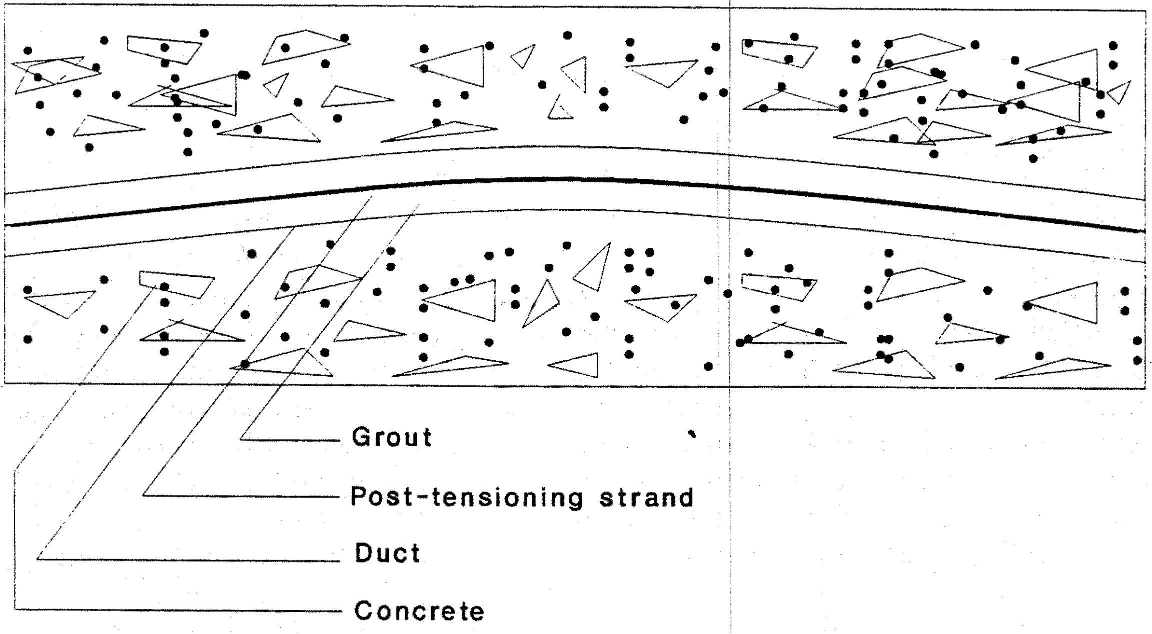


Figure 2. Longitudinal section of a concrete element with post-tensioning tendon.

Tendons are steel bars or wire strands, encased in the ducts, which are tensioned and anchored at the ends of hardened concrete elements to provide additional strength. If one or more tendons are allowed to corrode, the structure may then collapse without warning. Therefore, these tendons must be protected from corrosion. Use of an appropriate grout inside the post-tensioning ducts as a surrounding material that can provide protection against the corrosion is currently a common practice.

Generally, a grout mix used for post-tensioning applications is made up of cement, water, and one or more admixtures to reduce bleeding and to increase expansion of the mix. Anti-bleeding agents are used to reduce the bleeding in the grout. Aluminum powder is normally used as an expansive agent that reacts with the alkali of the cement and forms molecular hydrogen. This process causes a volume increase in the mix, a process that lasts approximately an hour after the initiation of the mix. The sedimentation of the suspension in the mix causes the cement particles to settle until the initial set of the mix and it also causes the free water, or the bleed water, to fill the overlying space. The bleed water is gradually reabsorbed in the hardened grout. In post-tensioned construction, sometimes a small bleed void remains at the top of a straight and horizontal tendon throughout its length after the bleed water is reabsorbed in the hardened grout. In the case of vertical tendons, the bleeding will occur at the top of the tendons due to the orientation of the duct. Bleed water in the grout mix will accumulate at the top due to its lower unit weight compared with the unit weight of the paste. When steel strands are present in the duct, due to the presence of the head pressure in the duct, the bleed water will be forced upward through the interstices of the strands. This results in an exaggerated bleed water accumulation in the top region of the duct.

The quality of grouting for post-tensioned ducts, i.e., its freedom from voids, is crucial when the long-term corrosion protection of prestressing steel is considered. Imperfect filling of the ducts may allow air, moisture, and aggressive chemicals into the ducts from the intermediate or end points of the tendons, causing corrosion of the strands. If an ungrouted segment of a duct is at a region of concrete that contains flaws such as cracks or delamination, air and moisture can reach inside the duct more easily. Satisfactory grouts must provide:

- Good bonding between the prestressing steel and the hardened grout along the entire length of the tendon. A grout with sufficient bond strength transmits all internal forces from the concrete to the tensioned steel over a limited length and relieves live load stress fluctuations at the end block regions.

- Protection against corrosion of the prestressing steel by completely filling the ducts and having high alkalinity and low permeability characteristics. Completely filling the ducts with a hardened grout also ensures that no water will accumulate in the ducts that can cause delamination of the surrounding concrete due to freezing and expansion of the water in the ducts.

BACKGROUND

The word "grout" seems to have its origin from the Middle English word "grut" meaning coarsely ground meal. The word was later used for porridge and, by analogy, came to be used for a liquid mortar of similar consistency. Initially, the word "grouting" was used only by masons and brick layers until it was adopted by tunnel and mine workers to mean the method of injecting a line slurry behind cast iron liners. The Prestressed Concrete Institute, PCI, defines grout as a mixture of cement and water with or without admixtures.(2) The American Concrete Institute, ACI, defines grout as "a mixture of cementitious material and aggregates to which sufficient water is added to produce pouring consistency without segregation of the constituents, or mixtures of other compositions but with similar consistency."(3) In the Middle Ages, Romans were aware of the potential uses of grouting. They used grout to strengthen weak walls, bridges, aqueducts, etc. In modern times, it was the French engineer Charles Berigny (1772-1842), who in 1802 effectively used grout mixes with a suspension of clay and lime to strengthen masonry walls in the port of Dieppe.(4)

In the United States, William E. Worthen used grouting in 1845 to strengthen a weak masonry pier.(4) Cement and clay-cement grouts were widely used in significant volumes to consolidate foundation strata and to create cut-off walls (grout curtains to prevent underground seepage under dams.(5) In the mid-1800's, specifications and practices were developed in detail for specialized types of grout and its application by the grouting industry. These specifications quickly became the unofficial grouting standards for the United States.

In 1958, V. R. Boardman investigated various types of grout mixes used for post-tensioned tendons in the ducts.(6) He suggested that pure portland cement grout might be a suitable mix to use in post-tensioning ducts, provided the mixing time was sufficiently long to eliminate bleeding. However, he observed that there was a slight reduction in compressive, shear, and tensile strengths of the grout when the mixing time was increased.

In post-tensioned construction, grouting is the process of pumping grout into the ducts in order to fill the space between the strands and the duct. Post-tensioned ducts are often flushed with water first, and then the grout is pumped in. This replaces the accumulated water in the ducts and removes debris and avoids blockages while filling the ducts with grout. Sometimes, a radioactive sodium iodine (I^{131}) solution mixed with water is pumped into the ducts prior to grouting. When the grout is pumped into the ducts, it replaces the radioactive solution. The radioactive solution may then be traced by means of a Geiger counter or scintillation counter in the duct to check whether the duct is completely filled.

The necessity of reducing the bleed phenomenon in grouts for post-tensioning work has been acknowledged for many years. This has led to the use of various additives that cause the grout to expand and/or to reduce bleed. About 20 years ago, polymers were used along with portland cement to produce grouts with insignificant bleed. Methyl cellulose (methocell) was used most frequently.(7) The grout was very stiff and was hard to mix and work with. Currently, metallic powders such as aluminum powder are the most common additives that are used as expansive agents. Expansive agents produce hydrogen or nitrogen gas bubbles in the mix by reacting with the cement, causing volume increases. However, grout mixes with expansive agents have performed well in some cases and in other cases, they have produced grouts with low strength and voids.

In 1970, Schupack investigated various grouting materials for vertical tendons used in nuclear concrete pressure vessels.(8) He observed that the bleeding was exaggerated in the presence of steel prestressing strands inside the post-tensioning ducts. He developed a new admixture, which is commercially marketed by Sika Chemicals, Inc., NJ, for controlling the bleed phenomenon in the cement grout. In his investigation of the water retentivity characteristics of various admixtures, he found that the vertical scale factor of pressure is an important parameter. As the height of the grout in the vertical duct increased, the pressure on the grout in the duct also increased, due to the gravity effect, which is termed as the vertical scale factor of pressure. Thus, he used a test where water was separated from the cement paste, under pressure, to determine the water retentivity characteristics of various grouts.

It is interesting to note that it appears that it is possible to formulate and produce practically non-bleeding grouts, however, some researchers believe that even with the use of suggested admixtures, significant quantities of free water will be released in long ducts.(9-12) To remedy the problem of bleed water in the ducts, some investigators have made suitable arrangements in various structures to drain out this free water.

The use of silicafume in grouts has also been investigated.(13,14) In these studies, silicafume was used as a partial replacement for cement and its dosage has ranged from 5 percent to 20 percent by weight of cement. The researchers observed that the use of silicafume reduces bleeding, exhibits the thixotropic properties in grout, decreases the chloride permeability, and increases the compressive strength. Thixotropy is the property of some wet grouts to be gel-like when stationary, but revert to liquid behavior when sufficiently agitated or pressured. Use of superplasticizers has been shown to increase the flowability of grouts. Superplasticizers are also called water-reducing admixtures because they are able to reduce the amount of required water in a given concrete or grout mixture by a factor as high as four, compared with mixes not containing the admixture.

The cost of grouting of ducts in post-tensioned bridges and buildings is normally a small portion of the total expense of the construction project, and the grout material cost is insignificant when compared with the grout pumping and placement cost. For this reason, little attention has been given to the selection and required specifications of the grouts during the engineering design stage. It appears that many transportation departments in the various States do not have a complete specification for grouting materials and procedures for post-tensioned bridge construction and often refer to other available data.

In order to get workable grout, the grout must flow easily inside the duct of the post-tensioned members. The flowability of different grout mixes can be evaluated by using the ASTM C939 standard flow-cone method.(15) The apparatus appears to be suitable only for highly flowable types of grout. For the thixotropic grouts, a quantitative flowability measurement has not been possible due to the gel-like character and high viscosity of these mixes. Prior to this work, there has been no attempt to improve the available test equipment and procedure, or to develop a new technique that would permit quantitative flowability of the thixotropic grouts.

OBJECTIVES

The selection of appropriate grout mixtures is an important factor for protecting post-tensioning tendons from corrosion in post-tensioned construction. The essential properties of an appropriate grout are high pH, high flowability without sedimentation, and segregation in the liquid state. In addition, when the grout is set, it should be durable, dense, adhesive to both the ducts and the post-tensioning steel, and have no shrinkage.

Most of the grout mixes used in post-tensioned construction are thixotropic. The present ASTM C939 procedure for testing the flowability of grout is not applicable to thixotropic grout. Therefore, a new test methodology must be used in order to quantitatively measure the flowability of such grout mixes.

Based on the above discussion, the objectives of this study were:

- To evaluate the performance of various grouts that contain different admixtures and to determine the most suitable grout mix design that may be used in the ducts of post-tensioned bridge elements. Such a grout mix could provide long-term corrosion protection for the post-tensioning steel of concrete bridge structures.

- To develop new testing instrumentation and procedures for measuring the flowability of thixotropic grout.

CHAPTER 2. EXPERIMENTAL PROCEDURE

TEST MATERIALS

Cement

The main element of the majority of grout mixes used in practice is the portland cement. This is a hydraulic cement that reacts with water to set and form a hard final product. Other cements used for grouting include blast furnace cement and microfine cement. In this study, type I cement was used with its standard properties categorized in the ASTM C150, "Standard Specification for Portland Cement."(15)

Additives

Grouts made up of portland cement shrink as they cure, and as a result, voids could be formed in the post-tensioning ducts, thus allowing chloride ions to migrate into the duct and cause corrosion of the tendons. Therefore, many transportation departments in various States recommend the use of some admixtures to reduce the shrinkage (or to achieve some expansion), stop bleeding, and make the grout more workable. Some admixtures contain expansive agents so that they can compensate for the characteristic grout shrinkage and can fill the voids that may form in the ducts. In this study, a series of the most commonly used admixtures in the post-tensioning practice was used in various grout mixes for evaluation of their overall performance. The following paragraphs present brief descriptions of the admixtures evaluated and/or used in this study. Water-to-cement ratios of 0.35, 0.40, and 0.45 were used for the mixes prepared with these admixtures. Some mixes with water-to-cement ratios of 0.35 or 0.40 resulted in grouts that were very thick in consistency and difficult to work with, and therefore, they were eliminated from further evaluation in the program.

Latex

Latex is a milky white fluid that consists of solid rubber particles dispersed in water. In other words, latex is a water emulsion of synthetic rubber obtained by polymerization. polyvinyl chloride, styrene-butadiene, acrylics, and polyvinyl acetates are the most commonly used polymer latex in the field. When latex is used, it reduces the amount of porosity in the portland cement paste and develops a stronger bond between the cement hydrates and steel or aggregates. In concrete, the desirable properties attributed to latex are enhanced if the concrete is allowed to gradually dry over a longer period of time.(14) Test results for studies on grouts containing latex indicate the following:(16-18)

- After one year of testing, grouts containing latex showed the least shrinkage among the types of grout mixes studied.

- Latex and superplasticizer did not appear to be a good combination in grout mixes. Many of these grouts exhibited bleeding and segregation.

- Grout mixes containing latex had lower compressive strength.

- Equipment was difficult to clean after mixing.

Due to its lower strength and related drawbacks, the use of latex was ruled out for further evaluation in this project.

Interplast-N

Interplast-N is a balanced blend of expanding, fluidifying, and water-reducing agent for the portland cement grouts. This admixture is manufactured by the Sika Chemicals Co. When it is used in a grout mix, it produces a slow and controlled expansion prior to the grout hardening. In this study, 1.0 percent of Interplast-N by weight of cement was used. The water-to-cement ratios used in mixes with the Interplast-N admixture were 0.35, 0.40, and 0.45.

Celbex 208

Celbex 208 is an off-white powder consisting of a balanced blend of organic polymers. The organic polymers act as powerful dispersant and thixotropic agents when added to cement/water mixes, virtually eliminating the bleed water and the formation of water lenses in the cementitious grouting of long vertical and horizontal ducts. This admixture is manufactured by Celtite, Inc., Georgetown, KY. The amount used in the grout mixtures in this study was 1.2 percent by weight of cement. The water-to-cement ratio used in the mixes with Celbex 208 was 0.45.

