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Improved Grouts for Bonded Tendons in Post-Tensioned Bridge Structures

Research and Development
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McLean, Virginia 22101-2296

FOREWORD

This report presents the results and conclusions of a research study focused on improving the corrosion performance of prestressing steel in bonded post-tensioned concrete bridge structures. Physical and mechanical property data were developed for several experimental grouts and these data were compared to more standard grout formulations. An accelerated corrosion test method was developed which evaluates the corrosion performance of prestressing steel embedded in grout. Several of the experimental and more standard grouts were evaluated with this newly developed method. A state-of-the-art review was conducted on the grouting technology for bonded post-tensioned tendons in bridge structures. This review is summarized in this report with the complete review published in report No. FHWA-RD-90-102. This report and the previously published report will be of interest to bridge engineers who are involved in building, designing, or writing specifications for bonded post-tensioned structures, and especially those involved in dealing with the grouting of the tendons.

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16. Abstract

Currently, there is a serious problem in the United States and elsewhere with the deterioration of concrete bridges due to corrosion induced by chloride (Cl^-) intrusion into the concrete. Historically the problem has been associated with conventionally reinforced concrete bridge structures as opposed to prestressed or post-tensioned structures. However, corrosion of steel tendons in prestressed concrete structures is of greater concern because the structural integrity of the bridge relies on the high tensile loading of the tendons. Any corrosion or corrosion-induced cracking of the tendon could lead to catastrophic failure of the structure. Grout is the final line of defense against corrosion of the steel tendon. Accordingly, FHWA initiated this study (i) to develop and test new mixture designs for grouts, (ii) to develop and perform accelerated corrosion test methods on the new grouts, and (iii) to compare the corrosion performance of the new grouts with the standard grouts.

Several modifiers and additives for grouts were examined, including: high-range water-reducers, flyash, silica fume, latex polymer modifier, expansive agents, anti-bleed additives, and corrosion inhibitors. It was shown that these additives can greatly affect the fluidity, open-time, bleeding/segregation, Cl^- permeability, and mechanical properties of the grouts. Several experimental grouts were designed which provided improved properties compared to the more standard grouts presently being used.

An accelerated corrosion test method (ACTM) was developed which evaluates the corrosion performance of steel tendons embedded in the grout. It was shown that any experimental grout that lowered the Cl^- permeability, increased the time for corrosion initiation and typically decreased the corrosion rate following initiation. The examination of the effect of calcium nitrite inhibitor required a modification of the as-specified ACTM, and the inhibitor addition appears to produce the most significant improvement in corrosion performance of steel tendons embedded in grout, although the data for this comparison are limited.

This report is the conclusion of the research study, critical review on the grouting technology for bonded tendons in post-tensioned bridge structures as described in the Interim Report FHWA-RD-90-102 dated November, 1990.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
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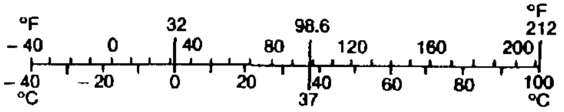

* SI is the symbol for the International System of Measurement

(Revised April 1989)

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CHAPTER 1

INTRODUCTION

Currently, there is a serious problem in the United States and elsewhere with deteriorating concrete bridges. The deterioration is due, in large part, to corrosion of reinforcing steel which occurs when the steel loses its ability to remain passive due mainly to chloride intrusion into the concrete. Historically, the problem has been associated with conventionally reinforced concrete bridge structures as opposed to bridges with prestressed or post-tensioned concrete members. In part, this situation may reflect on the fact that conventionally reinforced concrete structures have been in service longer and have not been built with as rigid quality controls as prestressed concrete bridges.

The first prestressed highway bridge in the United States was opened to traffic in 1950.(1) The vast majority of the 60,000 or so prestressed concrete bridges in the United States have been built since 1960. Post-tensioned concrete technology developed rapidly during the 1960's. The present practice involving the use of a rigid duct was first used around 1966 and was a major advance in minimizing the exposure of prestressing steel strands to corrosive environments. The oldest post-tensioned concrete bridge structures using presently accepted technology are less than 25 years old.

In post-tensioned structures, the prestressed steel tendon is encased in a duct. A post-tensioned structure that uses a grout to fill the voids in the duct is referred to as a bonded post-tensioned structure. Figure 1 shows a typical two-way, post-tensioned deck slab on a precast tee structural element. The purpose of the grout in the duct is two-fold: (1) to provide a non-corrosive environment in which the steel tendon can remain corrosion-free for the life of the structure, and (2) to provide a bond to the tendon so that anchorage failure (or removal of the anchorage) does not result in relaxation of the stresses within the tendon. The grout must provide an adequate bond strength and must fill all the interstices and voids within the duct and the individual strands of the tendon. In the United States, the grout material contains portland cement as the binder. The duct material is either metallic (steel) or plastic (polypropylene or polyethylene).

When steel corrodes in conventionally reinforced concrete structures, the result is first a delamination cracking of the concrete as corrosion products grow around the bar with subsequent loss of concrete cover (spalling) over the bar. This type of deterioration is responsible for millions of dollars in maintenance each year for reinforced concrete bridges and other structures.

The consequences of steel tendon corrosion in prestressed concrete structures are potentially of even greater concern. This is because the structural integrity of the bridge relies on the high tensile loading of the tendons, and loss of the tendon could lead to catastrophic failure of the structure. Moreover, the prestressing steel is generally of much higher yield strength than conventional rebar, making it inherently more susceptible to embrittlement in the presence of hydrogen generated by corrosion reactions. In prestressed structures, a small amount of corrosion (relative to

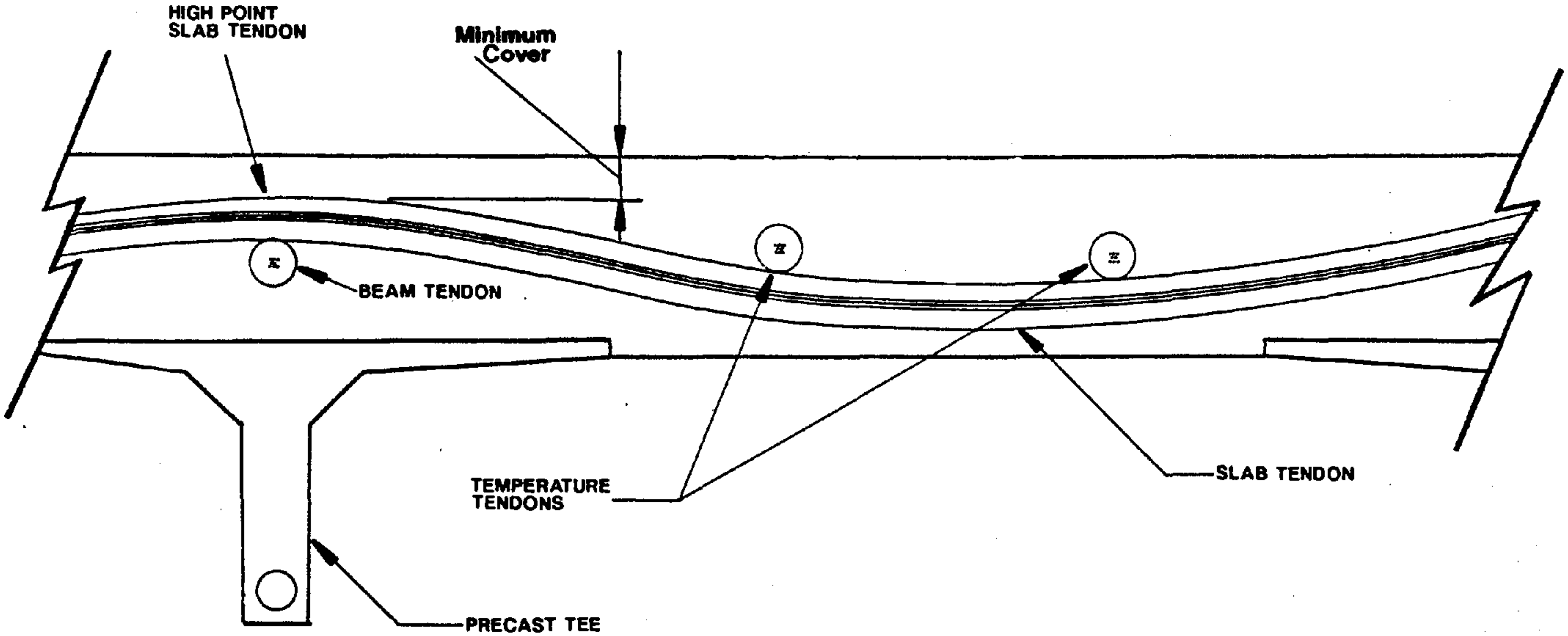
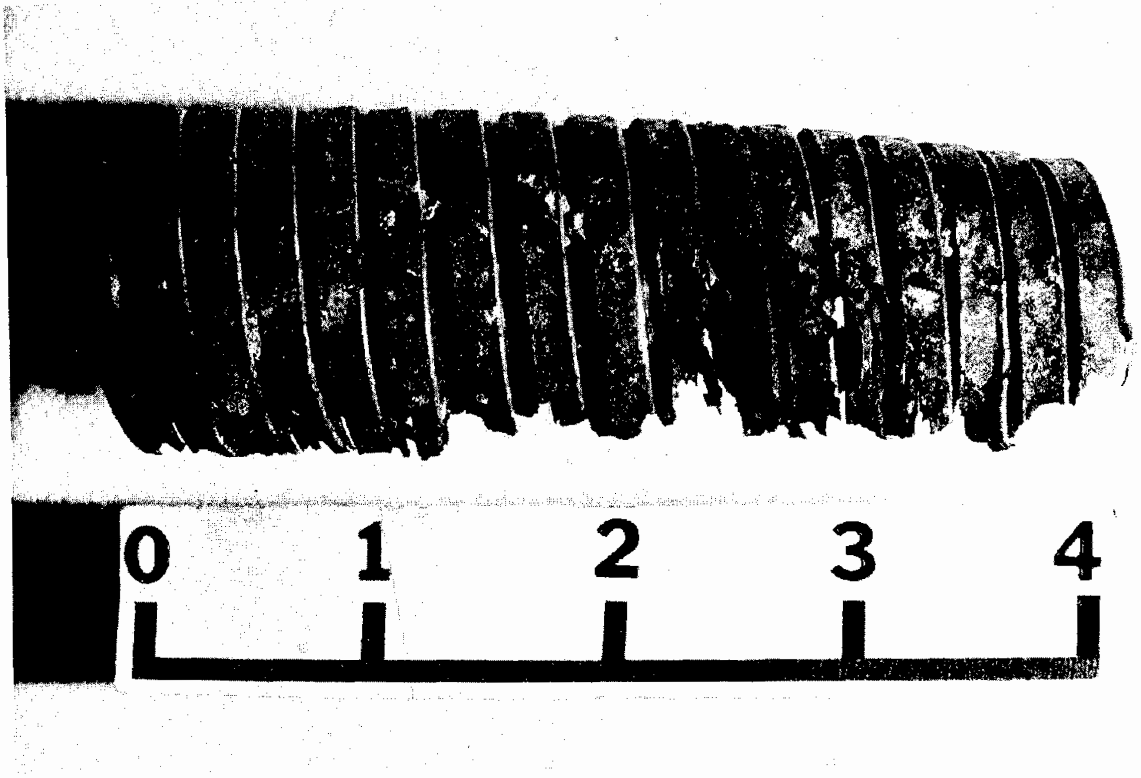


Figure 1. Section view of a typical two-way bonded post-tensioned deck slab on precast tees.

conventional rebar structures) could lead to failure of the tendon and (in the worst case) the collapse of the structure.

Such a catastrophic event has not yet occurred in the United States. However, there is direct evidence that steel tendons can corrode in bonded post-tensioned structures (figure 2). In this parking structure, chloride intrusion advanced to the level of reinforcement at high points in the deck slab causing corrosion of the steel duct and subsequently advancing through the grout itself to the point that corrosion was initiated on the steel tendons.

Since the grout is the final line of defense for the steel tendon in the event the duct is breached, it is of interest to examine grout technology with the goal being to optimize the ability of grouts to protect prestressed tendons against corrosion. Accordingly, the FHWA initiated a research program with the following objectives: (1) to develop and test new mixture designs for grout used in ducts so that the grout may provide long-term corrosion protection for the prestressing steel in post-tensioned concrete bridge structures and (2) to develop and perform accelerated corrosion test methods on the new grout mixtures to predict their performance over the design life of the bridge. In the following sections, the details, results, and conclusions of the research are presented.



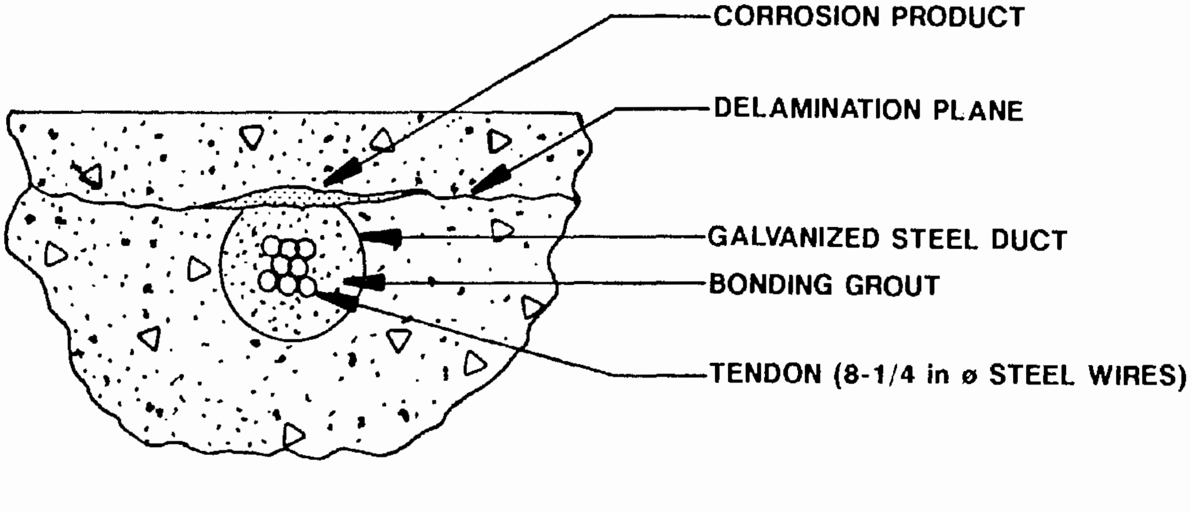


Figure 2. Corrosion of galvanized steel duct from a post-tensioned tee element in a parking structure deck slab. The corrosion zones occurred at the tendon high points in the slab.

1 in = 2.54 cm

CHAPTER 2

BACKGROUND

During the present research program, a detailed review of the literature was performed to determine the state-of-the-art of grouting materials and grouting technology for bonded post-tensioned tendons. The results of this literature review are presented in FHWA report no. FHWA-RD-90-102. In this section, the primary results and findings related to corrosion distress in bonded post-tensioned bridge structures are presented.

Corrosion associated with the steel tendons in prestressed concrete structures was first reported in the mid-1950's.(1,2) At that time, Monfore reported that the number of such failures was "exceedingly small" with the conclusion that corrosion of prestressed wire in concrete is not a common problem.(1) Of the failures reported by Monfore, only one occurred in a post-tensioned structure. In that case, grouting was delayed for 5 months due to a need to retension the tendons. After the delay, many of the cables were found to have strands which were broken due to corrosion.

A survey conducted in 1966 (NCHRP Report 90), indicated that the total number of prestressed bridges in service was approximately 12,000.(3) The great majority of these bridges (93 percent) were constructed with pretensioned members. In California, about half of the estimated 500 bridges in service in 1966 were post-tensioned and eight of these post-tensioned structures had ungrouted tendons. There were 927 post-tensioned bridges in the United States in 1966. A major conclusion of the survey was that corrosion failures of prestressing steel was not a widespread or serious problem with prestressed bridges in 1966. Maximum service life in 1966 for even the oldest bridges was only 15 to 16 years. No catastrophic failures had been reported for prestressed concrete bridges in 1966. For the few cases where serious corrosion of prestressing steel had occurred, the failures were explainable and the corrosion could have been avoided either by proper use of materials or through greater attention to accepted construction practices. NCHRP Report 90 also describes the result of laboratory tests investigating the effect of voids on rusting of steel in grouted ducts. These tests confirmed that corrosion of steel does occur in the cavities in an improperly filled duct.

In 1972, the Ontario Ministry of Transportation and Communication (Ontario MTC) conducted a study of 18 bridges having voided post-tensioned decks.(4) Strands were exposed and examined at 18 locations in 14 of the bridge decks. Cracks in the concrete were directly over or adjacent to the ducts in all but two locations. No significant corrosion of the prestressing strands was observed at any of the 18 locations examined. Light rusting was observed on the inside or the outside of 4 of the 18 ducts inspected. No significant or recent corrosion was observed on any metal duct.

In 1977, Bezouska reported on an evaluation of the quality of grout on a variety of post-tensioned concrete structures in California.(5) Particular attention was placed on the number and type of voids exposed and their probable causes. An objective of the Bezouska study was to evaluate whether the current specifications were adequate in assuring that voids in the hardened grout were "so minimal" so as to assure that no significant corrosion could take place. The findings of the examination were:

- The quality of the grout, as seen in the 96 duct openings in a total of 24 tendons in the 7 bridges was generally very good, and it was concluded that the current grout specifications and equipment appear to produce a satisfactory product.
- Water voids at the top surface are commonly found at the tendon high points, but this does not expose any tendon steel because the strands are pulled to the bottom of the duct at these places.
- The type of exposure caused by the strand bearing against the helical duct seam probably cannot be eliminated.
- The omitting of high point vents did not seam to have any visible effect on the quality of the result.
- The elimination of the expansive admixture has no apparent effect on the quality of the grout.

In 1978, Schupack reported on the results of a survey of the durability of post-tensioning tendons with particular regard to corrosion susceptibility in completed structures.(6) The survey cited 28 structures with an incidence of steel corrosion in some 200 tendons. The incidences that occurred were attributed to either: (1) the result of poor design details, (2) inadvertent exposure to known corrosive agents, or (3) poor construction practices. Schupack concluded that properly detailed and constructed post-tensioned tendon type structures can be expected to exhibit excellent performance from the standpoint of durability against corrosion. Out of the 28 corrosion incidents, 12 involved bonded tendons. These corrosion incidents involved the following circumstances:

- Failure of the grout to fully encapsulate the prestressing wires.
- Corrosion of the steel ducts with no corrosion of the prestressing wires.
- Corrosion of the prestressing wires due to inadvertent omission of grouts.
- Corrosion of the prestressing wires at junctions of aluminum trumpets and steel duct.
- Corrosion of steel duct following cracking/spalling of concrete cover.

In 1985, corrosion of steel was detected and investigated in a parking structure located in Ohio (built in 1965). The bonded post-tensioned elements utilized multiple 1/4 in (6.4 mm) diameter wires tensioned to about 4 tons (3630 Kg) each and grouted in metallic conduit. Corrosion of the post-tensioning system was first observed at the high points of the slab tendons when corrosion of the metallic conduits caused spalling of the overlying concrete. The concrete cover over the slab tendons at their high points is

3/4 in (19 mm). Subsequent concrete removal and inspection revealed corrosion of the tendon wires within the conduit ranging from a light rust, through various degrees of pitting, to corrosion-induced wire breakage.

In 1987, Libby described the failure of a bridge stringer in a bridge over a coastal bay.(7) The post-tensioned tendons consisted of bonded stress-relieved strands in semi-rigid galvanized metal ducts. The bridge had been in service for about 14 years when severe cracking was observed over the length of one-third of one end of one stringer. Research revealed that the ducts containing the prestressing tendons were severely corroded in the cracked end of the stringer. Individual prestressing strands near the top of the ducts were found to not be completely encased in grout (minor corrosion was observed on the exposed strands). Test results indicated that the chloride content of the concrete in the cracked length of the girder was abnormally high [3 percent of the cement content and the cement weight was 700 lb/yd^3 (415 Kg/m^3)]. Chloride ion content of the concrete in areas not cracked were low (less than 0.06 percent of the estimated cement content). Researchers speculated that the last truckload placed in the stringer contained an admixture containing a significant amount of chloride ion.

In a study reported in July 1989, seven prestressed concrete bridges in Illinois, Utah, Florida, and Texas were examined to detect the presence and consequences of reinforcing steel corrosion.(8) A number of these bridges contained post-tensioned members. No corrosion-related steel failures were observed in the post-tensioned members. Some steel corrosion was observed in unbonded tendons due to a lack of grease in the duct. Some corrosion in bonded, post-tensioned concrete was attributed to "poor grouting."

In summary, the performance record of post-tensioned concrete structures in the United States is excellent. It has been determined that there are relatively few documented examples of bonded post-tensioned structures in which corrosion of the prestressed tendons has occurred. Even in many of these instances, investigators of the structures speculated that corrosion might not have occurred if proper construction practices and designs had been followed. However, in one example (a mid-west parking garage), corrosion of imbedded strands in a post-tensioned construction occurred when a large section of galvanized duct was breached due to corrosion as a result of chloride migration. The corrosion attack resulted in failure of at least one wire of the seven-wire tendon. It is inevitable that additional instances of corrosion-related problems will be observed, as the average age of these structures continues to increase, deicing salts continue to be used, and the salts penetrate to greater depths within the concrete. The catastrophic nature of a serious failure within a bridge or parking garage makes it important for the industry to continue to improve upon its practices. All available technology which is economically feasible that could improve performance should be incorporated into standard practices.

One such area in which improvements are possible is the grouts used for filling the ducts containing the prestressed steel within the post-tensioned structure. Because grouts provide the final defense against corrosion of the prestressing steel tendons that support the structure, it is imperative to provide a grout that incorporates the state-of-the-art technology. Up to now, the majority of grouts used in bonded post-tensioned concrete structures has been a simple mixture of portland cement and water with water-cement ratios typically specified to fall below 0.44 to 0.50 and with expansive and non-bleeding additives sometimes specified.

CHAPTER 3

APPROACH

To accomplish the goals of this project, the Work Plan was divided into four primary tasks: Task A - Develop Accelerated Test Method, Task B - Develop Design Mixtures for Grout, Task C - Design and Conduct Laboratory Test Program, and Task D - Specifications for Grout Mixtures. In the following paragraphs, the details of the approach to each of these tasks are outlined.

TASK A - DEVELOPMENT OF ACCELERATED TEST METHODS

The purpose of task A was to develop an accelerated test method for testing grout design mixtures which will predict the effectiveness of the grout in preventing corrosion of prestressing steel over a 50-year life. The overall approach was to identify all of the test conditions, to establish the important variables, to determine the accelerated features of the test, and to design a detailed test procedure including the monitoring required, post-test examinations, and specimen configurations. Two of the most important requirements for the test method were: (1) the method should provide some means to accelerate corrosion and/or Cl^- permeability, and (2) the method should be designed so that it can be used routinely by civil engineering technicians.

In general, accelerated test methods are extremely difficult to design. It is even more difficult to ensure that the test method represents conditions expected over a specified period of time. It is typically very difficult to accelerate the corrosion process and the permeation of moisture and/or chlorides through the grout in the short time tests without altering the mechanism by which corrosion is occurring. Anodic polarization of the test specimen during exposure accomplishes the following three objectives: (1) it will tend to drive chlorides toward the specimen by providing a potential gradient, (2) it will tend to increase the rate of corrosion following breakdown of the passive layer when and if breakdown occurs, and (3) it will likely decrease the incubation time for passive film breakdown at a given chloride concentration. Therefore, the anodic polarization of the test specimen will tend to accelerate the corrosion process on the steel surface increasing the total amount of corrosion obtained during the short-term test; thereby, providing a significant measure of acceleration.

During task A, a series of preliminary tests were performed to examine specific methods and aspects of the overall test method. The purposes of these tests were: (1) to examine the effects of various test parameters on the corrosion of prestressing steel embedded in grout, and (2) to examine various procedures for accelerating the corrosion of prestressing steel embedded in grout. The preliminary tests included examining the following: (1) the effects of stress for passive conditions and active corrosion of prestressing steel embedded in grout, (2) the effects of different exposure conditions (salt fog versus complete immersion), (3) the effect of anodic polarization, and (4) the effect of grout cover.

Following these preliminary tests, an accelerated corrosion test method (ACTM) was developed and additional testing was performed to: (1) examine the performance of conventional grouts, (2) establish baseline data for the newly developed ACTM, and (3) to provide the first level of evaluation of the overall test method design. At the completion of the preliminary test utilizing the ACTM, a final test method was established for use in Task C - Design and Conduct Laboratory Test Program.

TASK B - DEVELOPMENT OF DESIGN MIXTURES FOR GROUT

The principle objective of task B was to develop grouts which provide long-term corrosion protection to prestressing steel. Engineering properties of experimental grouts were compared with those of grouts currently used in bonded post-tensioned concrete structures. The work in this task was divided into two primary subtasks: Current Grout Designs, and New Grout Designs.

Current Grout Designs

In this subtask, current grout design and construction practices employed for post-tensioned members were examined. The review of the state of the art performed in this subtask has been published as an FHWA Report entitled "Grouting Technology For Bonded Tendons In Post-Tensioned Bridge Structures" (FHWA-RD-90-102). Data sources consulted in this review included both open literature sources and contacts with industry and government agencies involved in bonded, post-tensioned concrete construction as either a supplier, a user, a specifier, or a contractor. The contacted sources included:

- American Concrete Institute (ACI).
- Prestressed Concrete Institute (PCI).
- Post-Tensioning Institute (PTI).
- U. S. Army Corps of Engineers (USACE).
- State Highway Departments In Virginia, Washington, Florida, Oregon, California, Kentucky, Tennessee, Indiana, and Illinois.
- American Association of State Highway and Transportation Officials (AASHTO).
- American Society for Testing and Materials (ASTM).
- Grouting Contractors.
- Duct and prestressing steel suppliers.
- Grout and grout additive suppliers.
- Grouting equipment suppliers.

- Federation Internationale de la Precontrainte (FIP).

- Portland Cement Association (PCA).

This review established that the majority of grouts used in bonded post-tensioned concrete structures have been a simple mixture of portland cement and water. The water-cement ratios are typically specified to be below 0.45 and expansive additives and/or non-bleeding additives are sometimes specified. The results of the review also indicated that these grouts are performing satisfactorily based on the history to date. However, this result may simply reflect the fact that the grouts have not truly been exposed for the bridge design life in adverse environmental conditions. In those few instances where the duct is breached and bonded post-tensioned tendons have corroded, chlorides have passed through the bonding grout to the tendons. Therefore, the laboratory program described below was intended to develop grouts with an improved ability (relative to historical grouts) to protect embedded steel tendons from corroding even in the event of a breached duct.

New Grout Designs

The goal for this subtask was to develop a grout which has the means to provide reduced chloride ion permeability and/or increased corrosion inhibition in grouts, while maintaining or improving emplacement characteristics. The desired changes in grout properties were sought through the use of additives and admixtures to the standard cement/water grout. The selection criteria for the property modification included:

1. High-range water-reducing admixtures (superplasticizers) to provide a reduction in water-cement ratio while maintaining adequate fluidity.
2. Additives to provide a reduction in chloride ion diffusion rate by modifying the microstructure, including silica fume (microsilica), flyash, and polymer modifiers.
3. Additives/admixtures to provide improved fluidity, open time, and resistance to bleeding and segregation including silica fume, thickening agents, and superplasticizers.
4. Aluminum powder to provide expansion in the fresh and hardened grout.
5. Calcium nitrite to provide corrosion inhibition.

The property measurements made on the grouts examined in task B included:

1. Fluidity - ASTM C939-87, the Standard Test Method For Flow of Grout (Flow Cone Method).
2. Unit Weight.

3. Setting Time - ASTM C953-87, the Standard Test Method For Time of Setting of Grouts For Preplaced Aggregate Concrete in the Laboratory.

4. Heat Evolution Behavior.

5. Expansion and Bleeding - ASTM C940-87, the Standard Test Method For Expansion and Bleeding of Freshly Mixed Grouts.

6. Bleeding/Segregation under pressure using a Gelman pressure filtration funnel.

The procedure in item 6 involves placement of a fluid grout mixture in a pressure vessel having at one end a Gelman Type A filter. Pressure is applied at the non-filter end of the pressure vessel with water forced from the grout through the filter which retains 99.7 percent of all particles greater than .01 mil (0.3 μm). The pressure at which water loss first occurs is measured for grouts and compared with an equivalent height of strand tendon.

Selection of Materials

Initially, screening trials were conducted to select admixtures and additives that were compatible with the portland cement used in the study. In most cases, each additive/admixture modifier category was represented by only one material. The following materials were selected for use in this study:

1. Portland Cement - A Type II portland cement, manufactured by Southwestern Portland Cement Company, Fairborn, Ohio, was selected as the cement for this investigation.

2. High-Range Water-Reducing (HRWR) Admixture - Mighty 150, marketed by Borden & Remington Corporation, Fall River, Massachusetts, was selected as the ASTM C494 Type F high-range water-reducing admixture for the investigation.

3. Silica Fume - The silica fume (also called microsilica) was used in the form of a dry powder which was obtained from Elkem Chemical Company, Pittsburgh, Pennsylvania. The product used here is identified as EMS 920.

4. Flyash - The flyash used in characterized as a Class F flyash (ASTM C618) marketed by American Electric Power Company, Columbus, Ohio. This flyash is provided by a single power plant and is widely used as a construction material in the Central Ohio area.

5. Polymer Modifier - Dow Chemical Company's (Midland, Michigan) Modifier A, a styrene-butadiene polymer modifier, was selected for use in the investigation. This product has been widely used over the past 15 years or so as a polymer-modifier in latex-modified concrete in many construction applications in the United States. It is supplied as a liquid with a solids content around 48 percent.

6. Corrosion Inhibitor - The only corrosion inhibitor with a history of use in commercial concrete applications is calcium nitrite. W.R. Grace Company, Cambridge, Massachusetts, supplied their DCI product for this investigation which is a liquid calcium nitrite corrosion inhibitor.

7. Expansion Agent - Because of its wide history of use in nonshrink grout products, aluminum powder was selected as the expansion agent for the experimental grouts. The aluminum powder used in the investigation was supplied by Alcan-Toyo America, Inc. Lockport, Illinois.

8. Anti-Bleed Agent - A number of thickening agents were evaluated and the material selected for use is a water soluble polysaccharide gum, manufactured by Kelco, Inc., San Diego, California. This material, identified as Welan Gum, dissolves readily in water and is stable over a wide of temperatures and pH.

9. Commercial Grout Admixture - The commercial grout admixture selected for evaluation was Celtite, Inc.'s (Georgetown, Kentucky) Celbex 209X. Celbex 209x is a free flowing powder consisting of a balanced blend of superplasticizer, thickener, and controlled expansion agent. It was especially developed for use with portland cement grouts to make them thixotropic and highly water retentive.

10. Sand - A silica sand (maximum particle size 50 mesh) was used in one of the candidate grouts. The Wedron 510 sand selected is manufactured by Wedron Silica Company, Wedron, Illinois.

Grout Preparation Procedures

Grouts were prepared using a 0.5 HP, high-shear mixer with a propeller-type mixing blade (3 tines) typically operating at around 500 r/min. Dry batch weight of the grout ingredients ranged from 4.4 to 8.8 lb (2000 to 4000 gm). On a volume basis, this yielded around 91.5 to 183 in^3 (1500 to 3000 cc) of grout. In the majority of instances, the grout had the rheological characteristics of a thick liquid which could be poured from the mixing container. Following mixing of the grout, specimens were prepared for property measurements.

The steps followed for mixing the grouts included:

1. All water added to mixing container (a stainless steel bucket with an internal diameter of 7.0 in (17.8 cm) and a height of 16.0 in (40.6 cm).

2. All of the portland cement is added.

3. The pozzolan (if used) is added in dry form.

4. The admixture(s) is added. An exception here is that the superplasticizer, when used, was added in Step 1 with the water.

5. The sand (if used) is added.

6. Steps 2 through 5 are taken with the mixer operating at 500 r/min. After all the grout ingredients are added, mixing is continued for 3 to 3-1/4 minutes.

The reason for adding the superplasticizer at Step 1 is that with a significant decrease in water content afforded by the superplasticizer, it is frequently difficult to gain a liquid response from the system if the superplasticizer is not added before all the cement is introduced.

Property Measurements in the Fresh State

Two or more grout batches were required to prepare enough material for all of the property measurements. In a number of instances, replicate batches were prepared to establish the precision of the tests. The properties of the grout were measured in both the fresh and hardened state. Property measurements made prior to hardening (fresh state) of the grout included:

1. Unit weight (density of concrete in the fresh state).
2. Time of set.
3. Initial fluidity and change in fluidity as a function of time.
4. Expansion/bleeding.
5. Bleeding/segregation under pressure (Gelman pressure filtration).

Grout unit weight. Unit weight is the density of the grout in the fresh state. It is expected that the unit weight of the grout will increase with decreased water-cement ratio and with the addition of fine aggregates to the system. Unit weight was measured by weighing a known volume of the fresh grout in a graduated cylinder.

Time of set. The time of initial and final set of the grouts was measured in accordance with ASTM C953-87, The Standard Test Method For Time of Setting of Grouts For Preplaced Aggregate Concrete in the Laboratory. This procedure uses the Vicat apparatus.

Initial setting time is defined as the time when a needle penetration of 1 in (25 mm) is obtained. Final set is defined as the time when the needle does not sink visibly into the sample.

Fluidity and open time measurements. Most of the grouts behaved rheologically as liquids so it was possible to use the flow cone procedure to quantify fluidity. The procedure used here is defined by ASTM C939-87, The Standard Test Method For Flow of Grout (Flow Cone Method). The flow cone is a funnel designed to hold 105.3 in^3 (1725 cc) of grout with the discharge end having a diameter of 0.5 in (1.27 cm). The time required for the 105.3 in^3 (1725 cc) of grout to exit the cone is measured as the efflux time of the grout. The efflux time of plain water is around 8 seconds. Any grout that passes completely through the flow cone under the force of gravity alone, regardless of total efflux time, can be defined as a pourable grout. For the present investigation, it is assumed that as long as a grout remains pourable, it can probably be pumped using conventional grout pumps. A few of the grouts developed a thixotropic behavior quite early in their history and would not pass through the flow cone. For other grouts, this thixotropic behavior developed at a much later time. In both of these instances, the fluidity of the grouts was then defined using the flow table procedure. The equipment and procedure for this test is defined in ASTM C230-90, The Standard Specification For Flow Table For Use in Tests of Hydraulic Cement. In this test, a molded, truncated cone of the test material is dropped through a height of 3/4 in (1.9 cm) on a 10 in (25.4 cm) diameter brass plate. The increase in diameter of the sample, following 25 drops, is measured and expressed as the flow in percent. At a flow of 152 percent, the sample is just starting to flow off of the brass plate. In the present investigation, the initial fluidity of the grout was measured as the flow cone efflux time 1 minute following the completion of the mixing step. Efflux times were then measured periodically (every 20 to 30 minutes) until the grout would no longer flow in a continuous stream through the cone. At this point, fluidity measurements were continued using the flow table.

Using the combined flow cone/flow table measurements of fluidity, an open time for the grouts was defined as the sum of the total time the grout remained pourable (passed through the flow cone) plus the time during which the grout retained a flow table flow value greater than 100 percent. The open time, thus defined, is related to the time during which the grout could be pumped. All of the fluidity measurements were conducted at 73F ± 2F (23C ± 1C). It is expected that the fluidity and open time values will be influenced in the field by higher and lower ambient temperatures.

Expansion/bleeding. Expansion and bleeding of the fresh grouts was measured using the procedure of ASTM C940-87, The Standard Test Method For Expansion and Bleeding of Freshly Mixed Grouts.

In this test, 48.8 in^3 (800 cc) of freshly mixed grout is placed into a 61 in^3 (1000 cc) graduated cylinder. The volume of the sample and the time at which the reading was made is recorded. Readings are recorded of the amount of bleed water on the grout surface at 15 minute intervals for the first 60 minutes and thereafter at hour intervals until two successive readings show no further expansion or bleeding. The expansion of the grout mixture and its bleeding is expressed as percentages of the initial volume of the grout.

Bleeding/segregation under pressure (Gelman). Normally, bleeding occurs simply as a result of sedimentation of cement and aggregate particles with free water rising to the surface. Another form of bleeding has been described when grouts under pressure are in contact with strand tendons. In this instance, bleeding occurs because of the filtering action of the void spaces between the strands.(9) Pressure from the grouting operation forces the grout against the strands where water passes through the interstices between the outer strand and the center wire, whereas solid particles in the grout do not. This filtering action is especially acute in strand tendons with a high vertical rise and bleeding can amount to up to 20 percent of the height of the vertical rise. A test procedure is available to measure the relative bleeding characteristics of grouts that simulates the condition experienced in grouting vertical tendons.(9) A small quantity of fluid grout 42.7 in^3 (about 700 cc) is placed in a pressure vessel having at one end a Gelman Type AE filter

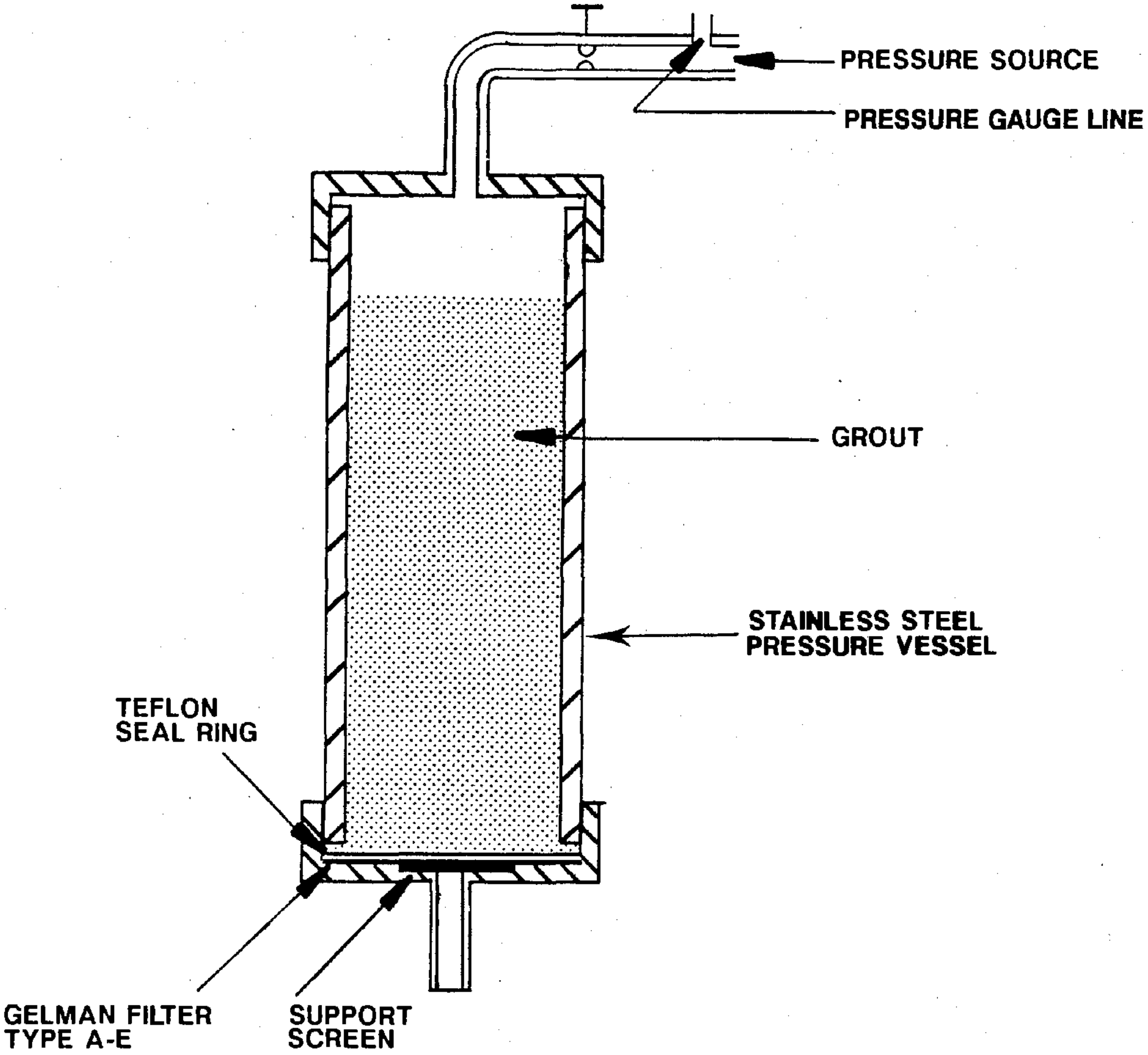


Figure 3. Device used to measure comparative bleeding characteristics of grouts intended for use in vertical post-tensioned ducts.