Celbex 209x

Celbex 209x is an off-white powder consisting of a balanced blend of superplasticizer, thickener, and a controlled expansion agent. It was designed to prevent sedimentation and to eliminate bleed water in the portland cement-based grouts. This admixture is manufactured by Celtite, Inc., Georgetown, KY. The amounts used in the mixes in this study were 0.8 percent and 1.3 percent by weight of cement. The water-to-cement ratio in the mixes was 0.45.

In-Pakt

In-Pakt is a dry ready-mix containing cement with refinement of nonferrous ingredients that is mixed with an equal amount of sand. In-Pakt exhibits a controlled gas generation during the initial setting of the mix. In-Pakt is manufactured by Intrusion-Prepakt, Inc., Cleveland, OH. The water-to-cement ratio used in the mix was 0.45.

Silicafume

The application of silicafume to grouting appears to have considerable potential for further development. Silicafume is a byproduct obtained during the production of silicon metal and ferrosilicon alloy. It consists of fine glassy spheres having a specific surface area of about 97,650 ft^2/lb (20,025 m^2/kg) compared with that of 1,465 to 1,950 ft^2/lb (300 to 400 m^2/kg) for normal portland cement. The effect of silicafume on the properties of concrete has been studied extensively.(19-21) In these investigations, silicafume was used either as a partial replacement for cement (up to 40 percent by weight) or as an additive to the cement (up to 20 percent by weight). The general findings of these studies were:

- For a given workability, concrete mixes containing silicafume required a higher water content compared with concrete mixes without the silicafume. However, the amount of required mixing water could be reduced by adding a superplasticizer.

- Concrete mixes containing silicafume had a higher compressive strength, higher electrical resistivity, lower permeability, lower chloride diffusion, and better frost resistance than mixes without the silicafume.

The use of silicafume in grouts has also been investigated recently.(13,21) In these studies, silicafume was used in grout mixes as a partial replacement for cement with amounts ranging from 5 to 20 percent by weight of cement. The findings of these studies were as follows:

- Silicafume significantly reduced bleeding and segregation in normal portland cement grouts.

- Silicafume grouts had much higher viscosity than the portland cement grouts without the silicafume. Superplasticizer could be used in grouts with silicafume to maintain adequate fluidity.

- Silicafume grouts exhibited thixotropic properties.

- Silicafume grouts had higher compressive strength, lower porosity and finer pore size distribution, and lower chloride permeability than normal portland cement grouts without the silicafume.

- Dry silicafume might cause handling problems because of the extreme fineness of the silicafume particles. Therefore, care must be taken to prevent excessive suspension of the silicafume particles in the air during the mixing process.

According to the above findings, the use of silicafume in grouts appears to be promising. In this investigation, silicafume was used as a replacement for cement by 5, 20, and 25 percent by weight of cement. The water-to-cement ratio used in the mixes was 0.40. M150 superplasticizer was also used to increase the flowability of the mix. The amounts of superplasticizer used in the mixes were 19, 47, and 59 oz (539, 1332, and 1673 g) per 100 lb (45.4 kg) of cement.

Superplasticizer M150

The superplasticizer used in this study, M150, met all the requirements of the ASTM C494-79 specification entitled "Standard Specification for Chemical Admixtures for Concrete." No chloride ions were present in the superplasticizer used in this study.

MIXING

Following the findings from a literature review and the recommendations from the various manufacturers of the several admixtures used in this study, the grouts were mixed in the following order:

1. Placed the full quantity of water in the mixing vessel.
2. Started and operated a dual blade high shear mixer at a speed of 850 r/min.
3. Gradually added the cement powder to the water, being careful to ensure that the cement was added to the water in the highly turbulent region. The best way to accomplish this was to add the cement over the rotor.
4. Gradually added the additives to be used in the test mixture.

In most cases, after all constituents were added, the grouts were mixed for 3 to 4 min. This was to simulate the required time for full-size, high-speed, high-shear mixers used in practice. The grout was uniform and free from lumps. If a superplasticizer was added to the mix, it was added before other additives.

TEST PROGRAM

A total of 15 grout mixes were prepared for evaluation in this study. They were:

1. Grout A : Control mix, no admixture, water-to-cement ratio: 0.35.
2. Grout B : Control mix, no admixture, water-to-cement ratio: 0.40.

3. Grout C : Control mix, no admixture, water-to-cement ratio: 0.45.

4. Grout D : 1.0 percent Interplast-N, water-to-cement ratio: 0.35.

5. Grout E : 1.0 percent Interplast-N, water-to-cement ratio: 0.40.

6. Grout F : 1.0 percent Interplast-N, water-to-cement ratio: 0.45.

7. Grout G : 0.8 percent Celbex 209x, water-to-cement ratio: 0.45.

8. Grout H : 1.3 percent Celbex 209x, water-to-cement ratio: 0.45.

9. Grout I : 1.3 percent Celbex 209x with 70 oz (1.98 kg) per 100 lb (45.5 kg) of cement with M150 superplasticizer, water-to-cement ratio: 0.45.

10. Grout J : In-Pakt, water-to-cement ratio: 0.45.

11. Grout K : 1.2 percent Celbex 208, water-to-cement ratio: 0.45.

12. Grout L : 5.0 percent silicafume with 19 oz (539 g) per 100 lb (45.4 kg) of cement with M150 superplasticizer, water-to-cement ratio: 0.40.

13. Grout M : 20.0 percent silicafume with 47 oz (1.33 kg) per 100 lb (45.4 kg) of cement with M150 superplasticizer, water-to-cement ratio: 0.40.

14. Grout N : 25 percent silicafume with 50 oz (1.42 kg) per 100 lb (45.4 kg) of cement with M150 superplasticizer, water-to-cement ratio: 0.40.

15. Grout O : 20.0 percent silicafume, 0.5 percent Interplast-N with 47 oz (1.33 kg) per 100 lb (45.4 kg) of cement with M150 superplasticizer, water-to-cement ratio: 0.40.

All of the above mixes were subjected to the following tests:

- Expansion and shrinkage test.
- Gelman pressure test.
- Compressive strength test (ASTM C942).(15)
- Flow test (ASTM C939).(15)
- Permeability test (AASHTO T227-831).(22)
- pH of water collected from the Gelman pressure test.

- Setting time with the Vicat apparatus.
- Corrosion test (visual observation).

EXPERIMENTAL PROCEDURE

Expansion and Shrinkage

For various mixes, plexiglass tubes with an internal diameter of 2.0 in (51 mm) were used in a vertical orientation and were all sealed at the lower end and marked at 39.4 in (1000 mm) from the base. Each grout mix was poured in the tubes with and without seven-wire steel prestressing strands. The tubes with the steel strands contained three strands in the vertical orientation at the center of each tube. Each selected grout was poured in the tubes starting from the bottom and was allowed to fill the tubes to the 39.4-in (1000-mm) mark. Each tube was then sealed at the top to eliminate the exposure of grout to the outside atmosphere. The grout and water levels in the tube were noted and recorded at 15-min intervals for the first hour and then at every hour. In order to observe the corrosion in the strands, the strands were initially made 12 in (305 mm) longer than the height of the grout columns in the tubes. Figure 3 shows the typical setup of the experiment.

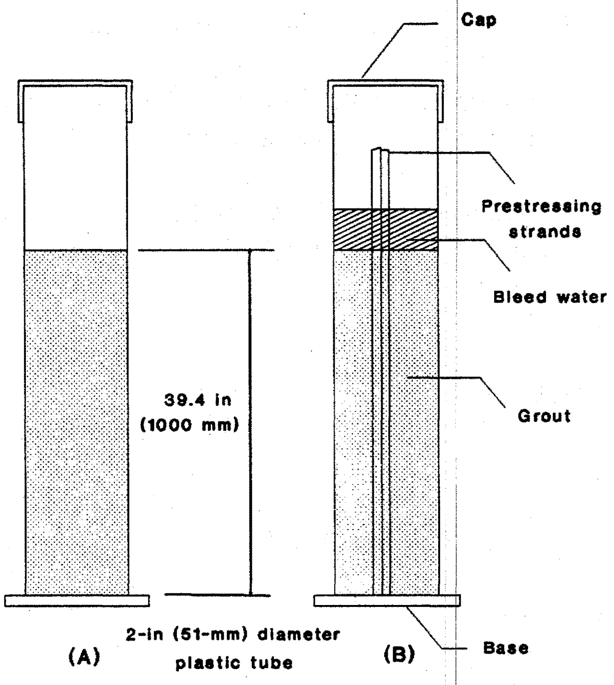


Figure 3. Plexiglass tubes containing grouts for expansion and shrinkage measurements. (Tube A has no prestressing strands, tube B has three seven-wire strands.)

Gelman Pressure Test

Due to the presence of head pressure in a grouted tube, strands in the tube function primarily as a filter, causing separation of water from the cement paste. Based on this principle, a pressure filter test was conducted using the Gelman pressure filter.(23) The Gelman pressure filter consists of a 1.75-in- (44-mm-) diameter by 5.5-in- (140-mm-) long cylindrical stainless steel vessel with removable upper and lower caps at the ends that are threaded on the main body. The upper cap is connected to a pressure tank through a flexible hose equipped with the appropriate control valves and gauges. The lower cap supports a metallic circular screen that in turn supports a cloth-type filter. The fiber used in this study was the type A/E glass fiber only allowing passage of particles that were smaller than 0.3 μm. Figure 4 shows a sketch of the Gelman pressure filter and figure 5 shows the setup for the Gelman pressure filter test in the laboratory. For each test, the vessel was filled with a grout mix and allowed to stand without being disturbed for 10 min. Pressure was then applied to the vessel in 10-lbf/in^2 (68.9-kPa) increments and held at each pressure level for a period of 3 min. The experiment was stopped at either 80 lbf/in^2 (551 kPa) or if the pressure in the cylinder dropped rapidly, whichever occurred first. The amount of bleed water that was forced out of the vessel at different pressure levels was recorded. The pH of the water collected for each mix was measured with a pH meter.

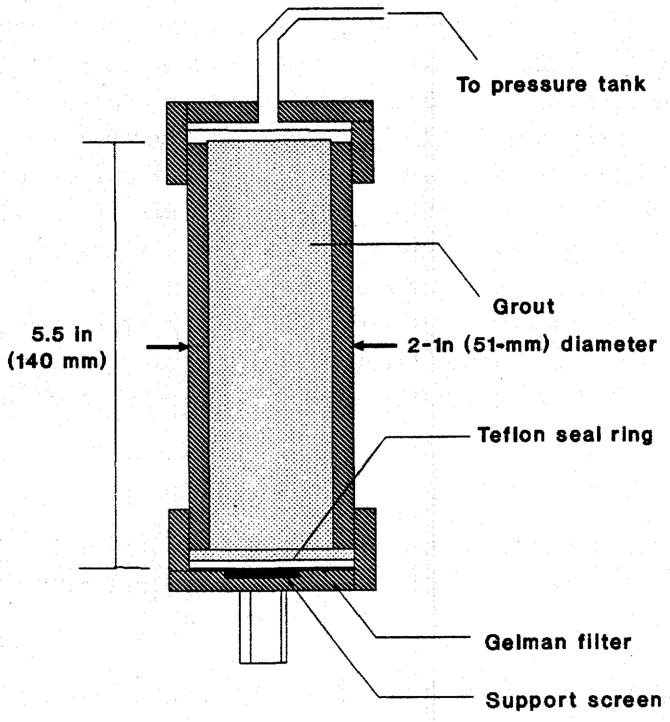


Figure 4. Schematic of Gelman pressure filter equipment.

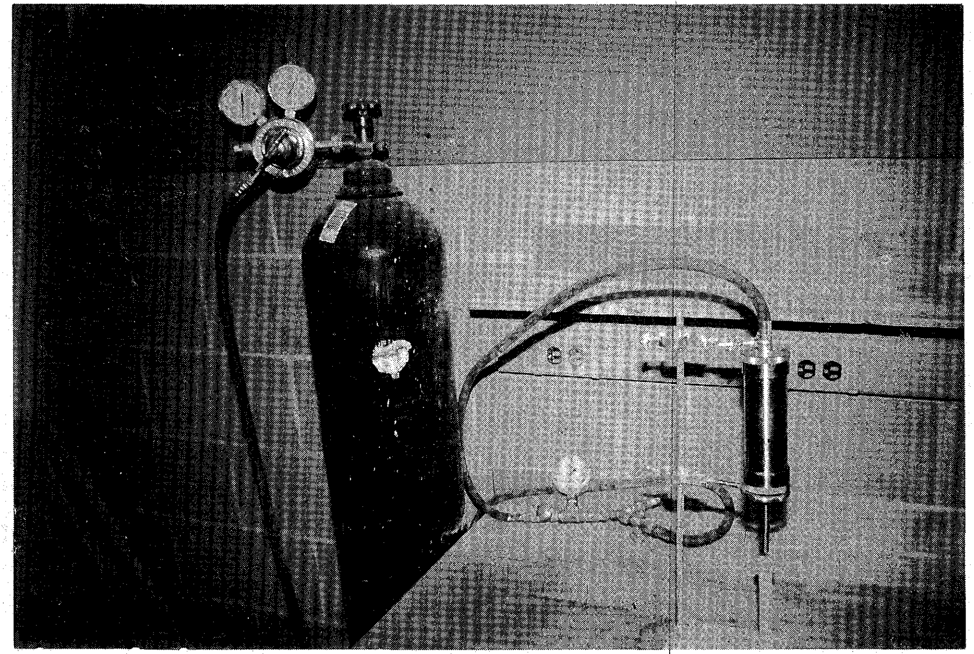


Figure 5. Laboratory setup for the Gelman pressure filter test.

Compressive Strength

The compressive strength of all grout mixes was measured by testing 2-in (51-mm) cubes according to the ASTM C942 standard.(15) The molds were filled halfway with freshly prepared grouts and the mixtures were puddled five times to release the entrapped air. The molds were filled again and puddled. The top surface for each mold was smoothed with a trowel. If the grout had an expansive agent, the expansion of the grout was contained within the mold by placing a 40-lb (18.2-kg) steel plate on top of the mold. After the casting was completed, the cubes were cured in the moist room for 24 h or until the final set. The relative humidity and the temperature in the moist room were 95 percent and 70 °F (21 °C). The cubes were then taken to the curing room and placed in lime water for curing. The compressive strengths at 7 and 28 d were determined by crushing the specimens using a 400,000-lbf (1,780-kN) capacity Tinus Olsen compression testing machine.