(Gelman Science, Inc., Ann Arbor, Michigan). See figure 3. Pressure is applied to the other end of the vessel with water forced from the grout through the filter which retains 99.7 percent of all particles >.012 mils (>0.3 microns). The pressure at which water loss first occurs is measured as well as the amount of water lost at a given pressure up to 80 psi in 10 psi (552 kPa in 68.9 kPa) increments.

Property Measurements in the Hardened State

Property measurements made in the hardened state included:

1. Compressive Strength.
2. Permeability.

Compressive strength. Compressive strength measurements were made following the procedures of ASTM C942-86, the standard test method for compressive strength of grouts for preplaced aggregate concrete in the laboratory. Specimens for this test are 2 in (5.08 cm) cubes. In instances where the grouts exhibit expansion prior to initial set, the test procedure provides for the placement of a plate over the cube mold to assure that expansion is confined. In the present investigation, compressive strength measurements were made at intervals of 1 day, 7 days, 28 days, and 90 days.

Permeability. The permeability of the grouts was measured using the procedure of AASHTO T277-83, The Rapid Determination of the Chloride Permeability of Concrete. This test measures the total electrical charge passed through a 2 in (5.08 cm) thick specimen that contacts sodium chloride solution on one side and an alkali hydroxide solution on the other side.

Normally, the test is run at a voltage of 60 V DC for 6 hours. It was found that when grouts were used instead of concrete, a higher total charge was passed which resulted in significant heating of the grout specimen. Subsequently, the test procedure, as applied to grouts, was conducted using an applied voltage of 30 V DC for 6 hours. This procedure accomplished the objective of minimizing the temperature rise in the specimen during the test.

This test procedure is particularly relevant to the evaluation of grouts inasmuch as it measures the resistance that the grout offers to the movement of chloride ion.

TASK C - DESIGN AND CONDUCT LABORATORY TEST PROGRAM

The purpose of task C was to use the ACTM developed in task A to evaluate the grout formulations developed in task B. The original proposal indicated that three grout formulations would be selected from the most promising grout designs developed in task B. Because the proposed ACTM is simpler than originally planned, five new grout formulations were studied in addition to two standard grout formulations.

Because the purpose of task A was to design the ACTM, the details of the test method are presented in chapter 4 as the results of task A and will not be repeated here. Utilizing the ACTM, a minimum of quadruplicate tests for each selected grout and each specimen type were performed to permit a minimum of statistics for data analysis. Because the specimen preparation procedures were altered during task C, the quadruplicate specimen tests were repeated for several of the grout formulations. The grout formulations examined in task C are given below:

- No. 1 Standard grout (w/c = 0.44).
- No. 1B Standard grout with a high water-to-cement ratio (w/c = 0.65).
- No. 5-1 grout containing HRWR, flyash and sand (w/c = 0.32).
- No. 6B grout containing HRWR and 10 percent silica fume (w/c = 0.365).
- No. 8-1 grout containing HRWR and latex additive (w/c = 0.29).
- No. 10-1 Standard grout containing $Ca(NO_2)_2$ inhibitor (w/c = 0.44).
- No. 11-1 Superplasticized grout containing an expansive additive and an anti-bleed additive (w/c = 0.365).

For each of the above grout formulations, an initial twelve specimens were cast; four standard specimens, four precracked specimens, and four specimens to be used as backup specimens as needed.

For performing the laboratory test program, eight identical experimental setups were constructed. Potential and current data for each of the eight test cells were collected using a computer-based data acquisition system. Following collection of the data, the data were downloaded into a plotting routine and the data for each test specimen plotted as current versus time.

TASK D - SPECIFICATIONS FOR GROUT MIXTURES

The purpose of task D was to summarize the desired requirements to provide an improved grout for use in post-tensioned bridge structures. The results of tasks B and C were reviewed to identify the desired characteristics of grouts for bonded post-tensioned concrete constructions and to establish how these characteristics can best be measured. These characteristics included:

1. Adequate fluidity to assure that grout travel through the entire duct length is achieved with the available placement equipment.

2. Sufficient open time (delayed set) to assure that the fluidity remains at the desired level for a sufficient time period.

3. Acceptable consistency to minimize the potential for bleeding, segregation, and the creation of water lenses or voids.

4. Negligible shrinkage to minimize shrinkage cracking.

5. Adequate strength to assure transfer of the stress from the tendon to the structural member.

6. Resistance to damage from the effects of freeze/thaw cycling.

7. Ability to provide corrosion protection to the steel tendons.

Generally speaking, the requirements for strength and freeze/thaw resistance have not been difficult to meet even with the simple cement/water systems used in much of the work to date. The actual strength level necessary for the grout to adequately transfer stresses from the tendons is quite modest 2000 to 3000 psi (13790 kPa to 20685 kPa) and is easily achieved by a cement grout having a water-cement ratio under 0.50. The consequences of freeze/thaw cycling of grouts in this application are minimized in view of the unlikelihood of the grout achieving critical moisture saturation and the fact that the grout is confined by the duct material.

In the other performance areas, there is need for improvement. This largely relates either directly or indirectly to the ability of the grout to protect the steel tendon from corrosion, especially in the event that the duct is breached. These improvements are concerned not only with material properties of the grout, but with the means of specifying, testing, and qualifying grouts for this application.

Specifications for grouts for bonded post-tensioned concrete applications are discussed based on the following critical areas:

1. The identification and control of factors influencing the achievement and maintenance of a suitable grout fluidity.

2. The need for anti-bleed additives in the grout.

3. The need for an expansive additive in the grout.

4. The identification and implementation of factors providing for improved resistance to corrosion of steel embedded in the grouts.

Consideration was also given to the cost effectiveness of the various grouts evaluated in the present program as related to the achievement of the desired grout characteristics.

Considerable new information was developed in the present program regarding (1) deficiencies in the present specifications of grouts for bonded, post-tensioned construction and (2) the means to provide more control of grout properties than was possible in the past.

The information developed in the present program should permit the "tailoring" of grout mixtures to specific job requirements. This approach acknowledges that it may be inappropriate to recommend or specify a single generic grout for bonded, post-tensioned applications. There are numerous construction and environmental parameters that influence the grouting operation. The approach recommended here is to recognize and address these variables and attempt to specify a grout uniquely suited to the project at hand.

CHAPTER 4

RESULTS

In the following sections, the results of the four primary tasks are presented:

- Task A - Development of Accelerated Corrosion Test Method.
- Task B - Development of Design Mixtures for Grout.
- Task C - Design and Conduct Laboratory Test Program.
- Task D - Specifications For Grout Mixtures.

In task A, the ACTM was developed with all the procedures for performing the ACTM and for preparing the test specimens specified. Therefore, task A describes the detailed approach that is used to conduct the laboratory corrosion test program performed in task C. In task B, the grouting technology for bonded tendons in post-tensioned bridge structures was reviewed and a topical report issued. Task B also included the selection of new grout design mixtures and the testing of these mixtures to establish their mechanical and physical properties. In task D, the results from tasks B and C were utilized to identify the primary characteristics of grout mixtures which may affect corrosion and placement of the grout.

TASK A - DEVELOPMENT OF ACCELERATED CORROSION TEST METHOD

Preliminary Tests

Several preliminary tests were performed to examine various aspects of accelerating corrosion for steel embedded in grout and to establish the important variables to be included in the ACTM. Preliminary testing was performed in three primary areas:

1. Grouted specimens.
2. Stressed specimens.
3. Cyclic potentiodynamic polarization (CPP) tests.

Grouted Specimens

The purposes of the preliminary tests involving grouted specimens were to determine the following:

1. The ability to anodically polarize specimens.
2. The best means of incorporating the cathode.
3. Polarization level.

4. The accelerating effect of anodic polarization versus freely corroding conditions.

5. The best means of incorporating a reference electrode into the grout specimen.

6. The accelerating effect of salt fog exposure versus immersion.

The initial tests performed utilized conventional reinforcement bars, 0.37 in (0.95 cm) diameter, cast with a 0.19 in (0.48 cm) grout cover. With the methods used, it was very difficult to get crack-free specimens. For example, one specimen which was polarized to +0.30 V (saturated calomel electrode, SCE) in a 5 percent NaCl solution immediately climbed to an anodic current of 0.25 mA. Because this current was localized to a few cracked areas, the current density was quite high and corrosion products very rapidly poured out of the cracks. Tests on similar specimens indicated that the passive current at this potential is expected to be less than .005 mA. Although these tests were quite preliminary and performed utilizing conventional reinforcement bars, as opposed to prestressing steel, the data indicated that cracks in the grout cover produced a rapid increase in the anodic current density and resulted in rapid corrosion of the imbedded steel. These tests indicated the critical nature of preparing specimens which have no cracks in the grout cover.

For all of the preliminary grouted specimen tests, a conventional grout was selected for use. This grout was Type II Portland Cement with a 0.44 water-cement ratio with no additives. The grouted steel specimens consisted of a single (center wire) of a 0.5 in (1.27 cm) 7-wire strand 10 in (25.4 cm) in length with a 0.17 in (0.43 cm) thick grout cover. A single wire of a 7-wire strand was selected because a single wire is all that can be effectively loaded in a relatively small laboratory test set-up (if loading were required). The steel specimen was masked off at either end at the grout-air interface to prevent end effects with a 4.0 in (10.2 cm) section of steel exposed within the grout (see figure 4). Curing consisted of leaving the grouted steel specimens in the plastic molds for 24 to 48 hours, followed by removing the specimens and immersing them in a saturated $Ca(OH)_2$ solution for a minimum of 7 days. Prior to testing, a platinum clad counter electrode was wrapped around the specimen to permit polarization (see figure 4).

The test matrix developed included salt fog (5 percent NaCl) exposures, 5 percent NaCl solution immersion tests, and 100 percent humidity chamber exposure. Specimens were tested for each of these three exposure conditions utilizing the following three levels of polarization: (1) no polarization (freely corroding), (2) polarization with a low voltage between the anode (steel in grout) and cathode (platinum wire), and (3) polarization with a high voltage between anode and cathode. Because a reference electrode is nearly impossible to arrange for the vapor phase test, the polarization is being controlled by a constant voltage applied between the anode and cathode. The polarized potential of the test specimen was monitored periodically during these preliminary tests. Time to corrosion initiation is the primary parameter of interest in this study. For the polarized specimens, this is determined by monitoring the current as a function of time. For the freely corroding conditions, the time to corrosion initiation is determined by measuring the polarization resistance as a function of time. Because the

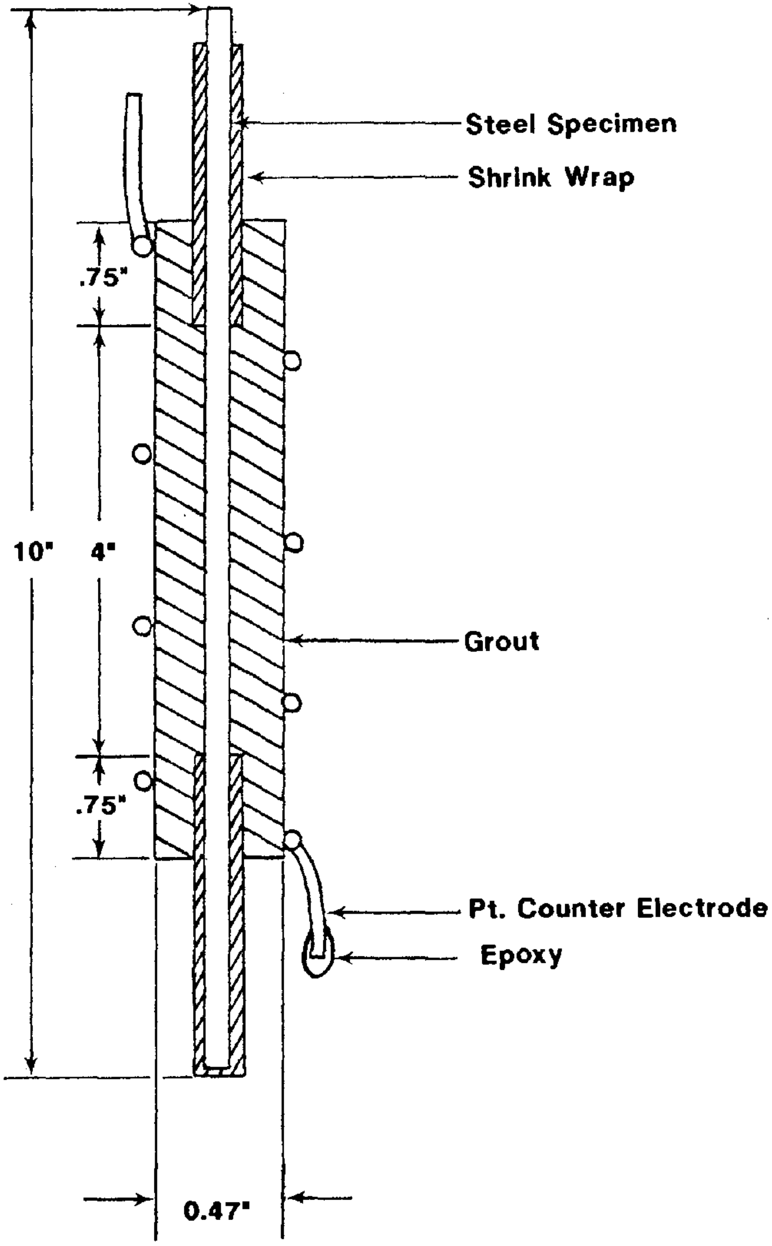


Figure 4. Schematic diagram of grouted test specimen with Pt counter electrode attached.

polarization resistance is inversely proportional to the corrosion rate, a decrease in polarization resistance indicates the onset of corrosion.

Figures 5 through 7 show the polarization resistance (PR) versus time for triplicate specimens in 5 percent NaCl solution, salt fog cabinet, and 100 percent humidity cabinet, respectively. These data show that the PR values for the 5 percent NaCl solution and the salt fog cabinet are much smaller than in the 100 percent humidity cabinet from the beginning of the tests. This indicates a much higher corrosion rate for the specimens exposed in the 5 percent NaCl solution and the salt fog cabinet. Furthermore, a transition from high PR values (low corrosion) to low PR values (high corrosion) was observed for the 5 percent NaCl solution tests during the first 50 hours of the test period. This transition is not as well defined in the salt fog cabinet. The values of the free-corrosion potential for the 5 percent NaCl solution tests are approximately -0.6 V (SCE) which is quite active indicating passive film breakdown. As expected for the 100 percent humidity cabinet tests, no chlorides, the PR values are quite high for steel embedded in grout. In general, the data for the specimens immersed in a 5 percent NaCl solution are much more stable with less variation from measurement to measurement than those performed in the two atmospheric exposures.

Polarized tests were also performed in 5 percent NaCl solution, salt fog cabinet, and 100 percent humidity cabinet. Measurement of the level of polarization utilizing a reference electrode is only feasible for the totally immersed 5 percent NaCl conditions. Figure 8 shows the current and polarized potential as a function of time for a specimen polarized with a constant voltage between the working and counter electrodes of 1 V. It is seen that a transition in the current from near zero up to 0.22 mA occurs quite rapidly after approximately 35 hours. A corresponding transition in the polarized potential from positive values to negative values occurs simultaneously with the current transition. This transition in the polarized potential is due to the fact that polarization is being maintained as a constant voltage between the counter and working electrodes and the polarized potential is free to vary depending on the conditions at the steel surface. Table 1 presents the data from several specimens which were polarized with either a 0.5 V or 1.0 V applied voltage between the working and counter electrodes for 5 percent NaCl solutions, salt fog cabinet exposures, and 100 percent humidity exposures. For the 5 percent NaCl solution tests, two trends are apparent: (1) the time to breakdown for an applied voltage of 1.0 V is less than for an applied voltage of 0.5 V, and (2) the current following breakdown is much greater for an applied voltage of 1.0 V than for 0.5 V.

Salt fog exposures were performed for an applied voltage of 0.5 V. The time to breakdown was greater for the salt fog exposures at 0.5 V applied voltage than for the 5 percent NaCl solution tests. As expected, no breakdown in the passive conditions occurred for the specimen exposed to 100 percent humidity (no chlorides).

Based on these tests, the 5 percent NaCl solution provided the greatest degree of acceleration. Also, the conditions of a totally immersed specimen in a 5 percent NaCl solution provides a much easier test protocol as compared to exposures in the salt fog cabinet. Also, the freely corroding tests do not provide any clear advantage over the polarized tests, and the polarized tests are easier to monitor than the freely corroding tests.

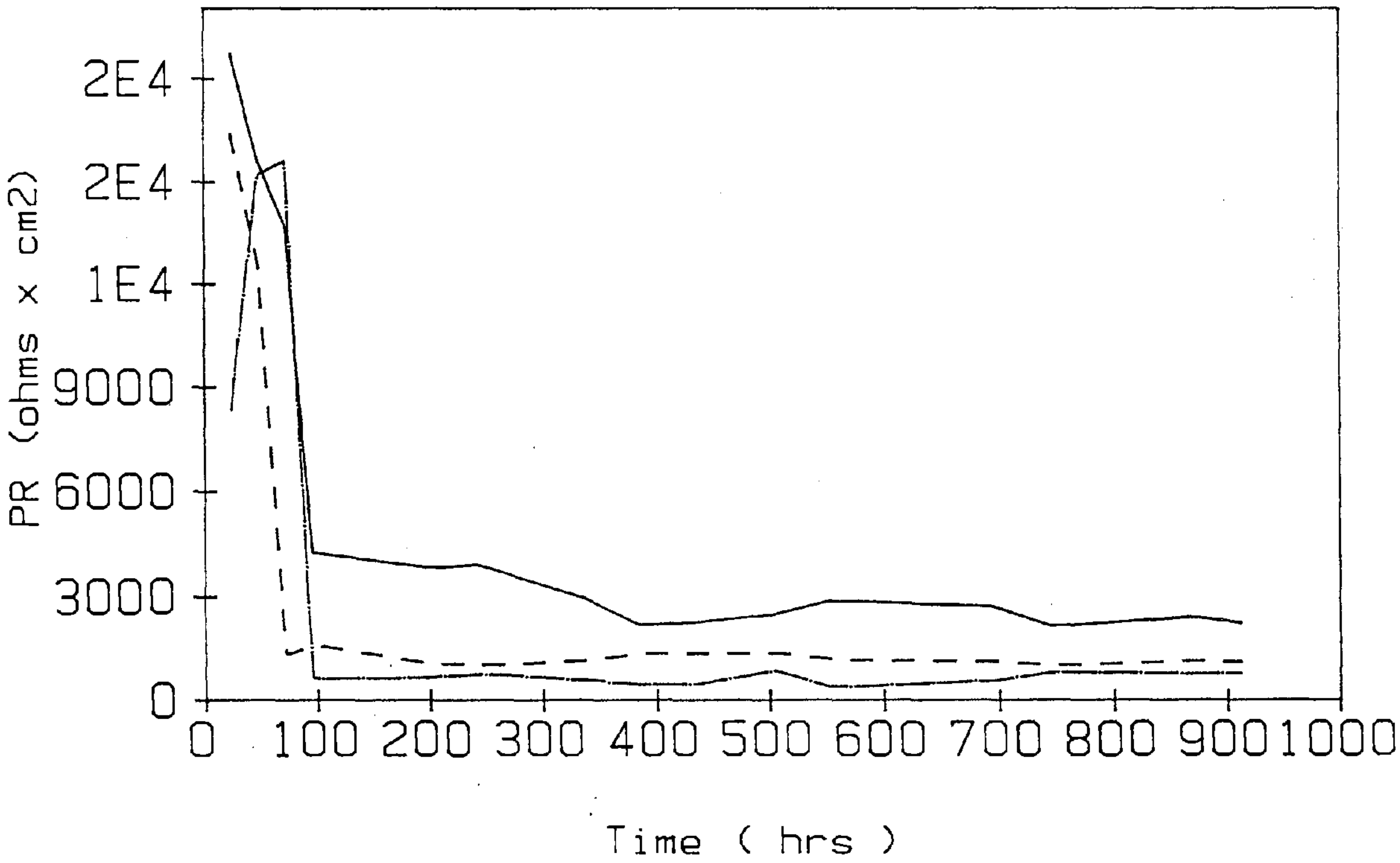


Figure 5. Polarization resistance versus time for triplicate freely corroding grouted specimens in 5 percent NaCl solution.