Flow Test

The flow cone test for grout mixes was performed according to the ASTM C939 standard.(15) The following test procedures were used to determine the flow times of the grouts used in this study:

1. The cone was wetted by filling the cone with water and letting it discharge 1 min before testing the grout.

2. The discharge tube was blocked with the tip of a finger.

3. The grout was poured into the cone until it reached the tip of the pointer, which was set at 1,725 ml.

4. The finger was removed from the discharge tube and the time from initial discharge until the first break in the continuous flow from the discharge tube was measured.

5. It was determined whether light was visible through the discharge tube. If light could not be seen, the flow cone test was considered not to be applicable for testing a grout mix of this consistency.

The flow cone test was performed twice for each mix and the average of the flow times was considered to be the flow time for the mix.

Permeability Test

The test for chloride solution permeability was performed on grouts used in this study in accordance with the AASHTO T277-89 designation, "Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete."(24) The test setup consisted of a closed loop electrical circuit that included a grout sample as a resistor in series with a power source and a 100-mV shunt. The magnitude of the current passing across the specimen is an indication of the degree of the chloride permeability in the grout sample. After placing each grout sample in the electrical circuit of the test equipment, the following procedure was used to determine the extent of the permeability in the grout specimens of this study:

1. The power supply in the system was set at an output of 60V and a 100-mV shunt was used in conjunction with a 4½-digit digital voltmeter. This allowed the display on the voltmeter to directly indicate the amount of the current in the circuit in milliamperes.

2. Measurements on the current were taken every 15 min. Also, the temperature of the solutions in both cell blocks was recorded every 15 min. If the temperature in the cell blocks was above 88 °C, then the experiment was discontinued to avoid damage to the cells. Otherwise, each experiment was carried out for a duration of 6 h.

3. A curve of the circuit current (in amperes) vs. time (in seconds) was constructed for each test, and the area under that curve was integrated to obtain the corresponding electrical charge in ampere-seconds, or coulombs.

The charge passed through the specimen is taken as being directly proportional to the permeability of the specimen.(22) Therefore, the charge passed through the different specimens used in the study could indicate the relative permeability of the specimens.

pH of Bleed Water

The pH values of the bleed water collected for different grout mixes used in this study were measured. The pH meter used to measure pH values was model 671P, manufactured by Jenco Electronics Ltd. The pH value of the bleed water is an important factor when evaluating the cause of corrosion in steel strands surrounded by different grout mixes.

Setting Time

The setting times for various grout mixes used in this study were determined using the Vicat apparatus according to the ASTM C191 standard.(15) The grout setting time is a function of the amount of admixture and water used in preparing the grout and is indicative of the time from initial mixing where the grout remains workable until it is pumped in the post-tensioning ducts. In using the Vicat apparatus, a thin film of paraffin wax was applied to the base of the conical ring and the ring was placed on the base plate of the apparatus. The conical ring was filled with a freshly prepared grout within 2 min of completion of the initial mixing. A sharp-edged trowel was used to smooth the top surface of the grout in the ring. The time at the completion of molding of the grout in the ring was read as the start of measurement of the set time. The specimen was stored in the moist room for approximately 3 h. The extent of penetration of the 1-mm diameter needle of the Vicat apparatus into the specimen was determined every 15 min. The initial set was noted as when the needle ceased to pass a point marked at 5 mm above the base plate within 30 s after the needle was dropped on the specimen. The final set was noted when the needle could not be seen penetrating into the grout sample.

Corrosion

The prestressing strands that were extended above the grout level in the test tubes used for expansion and shrinkage evaluation, were cut and examined for evidence and extent of corrosion. The corroded strands were cleaned with a wire brush and the depth and extent of the local corrosion areas were measured. Visual examination of the corroded regions of the strands was also performed under a microscope.

CHAPTER 3. NEW TEST PROCEDURE FOR MEASURING FLOWABILITY OF GROUTS

The flowability of grout is an important characteristic parameter since it directly affects grout placement, through pumping, in confined spaces such as inside the ducts of the post-tensioned structural members. A good grout must be able to flow easily and fill the duct completely without any voids. A metallic funnel, called a flow cone, has been used to measure the flowability of grouts in terms of the time taken for a specified volume of grout mix to discharge from the cone. The most common test method has been the ASTM C939 standard, "Flow of Grout for Preplaced Aggregate Concrete." The ASTM C939 standard describes the geometrical configuration of a flow cone made of stainless steel with physical dimensions as shown in figure 6, as well as the relevant test procedure.

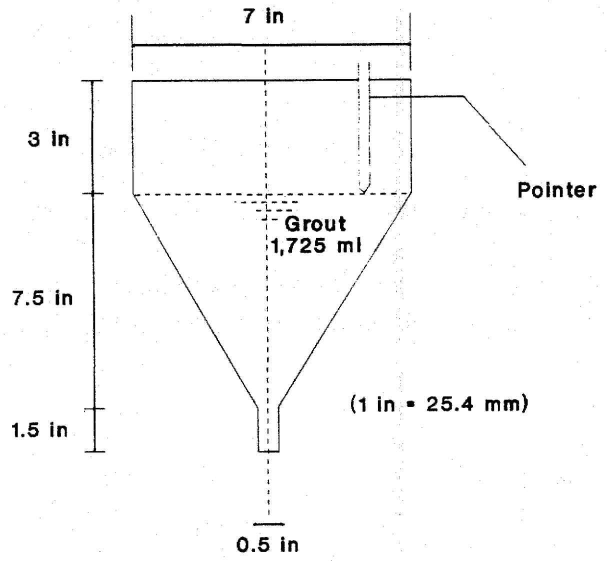


Figure 6. Schematic of the ASTM flow cone standard C939.

For this test, the size and condition of the discharge tube at the bottom of the cone are the key factors in obtaining repeatable measurements. The time it takes for a mix to discharge through the discharge tube in the cone gives an indication of the flowability of the mix. However, the test is not suitable for mixes with a thick consistency where no flow will take place through the cone. Based on the ASTM C939 standard, if the flow time through the cone exceeds 35 s, the test is not valid and instead, the flowability should be determined by using the flow table described in the ASTM C109 standard.

Some additives, such as Interplast-N, Celbex 208, Celbex 209x, etc., introduce thixotropic characteristics when added to the portland cement.

The point at which the grout changes from a gel-like state to a fluid state is called the Bingham yield point. Figure 7 shows the flow of a thixotropic grout through a varied crack section in the rock.(4) The shearing strain of the grout increases as the cross section of the crack decreases. It can be seen in the figure that the velocity of the grout flow increases when the passage area is decreased, which is similar to the condition that exists for flow of a grout inside the post-tensioning ducts.

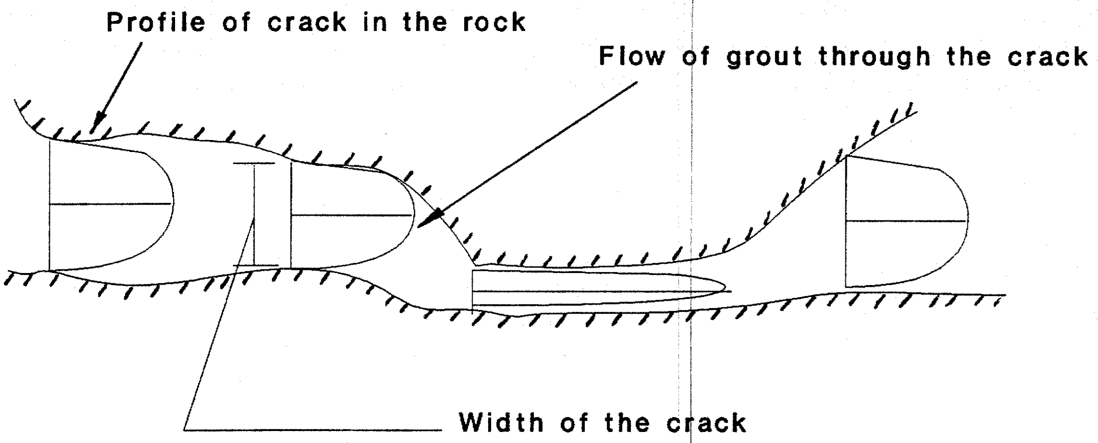


Figure 7. Flow of thixotropic grout in a varying cross section.(4)

The thixotropic property of grout under pressure can also be observed by considering a plot of the shearing stress vs. the shearing strain, as shown in figure 8.

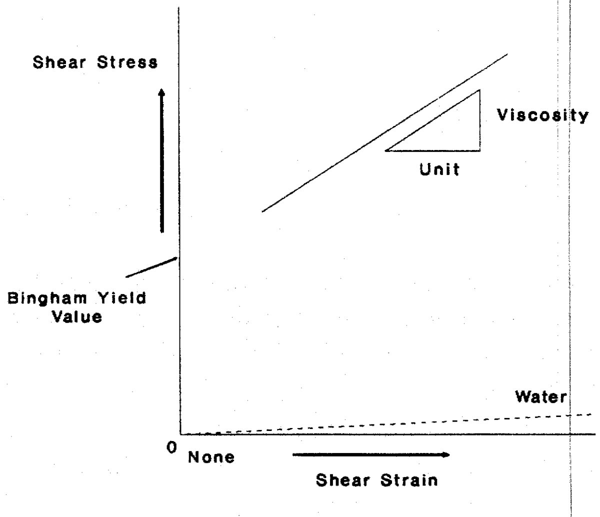


Figure 8. Shearing stress-strain relationship for grouts and indication of the thixotropic state.(4)

There is no flow of grout until the shearing stress approaches the Bingham yield value, after which a linear flow behavior is observed. The linear shearing stress-strain relationship has a gradient that is related to the grout's viscosity. In the ASTM flow cone test, the grout is allowed to flow freely due to its own weight. Thixotropic grouts may not show flowability until they are agitated or pressured. Therefore, the ASTM flow cone test may not show any thixotropic grout flow. As a result, it was concluded that using the ASTM flow cone test may not allow quantitative evaluation of the flowability of different grouts used in this study. New testing equipment and procedures were designed and developed during this study that will allow quantitative measurement of the flowability of thixotropic grout.

The new test device consists of a 3.75-in- (95-mm-) diameter, 8.0-in- (203-mm-) long cylindrical brass vessel that allows various pressure levels, up to a maximum pressure level of 200 lbf/in^2 (1,378 kPa), to be applied to a grout mix placed in the vessel (see figure 9).

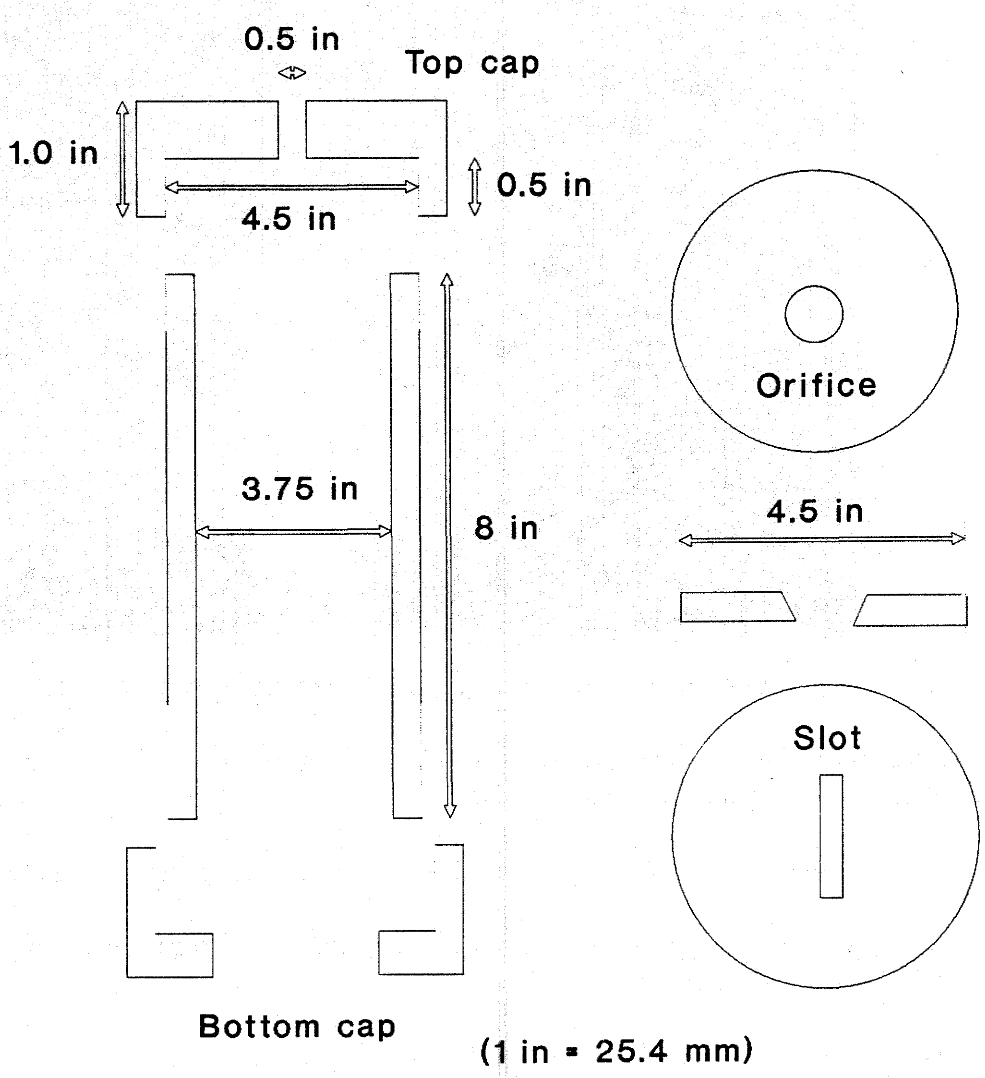


Figure 9. Schematic of the pressurized flow test equipment.

The cylinder has removable top and bottom caps. The top cap is connected through a flexible hose to a pressure tank. The bottom cap is designed such that it can accommodate and support a 0.125-in- (3.2-mm-) thick removable circular brass plate. Different plates with different orifice, or opening, sizes may be supported by the bottom cap of the cylinder. At the center of each circular plate, an opening with 45° slant edges is cut through each plate. This allows a smooth flow through the opening of grout under pressure. Seven different circular orifice sizes and three rectangular slot sizes were cut on the circular plates and were used during this study. The diameter of the circular orifice openings in the plates are: 0.063, 0.094, 0.125, 0.187, 0.25, 0.5, and 0.75 in (1.6, 2.4, 3.2, 4.7, 6.4, 12.7, and 19.1 mm). The sizes of the rectangular openings at the center of the circular plates are: 0.051 by 1.375 in (1.3 by 34.9 mm), 0.076 by 1.5 in (1.9 by 38.1 mm), and 0.1 by 1.5 in (2.5 by 38.1 mm). Figure 10 shows the laboratory setup for the experiment.