1 $in^2 = 6.45\ cm^2$

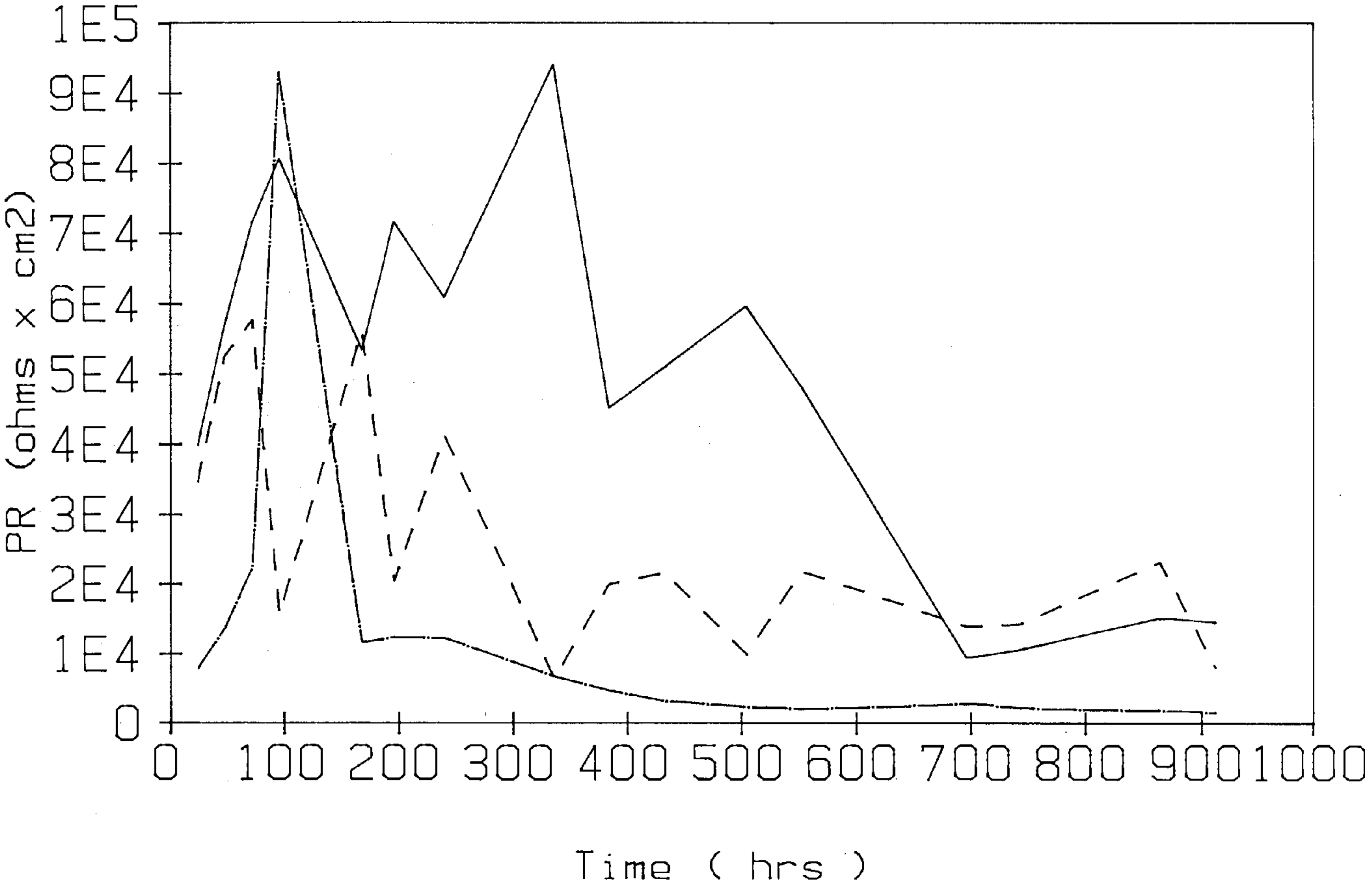


Figure 6. Polarization resistance versus time for triplicate freely corroding grouted specimens in salt fog cabinet.

1 in^2 = 6.45 cm^2

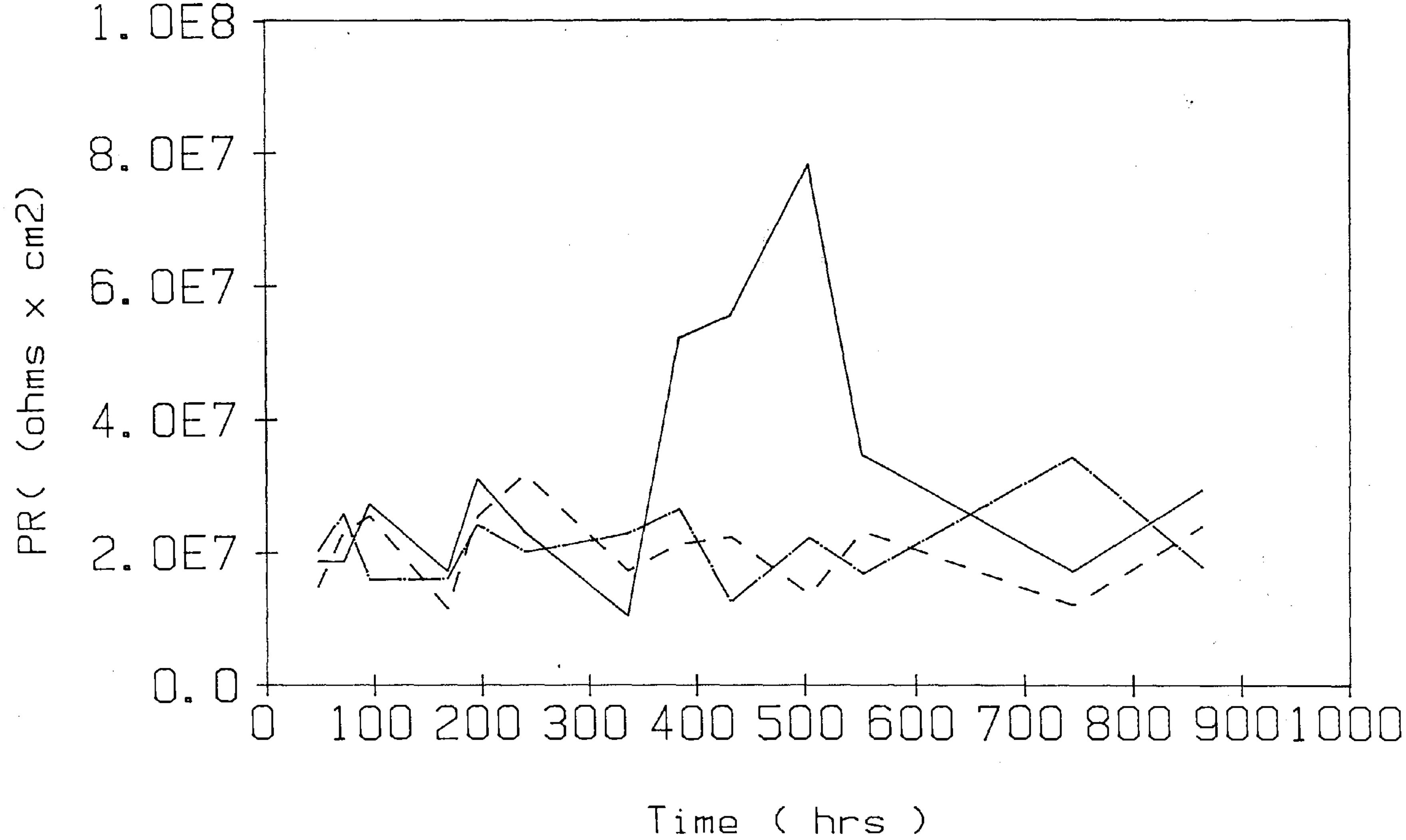


Figure 7. Polarization resistance versus time for triplicate freely corroding grouted specimens in 100 percent humidity cabinet.

1 in^2 = 6.45 cm^2

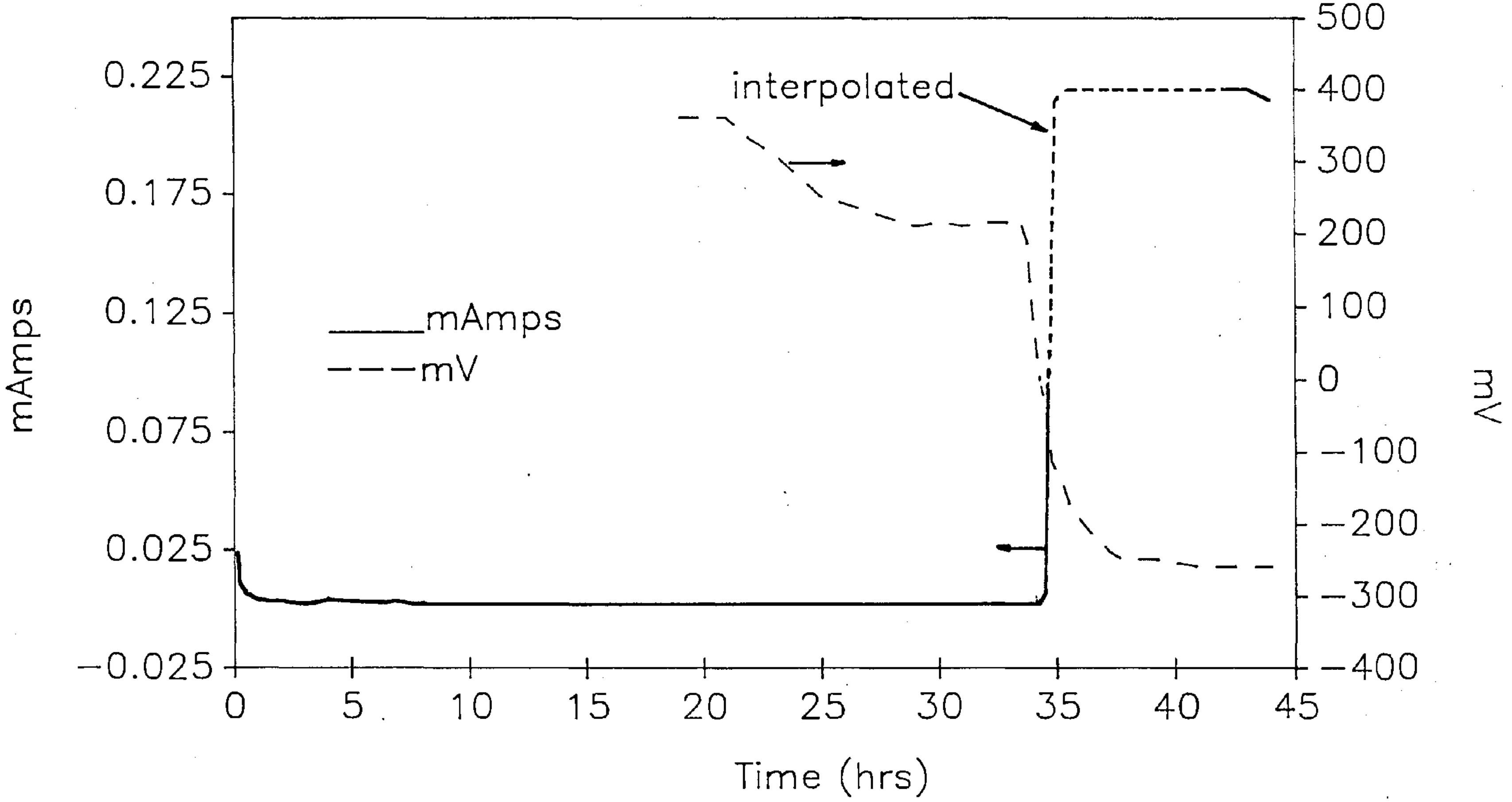


Figure 8. Comparison of current versus time with potential versus time for grout specimens exposed to 5 percent NaCl solution and polarized with an applied voltage of 0.5 V.

Table 1. Data for time to breakdown of passivity (corrosion initiation) for polarized grouted specimens.

Test Condition	Specimen	Applied Voltage, V	Time To Breakdown, Hours	Current Prior To Breakdown µA/cm2	Current Following Breakdown µA/cm^2
5% NaCl Solution	A	0.5	48-90	0.2	11
5% NaCl Solution	B	0.5	48-90	0.4	23
5% NaCl Solution	C	0.5	43-48	0.4	14
5% NaCl Solution	D	0.5	90-114	<0.1	44
5% NaCl Solution	E	1.0	17-25	<0.1	290
5% NaCl Solution	F	1.0	17-25	<0.1	180
Salt Fog	3138	0.5	124	5	140
Salt Fog	3137	0.5	166	6	50
Salt Fog	3136	0.5	127	2	70
100% Humidity	G	1.0	(a)	<0.0001	(a)

(a) No breakdown occurred.

1µA/cm^2 = 6.4 µA/in^2

Stressed Specimens

The effects of an applied stress to the test specimen on the corrosion behavior were examined utilizing a single wire of a 7-wire strand immersed in a saturated $Ca(OH)_2$ solution. The saturated $Ca(OH)_2$ solution simulated the expected pore solution within the grout. An aqueous solution provided a much easier test protocol than required for a specimen with a grout cover. The load was selected to produce a 140 ksi (965.3 MPa) stress which corresponds to the expected stress on a 7-wire strand in a bridge structure. The tests performed were:

1. Fully loaded in $Ca(OH)_2$ solution with no NaCl added and monitor polarization resistance as a function of time.

2. Fully loaded in $Ca(OH)_2$ solution with 5 percent NaCl added and monitor polarization resistance as a function of time.

3. Unloaded in $Ca(OH)_2$ solution with no NaCl added and monitor polarization resistance as a function of time.

4. Unloaded in $Ca(OH)_2$ solution with 5 percent NaCl added and monitor polarization resistance as a function of time.

Comparison of table 2 to 3 indicate that the presence of chlorides greatly increases the corrosion rate of the specimens as would be expected. Comparing table 2 to 4 and table 3 to 5 indicate that the presence of 140 ksi (965.3 MPa) stress has no effect on the measured corrosion rates for the specimens.

CPP Tests

CPP tests were performed on the following four conditions:

1. Saturated $Ca(OH)_2$ with no applied stress.

2. Saturated $Ca(OH)_2$ with 240 ksi (1654.8 MPa) applied stress.

3. Saturated $Ca(OH)_2$ plus 5 percent NaCl with no applied stress.

4. Saturated $Ca(OH)_2$ plus 5 percent NaCl with 240 ksi (1654.8 MPa) applied stress.

The tests were performed on the center wire of a 7-wire strand tendon. The test setup was identical to that for the stressed specimens test described above. Polarization curves were performed using standard CPP techniques as described in ASTM Standard G61-78 "Conducting Cyclic Potentiodynamic Polarization Measurements For Localized Corrosion."

The polarization behavior for the steel tendons in saturated $Ca(OH)_2$ both with and without stress applied show very similar passive behavior exhibiting extremely low corrosion rates. Upon examination of the specimens,

Table 2. Free-corrosion potential and polarization resistance as a function of time for prestressed steel exposed to saturated $Ca(OH)_2$ solution with no chlorides and with load applied.

Exposure Time, Days	Stress, ksi	PR, ohm * cm^2	Corrosion Rate, µm/yr	Free-Corrosion Potential, V, SCE
9	140	$1.5 * 10^7$	0.04	-0.169
14	140	$1.7 * 10^6$	0.34	-0.173
16	140	$2.5 * 10^6$	0.23	-0.150
28	140	$2.9 * 10^6$	0.20	-0.151
48	140	$7.5 * 10^6$	0.08	-0.136
55	140	$8.3 * 10^6$	0.07	-0.127
71	220	$3.5 * 10^6$	0.17	-0.119
89	220	$7.9 * 10^6$	0.07	-0.130
106	220	$7.6 * 10^6$	0.08	-0.039
112	220	$6.5 * 10^6$	0.09	-0.067
127	220	$7.3 * 10^6$	0.08	-0.087

1 ksi = 6.9 MPa
1 ohm*cm^2 = 0.16 ohm*in^2
1 µm/yr = 0.04 mil/yr

Table 3. Free-corrosion potential and polarization resistance as a function of time for prestressed steel exposed to saturated $Ca(OH)_2$ solution with 5 percent NaCl and with load applied.

Exposure Time, Days	Stress, ksi	PR, ohm * cm^2	Corrosion Rate, µm/yr	Free-Corrosion Potential, V, SCE
3	140	5,800	100	-0.462
8	140	5,500	106	-0.499
10	140	4,400	133	-0.516
22	140	4,900	115	-0.541
42	140	10,900	54	-0.523
49	140	10,500	56	-0.536
65	220	6,500	90	-0.544
83	220	8,500	69	-0.545
94	220	5,700	101	-0.579
106	220	4,200	138	-0.562
121	220	5,800	100	-0.564

1 ksi = 6.9 MPa
1 ohm*cm^2 = 0.16 ohm*in^2
1 µm/yr = 0.04 mil/yr

Table 4. Free-corrosion potential and polarization resistance as a function of time for prestressed steel exposed to saturated $Ca(OH)_2$ solution with no chlorides and no load applied.

Exposure Time, Days	PR, ohm * cm^2	Corrosion Rate, µm/yr	Free-Corrosion Potential, V, SCE
11	$3.6 * 10^6$	0.16	-0.169
18	$4.2 * 10^6$	0.14	-0.159
34	$3.3 * 10^6$	0.18	-0.129
52	$6.9 * 10^6$	0.08	-0.128
63	$5.3 * 10^6$	0.11	-0.125
75	$5.9 * 10^6$	0.10	-0.085
90	$6.2 * 10^6$	0.09	-0.104
103	$8.2 * 10^6$	0.07	-0.110
118	$9.7 * 10^6$	0.06	-0.085

1 ohm*cm^2 = 0.16 ohm*in^2
1 µm/yr = 0.04 mil/yr

Table 5. Free-corrosion potential and polarization resistance as a function of time for prestressed steel exposed to 5 percent NaCl and no load applied.

Exposure Time, Days	PR, ohm * cm^2	Corrosion Rate, µm/yr	Free-Corrosion Potential, V, SCE
11	6,500	90	-0.505
18	5,300	110	-0.515
34	5,800	101	-0.541
52	6,900	85	-0.534
63	5,800	100	-0.527
75	6,600	88	-0.552
90	4,700	123	-0.551
103	5,500	105	-0.574
118	5,400	107	-0.555

1 ohm*cm^2 = 0.16 ohm*in^2
1 µm/yr = 0.04 mil/yr

no visible corrosion, either general or localized, was identified on the test specimens. The polarization parameters for the free-corrosion potential (E_{cor}), corrosion current (i_{cor}), passive current density (i_{pas}), pitting potential (E_{pit}), and protection potential (E_{prot}) were determined from the polarization curves and the values for these parameters are presented in table 6. Although some variation is observed for these parameters, very little significance can be attributed to the application of stress. For example, reproducibility to within approximately 50mV for the potential parameters and a factor of 2 for the current parameters for repetitions of the same test condition is not unusual. The polarization behavior for the stressed and unstressed specimens with 5 percent NaCl added also show similar behavior. As is seen from the polarization parameters in table 6, there is somewhat more variation than observed for the no chloride conditions, but the variation observed is still not significant. Both the stressed and the unstressed conditions indicated breakdown of the passive film at relatively negative potentials and a large hysteresis loop that indicates that for longer term tests, localized attack would be expected because the free-corrosion potential is more positive than the protection potential.

Table 6. Polarization parameters for CPP tests.

Test Condition	E_{cor}, mV	i_{cor}, A/cm^2	i_{pas}, A/cm^2	E_{pit}, mV	E_{prot}, mV
Stressed - 5% NaCl	-480	$5.2 * 10^{-7}$	$2.5 * 10^{-6}$	-240	-550
No Stress - 5% NaCl	-415	$2.2 * 10^{-7}$	$1 * 10^{-6}$	-305	<-500
Stressed - No Cl^-	-240	$3.8 * 10^{-8}$	$2.5 * 10^{-7}$	+575	+575
No Stress - No Cl^-	-300	$4.0 * 10^{-8}$	$4.2 * 10^{-7}$	+580	+580

1 A/cm^2 = 6.4 A/in^2

The effect of stress on the polarization behavior for the prestressing steel in a saturated $Ca(OH)_2$ solution appears to be minimal. This is similar to the conclusion drawn for the freely corroding specimens in which the corrosion rate was measured based on polarization resistance techniques for stressed and unstressed conditions.

ACTM Design

In this subtask, the ACTM was designed based on the results of the preliminary experiments and consideration of several variables which were, at least, initially considered important to developing an accelerated test method for determining the corrosion performance of prestressing steel in a bonded post-tensioned concrete structure. Consideration was given to the following variables:

1. Freeze-thaw cycles.
2. Wet-dry cycles.
3. Temperature.
4. Acceleration of Cl^- migration.
5. Acceleration of corrosion.
6. Specimen loading.
7. Types of ducts.
8. Types of prestressing steel.
9. Grout cover.
10. Grout curing.

A discussion of each of the above considerations is given below.

Because the application of post-tension bonded concrete structures encapsulates the grout in a steel or plastic duct, it is not believed that freeze-thaw durability of the grout is a significant concern.

The application under study (bonded post-tensioned structures) involves grout being pumped into a duct containing the steel tendons. It is not expected that the grout would experience wet-dry cycles during operation. Therefore, wet-dry cycles are not incorporated in the ACTM.

Temperature can be used to help accelerate the Cl^- permeation and corrosion process. Preliminary tests on the conventional grout have not required the higher temperature to accelerate the test. Corrosion was initiated within a reasonable amount of time. Because this remained true for the ACTM tests performed in task C, the ACTM was performed at room temperature 70 to 77°F (21 to 25°C).

Acceleration of Cl^- migration is accomplished by two means in the ACTM: (1) minimum grout cover, and (2) applied voltage. In the ACTM, a voltage is applied between the tendon and a counter electrode in the test solution with the tendon having a positive charge. This will tend to accelerate the migration of the negative Cl^- ions through the grout toward the tendon. The degree of acceleration will depend upon the level of applied voltage.

Accelerating corrosion is of primary interest in this program. However, it is highly unlikely that an accurate means of providing for "50 years worth of corrosion" can be developed. In fact, if passivation of the prestressing steel breaks down and corrosion is initiated, then a few months to a few years of corrosion will likely be sufficient to cause failure of the prestressing steel. Therefore, the most important factor is the initiation of corrosion.

One only has to refer to the voluminous data for pit initiation of stainless steel by Cl^- ions to appreciate the difficulty of predicting such initiation events with any accuracy. Therefore, the ACTM is designed to accelerate the initiation of corrosion. This is accomplished by increasing the Cl^- concentration in contact with the grout surface and by the application of a voltage between the steel tendon and the counter electrode. The results of the ACTM is a ranking of the new grout formulations as compared to the "conventional" grouts in terms of time to corrosion initiation and rate of corrosion following initiation.

Specimen loading was examined in the previously discussed Preliminary Tests section. The data indicated that there is little or no difference in the corrosion behavior for loaded versus unloaded steel tendons immersed in saturated $Ca(OH)_2$ solution or saturated $Ca(OH)_2$ solution with 5 percent NaCl added. Tests were performed at zero, 140 ksi (965.3 MPa), and 220 ksi (1516.9 MPa) applied stress. Based on these results, loading of the steel tendons is not performed as part of the ACTM.

The original work plan included the examination of two types of ducts: (1) plastic, and (2) galvanized metal. Because all presently used grouts have a high pH portland cement base, corrosion failure of the tendon only occurs when a threshold level of Cl^- migrates to the tendon surface, thereby initiating active corrosion. Furthermore, since the tendon is encased in a plastic or metal casing, failure of the tendon must first result in failure of the casing (with the exception of the anchors). Therefore, in any relatively short-term accelerated corrosion test, the casing must be breached to permit Cl^- migration through it. The ACTM has a 4 in (10.2 cm) section of casing removed which simulates the worst case condition of a severe casing failure. This is not an unrealistic condition and just such a failure was observed in which the top 50 percent of a galvanized casing was corroded completely away resulting in the failure of the tendon. It is suggested that the performance of ducts should be tested in longer term, large scale tests which are not within the scope of the present program.

Examining the effects of the type of prestressing steel, bar versus 7-wire strand, was part of the original work plan. The 7-wire strand is of most interest because it is presently more widely used and because its geometry makes it more difficult to achieve complete cover of all strands. Furthermore, the type of steel is not expected to have a major effect on the corrosion performance of prestressing steel in grout. Therefore, the 7-wire strand tendon was selected for testing in the ACTM.

One of the most important aspects of the corrosion of grouted tendons is the depth of grout cover. In a typical structure, the grout cover can vary from near zero to 0.5 in (1.27 cm) or more. The grout mitigates corrosion in the following ways: (1) promotes passivity of the steel due to its high pH; (2) impedes migration of Cl^- to the steel surface, which can cause the breakdown of the passive film and initiate corrosion; and (3) if inhibitors are added, the grout can further inhibit corrosion even in the presence of Cl^-. If significant grout cover is present, impeding the Cl^- migration is likely the important property of a grout for mitigating corrosion. If little or no cover is present, inhibiting properties of the thin layer of grout is likely more important in mitigating corrosion. Thereby, the initial ACTM considered a range of grout cover as well as the possibility of cracks, or flaws, in the grout.

The manner in which the grouts are cured also has a significant effect on the properties of the grout which affect corrosion performance. Curing the grouts in a restricted mold that is water and air tight provides conditions similar to those expected during actual construction. Table 7 summarizes the test conditions and grout properties discussed above.

In the following paragraphs, the ACTM is described in detail. It should be recalled that the ACTM is designed to establish the corrosion protection provided by experimental grouts to establish whether significantly increased corrosion mitigation can be expected over a 50-year life of a structure. The focus of the ACTM is on the grout and not the total post-tensioning system which would include a detailed investigation of the entire system including tendon, grout, casing, and concrete cover. Also, many of the mechanical and physical properties of the grout will be examined through standard test methods being performed in task B. The ACTM is designed to be just another performance test for the grout. A decision for the usefulness of a grout in post-tensioned structures will be a combination of standard test methods for establishing physical and mechanical properties and the newly developed ACTM for establishing corrosion performance.

The following is a list of conditions that are examined in the ACTM.

1. Grout with a nominal grout cover, 0.15 in (0.38 cm), (standard specimen).
2. Grout with a minimum grout cover (dipped specimen).
3. Grout with a nominal grout cover with a preformed crack (precracked specimen).
4. Use 0.5 in (1.27 cm) diameter 7-wire strand as specimen.
5. No load applied to specimen.
6. Cast and cure grout-tendon specimen in a restrictive water-tight mold to simulate field conditions for grout curing.
7. Remove a section of the plastic mold (mold simulated duct) which simulates large areas of perforation in the casing and accelerates the test by increasing exposed grout area for Cl^- migration.

The standard and precracked grouted test specimens are prepared as follows:

1. Cut 0.5 in (1.27 cm) diameter 7-wire tendon into 10.5 in (26.7 cm) length.
2. Clean and degrease tendon specimen using acetone.
3. Mask off 5 in (12.7 cm) at top of tendon specimen and 1.5 in (3.8 cm) at bottom of tendon specimen using a coal tar epoxy (Carbomastic 14) or equivalent.

Table 7. Summary of test conditions and grout properties for the ACTM.

Condition/Property	Included In ACTM	Comments
Freeze-Thaw	No	Condition not applicable.
Wet-Dry Cycles	No	Not realistic condition.
Temperature	Yes	Held constant, could be used for acceleration, if needed.
Specimen Loading	No	Loading was shown not to have an effect.
Cl^- Migration	Yes	Accelerated by ACTM.
Type of Casing	No	Test worst case, i.e., breach in casing.
Type of Prestressing Steel	Yes	Test 7-wire strand only.
Grout Cover	Yes	Test with different cover thicknesses.
Inhibiting Properties	Yes	Test procedures designed to examine inhibiting properties.
Presence of Crack or Flaws	Yes	Precracked specimens a part of the ACTM.
Simulation of Curing	Yes	Curing of grout specimen will simulate actual practice.
Acceleration of Corrosion	Yes	ACTM accelerates corrosion by anodic polarization and maximizing Cl^- at the grout surface.

4. Cut 10.5 in (26.7 cm) length of 0.75 in (1.9 cm) Schedule 40 PVC pipe for use as the restrictive mold (duct).

5. Fill concave portion of standard PVC pipe cap with epoxy and glue end cap to one end of the pipe mold.

6. Insert tendon specimen with bottom washer in place. Washer will keep tendon centered in mold.

7. Fill pipe mold slowly letting grout flow down one side, filling the entire mold. Vibrate mold for 2 minutes, or until no bubbles appear, to ensure air bubbles have been removed.

8. Position washer at top of tendon specimen, taking care not to create air voids beneath washer. Vibrate again for short time.

9. Over-fill top of pipe mold and glue end cap with predrilled vent hole on top of mold taking care to minimize air entrapped in end cap (see figure 9). Seal vent hole with a self-tapping screw.

10. Cure grouted specimens for a minimum of 28 days.

11. Directly prior to testing (< 24 hr) place pipe mold in lathe and carefully cut a 4.5 in (11.4 cm) gauge section out of the pipe down to the grout (see figure 10). Care should be taken not to disturb the grout anymore than necessary.

12. Mask off a 4 in (10.2 cm) section of the exposed grout. Seal the exposed grout/mold joints with epoxy (Sikaguard 62) or equivalent. While applying sealant, keep exposed grout wet by wrapping section in a water soaked paper towel. Also, seal cap ends to mold. When epoxy is semi-cured, place specimens in solution of saturated $Ca(OH)_2$.

13. Using the lathe, cut off top end cap down to the steel tendon to permit electrical contact to the tendon (see figure 10).

14. Place grouted specimen with gauge section cut out of plastic pipe directly into saturated $Ca(OH)_2$ solution to prevent drying out.

Following removal of a section of pipe mold and exposure of the 4.5 in (11.4 cm) gauge section of grout, the specimen is carefully inspected for surface cracks or air voids within the exposed grout. Any visible crack or void constitutes rejection of the specimen. Eight acceptable grout specimens are required for testing. Four of these eight specimens are precracked to evaluate the influence of flaws in the grout on the corrosion behavior as determined by the ACTM. The following procedures were used to produce precracked specimens:

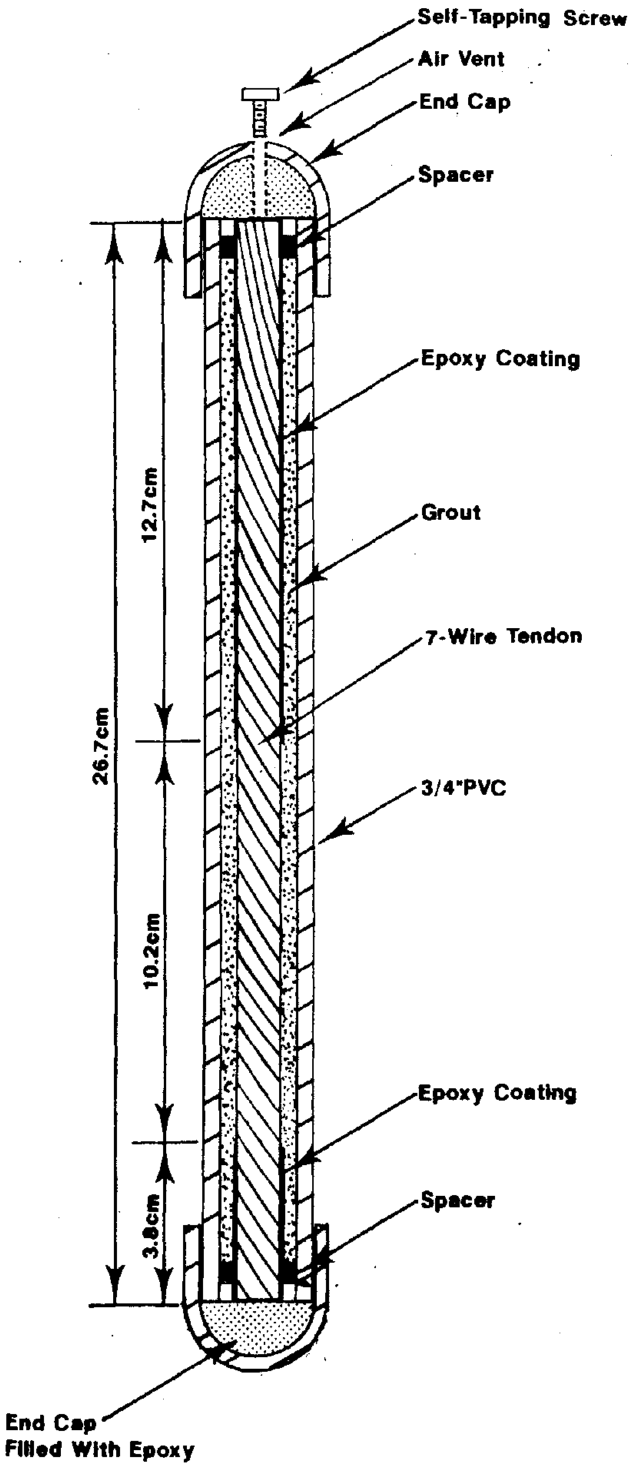


Figure 9. Schematic diagram of grouted pipe specimen prior to cutting gauge section.

1 in = 2.54 cm

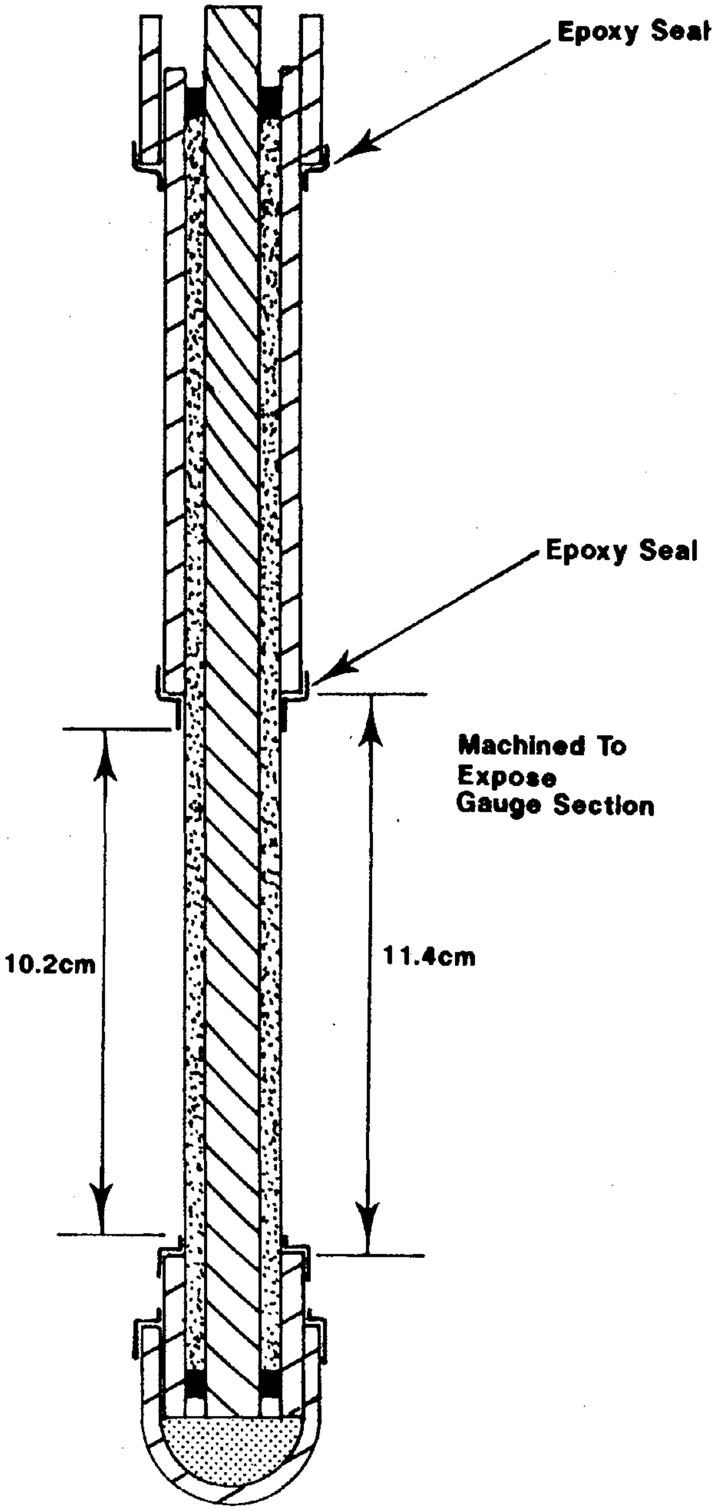


Figure 10. Schematic diagram of final grouted test specimen ready for testing.

1 in = 2.54 cm

1. Place the grout specimen in the test fixture as shown in figure 11.
2. While measuring the deflection with micrometer, apply a load by turning bolt to produce defection in 20 mil (508 μm) increments.
3. After each 20 mil (508 μm) increment, examine grout surface for cracks.
4. At the first sign of visible cracks, unload the grout specimen and label it as a precracked specimen ready for testing.

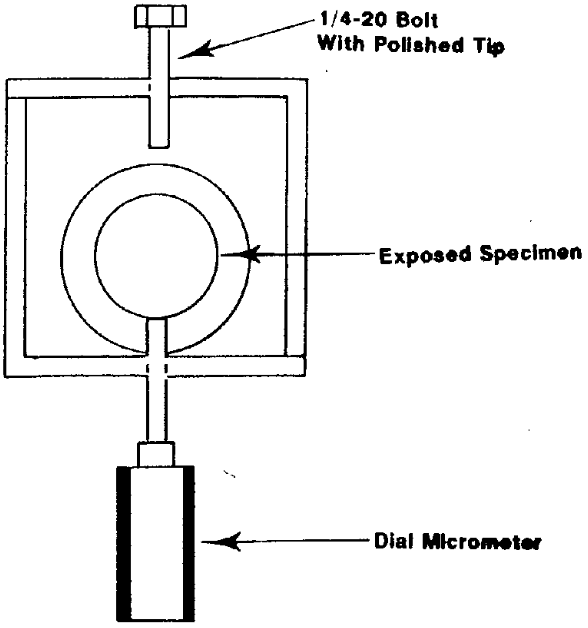
The third type of specimen to be prepared is the minimum grout cover specimen. Four each of these specimens are also prepared. These specimens are prepared by the following procedure:

1. Prepare tendon specimen and mask off surface with an epoxy as previously described for the standard grout specimen.
2. Dip the specimen into the grout and pull out slowly. Do not repeat.
3. Permit to cure for 4 to 8 h in a 100 percent humidity atmosphere prior to immersion for 28 days in a saturated $Ca(OH)_2$ solution.

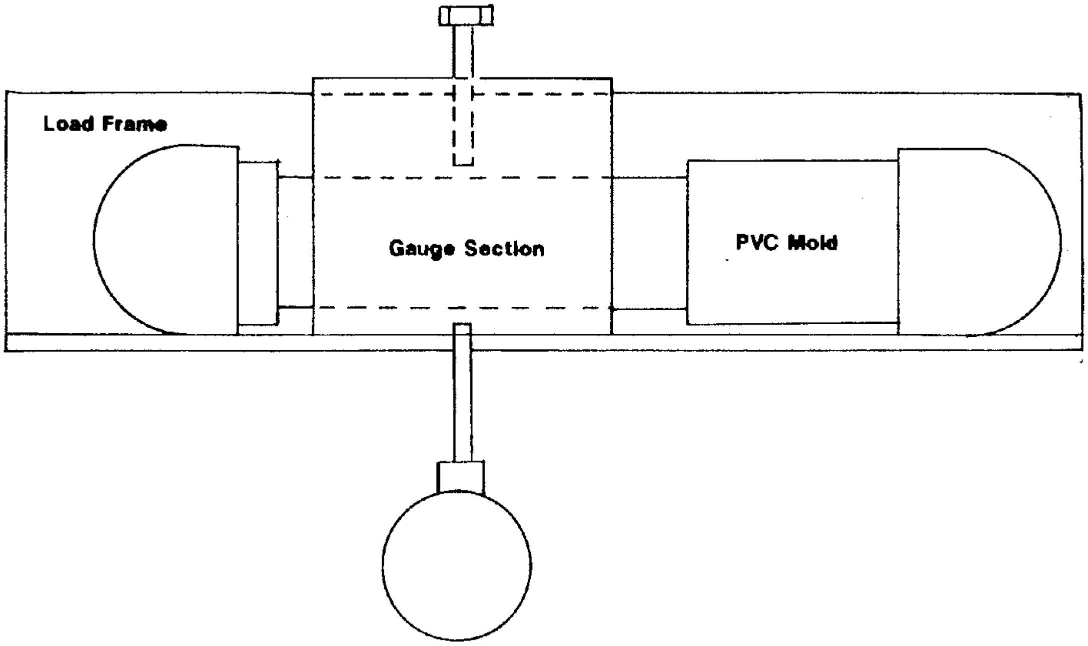
It should be noted that following the performance of several ACTM tests using these specimens in task C, this portion of the ACTM protocol was eliminated.