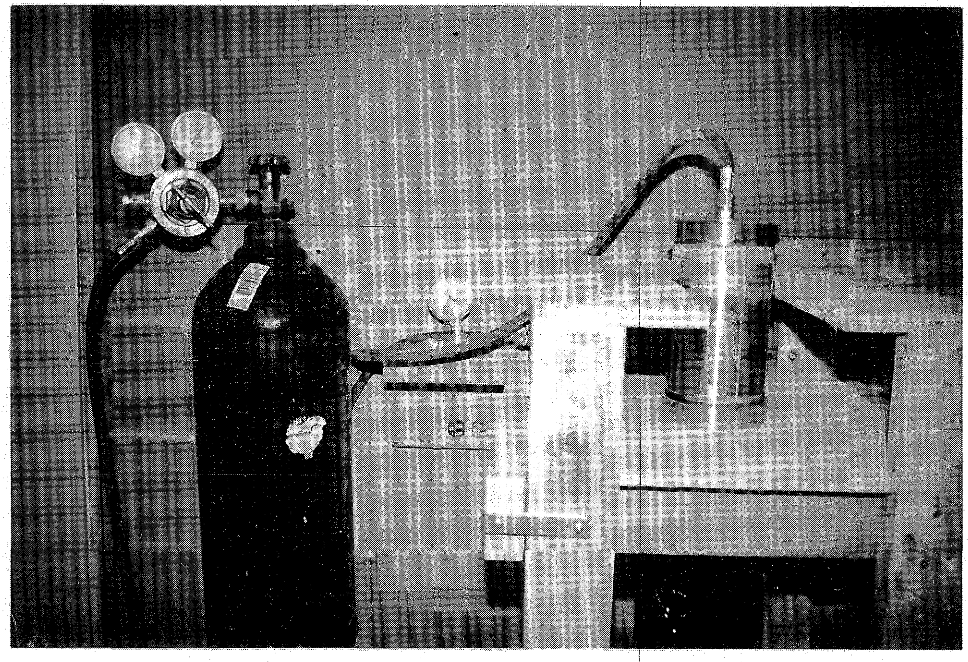


Figure 10. Experimental setup for the pressurized flow test.

The test procedure to measure the flowability of a grout mix using the new pressurized flow test equipment is suggested as follows:

1. Place the required orifice plate in the bottom cap and tighten the cap on the cylinder.
2. Wet the cylinder by filling it with water and later discharging the water within 1 min before testing the grout.
3. Block the orifice opening with the tip of a finger.
4. Place the grout into the cylinder until it is filled to the top.

5. Close the upper cap and attach it to the pressure tank, applying the required pressure.
6. Simultaneously start measuring time and remove finger from the orifice opening.
7. Read the time passed at the first break in continuous flow from the orifice.
8. Use the recorded time between steps 6 and 7 as an indication of the flowability of the mix.

CHAPTER 4. RESULTS AND DISCUSSIONS

EVALUATION OF GROUTS

A total of 15 grout mixes were evaluated in this study. Each mix was subjected to the tests listed in the previous chapter. The results and discussions for the 15 mixes used in this study are presented in the following sections.

Grout Without Admixture (Control Group)

Grout mixes denoted as A, B, and C did not contain any admixtures, and had water-to-cement ratios of 0.35, 0.40, and 0.45, respectively. As shown in figure 3, the variation of the water and grout levels in the tubes were recorded for each mix at 15-min time intervals. A graph was plotted showing the percentage of expansion and shrinkage by volume of the mix vs. time. No expansion was observed for these mixes. The shrinkage for these grouts ranged from 2 percent to 2.5 percent by volume. As the water-to-cement ratio in these mixes increased from 0.35 to 0.45, small increases were observed in the shrinkage of the grouts. Ninety percent of the shrinkage was observed during the first 3 hours from the time the grout was mixed. Figures 11 through 13 show the extent of shrinkage for the control mixes with the water-to-cement ratios of 0.35, 0.40, and 0.45, respectively. In each figure, an additional graph shows the effect of the presence of steel strands on the expansion or shrinkage of the mixes. Figures 11 through 13 also show results for other mixes used in this study where significant expansion resulted in some mixes where specific additives were used.

As shown in figures 14 through 16, there was considerably more bleeding and free bleed water in the tubes that contained the steel strands. The head pressure from the weight of the cement paste caused the bleed water to migrate upward through the interstices of the strands to the top of the grout level in the tube. In the figures, the effect on the grout bleeding in different mixes from the admixtures used in this study are also shown. This phenomenon has a significant effect on the performance of grouts used to fill the ducts of post-tensioned structures. Grouts that have been tested in the laboratory and show little or no bleeding with the absence of the strands could exhibit excessive bleeding inside the post-tensioning ducts. Unfortunately, bleeding of the grout inside the post-tensioning ducts are not usually noticed, which could cause extensive corrosion of the strands.

The Gelman pressure test was also used to evaluate the bleeding characteristics for these grouts. The control grouts could not sustain the 80 lbf/in^2 (551 kPa) of maximum applied pressure since the mixes became excessively porous due to the loss of water and a pressure drop in the vessel. As the water-to-cement ratio was increased in the grouts, the amount of the collected bleed water increased. This was due to the presence of higher water content in the mix. Figure 17 illustrates the amount of total bleed water discharged from the vessel for the different grout mixes used in this study. It can be seen from the figure that all admixtures used in this study improved the bleeding problem of the control grouts.

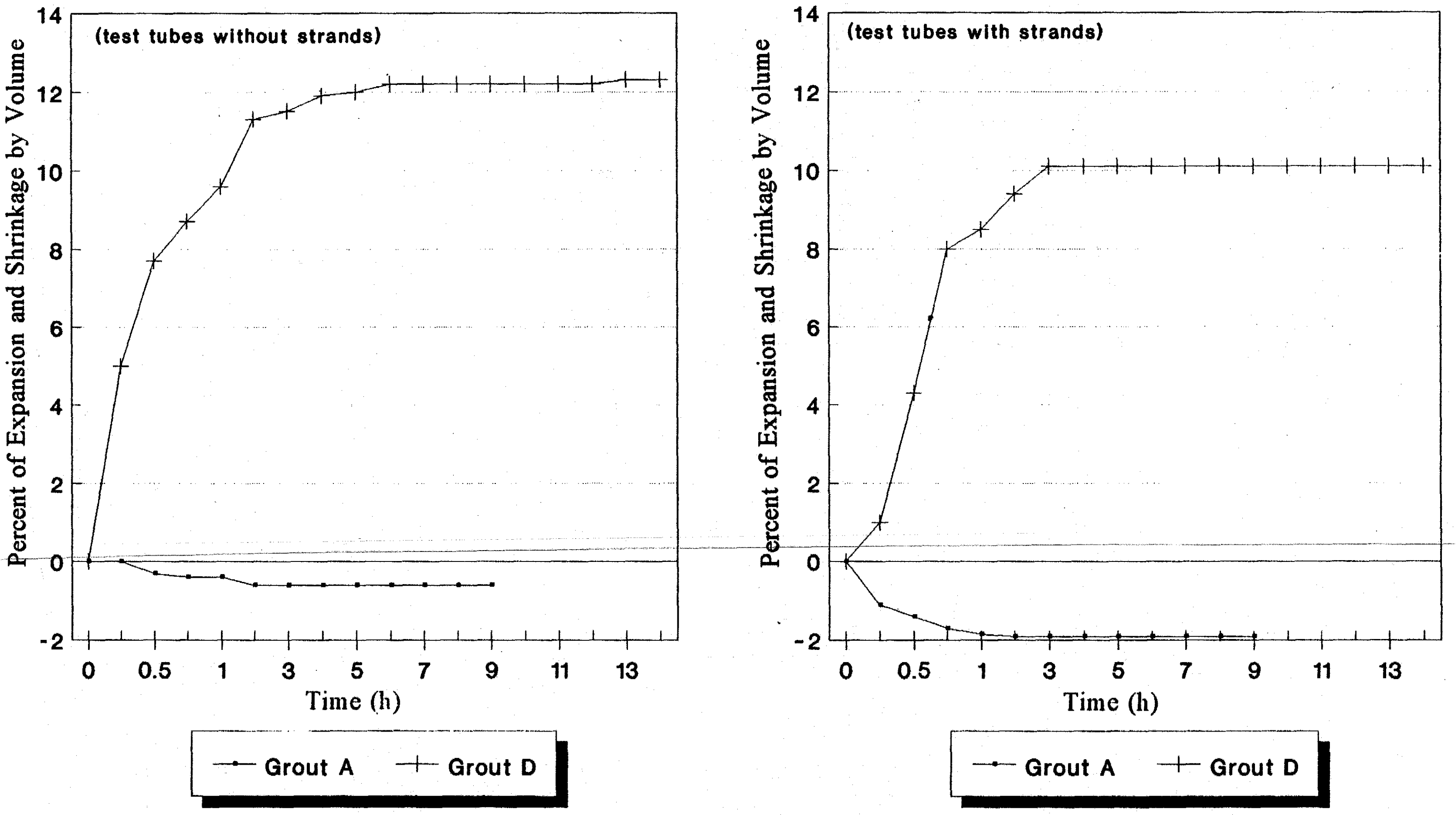


Figure 11. Expansion and shrinkage by volume of grouts, water-to-cement ratio: 0.35.

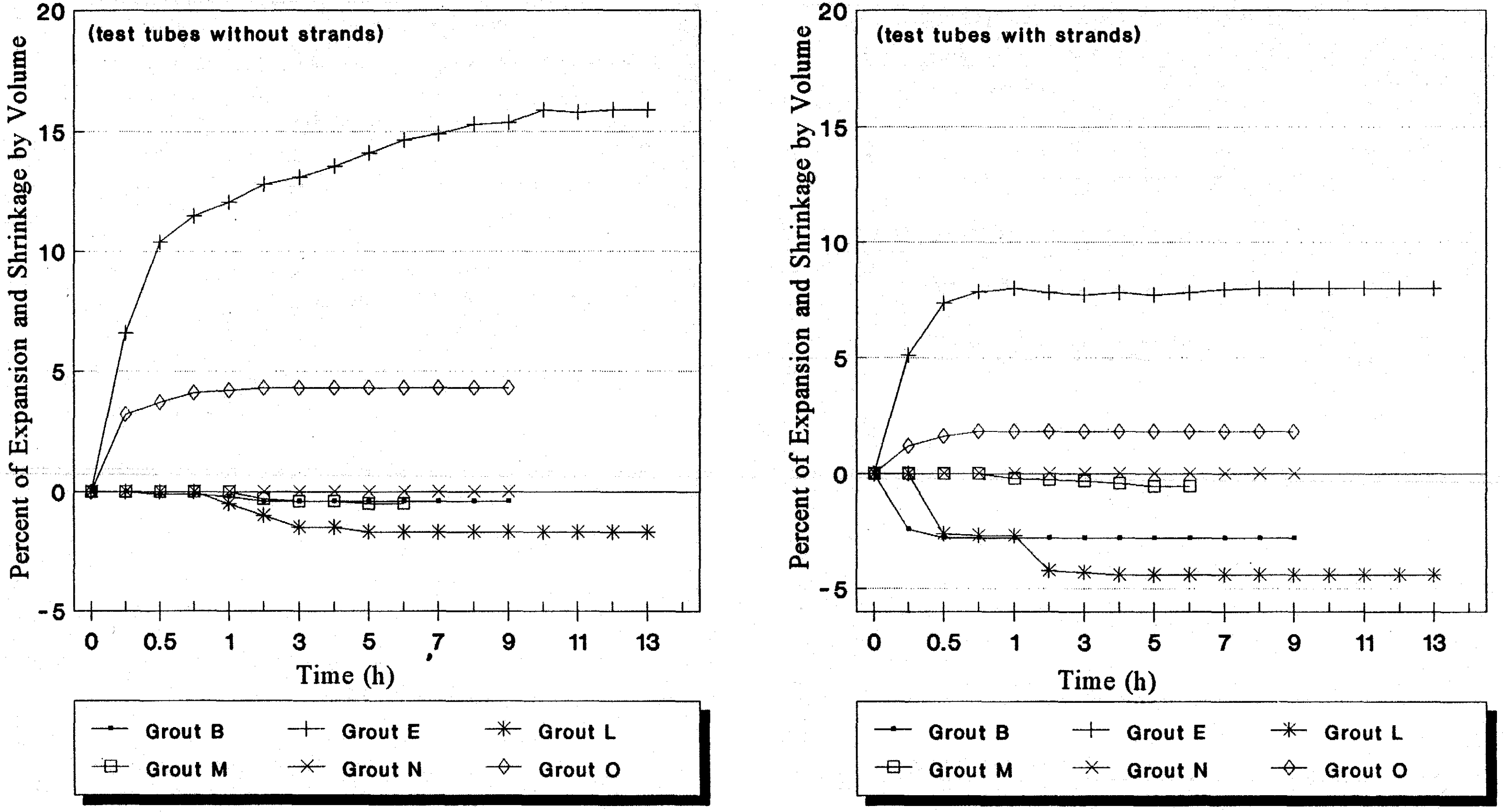


Figure 12. Expansion and shrinkage by volume of grouts, water-to-cement ratio: 0.40.

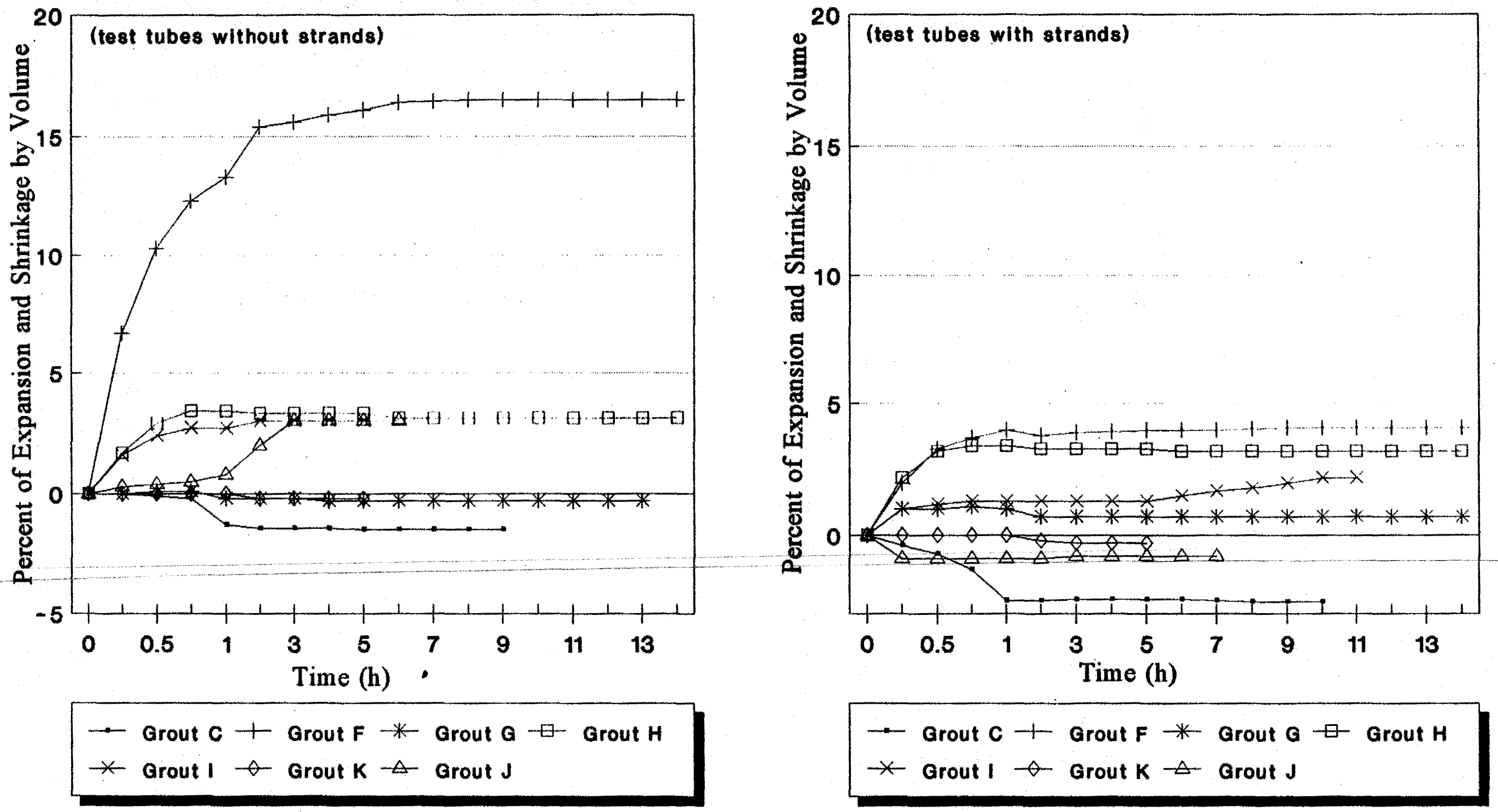
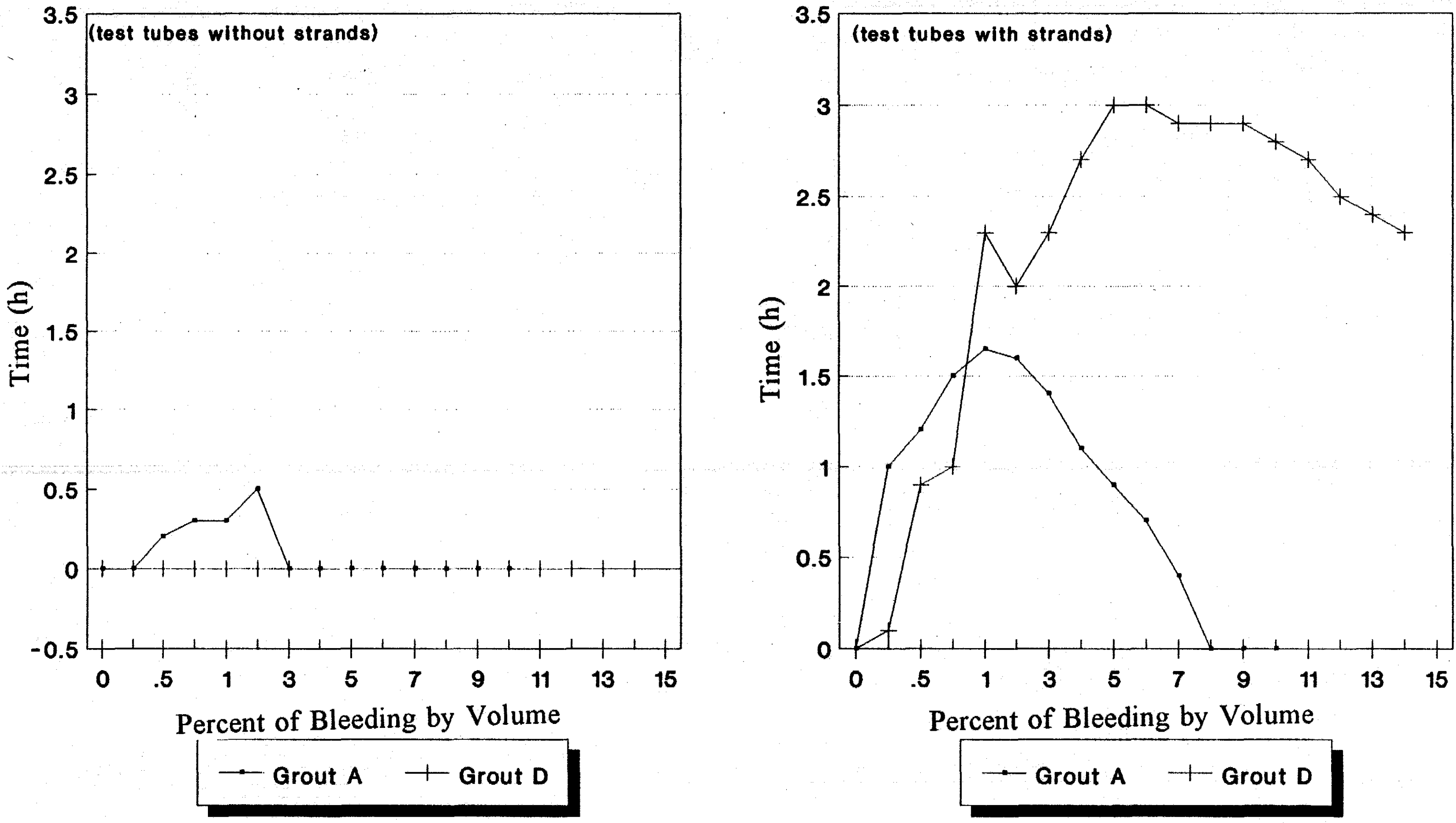


Figure 13. Expansion and shrinkage by volume of grouts, water-to-cement ratio: 0.45.


(test tubes without strands)

(test tubes with strands)

Figure 14. Bleeding in the grouts, water-to-cement ratio: 0.35.

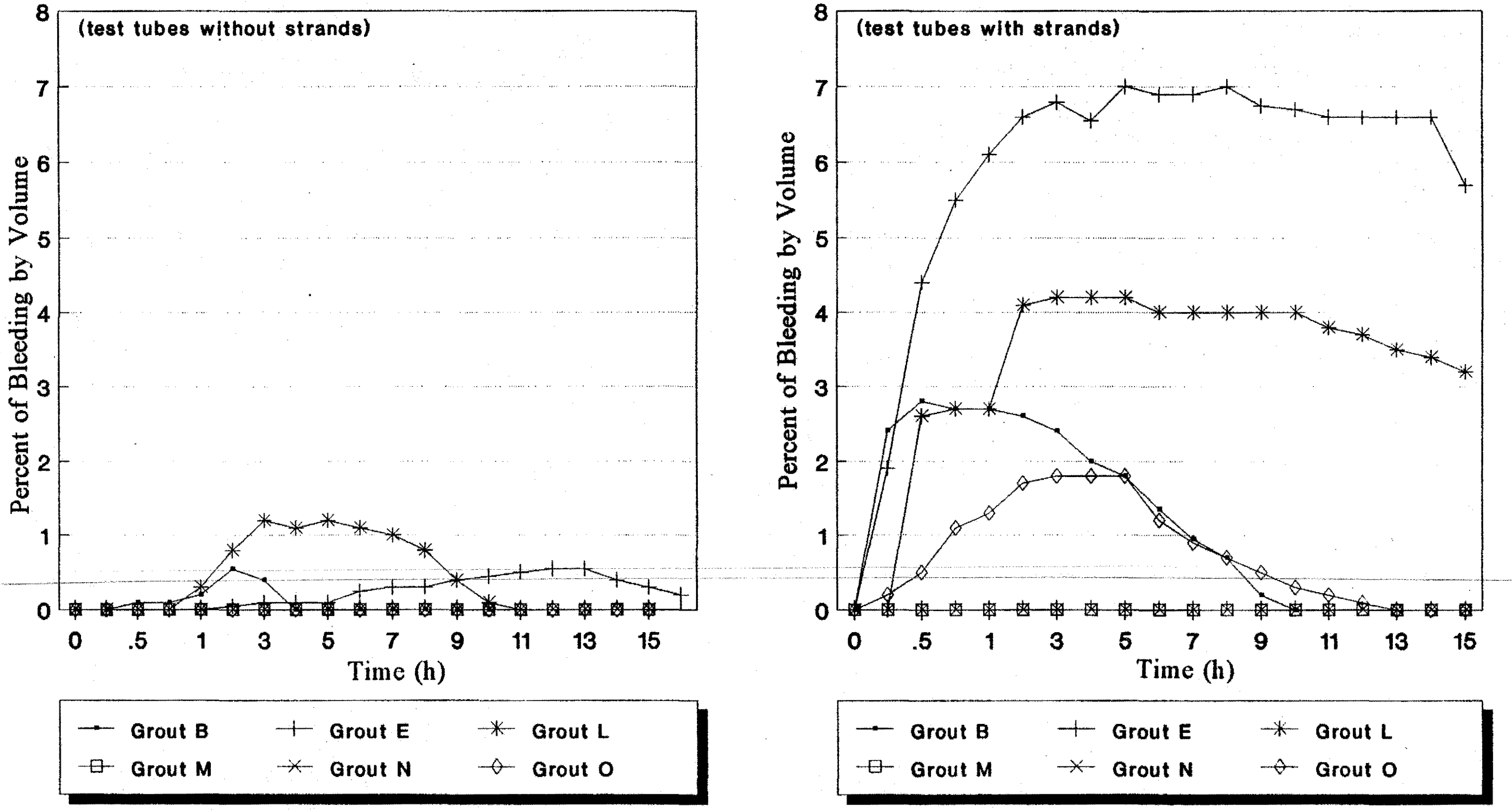


Figure 15. Bleeding in the grouts, water-to-cement ratio: 0.40.

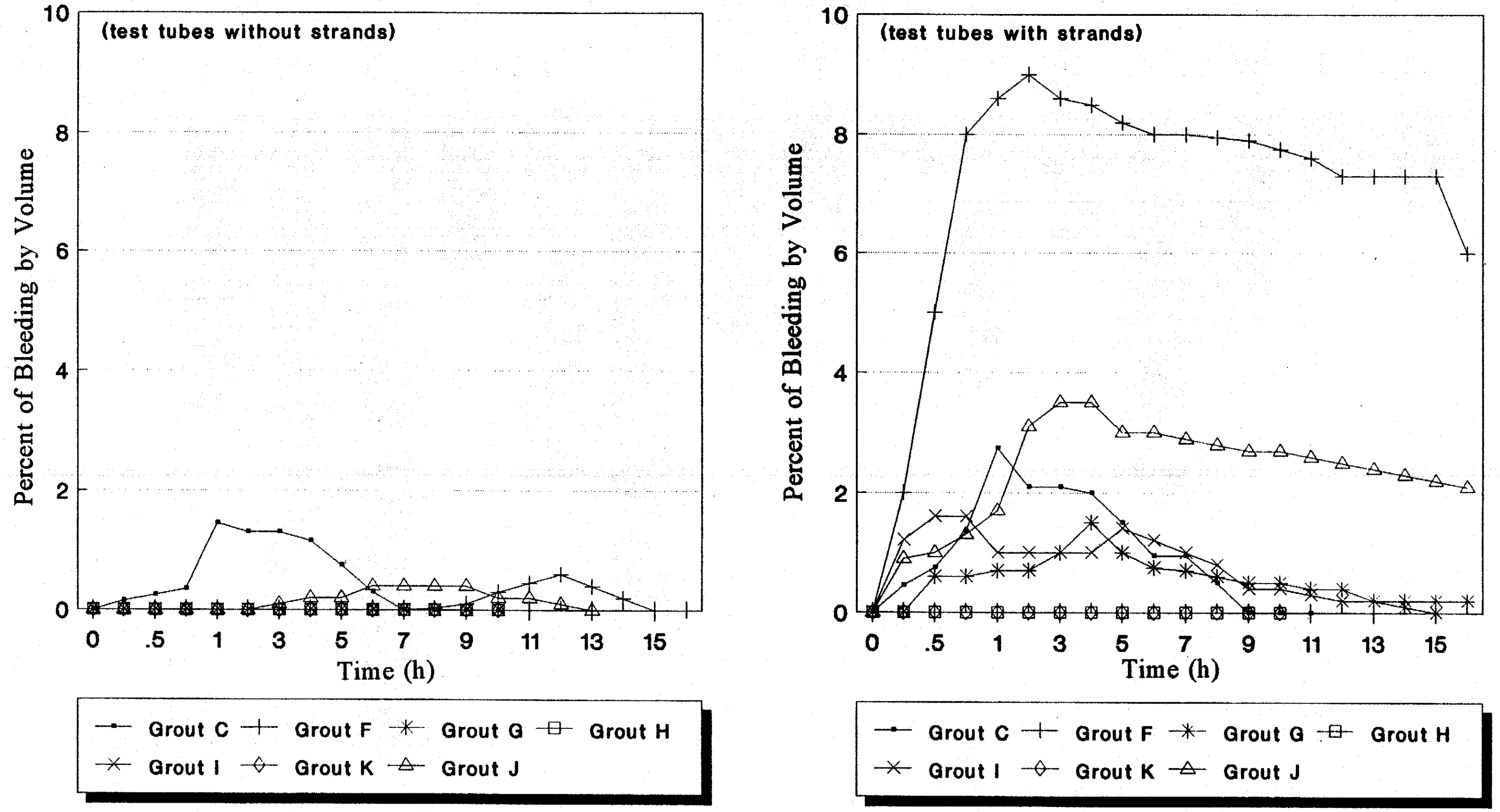
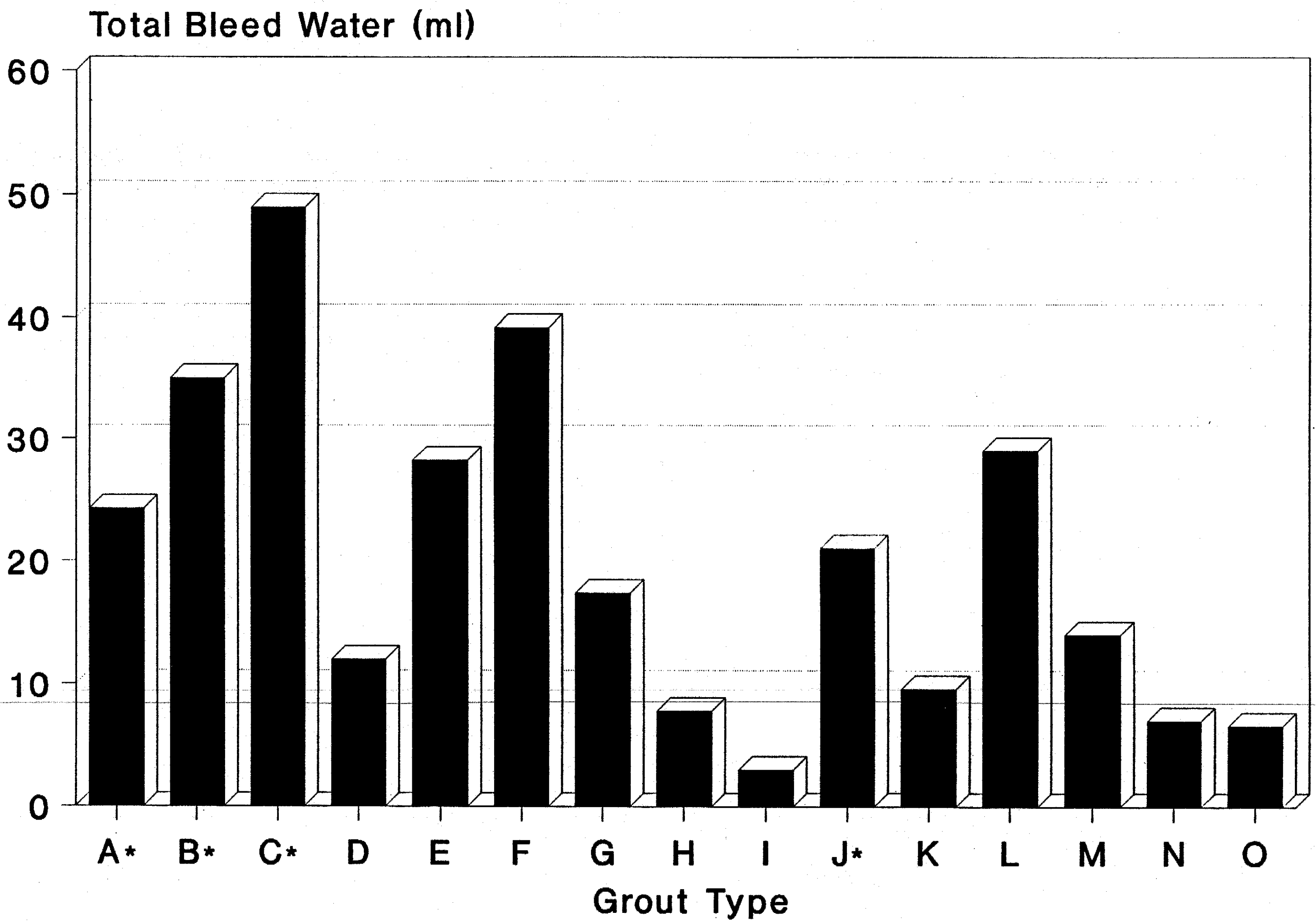