Upon preparation of the three types of specimens (standard grout specimen, precracked specimen, and minimum cover specimen), the ACTM is performed identically for the quadruplicate specimens of each type. The following procedure is used to perform the ACTM:

1. Set up the test cell arrangement as shown in figure 12 with the grouted test specimen immersed in a 5 percent NaCl solution.
2. A potentiostat is used to polarize the grouted test specimen. Connect the potentiostat as shown in figure 13 with the potentiostat in the "isolated" or "disabled" mode.
3. If the potentiostat has current and potential outputs, use them to monitor current and potential.



END VIEW



SIDE VIEW

Figure 11. Schematic diagram of the test fixture for producing precracked specimens.

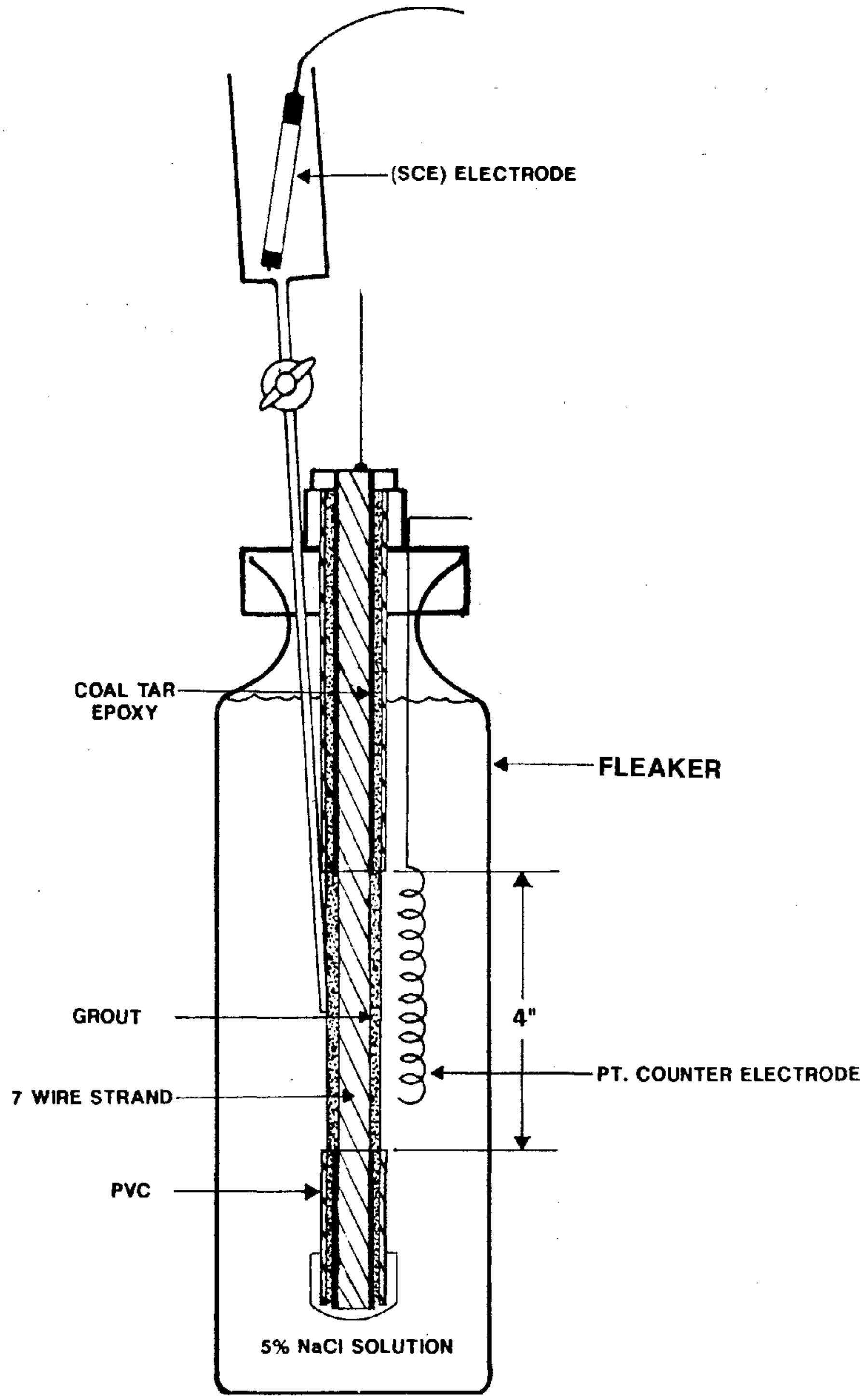


Figure 12. Schematic diagram of ACTM test cell arrangement.

1 in = 2.54 cm

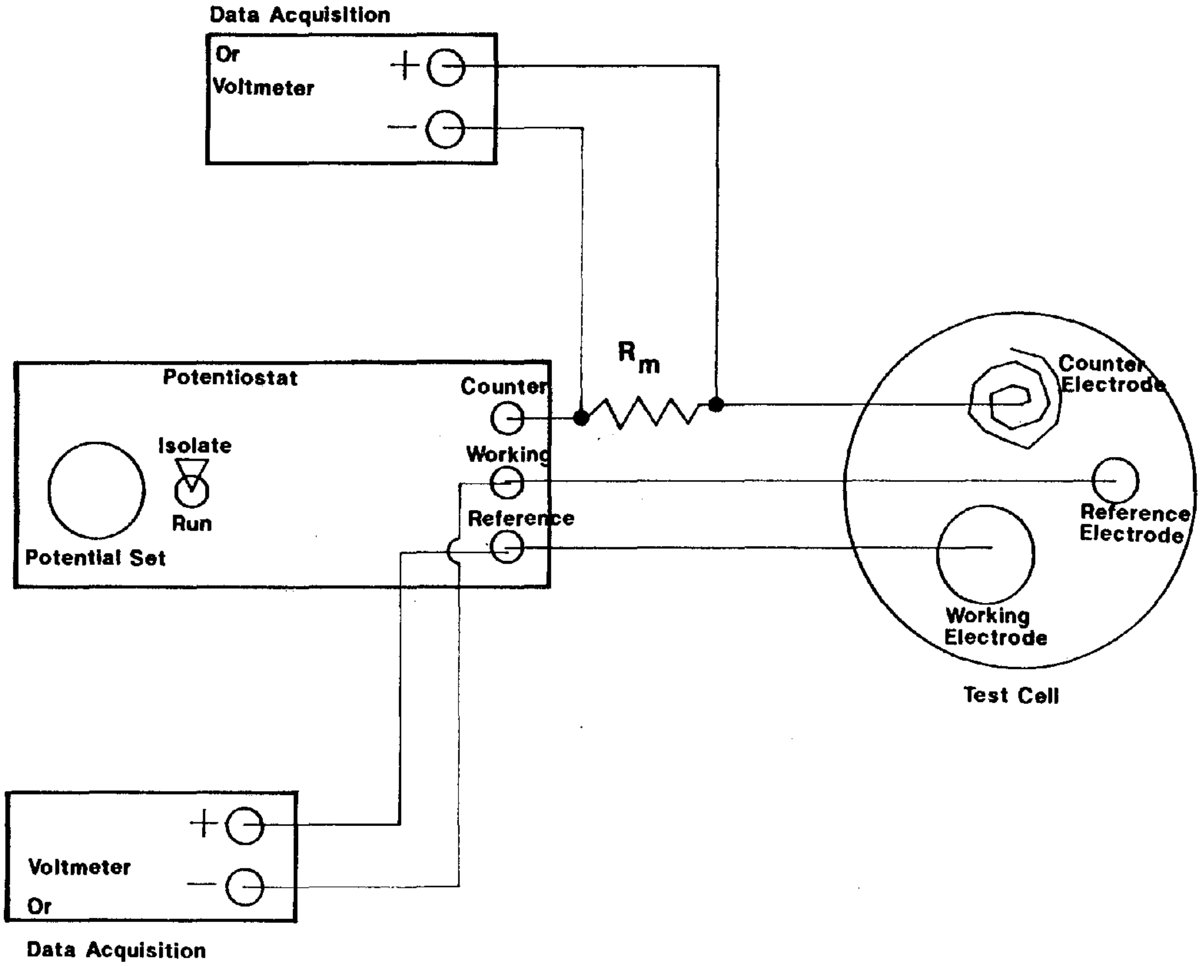


Figure 13. Wiring diagram for the ACTM.

4. If the potentiostat does not have current and potential outputs; use a series resistor in the counter electrode lead to monitor current (voltage drop across the resistor: I = V/R)[1-3] and monitor potential at the output of the working and reference electrode parts of the potentiostat.[4-5]

5. Set the potentiostat to apply +0.6 V (SCE).

6. Within 5 to 10 minutes of immersion, apply the +0.6 V (SCE) by switching the potentiostat from the "isolate" or "disable" mode to the "run" mode.

7. Record current and potential periodically during the test (every 10 to 30 minutes is sufficient).

8. Plot current versus time until a rapid current increase signifies the initiation of corrosion.

9. Allow tests to continue for 48 hr following initiation of corrosion.

10. Review the recorded potentials to ensure that +0.6 V (SCE) was maintained during the test.

11. Dismantle cell and remove test specimen.

12. For standard grout specimen, section the bottom end of the specimen through the plastic pipe mold. Examine to see if any voids exist in the interstices of the 7-wire strand or if the grout penetrated and filled in the interstices.

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[1] Measurement of voltage across a resistor in the counter electrode load must be accomplished with an electrically isolated (floating ground) device that has an input impedance 100 times the resistance of the measurement resistor (R_m).

[2] With the voltage measurement device hooked up across R_m as shown in figure 13, a positive value indicates anodic current and a negative value indicates cathodic current.

[3] Depending on the voltage range of the voltage measurement device and the current to be measured, a 100 ohm or 1,000 ohm resistor should be adequate (this study used a 100 ohm resistor with a ±5 V input voltage range).

[4] The potential measurement between the working and reference electrode should be made with a relatively high input impedance voltmeter (10^8 ohm minimum).

[5] Connecting the potential measurement device as shown in figure 13 minimizes the possibility of ground loops harming the reference electrode; but the potential measured is the reversed sign on standard electrochemical convention (therefore, if +0.6 V is applied by the potentiostat, a -0.6 V should be measured by the potential measurement device).

The above test methods have incorporated several modifications made to the specimen preparation and to the ACTM test procedures during the course of performing the ACTM on several specimens in task A. One primary modification was going from a voltage applied polarization to using a potentiostat which controls the potential between the working electrode (the grouted test specimen) and a standard reference electrode (saturated calomel electrode, SCE). Because the decision was made to use an aqueous solution of 5 percent NaCl with total immersion of the grouted specimen, potentiostated tests were possible and provide for much better potential control. Also, the counter electrode is inserted next to the test specimen as opposed to rapping around the test specimen as previously performed. Again, this is made possible because of the totally immersed conditions for the grouted specimen in the final ACTM test. Also, the specimen preparation is a result of a series of modifications to minimize cracking of the specimen upon removal of the specimen from a mold and unwanted corrosion of the test specimen at points where the specimen is masked off. One final modification from the preliminary tests previously described is that because stress was not applied to the steel specimen, a full 7-wire strand was used as the specimen as opposed to a single wire of the 7-wire strand tendon. For consistency, data that has been produced using the final ACTM procedure is included in the data presented in task C.

TASK B - DEVELOPMENT OF DESIGN MIXTURES FOR GROUT

Work performed in this task was divided into two primary subtasks: Current Grout Designs and New Grout Designs.

Current Grout Designs

In this subtask, current grout designs and construction practices employed for post-tensioned members were examined. The review of the state-of-the-art performed in this subtask has been published as an FHWA Report entitled "Grouting Technology For Bonded Tendons In Post-Tensioned Bridge Structures" (FHWA-RD-90-102). One of the primary data sources for establishing the present grouting practices, and in particular, the specifications used for the grout were the State Highway Departments. The primary information gathered from the State Highway Departments were the types of grouts that have been used in bonded post-tensioned highway structures and identification of the types of quality control tests performed to ensure an adequate grout and the general specifications used by the State Highway Departments for specifying a grout. Although this information was discussed in detail in the topical report, the summary tables of the details of this information were not provided. Those tables that summarize the data collected from the State Highway Departments are presented in appendix A of the present report.

Because the details of this review have already been published in an FHWA report, the conclusions are summarized below.

The technology of post-tensioned concrete structures in the U.S. is about 25 years old. In general, the performance record of these structures is an excellent one. It was determined that there are relatively few documented examples of bonded post-tensioned structures in which corrosion of the prestressed tendons has occurred. Even in many of these instances, investigators of the structures speculated that corrosion might not have occurred if proper construction practices and designs had been followed. However, in one example (a midwest parking garage), corrosion of embedded strands in a post-tensioned construction occurred when a large section of the galvanized duct was breached due to corrosion as a result of chloride migration. The corrosion attack resulted in failure of at least one wire of the 7-wire tendon. This example shows the importance of the quality and depth of the concrete covering the ducts. It is inevitable that additional instances of corrosion-related problems will be observed, as the average age of these structures continues to increase, deicing salts continue to be used, and the salts penetrate to greater depths within the concrete. The catastrophic nature of a serious failure within a bridge or parking garage makes it important for the industry to continue to improve upon its practices. All available technology which is economically feasible and that could improve performance should be incorporated into standard industry practice.

One such area in which improvements are possible is the grouts used for filling the ducts containing the prestressed steel within the post-tensioned structure. Because the grouts provide the final defense against corrosion of the prestressing steel tendons that support the structure, it is imperative to provide a grout that incorporates the state-of-the-art technology. Up to now, the majority of grouts used in bonded post-tensioned concrete structures has been a simple mixture of portland cement and water with water/cement ratios typically specified to fall below 0.44 and 0.50 and with expansive and non-bleeding additives sometimes speficied.

Based on a review of the grouts used to date and on the current technology of additives developed primarily for use in concrete to reduce permeability to chloride ion, the next generation of grouts could be improved in the following areas:

1. A reduced permeability to chloride penetration.
2. An improved ability to inhibit corrosion when chloride ions penetrate down to the prestressing steel.
3. Improved rheological and emplacement characteristics which reduce the risk that voids remain in the ducts being grouted.

Of principle importance to the rheological and emplacement characteristics are:

1. Fluidity of the grout.
2. The time dependency of the grout fluidity (open time).
3. The propensity of the grout to bleed or segregate, especially when under pressure and in contact with stranded prestressing steel elements.

New Grout Designs

Ten different grout series were evaluated in task B. The distinction between the various series was done on the basis of grout additives. The following provides a brief description of the different series examined.

1. Series 1: Standard Grout - The standard grout was chosen to be representative of grouts that have been used for many years in U.S. practice. It is a simple mixture of Type II portland cement and water with a water-cement ratio of 0.44.

2. Series 2: Commercial Anti-Bleed Admixtures - This grout also has a "normal" water-cement ratio (0.45) but contains a commercially available anti-bleed admixture that has been fairly widely used in recent years (Celtite Inc.'s Celbex 209X).

3. Series 3: High-Range Water-Reducer - The use of a superplasticizer provides significantly reduced water-cement ratios (15 percent to 30 percent water reduction) while maintaining the same level of fluidity. This series provides reduced water content grouts that are otherwise comparable (from a materials point of view) to the standard grout.

4. Series 4 and 10: Corrosion Inhibitor - The corrosion inhibitor (calcium nitrite) was used in grouts at both normal (Series 10) and reduced (Series 4) water-cement ratios. These series are unique in that it is the only grout that can possibly contribute to an improved resistance to tendon corrosion after the chloride ion has reached the steel.

5. Series 5: High-Range Water-Reducer Plus Flyash and Sand - This series was formulated in an effort to produce a relatively impermeable grout that would function at the same performance level as silica fume grouts while costing less.

6. Series 6: High-Range Water-Reducer Plus Silica Fume - Silica fume replacements up to 20 percent of cement weight were evaluated. Superplasticizers are required in these systems to achieve the desired level of fluidity at a reduced water content.

7. Series 8: High-Range Water-Reducer Plus Latex - There is very little in the literature concerning the use of superplasticizers with latex modifiers in portland cement-based systems. In the present investigation, success was achieved in producing low water-cement ratio, latex-modified grouts.

8. Series 9: Expansive Agent - This grout series was evaluated at both normal and reduced water-cement ratio levels using an aluminum powder as the expansion-causing agent.

9. Series 11: High-Range Water-Reducer Plus Expansive Agent Plus Anti-Bleed Additive - This series was evaluated to learn the effect of the expansive additive on the performance of Grout Series No. 3 and No. 12.

10. Series 12: Anti-Bleed Additive - In this grout series, a water soluble, polysaccharide gum, providing superior anti-bleed behavior, was evaluated.

A summary of the eleven grout series is presented in table 8.

Series No. 1 - Standard Grout Properties and Behavior

The standard grout used in the investigation is a simple mixture of Type II portland cement and water with a water-cement ratio of 0.44 (see table 9). The properties and behavior of the standard grout are summarized in table 10.

At a water-cement ratio of 0.44, the standard grout had a unit weight of 118 lb/ft^3 (1890 kg/m^3) and an initial flow cone efflux time of 18 seconds. The grout poured uniformly with no disruption or tearing of the grout stream. The standard grout showed very little bleeding at normal atmospheric pressure but did lose almost half of its total water at a pressure (gauge) of 80 psi (552 kPa). It is estimated that the standard grout remains pumpable for over 3 hours at 73^0F (23^0C). The standard grout showed good strength gain behavior with a 7 day compressive strength of 6000 psi (41370 kPa) and a 90 day compressive strength of almost 10,000 psi (68950 kPa). Tested at 30 V, the standard grout showed a rapid permeability test current flow of 2400 coulombs in 6 hours.

Series No. 2 - Effect of Commercial Anti-Bleed Admixture on Grout Properties and Behavior

The commercial anti-bleed admixture selected for the investigation is Conbex 209X supplied as a powder by the Celtite Corporation. The composition of the admixed grout is shown in table 11. The properties of Grout 2-1 are summarized in table 12.

The use of the anti-bleed admixture required a slight increase in the water-cement ratio from 0.44 to 0.46 to maintain an initial pourable consistency. Despite being pourable, the admixed grout had a significantly higher viscosity than the standard grout (flow cone efflux time of 59 seconds vs. 18 seconds). However, the admixed grout remained in a pumpable condition for over twice as long as the standard grout.

The admixed grout had a slight reduction in unit weight relative to the standard grout, reflecting in part, the entrained air derived from the expansive additive. This feature, along with the slightly higher water-cement ratio, was responsible in part for the reduced compressive strengths of the admixed grout relative to the standard grout (30 to 40 percent). Despite this reduction, the admixed grout did have a compressive strength over 5000 psi (34475 kPa) at 28 days (5580 psi or 38474 kPa).

Table 8. Summary of grout compositions evaluated in the present investigation.

Series 1:	Standard Grout
Series 2:	Commercial Anti-Bleed Admixtures
Series 3:	High-Range Water-Reducer (HRWR)
Series 4:	Corrosion Inhibitor/HRWR
Series 5:	HRWR/Flyash/Sand
Series 6:	HRWR/Silica Fume
Series 8:	HRWR/Latex
Series 9:	Expansive Agent
Series 10:	Corrosion Inhibitor
Series 11:	HRWR/Expansive Agent/Anti-Bleed Additive
Series 12:	Experimental Anti-Bleed Additive

Note: All grouts contained the same Type II portland cement. When a HRWR is used, the water to cementitious materials ratio is less than 0.37, When no HRWR is used, the water to cementitious materials ratio is 0.44 to 0.46.

Table 9. Standard experimental grout containing no admixtures (Series No. 1).

Constituent	Composition 1
Type II Portland Cement	100 parts by weight
Water (w/c = 0.44)	44 parts by weight

Table 10. Properties and behavior of standard grout at a water-cement ratio of 0.44 (series no. 1).

Unit Weight, lb/ft^3	Initial Flow Cone Efflux Time, sec.[a]	Bleeding Percent[b]	Expansion Percent[b]	Bleeding Under Pressure[c]		Grout Open Time, Hr:Min (Estimated Time Grout Remains Pumpable at 74°F)
				Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi	
118	18	0.1	0	0	48	3:20

Setting Time[d]		Heat Evolution Behavior		Compressive Strength, psi[e]				Rapid Permeability Test Results[f]	
								Current Flow - Coulombs	
Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min	1d	7d	28d	90d	60V	30V
5:15	7:00	150	9:50	2700	5960	7840	9860	37,000	2,400

[a] ASTM C939
[b] ASTM C940
[c] Gelman pressure filtration procedure
[d] ASTM C953
[e] ASTM C942
[f] AASHTO Designation T277-83

1 lb/ft^3 = 16.2 kg/m^3
1 psi = 6.9 kPa
5(F-32)/9 = C

Table 11. Experimental grout containing a commercial anti-bleed admixture (Series No. 2-1).

Constituent	Composition 2-1
Type II Portland Cement	100 parts by weight
Water (w/c = 0.44)	44 parts by weight
Conbex 209X	1.5 percent based on cement weight

Table 12. Properties and behavior of grout containing 1.5 percent (by weight of cement) of a commercial anti-bleed admixture (Conbex 209X) at a water-cement ratio of 0.46 (series no. 2-1).

Unit Weight, lb/ft³	Initial Flow Cone Efflux Time, sec.(a)	Bleeding Percent(b)	Expansion Percent(b)	Bleeding Under Pressure(c)		Grout Open Time, Hr:Min (Estimated Time Grout Remains Pumpable at 74°F)
				Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi	
115	59	0	1.3	30	5	8:00

Setting Time(d)		Heat Evolution Behavior		Compressive Strength, psi(e)				Rapid Permeability Test Results(f)	
								Current Flow - Coulombs	
Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min	1d	7d	28d	90d	60V	30V
14:00	23:30	155	11	115	3410	5580	6530	59,000	14,500

(a) ASTM C939
(b) ASTM C940
(c) Gelman pressure filtration procedure
(d) ASTM C953
(e) ASTM C942
(f) AASHTO Designation T277-83

1 lb/ft³ = 16.2 kg/m³
1 psi = 6.9 kPa
5(F-32)/9 = C

The admixture had a significant beneficial effect on the water retention of the grout under pressure. A pressure of 30 psi (207 kPa) was required to affect any water loss, and at 80 psi (552 kPa) (gauge), only 5 percent of thetotal water was removed from the admixed grout (compared to almost 50 percent for the standard grout).

The admixture had a significant adverse effect on the permeability of the grout as reflected in the rapid perm test. For the admixed grout, the 6 hour current flow at 30 V was 14,500 coulombs for the admixed grout compared with 2,400 coulombs for the standard grout.

In summary, at an additional rate of 1.5 percent by weight of cement, the commercial admixture had a beneficial effect on the water retention under pressure of the grout and provided a modest expansion (1.3 percent) with an increase in the time that the grout remained pumpable. At this addition rate, the grout did have an adverse (but acceptable) effect on compressive strength development and a significant adverse effect on the chloride permeability of the grout.

Series No. 3 - Effect of High-Range Water-Reducer on Grout Properties and Behavior

The compositions of the grouts containing the high-range water-reducing (HRWR) admixture are shown in table 13. For the admixture dosage rate used here, considerable bleeding occurred in the grouts at water-cement ratios above 0.37. The grout selected for further study had a water-cement ratio of 0.365 at a HRWR level of 15 oz/cwt (9.7 ml/kg). The properties of this grout are summarized in table 14.

Table 13. Experimental grout containing a high-range water-reducing (HRWR) admixture (Series No. 3).

Constituent	Composition 3
Type II Portland Cement	100 parts by weight
Water (w/c = 0.32-0.44)	32-44 parts by weight
HRWR Admixture	10 to 20 fl. oz. per 100 lb. of cement

1 fl oz/lb = 65 ml/kg

Table 14. Properties and behavior of grout containing 15 oz/cwt of a high-range water-reducing (HRWR) admixture (Mighty 150) at a water-cement ratio of 0.365 (series no. 3).

Unit Weight, lb/ft³	Initial Flow Cone Efflux Time, sec.(a)	Bleeding Percent(b)	Expansion Percent(b)	Bleeding Under Pressure(c)		Grout Open Time, Hr:Min (Estimated Time Grout Remains Pumpable at 74°F)
				Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi	
120	19	0.15	0	10	38	4:20

Setting Time(d)		Heat Evolution Behavior		Compressive Strength, psi(e)				Rapid Permeability Test Results(f)	
								Current Flow - Coulombs	
Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min	1d	7d	28d	90d	60V	30V
8:06	10:00	180	12:00	4170	8000	9530	10,980	24,000	4,300

(a) ASTM C939
(b) ASTM C940
(c) Gelman pressure filtration procedure
(d) ASTM C953
(e) ASTM C942
(f) AASHTO Designation T277-83

1 lb/ft^3 = 16.2 kg/m^3
1 psi = 6.9 kPa
5(F-32)/9 = C

At an HRWR level of 15 oz/cwt (9.7 ml/kg), the admixed grout had the same initial flow (cone efflux time of 19 seconds) as the standard grout while providing a water reduction of almost 20 percent. Relative to the standard grout, the admixed grout showed equal or improved pumping time and strength development. The admixed grout at the reduced water-cement ratio showed only a slightly improved water retention capacity. The admixed grout lost 40 percent of its total water at 80 psi (552 kPa) (gauge) while the standard grout lost 50 percent of its total water at 80 psi (552 kPa). The admixed grout had a rapid permeability current passed of 4300 coulombs compared to 2400 coulombs for the standard grout.

In summary, the use of a HRWR admixture provided for the maintenance of adequate fluidity and working time in the grout at a 20-percent reduction in water content. Relative to the standard grout, the grout containing the HRWR showed improvements in the rate of strength development and in the water retention capacity under pressure. An expected reduction in chloride permeability brought about by the lower water-cement ratio of the admixed grout (relative to the standard grout) was not seen in the present investigation.

Series No. 4 and 10 - Effect of Calcium Nitrite Corrosion Inhibitor on Grout Properties and Behavior

Grouts containing the calcium nitrite corrosion inhibitor (W.R. Grace Company - DCI) were prepared at water-cement ratios of 0.365 (Grout No. 4-1) and 0.44 (Grout No. 10-1). The compositions are shown in table 15. Properties of the Grout No. 4-1 are summarized in table 16.

Table 15. Experimental grouts containing a calcium nitrite corrosion-inhibiting admixture (Series Nos. 4-1 and 10-1).

Constituent	Composition 4-1	Composition 10-1
Type II Portland Cement	100 parts by weight	100 parts by weight
Water	34.7 parts by weight (w/c = 0.365)[(a)]	42.7 parts by weight (w/c = 0.44)[(a)]
HRWR Admixture	15 fl. oz. per 100 lb. of cement	None
Calcium Nitrite Corrosion-Inhibiting Admixture (W. R. Grace - DCI)	6 gallons/yd^3 of grout	6 gallons/yd^3 of grout

(a) Includes mixing water and water contribution from admixtures.
1 fl oz/lb = 65 ml/kg
1 gal/yd^3 = 4.9 l/m^3

Table 16. Properties and behavior of grout containing 6 gallons/yd^3 of a corrosion-inhibiting admixture at a water-cement ratio of 0.365 (series no. 4-1).

Unit Weight, lb/ft^3	Initial Flow Cone Efflux Time, sec.$^{(a)}$	Bleeding Percent$^{(b)}$	Expansion Percent$^{(b)}$	Bleeding Under Pressure$^{(c)}$		Grout Open Time, Hr:Min (Estimated Time Grout Remains Pumpable at 74°F)
				Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi	
121	22	0.60	0	0	44	3:15

Setting Time$^{(d)}$		Heat Evolution Behavior		Compressive Strength, psi$^{(e)}$				Rapid Permeability Test Results$^{(f)}$	
								Current Flow - Coulombs	
Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min	1d	7d	28d	90d	60V	30V
6:50	8:45	157	13:00	1700	6225	8740	9710	32,000	4000

(a) ASTM C939
(b) ASTM C940
(c) Gelman pressure filtration procedure

(d) ASTM C953
(e) ASTM C942
(f) AASHTO Designation T277-83

1 lb/ft^3 = 16.2 kg/m^3
1 psi = 6.9 kPa
5(F-32)/9 = C

No property data was obtained on Grout No. 10-1. Only ACTM specimens were prepared from this grout. The main objective of property measurements on the corrosion inhibitor-containing grout was to assure that the inhibitor had no adverse effect on the properties of the grout in the fresh and hardened state while, hopefully, providing the desired corrosion-inhibiting function in the hardened grout. A comparison of the data shown in table 16 with property data on the same grout without the corrosion-inhibiting admixture (table 14 - Series 3) confirms this desired result. The only exception is a lower 1 day compressive strength for the grout containing the corrosion inhibitor. This is an unexpected result as the calcium nitrite corrosion inhibitor is expected to act as a set accelerator. However, in the present case, the set-retarding function of the HRWR appears to offset this function.

Series No. 5 - Effect of Fine Aggregate (Sand) Additions On Grout Properties And Behavior

Grout composition were studied which contained Type II portland cement and a fine silica sand. The silica sand has a maximum particle size of 50 mesh. The sanded Series No. 5 grouts also contained flyash, a high-range water-reducter (HRWR), and an anti-bleed additive (polysaccharide gum).

The composition of the grout is shown in table 17 (Composition 5-1). Property data on this grout is summarized in table 18.

Table 17. Experimental grout containing a fine silica sand and flyash (Series No. 5-1).

Constituent	Composition 5-1
Type II Portland Cement	100 parts by weight
Flyash	33 parts by weight
Silica Sand	52 parts by weight
Water [w/(c + flyash) = 0.32]	43 parts by weight
Polysaccharide Gum	0.05 parts by weight
HRWR Admixture	40 fl. oz. per 100 lb. of cement

1 fl oz/lb = 65 ml/kg

Table 18. Properties and behavior of grout containing fine silica sand and flyash at a water-cement ratio of 0.32 (series no. 5-1).

Unit Weight, lb/ft^3	Initial Flow Cone Efflux Time, sec.$^{(a)}$	Bleeding Percent$^{(b)}$	Expansion Percent$^{(b)}$	Bleeding Under Pressure$^{(c)}$		Grout Open Time, Hr:Min (Estimated Time Grout Remains Pumpable at 74°F)
				Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi	
128.6	86	0	0	40	5	5:00

Setting Time$^{(d)}$		Heat Evolution Behavior		Compressive Strength, psi$^{(e)}$				Rapid Permeability Test Results$^{(f)}$	
								Current Flow - Coulombs	
Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min	1d	7d	28d	90d	60V	30V
16:10	18:45	132	24:00	900	6450	8400	13,385	6960	370 (140)

(a) ASTM C939
(b) ASTM C940
(c) Gelman pressure filtration procedure
(d) ASTM C953
(e) ASTM C942
(f) AASHTO Designation T277-83

1 lb/ft^3 = 16.2 kg/m^3
1 psi = 6.9 kPa
5(F-32)/9 = C

Sanded grouts containing up to 28 percent of the Wedron 510 sand were prepared with water-cement + flyash ratios in the 0.27 to 0.32 range. These grouts had a pourable fluidity and maintained their pumpability for up to five hours. Although initially pourable, these grouts were quite viscous with Grout Composition 5-1 showing an initial flow cone efflux time of 86 seconds at a water-cement + flyash ratio of 0.32.

The HRWR addition retarded the 1-day strength development in Composition No. 5-1 (900 psi or 6206 kPa) with the 7-, 28-, and 90-day strengths equal or exceeding the strengths developed by the standard grout. In fact, the 90-day strength of the sanded grout (13385 psi or 92290 kPa) was the highest strength grout developed in the present program. The sanded grouts showed virtually no bleeding. Grout No. 5-1, in the pressure filtration test, required 40 psi (275 kPa) before any water loss was effected and only 5 percent of the total free water was removed at a pressure of 80 psi (552 kPa). Sanded Grout No. 5-1 provided one of the better results obtain in the rapid permeability test.

The use of fine aggregate (sand) in these grouts has the potential for reducing overall grout cost without having any adverse effect on engineering properties relevant to the bonded post-tensioning application. In fact, properties such as strength development and bleeding behavior may be improved by the sand addition. It is also expected that the volume stability of sanded grouts will be superior to that of unsanded grouts (reduced drying shrinkage strain). It remains to determine the overall pumpability of these relatively viscous, high unit weight grouts.

Series No. 6 - Effect of Silica Fume on Grout Properties and Behavior

Grout compositions were studied which contained Type II portland cement and silica fume additions of 5, 10, 15, and 20 percent of cement weight. In all of the silica fume grouts, it was necessary to use the HRWR to achieve and maintain satisfactory fluidity characteristics. The composition for two of the silica fume grouts that were studied most extensively in the present investigation are shown in table 19 (Composition 6B - 10 percent silica fume; and Composition 6D - 20 percent silica fume).

Table 19. Experimental grouts containing 10- and 20-percent silica fume (Series Nos. 6B and 6D).

Constituent	Composition 6B	Composition 6D
Type II Portland Cement	100 parts by weight	100 parts by weight
Silica Fume (sf)	11 parts by weight	25 parts by weight
Water (w/c + sf = 0.365)	41 parts by weight	46 parts by weight
HRWR Admixture	15 oz to 55 oz per 100 lb of cement	15 oz to 55 oz per 100 lb of cement

1 fl oz/lb = 65 ml/kg

The silica fume was added as a dry powder and preblended with the other dry grout ingredients. The amount of HRWR required to achieve a starting fluidity of a 20- to 30-second flow cone efflux time increased with increasing silica fume content (see figure 14). The 20 to 30 second efflux time was arbitrarily chosen to represent a "satisfactory" initial fluidity for these relatively dense, low water content grouts. In fact, any grout that passes completely through the flow cone, regardless of total efflux time, can be defined as a pourable grout. To maintain a water to cement plus silica fume ratio of 0.365 at the desired fluidity level, a silica fume content of 5 percent required a 0.7 percent addition of HRWR (19 oz/cwt 12.4 ml/kg) while a 20-percent silica fume content required a 1.7 percent addition (47 oz/cwt or 30.6 ml/kg). These silica fume grouts had an efflux time of 20 to 30 seconds for up to 1 hour at 75^{0}F (24^{0}C) as shown in figure 15.

The time during which the silica fume grouts remain pumpable can be controlled by controlling the quantity of HRWR used. This phenomenon is shown in figure 16 for a 10-percent silica fume grout (Grout 6B). At the 10-percent silica fume addition, the open time of the grout varied from 1 and 1/2 hours to 8 hours when the HRWR was increased from 25 oz/cwt (16.2 ml/kg) to 55 oz/cwt (35.8 ml/kg).

All of the silica fume grouts representing the data points in figures 14, 15, and 16 had a water to cement plus silica fume ratio of 0.365. The grouts showed good stability in slurry form and showed no tendency to segregate or bleed in an unpressurized condition.

The initial fluidity and open time of the silica fume grouts were also controlled by the starting water to cement plus silica fume ratio. This relationship is shown in figure 17 for water to cement plus silica fume ratios of 0.35, 0.40, and 0.45 for the grout containing 10-percent silica fume and 25 oz/cwt (16.2 ml/kg) of HRWR. At the lowest water to cement plus silica fume ratio (0.35), the initial fluidity was 37 seconds efflux time and remained in a pourable condition for about 1 and 1/2 hours. At the highest water to cement plus silica fume ratio of 0.45, the initial fluidity was 14 seconds efflux time and the grout still had an efflux time of around 20 seconds after 2 and 3/4 hours. At the highest water to cement plus silica fume ratio (0.45), the grout did exhibit slight bleeding.

A complete set of property data was obtained on silica fume grouts containing 10-percent silica fume (Composition 6B) and 20-percent silica fume (Composition 6D). These results are summarized in table 20. Relative to the standard grout, the use of silica fume (10- and 20-percent cement replacement) in conjunction with a HRWR provided significant improvements in water retention capacity (under pressure) and in chloride ion permeability. These benefits were achieved without sacrificing strength and working time characteristics.

Series No. 8 - Effect of Latex Polymer Modifier on Grout Properties and Behavior

Acrylic and SBR latex polymer modifiers were evaluated. The SBR latex modifier (Modifier A - Dow Chemical Company) provided the most stable grout and the most consistent properties. The latex addition was 15 percent

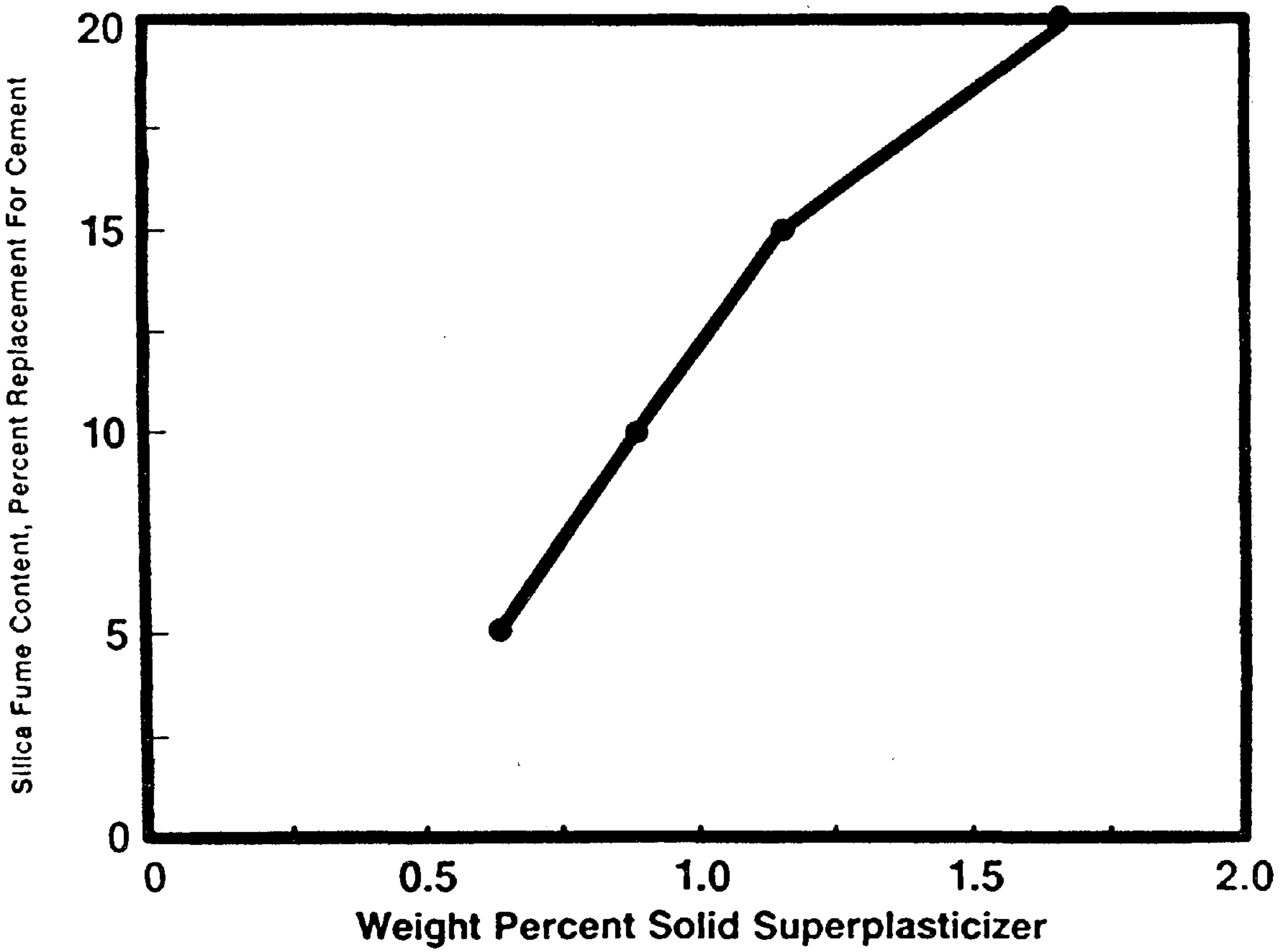


Figure 14. Quantity of superplasticizer (M150) required to maintain the same fluidity (efflux time of 20 to 30 seconds) in a Type II portland cement grout as a function of silica fume replacement of cement [w/(c + sf)] = 0.365.