Figure 16. Bleeding in the grouts, water-to-cement ratio: 0.45.



* Pressure dropped before 80 lbf/in^2 (551 kPa)

Figure 17. Results of Gelman pressure test indicating bleed water for grouts used in this study.

As the water content in the mix increased, due to an increase in the water-to-cement ratios, the initial setting time of the grout mixes also increased. The compressive strength of the mixes used in the study decreased as the water-to-cement ratio in the mixes increased. Grout C had a lower compressive strength when compared with grouts A and B. The 28-d compressive strength values for these mixes were in the range of 7,400 to 8,000 lbf/in^2 (50,986 to 55,120 kPa). The flow test was performed according to ASTM standard C939. Grout C showed an efflux time of 14 s. Due to the high viscosity of grouts A and B, there was no flow through the flow cone (see table 1). The high water-to-cement ratio in grout C caused the grout mix to be more flowable.

Table 1. Flow time for various grouts using the ASTM flow cone test and the new pressurized flow test.

Grout Types	ASTM Flow Cone Test (C939)	Pressurized Flow Test (Applied Optimum Pressure: 35 lbf/in^2)
Grout A	No Flow	14.4 s
Grout B	No Flow	11.8 s
Grout C	14.0 s	10.8 s
Grout D	No Flow	15.1 s
Grout E	No Flow	13.0 s
Grout F	20.1 s	11.2 s
Grout G	2 min 30 s	11.3 s
Grout H	No Flow	14.7 s
Grout I	23.0 s	11.0 s
Grout J	17.0 s	No Flow (sand)
Grout K	1 min 50 s	13.3 s
Grout L	14.2 s	13.3 s
Grout M	27.0 s	11.1 s
Grout N	28.0 s	11.9 s
Grout O	23.0 s	10.9 s

(1 lbf/in^2 = 6.89 kPa)

The permeability test was performed using specimens made from grout mixes A, B, and C according to the AASHTO T277-89 standard. The testing of some of the mixes was stopped short of the normal 6-h test period when the temperature of the solutions in the cell blocks rose above 88 °C. The high temperature resulted from the presence of higher current in the grout sample, which generally has a higher permeability compared to a concrete sample. A comparative study of the permeability of the grouts used in this study was made by comparing the total electric charge passing through each specimen in 90 min. Grout C, with a higher water content, was more permeable when compared to grouts A and B. It was found that as the water-to-cement ratio in the mixes increased, the mixes became less dense and more porous. This finding is also in agreement with the results from the Gelman pressure test. The total charge passing through specimens A, B, and C were 3,453; 5,981; and 8,357 coulombs, respectively, indicating the extent of permeability in these mixes. The results of the permeability test for all of the mixes studied here are presented in figure 18.

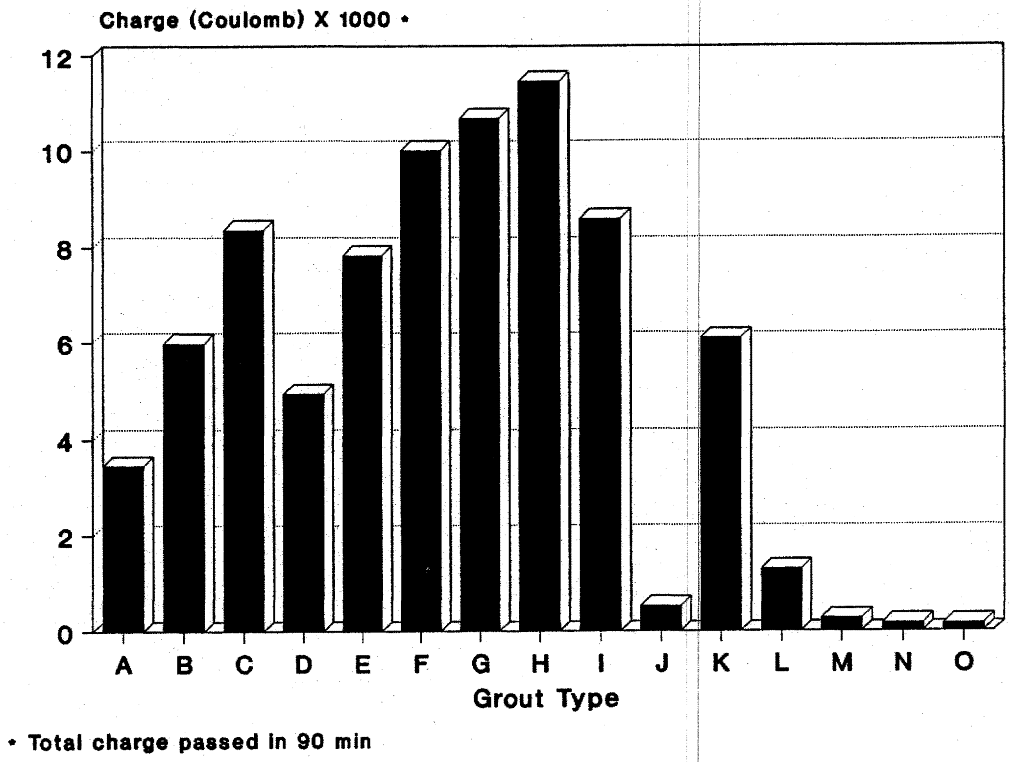


Figure 18. Results of permeability test for grouts using AASHTO T277-89 standards.

The measured pH values on the collected bleed water from all grouts used in this study were in the vicinity of 13. This indicates that the bleed water mainly included an alkaline environment. No corrosion was observed in the strands surrounded by grouts A and B. A 0.0005-in (0.0125-mm) layer of corrosion was present on the surface of the strands that were used in grout C. The corrosion was only observed on the strands in grout C due to the presence of bleed water. The bleed water was completely reabsorbed in the grout after 9 h.

Interplast-N

Interplast-N was used in three mixes as an admixture with expansive properties. The expansion of the grout due to the use of Interplast-N is a result of gas formation in the presence of water, causing an increase in the volume of the mix. A moderate expansion of grouts inside of post-tensioning ducts is desirable since it could lead to filling some of the possible voids in the ducts. Three mixes with water-to-cement ratios of 0.35, 0.40, and 0.45 were designed and prepared using this admixture. The amount of the Interplast-N added to each mix was 1.0 percent by weight of cement. Grout mixes with this admixture showed expansion ranging from 4 to 16.5 percent. Ninety percent of the expansion occurred within the first 2 h of the initial mixing of the grouts. Grouts in the tubes without steel strands showed 2 to 12 percent more expansion when compared to those in the tubes that contained strands. It was observed, however, that the tubes with strands contained more accumulated free bleed water above the grout level. As the water-to-cement ratio increased in these mixes, the amount of free bleed water accumulated at the top of the grout increased. Graphs shown in figures 14 through 16 illustrate the exaggeration in bleeding in the tubes in the presence of steel strands. The bleed water above the grout level inside the tube remained for a period of more than 20 h before it was reabsorbed into the grout.

Evidence of significant corrosion was observed within 3 d in the upper ungrouted sections of the strands that were exposed to the accumulated bleed water in the tubes. As shown in figure 3, the upper sections of the test tubes were left ungrouted to allow for measuring the amount of bleed water in each mix. The bleed water in the tube was attributed to the corrosion of the prestressing strands. After a period of 6 mo, the strands were removed, cleaned with a wire brush, and examined further under a microscope. A corrosion pitting effect was observed in the upper section of all of the strands in the grout mixes prepared with this admixture. Corrosion pits approximately 0.115 in (2.9 mm) wide and 0.013 in (0.33 mm) deep were measured on the surface of the steel strands placed in grout D. Corrosion pits of 0.2 in (5.0 mm) wide and 0.014 in (0.35 mm) deep were measured on the surface of the strands placed in grout F. Figure 19 shows two photographs, with magnifications of 1:1 and 1:4, of the extent of corrosion on the surface of the prestressing strands placed in grout D. It must be noted, however, that no significant corrosion was observed in the portion of the strands fully covered by these grouts.

Using these mixes, an experiment was performed by placing the grouts and steel strands in tubes that were filled to the top and were sealed. A 100-lb (45.4-kg) weight was placed on the top to prevent expansion of the grouts outside the tube. It was found that no significant corrosion occurred in the strands embedded in these mixes. This observation was made after the strands were removed from the grouts after 28 d of the initial mixing and placing of the grouts in the tubes. It was concluded that if grouting of a post-tensioning duct is completed without the presence of a void in the duct, the use of Interplast-N as an admixture does not have a significant effect on the corrosion of the post-tensioning steel in the duct. However, a void-free grouting of post-tensioning ducts in bridge structures may not be done with a high degree of reliability under the field condition. Thus, use of Interplast-N should be handled

handled with caution. A more detailed study, including evaluation of all possible chemical interactions for these mixes, is needed to determine the effect of Interplast-N on corrosion of the post-tensioning steel inside of the post-tensioning ducts.

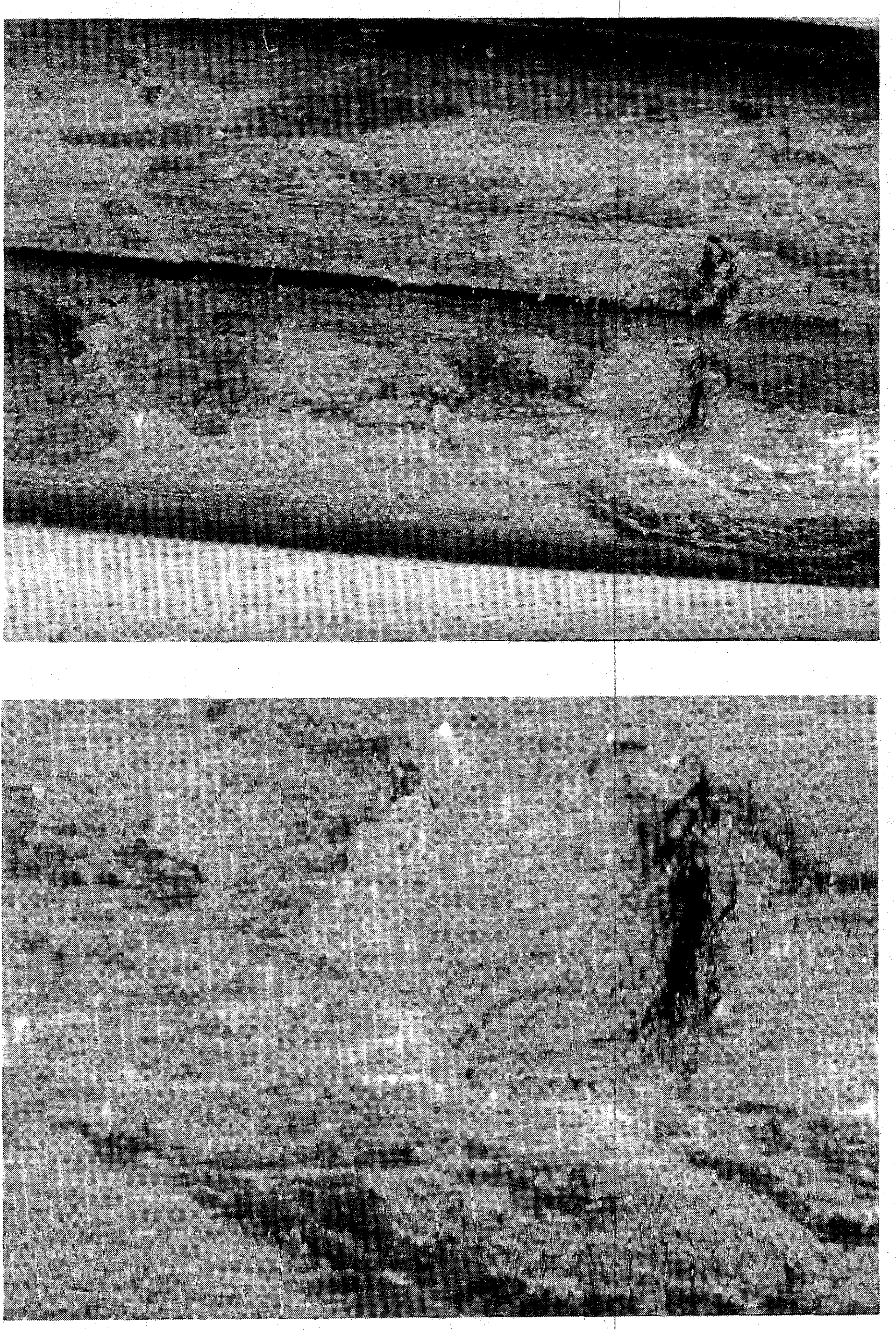


Figure 19. Corrosion of strands in grout D (magnification is 1:1 and 1:4).

All specimens that included Interplast-N exhibited very low compressive strength. The range of compressive strength values were from 3,750 to 4,500 lbf/in^2 (25,837 to 31,005 kPa). Since these grouts contained an expansive agent, the pore structure increased in the mix, causing a lower compressive strength. Although very high compressive strength is not required for grouts used for post-tensioning applications, it is desirable to have a minimum compressive strength of approximately 4,000 lbf/in^2 (27,560 kPa) to provide adequate bonding of the steel to the surrounding grout.

The permeability of these grouts was found to be high. The total charge passing through the specimens made of grout D, E, and F were 4,939; 7,824; and 10,000 coulombs, respectively. The expansion in these grouts, due to the addition of Interplast-N, contributed to the specimen's higher porosity and permeability. The permeability also increased in those mixes where the water-to-cement ratio values were higher. High permeability in grouts used for post-tensioning applications is not desirable since they facilitate penetration of aggressive chemicals (such as chloride ions) in the grout, causing corrosion of the post-tensioning steel.

As shown in figures 14 through 16, these mixes produced the most bleed water in the presence of steel strands when compared to other mixes used in this study. This is also directly related to the fact that they produced the highest volume expansions. The Gelman pressure test also indicated that the bleeding increased in these mixes as the water-to-cement ratio was increased (see figure 17). This increase in bleeding was also observed in the test tubes used for evaluation of the expansion and shrinkage. In spite of the presence of corrosion in the prestressing strands, the measured pH values of the bleed water for these mixes was approximately 13, indicating an alkaline environment. Due to the high viscosity of grouts D and E, there could be no discharge through the flow cone. The high water-to-cement ratio in grout F caused the grout mix to be more flowable, having an efflux time of 20.1 s.

Celbex 209x

Initially, two mixes with a water-to-cement ratio of 0.45 were made using this admixture. The amount of the admixture added to the mixes was 0.8 and 1.3 percent by weight of cement. As shown in figure 13, grouts G and H had a maximum expansion of 0.1 and 3.4 percent by volume, respectively, after the first hour of the initial mixing. No bleeding was observed for grout H in the tubes with or without strands. Grout G experienced no bleeding when no strands were present and it exhibited a 1.0 percent bleeding by volume in the tube that contained steel strands. As shown in figure 17, the amount of the bleed water resulting from the Gelman pressure filter test was also smaller for grout H compared to that of grout G. Since there was less bleeding in these grouts, as compared to the grouts that contained Interplast-N, the resulting corrosion on the surface of the strands was less severe. A 0.0005-in- (0.0125-mm-) thick layer of surface corrosion was observed in grout G after 3 d from the beginning of the test. The prestressing strands in the tube with grout H had a 0.00025-in- (0.006-mm-) thick layer of surface corrosion distributed throughout the length of the strands. The initial setting time for grout G was 6 h and for grout H, it was more than 24

h. As the percentage of the admixture added to the grout mixes was increased, both the expansion and permeability of the grout specimens increased. The expansion in the mix caused the grout to become more porous. The permeability of grout H was the highest among all of the mixes evaluated in this study (see figure 18). The total amount of charge passing through grout specimens G and H was 10,680 and 11,460 coulombs, respectively.

With the use of this admixture, a consistent mix could not be achieved until the speed of the mixer was increased from 850 r/min to 1,000 r/min. Due to the high viscosity of grout H, there could be no discharge of the grout from the flow cone. Grout G exhibited an efflux time of 2 min 30 s.

M150 superplasticizer was added to grout H to make the grout more flowable and this new mix was designated as grout I. In order to determine the optimum amount of the superplasticizer to be added to the mix, trial mixes with 10 to 70 oz (283 to 1,985 g) of superplasticizer/100 lb (45.4 kg) of cement were prepared. The optimum mix included 70 oz (1,985 g) of superplasticizer/100 lb (45.4 kg) of cement, which gave an efflux time of 23.0 s. For grout I, expansions by a volume of 2.2 and 3.0 percent were observed in the tubes with and without strands, respectively. No bleeding was observed in the mix in the tube without strands, but 1.5 percent bleeding was observed in the tube that contained strands. The bleed water collected from the Gelman pressure test measured 3 ml and had a pH value of 12.5. Grout I was less permeable when compared to grouts G and H. This was due to the addition of the superplasticizer to the mix that resulted in a more consistent mix. The total amount of charge passing through the specimen made with grout I was 8,584 coulombs. The prestressing strands in the tube with grout I showed a surface corrosion of 0.001 in (0.005 mm) that was distributed throughout the length of the strands.

As the percentage of the admixture added to the grout increased, the compressive strength decreased. It was found that the increase in the admixture caused an expansion of the specimen, resulting in a decrease in strength. The 28-d compressive strength values for grout mixes G, H, and I were 5,175; 4,534; and 4,450 lbf/in^2 (35,655; 31,240; and 30,660 kPa), respectively.

In-Pakt

Grout J, with a water-to-cement ratio of 0.45, consisted of a ready-mix grout/admixture called In-Pakt. Sand is used in this grout mix in a ratio of 1:1 to cement. As shown in figure 13, this mix when placed in a tube without strands showed an expansion of 3.0 percent. In a tube with strands, the mix showed a volume shrinkage of 0.9 percent. As stated earlier, the head pressure in the tube caused the bleed water to migrate upwards through the interstices of the strands. Therefore, shrinkage occurred as a result of the reduction of the water content in the grout. As shown in figure 16, approximately 3.5 percent by volume of bleed water was measured in the tube with strands and only 0.4 percent by volume was measured in the tube without strands. Due to the presence of sand particles in the mix, the specimen was very dense after the final set. When the permeability test was performed, the total charge passing through the specimen was only 523 coulombs. This indicated that the permeability of the specimen was relatively low compared to that of specimens made from grouts A through I.

The measured pH value of the bleed water collected from grout I was 13, indicating an alkaline environment. The presence of water around the strands above the grout level for more than 15 h before it was absorbed into the grout, caused pitting surface corrosion of the steel. Corrosion pits approximately 0.1 in (2.54 mm) wide and 0.004 in (0.11 mm) deep were measured on the surface of the strands that were embedded in this mix. The mix was workable and had an efflux time of 17 s. The compressive strength of the specimen made of grout I was 4,108 lbf/in^2 (28,304 kPa) and the initial setting time was 7 h and 50 min.

Celbex 208

Celbex 208 was used as an anti-bleed admixture in grout K, having a water-to-cement ratio of 0.45. The amount of the admixture added was 1.2 percent by weight of cement. As soon as the admixture was added to the mix, the mix became thixotropic. The efflux time measured on the flow cone was 1 min 50 s. As shown in figure 13, no significant expansion or shrinkage of the mix was observed in the tubes with or without strands. About 2 percent more bleeding was observed in the tube with strands. In the chloride permeability test, the total charge passing through a specimen made of this mix was 6,082 coulombs. Grout K was less permeable than grout C, with the same water-to-cement ratio. The initial setting time for the grout was 14 h. The Gelman pressure test produced 9.6 ml of bleed water with a pH of 13 (see figure 17). Since there was little bleeding from the grout mix, the observed corrosion in the strands was less severe. A 0.001-in- (0.025-mm-) thick layer of surface corrosion was uniformly distributed throughout the length of the prestressing strands. The compressive strength of a specimen made of this mix was 5,730 lbf/in^2 (39,480 kPa).

Silicafume

Silicafume was used as a partial replacement for cement in four grout mixes evaluated in this study. Initially three mixes, grouts L, M, and N, were prepared with 5, 20, and 25 percent, respectively, cement replaced with silicafume. These grouts became very thick, or thixotropic, and were hard to mix as soon as the silicafume was added. It was decided to add M150 superplasticizer to the mixes to make them more workable. Trial mixes were made to determine the optimum amount of superplasticizer to be added to the mixes. Three different amounts of superplasticizer were used for each of the mixes described earlier. All of the mixes using the silicafume had a water-to-cement ratio of 0.40.

As the percentage of the silicafume replacement for cement increased, the shrinkage in the grout mixes decreased. This was due to the presence of microfine particles of silicafume that provided additional surface areas and occupied the fine pores in the mix, thus increasing the water retentivity and reducing shrinkage and bleeding of the mix. As shown in figure 12, in the tube without strands, a 1.7 percent shrinkage was observed for grout L (5 percent silicafume) and no shrinkage was observed for grout N (25 percent silicafume). Similar observations were made in the tubes with strands, but the shrinkage for grout L was 4.5 percent. To achieve an expansion in the mix, 0.5 percent by weight of cement of Interplast-N was added to grout M, and the mix was designated as grout O. Grout O had an expansion of 4.3 percent in the tube without strands and 1.8 percent in the tube with strands. As shown in figure 15, no significant bleeding was observed in grouts M and N in the tubes with and without strands. Grout L showed bleeding of 1.2 and 4.2 percent by volume in the tubes with and without strands, respectively. Grout O showed no bleeding when no strands were present in the tube, but it showed 1.8 percent bleeding in the presence of strands. This indicated that the presence of Interplast-N in the mix contributed to some bleeding in the mix.

The compressive strengths of the grout mixes increased as the percentage of silicafume increased. The compressive strengths at 28 d for these mixes were in the range of 8,500 to 9,200 lbf/in^2 (58,565 to 63,388 kPa). Similar results were observed by Hope and Ip.(18)

The initial setting times for grouts L, M, N, and O ranged from 7 to 10 h. The flow characteristics of these grouts were measured quantitatively with the ASTM standard C939 flow cone. Grout L had the least efflux time of 14.2 s and grout N had the highest efflux time of 28.0 s. The bleed water collected from the Gelman pressure test for mixes L through O is shown in figure 17. The amount of bleeding decreased as the percentage of silicafume in the grout increased, except where Interplast-N was added. This decrease in the amount of bleeding was also observed in the tubes for the expansion and shrinkage tests.

The chloride permeability test was performed for each of the four mixes. The total charge passing through the specimens for grouts L, M, N, and O were 1,292; 171; 157; and 270 coulombs, respectively. As shown in figure 18, grout N is the least permeable of all the mixes evaluated in this study. All specimens made by the addition of silicafume resulted in less permeable mixes compared to other grouts used in this study. Hope and Ip also had similar observations during their investigation of grouts containing silicafume.

The measured pH values of the bleed water collected from mixes L through O were in the range of 12.5 to 13.0. The presence of a small amount of moisture above the grout level and around the strands caused a very thin layer of surface corrosion on the strands near the top of the grout level. The thickness of the corrosion layers formed on the surface of the strands placed in the tubes containing mixes L, M, N, and O were 0.001, 0.0005, 0.00025, and 0.0005 in (0.025, 0.012, 0.006, and 0.012 mm), respectively. The strands surrounded by grout N showed the least amount of corrosion. Figure 20 shows the surface corrosion appearing on the strands embedded in grout O with magnifications of 1:1 and 1:4.

Mixes with 20 to 25 percent of cement replaced with silicafume, along with the addition of a superplasticizer, appeared to be the most suitable mix for grouting the ducts of post-tensioned bridges. Grout N showed the most superior performance among all the mixes by having a low permeability, high compressive strength, minimal bleeding, good protection against corrosion, and good flowability. The initial setting times for grouts M and N were

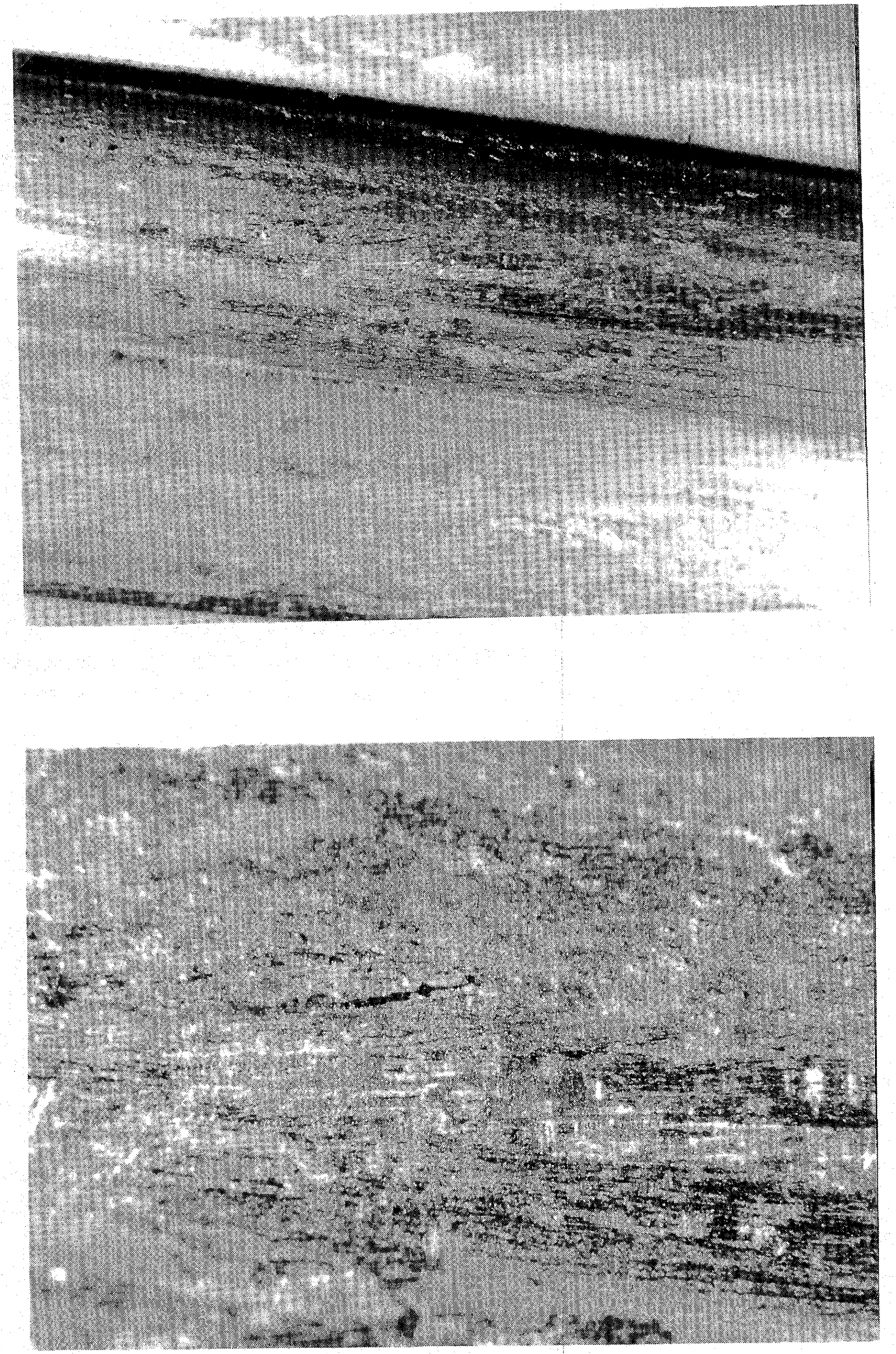


Figure 20. Corrosion of strands in grout O (magnification is 1:1 and 1:4).

9 h 30 min and 6 h 15 min, respectively, which provides adequate working time in the field. Since the bleed water was alkaline and the water was reabsorbed completely into the grout in the tubes within 12 h, the strands showed minimal corrosion. While the addition of 0.5 percent Interplast-N in grout O improved the grout performance by providing some expansion, the resulting bleeding could have a detrimental effect by causing corrosion of the strands surrounded by the mix. Although no additional corrosion of the strands were observed in this study for mix O compared to mix M, additional evaluation of the effect of Interplast-N on corrosion of steel is required.

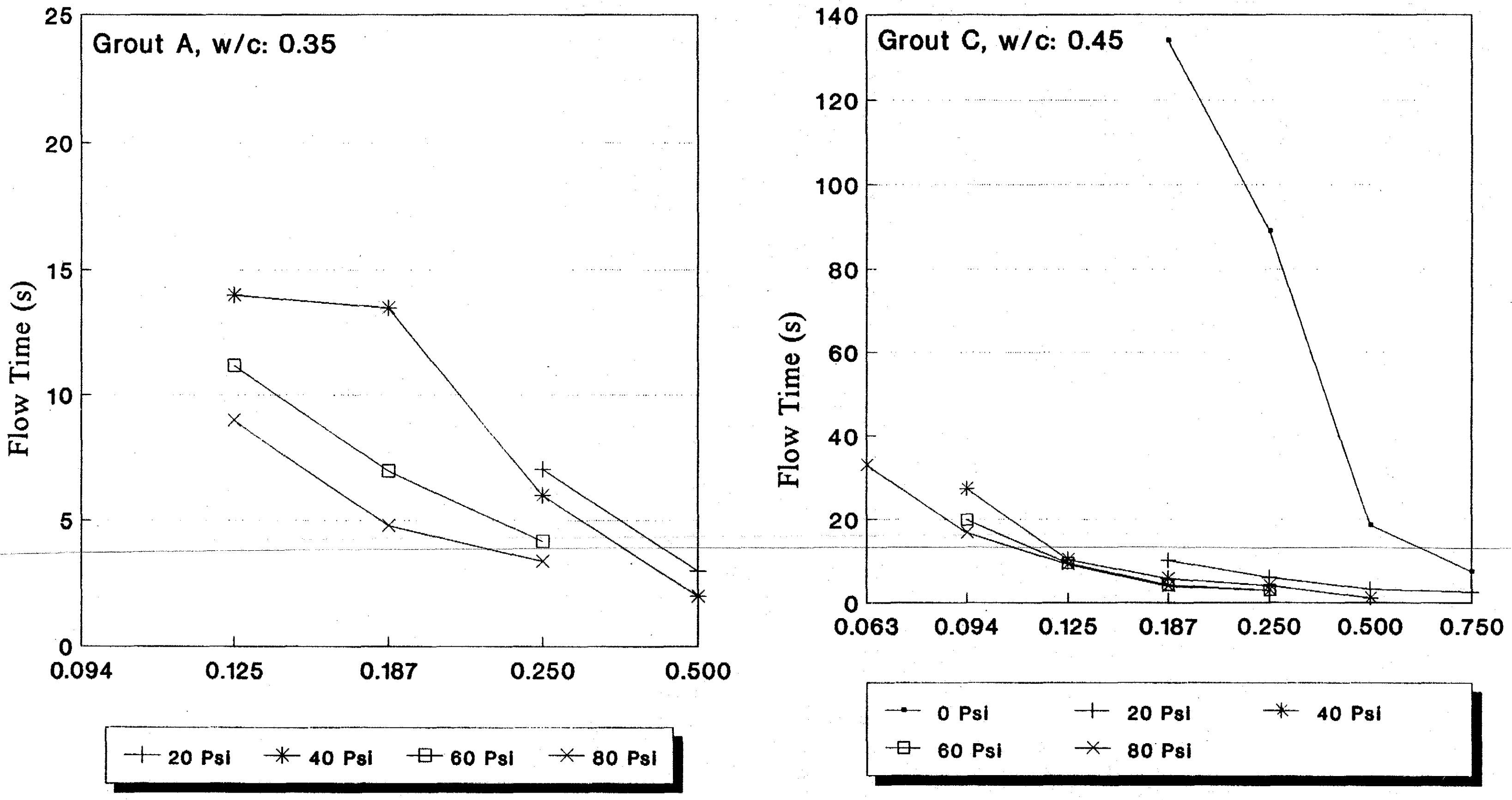
PRESSURIZED FLOW TEST

From the results of the ASTM flow cone test performed during this study and from the observations made during the preparation of the different mixes, it was initially decided to choose mixes with very high and very low viscosities using the new pressurized flow test equipment in order to establish the optimum required orifice size. It was decided to use control grouts A and C in the study, with water-to-cement ratios of 0.35 and 0.45, respectively. The pressure levels applied to the grouts that were placed in the vessel of the apparatus ranged from 0 to 80 lbf/in^2 (0 to 551 kPa) in increments of 20 lbf/in^2 (138 kPa). Graphs were constructed to show the relationship between the flow time and the various orifice sizes under different pressure levels. These graphs indicated the most suitable orifice size to be used in the apparatus that will result in a wide range of quantitative data related to the time of flow for various grout mixes.

Initially, orifice plates with circular opening diameters of 0.063, 0.094, 0.125, 0.187, 0.25, 0.5, and 0.75 in (1.6, 2.4, 3.2, 4.7, 6.4, 12.7, and 19.1 mm) were used to test grout C. An orifice diameter of 0.063 in (1.6 mm) was immediately found to be too small for the flow of a grout with a very low viscosity. Only at an 80-lbf/in^2 (551-kPa) pressure level was there a small, but measurable, flow. Orifice sizes of 0.094 and 0.125 in (2.4 and 3.2 mm) produced a flow only for pressure levels above 40 lbf/in^2 (276 kPa). Grout C was able to pass through orifice sizes of 0.187 and 0.25 in (4.7 and 6.4 mm) when the pressure level was at or above 20 lbf/in^2 (138 kPa). Orifice sizes of 0.5 and 0.75 in (12.7 and 19.1 mm) were so large that the measured flow times under a 20-lbf/in^2 (138-kPa) pressure level were very small with no significant distinction between the two. Curves showing the characteristic relationship between the flow times and pressure levels for various orifice sizes are illustrated in figure 21. Tests were also carried out using the orifice plates with the three rectangular slots as described earlier. Grout C could exhibit a flow for all of the slot sizes at a zero pressure level. As the pressure increased, all of the relevant measured flow times were so small that a reliable comparison and distinction could not be made. Therefore, the orifice plates with rectangular slot openings were eliminated from the study.

Based on the initial experiments performed in this study, five plates with orifice sizes of 0.094, 0.125, 0.187, 0.25, and 0.5 in (2.4, 3.2, 4.7, 6.4, and 12.7 mm) were selected and used for further evaluation using other grout mixes investigated in this study. Additional tests indicated that the 0.094-in (2.4-mm) orifice size was too small for the flow of grouts with higher viscosities. The orifice sizes of 0.125 and 0.187 in (3.2 and 4.7 mm) permitted grout flow at and above 40-lbf/in^2 (276-kPa) pressure levels. The 0.25-in (6.4-mm) orifice size allowed grouts to flow for pressure levels above 20 lbf/in^2 (138 kPa). The grout flow times with the 0.5-in (12.7-mm) orifice size were about 3 s for most mixes, indicating an unsuitable orifice size.

It was concluded that an optimum orifice size for the pressurized flow test apparatus was 0.125 in (3.2 mm). Further tests and evaluation determined that the optimum applied pressure level for investigation of the time of flow for all mixes was 35 lbf/in^2 (241 kPa). At this pressure level, grout A had a flow time of 14.4 s, but when the pressure was reduced to 30 lbf/in^2 (207 kPa), the applied pressure was not enough to force the grout through the orifice. Table 1 gives a comparison of the results from the current ASTM standard C939 flow cone test and the new pressurized flow cone test. Contrary to the ASTM standard flow cone test, a quantitative measurement of flow was possible with the new pressurized flow testing equipment for all grouts, including those showing thixotropic properties. The flow times for all of the grouts measured with the new pressurized flow test were quantitatively distinguishable. For example, grouts A and B, which resulted in no flow using the current ASTM standard flow cone, exhibited flow times of 14.4 and 11.8 s using the new pressurized flow cone test. Grout J, containing In-Pakt plus sand in the mix, did not pass through the 0.125-in (3.2-mm) orifice at 35 lbf/in^2 (241 kPa). The sand particles in the mix obstructed the orifice, thus preventing flow of the grout. Therefore, this test method, at its present state, may not be applicable for the grout mixes containing aggregates. As shown in table 1, the measured flow times using a pressure level of 35 lbf/in^2 (241 kPa) through a 0.125-in (3.2-mm) orifice ranged from 10 to 15 s for the different grouts. It may be concluded that while the present setup for the new pressurized flow time allows a quantitative measurement of the flow times for various mixes, it will be more advantageous to make further improvements to achieve a wider range for the measured times. This may be done easily through experimentation using a slightly smaller orifice size or a lower pressure level or a combination of both.



1 in = 25.4 mm
1 psi = 1 lbf/in^2 = 6.89 kPa

Figure 21. Comparison of flow times for grouts A and C.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The primary objective of this research was to develop a grout mix that could provide effective protection against corrosion of prestressing steel in the post-tensioning tendons of bridge structures. This can be achieved if the grout has the following qualities:

- It must be impermeable to the chloride ions and be free of harmful chemicals.
- It should have no bleeding.
- It should be able to flow easily, i.e., it should be easy to work with.
- It should be expansive so that it can fill the voids formed in the process of filling the post-tensioning ducts.
- It should be able to provide adequate bond strength to minimize stress fluctuations in the end-anchorage regions.

Based on the test results of the various grout mixes used in this study, the use of silicafume as a partial replacement for cement proved to be most promising. Grout mixes with silicafume replacement in the range of 20 to 25 percent, in conjunction with a superplasticizer, had minimal bleeding, very low permeability, and high compressive strength. When an appropriate amount of superplasticizer was used, the flowability of these grouts was significantly improved. Since there was less bleeding in the mix, the surface corrosion in the prestressing strands was minimal. To achieve an expansion in the grout, an admixture with an expansive agent, i.e., Interplast-N, was used in the mix. It was found that grout mixes with expansive agents and silicafume in the range of 20 to 25 percent could result in a suitable mix for grouting the ducts of post-tensioned bridge structures if no adverse effect is observed on the corrosion of the steel. In this study, the use of Interplast-N caused additional bleed water to result. This may cause some corrosion of the steel.

Most of the grout mixes used in post-tensioned construction are thixotropic. The present ASTM standard C939 procedure for determining the flowability of grouts is not applicable to thixotropic mixes. Therefore, a new test apparatus and methodology were developed in this study in order to quantitatively measure the flowability of such grouts. The new equipment consists of a 3.75-in (95-mm) diameter brass cylinder 8 in (203 mm) long, with a top cap connected to a pressure tank and a bottom cap supporting replaceable orifice plates. A quantitative measurement of the flowability of all grouts, including those with thixotropic properties, may be possible using the new pressurized flow test equipment. Flow times for the grouts that were discharged through the orifice of the vessel of the apparatus under a specified pressure level may be measured and recorded following a procedure described earlier in this report.

RECOMMENDATIONS

In this study, it was found that the extent of the surface corrosion observed on the exposed (ungrouted) section of the prestressing steel strands placed in different grout mixes varied significantly. To better define the cause of the corrosion, it is recommended that a more detailed study, including a thorough chemical analysis and consideration of interactions among the various admixtures and constituents, be performed. Since it was outside the scope of this study, and the proprietary rights on the constituents in the admixtures used are held by their manufacturers and could not be made available for this study, it was not possible to perform the required detailed investigation here. Such information has a significant and direct effect on the different surface corrosions of the strands, as shown in this study. Therefore, it is recommended that a future study be initiated to obtain the required information and determine why some admixtures have more severe corrosive reactions than others in spite of the presence of an alkaline environment in these mixes.

It is also recommended that additional experimental work be performed to further develop and improve upon the new pressurized flow test equipment and methodology. In this study, the flowability of each mix is assumed to be related to the time it takes for the mix to pass through the orifice of the test pressure vessel under a constant pressure of 35 lbf/in^2 (241 kPa). Since various thixotropic grout mixes could change to a flowable state under different pressure levels, it may be possible to devise a flowability classification for these mixes based on the applied pressure levels. This approach may result in grout flowability measurements that are directly related to the thixotropic characteristics of the mixes.

The new testing approach for measuring the flowability of grouts also has to be tested for various types of grouts under field conditions and the results should be compared with the laboratory findings.

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