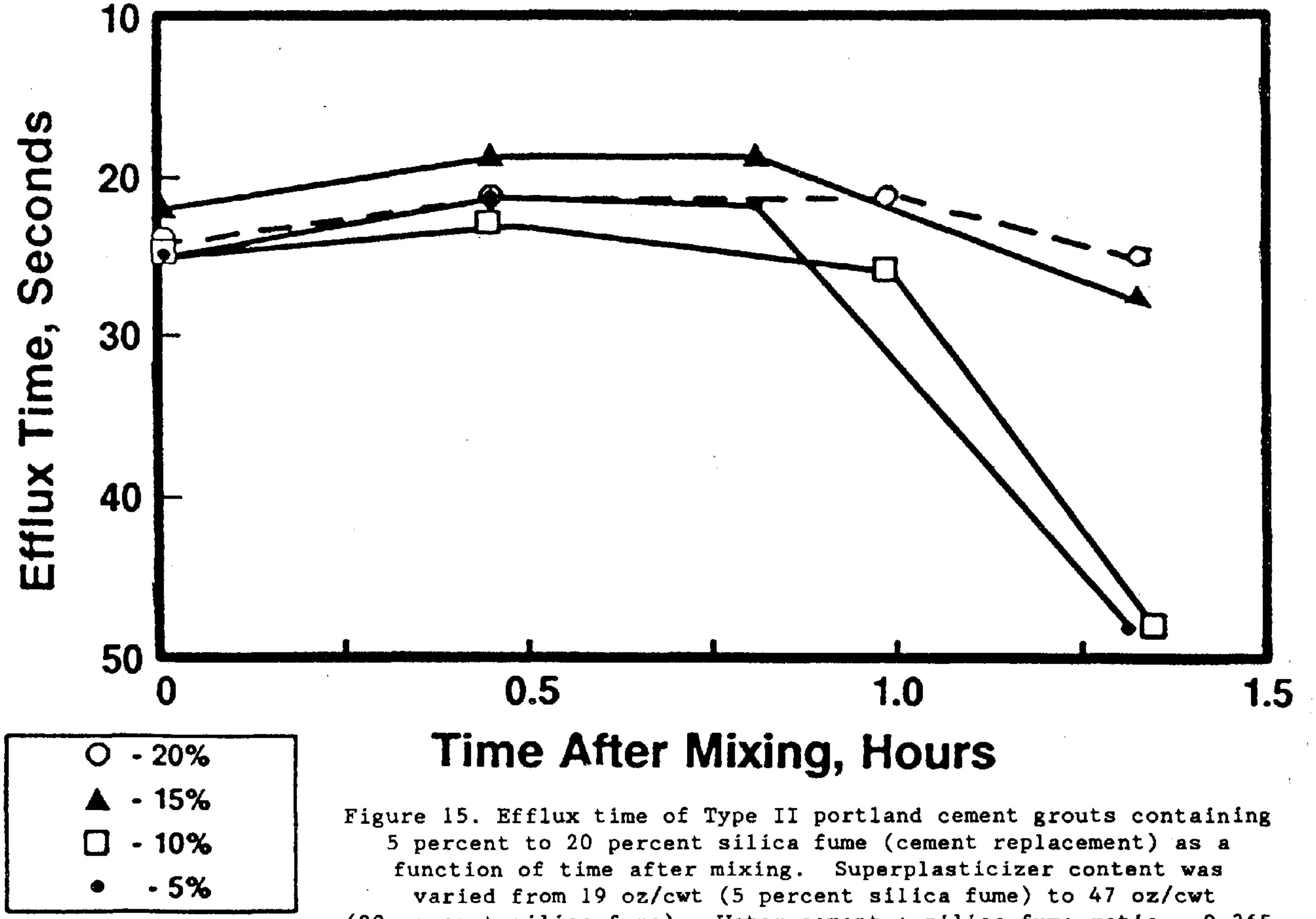


Figure 15. Efflux time of Type II portland cement grouts containing 5 percent to 20 percent silica fume (cement replacement) as a function of time after mixing. Superplasticizer content was varied from 19 oz/cwt (5 percent silica fume) to 47 oz/cwt (20 percent silica fume). Water-cement + silica fume ratio = 0.365.

1 oz/cwt = 0.65 ml/kg

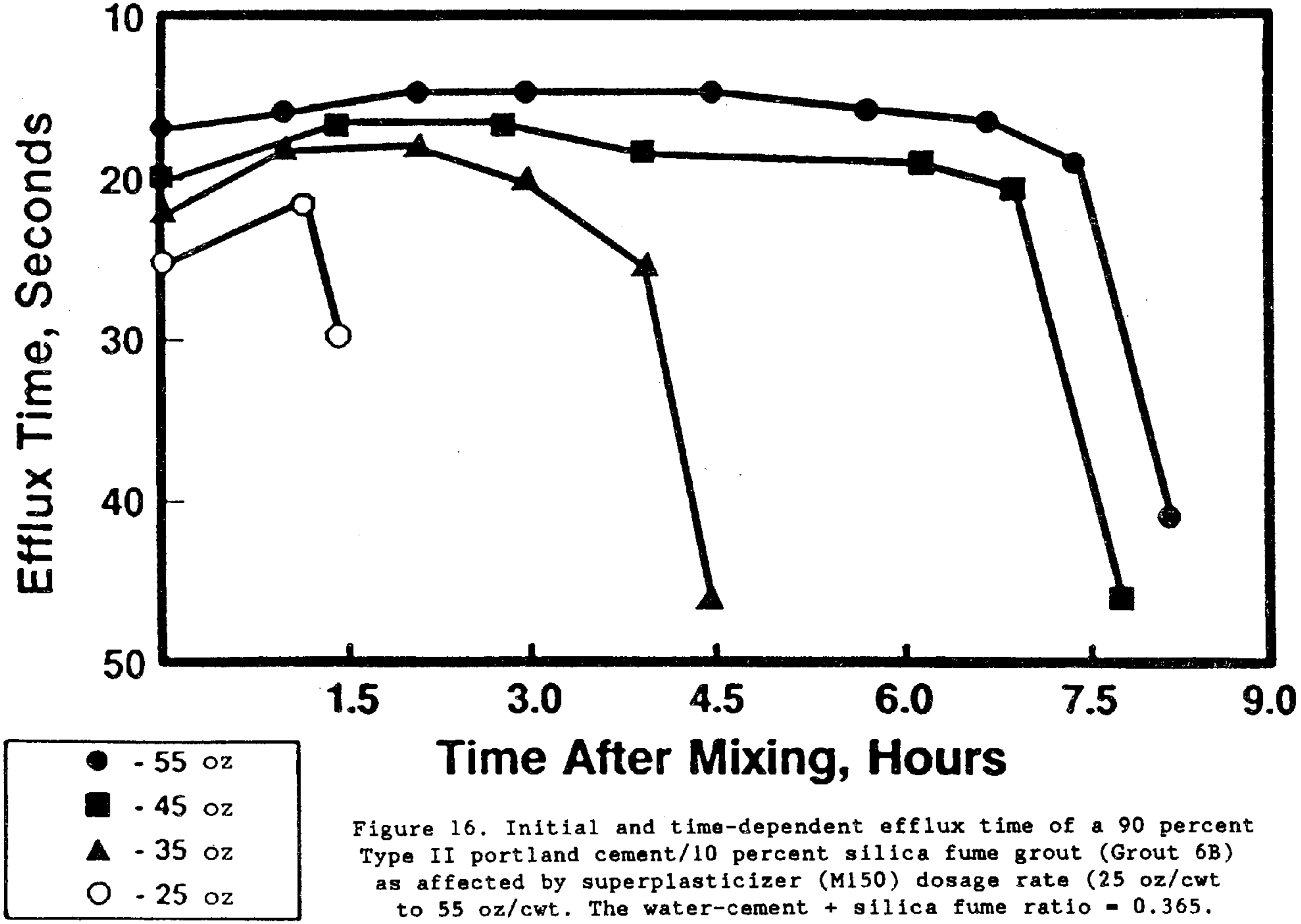


Figure 16. Initial and time-dependent efflux time of a 90 percent Type II portland cement/10 percent silica fume grout (Grout 6B) as affected by superplasticizer (M150) dosage rate (25 oz/cwt to 55 oz/cwt. The water-cement + silica fume ratio = 0.365.

1 oz/cwt = 0.65 ml/kg

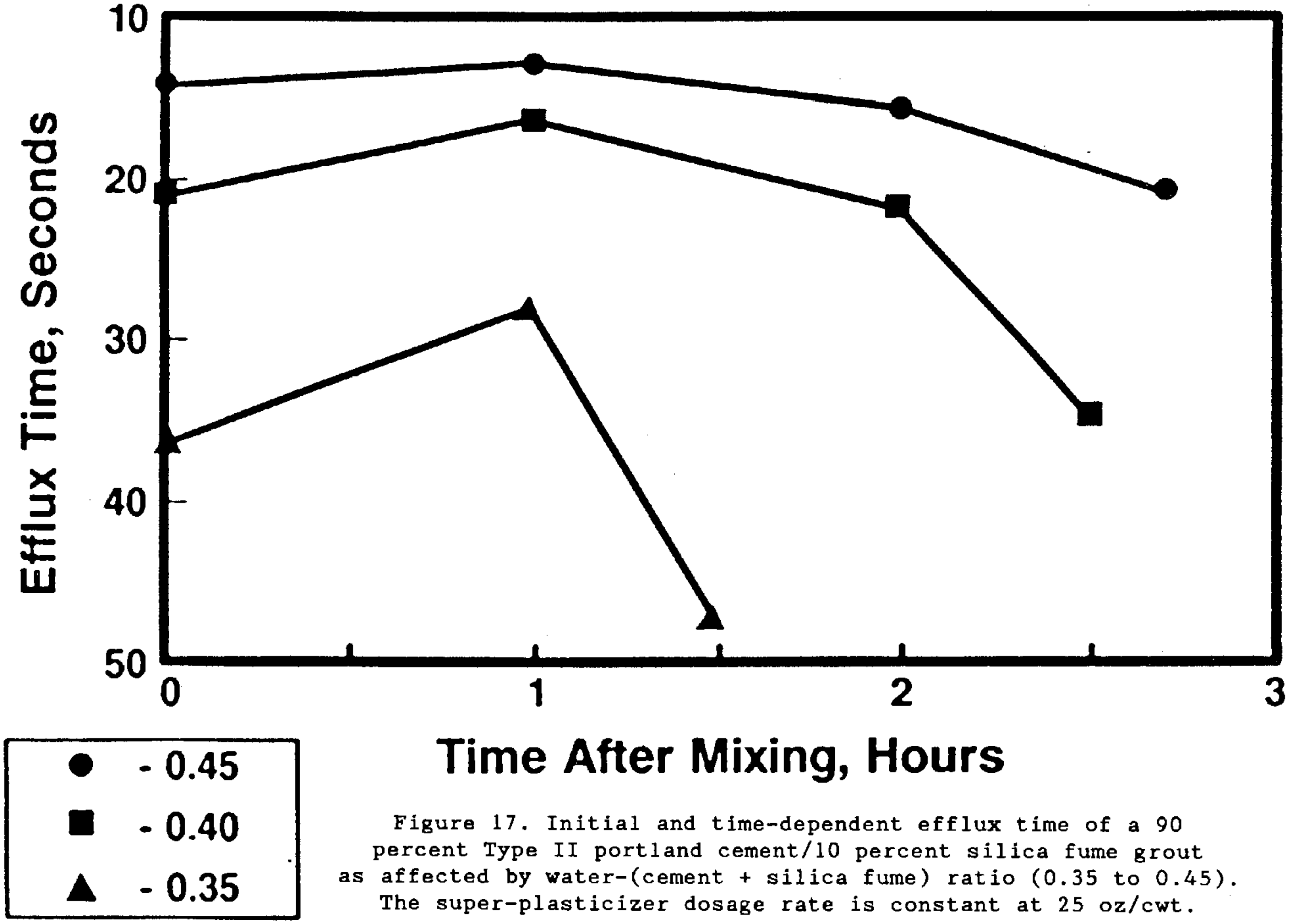


Figure 17. Initial and time-dependent efflux time of a 90 percent Type II portland cement/10 percent silica fume grout as affected by water-(cement + silica fume) ratio (0.35 to 0.45). The super-plasticizer dosage rate is constant at 25 oz/cwt.

1 oz/cwt = 0.65 ml/kg

Table 20. Summary of property data on experimental grouts containing 10 percent silica fume cement replacement (Composition 6B) and 20 percent silica fume cement replacement (Composition 6D) at a water to cement plus silica fume ratio of 0.365 (series No. 6).

Grout	Unit Weight, lb/ft^3	Initial Flow Cone Efflux Time, sec.(a)	Bleeding Percent(b)	Expansion Percent(b)	Bleeding Under Pressure(c)		Grout Open Time, Hr:Min (Estimated Time Grout Remains Pumpable at 74°F)
					Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi	
Comp. 6B	116	28	0	0	10	16	1:53
Comp. 6D	117	27	0	0	30	6	6:00

Grout	Setting Time(d)		Heat Evolution Behavior		Compressive Strength, psi(e)				Rapid Permeability Test Results(f)	
									Current Flow - Coulombs	
	Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min	1d	7d	28d	90d	60V	30V
Comp. 6B	6:50	9:00	170	11:00	3310	7130	10,030	11,620	270	900-1000
Comp. 6D	10:23	12:00	150	15:00	1930	6760	8830	9340	590	150

(a) ASTM C939
(b) ASTM C940
(c) Gelman pressure filtration procedure
(d) ASTM C953
(e) ASTM C942
(f) AASHTO Designation T277-83

1 lb/ft^3 = 16.2 kg/m^3
1 psi = 6.9 kPa
5(F-32)/9 = C

(percent of cement weight based on dry latex solids). In conjunction with the use of the HRWR at an addition rate of 15 oz/cwt (9.7 ml/kg), a water-cement ratio of 0.29 was achieved in a grout with an initial efflux time of 16 seconds and an open time of over 5 hours. The grout showed no bleeding or segregation.

The composition of the latex-modified grout (Composition 8-1) is shown in table 21 and the properties of the grout are summarized in table 22. The curing of the latex-modified grouts differed from that of the other grouts. Latex-modified grouts, following a 24-hour mold curing period, were sealed in polyethylene containers so that some drying could occur to deposit the latex film (autogenous drying).

Table 21. Experimental grout containing SBR latex polymer modifier admixture (Series No. 8).

Constituent	Composition 8
Type II Portland Cement	100 parts by weight
Dow Modifier A:SBR Latex Polymer Modifier	31.5 parts by weight
Water (w/c = 0.29)[a]	13 parts by weight
HRWR Admixture	15 fl oz per 100 lb of cement

[a] Water-cement ratio = 0.29 (includes mixing water and water contribution from latex polymer solution.

1 fl oz/lb = 65 ml/kg

Shown in table 22, the latex-modified grout had an excellent fluidity (initial flow cone efflux time = 16 seconds) that was maintained in a pumpable condition for over 5 hours. Relative to the standard grout, the latex-modified grout showed a significant improvement in water retention capacity and a reduced chloride ion permeability. The 1-day compressive strength of the latex-modified grout was 65 percent that of the standard grout while strengths at 7, 28, and 90 days were equal.

In summary, the use of an SBR latex in conjunction with a HRWR provided significant improvements in grout properties relative to the standard grout in the application of interest. The latex-modified grout showed the best performance of all grouts tested here in the pressure filtration test. A pressure of 50 psi (345 kPa) was required before any water was lost from the grout, and at a final pressure of 80 psi (552 kPa) only 1 percent of the total water was removed from the latex-modified grout (Composition 8-1).

Table 22. Summary of property data on experimental grout containing SBR latex modifier (Composition 8-1) at a water-cement ratio of 0.29 (series no. 8).

Unit Weight, lb/ft^3	Initial Flow Cone Efflux Time, sec.(a)	Bleeding Percent(b)	Expansion Percent(b)	Bleeding Under Pressure(c)		Grout Open Time, Hr:Min (Estimated Time Grout Remains Pumpable at 74°F)
				Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi	
117	16	0	0	50	1	5:20

Setting Time(d)		Heat Evolution Behavior		Compressive Strength, psi(e)				Rapid Permeability Test Results(f)	
								Current Flow - Coulombs	
Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min	1d	7d	28d	90d	60V	30V
9:57	11:15	155	16:00	1775	5710	7150	9190	15,000	1600

(a) ASTM C939
(b) ASTM C940
(c) Gelman pressure filtration procedure

(d) ASTM C953
(e) ASTM C942
(f) AASHTO Designation T277-83

1 lb/ft^3 = 16.2 kg/m^3
1 psi = 6.9 kPa
5(F-32)/9 = C

Series No. 11 - Effect of Expansive Additive on Grout Properties and Behavior

Opinion is divided as to the merit of incorporating an expansion-causing additive in grouts for bonded, post-tensioned construction. In this program, a grout composition (Composition 11L) was developed to study this variable. Composition 11L is shown in table 23. The properties of Grout 11L are summarized in table 24.

Table 23. Experimental grout containing an aluminum powder expansion-causing additive (Series No. 11).

Constituent	Composition 11
Type II Portland Cement	100 parts by weight
Aluminum Powder (Alcan No. 44)	0.0075 parts by weight
Polysaccharide Gum	0.01 parts by weight
Water (w/c = 0.338)	32.7 parts by weight
HRWR Admixture	32 fl oz per 100 lb of cement

1 fl oz/lb = 65 ml/kg

The performance of Composition 11L somewhat paralleled the performance of the grout containing the commercial anti-bleed admixture (Composition 2-1 at a water-cement ratio of 0.46). Although Composition 11L at a water-cement ratio of 0.34 was initially pourable, it was quite viscous (initial flow cone efflux time of 57 seconds). The grout first yielded water at a pressure of 30 psi (207 kPa) and the percent of the total water removed at 80 psi (552 kPa) was 7 percent. The grout had an open time of 7-1/2 hours and had a compressive strength at all ages up to 90 days about 60 to 70 percent of that for the standard grout with no admixtures at a water-cement ratio of 0.44. Similar to the grout containing the commercial anti-bleed admixture, Grout 11L containing the experimental anti-bleed admixture showed a relatively high value in the rapid permeability test (7200 coulombs passed in 6 hours at 30 V).

One interesting and unexpected phenomenon associated with Composition 11L was the nature of the expansion caused by the aluminum powder. In simple cement/water systems, a powdered aluminum additive typically provides some expansion within 15 minutes to 60 minutes after water/cement contact time. The expansion behavior of Composition 11L is shown in figure 18. No expansion occurred in the grout for up to 3 hours after mixing. At that point (3 hours) the grout began to expand and showed a final expansion value of 9 percent after 6 hours.

Table 24. Summary of property data on experimental grout containing an experimental anti-bleed additive, an HRWR, and an expansion-causing additive (Composition 11L) at a water-cement ratio of 0.338 (series no. 11).

Unit Weight, lb/ft^3	Initial Flow Cone Efflux Time, sec.(a)	Bleeding Percent(b)	Expansion Percent(b)	Bleeding Under Pressure(c)		Grout Open Time, Hr:Min (Estimated Time Grout Remains Pumpable at 74°F)
				Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi	
126	57	0	0	30	7	7:30

Setting Time(d)		Heat Evolution Behavior		Compressive Strength, psi(e)				Rapid Permeability Test Results(f)	
								Current Flow - Coulombs	
Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min	1d	7d	28d	90d	60V	30V
13:00	13:50	N.D.	N.D.	1850	4810	5440	6225	N.D.	7200

(a) ASTM C939
(b) ASTM C940
(c) Gelman pressure filtration procedure
(d) ASTM C953
(e) ASTM C942
(f) AASHTO Designation T277-83

1 lb/ft^3 = 16.2 kg/m^3
1 psi = 6.9 kPa
5(F-32)/9 = C

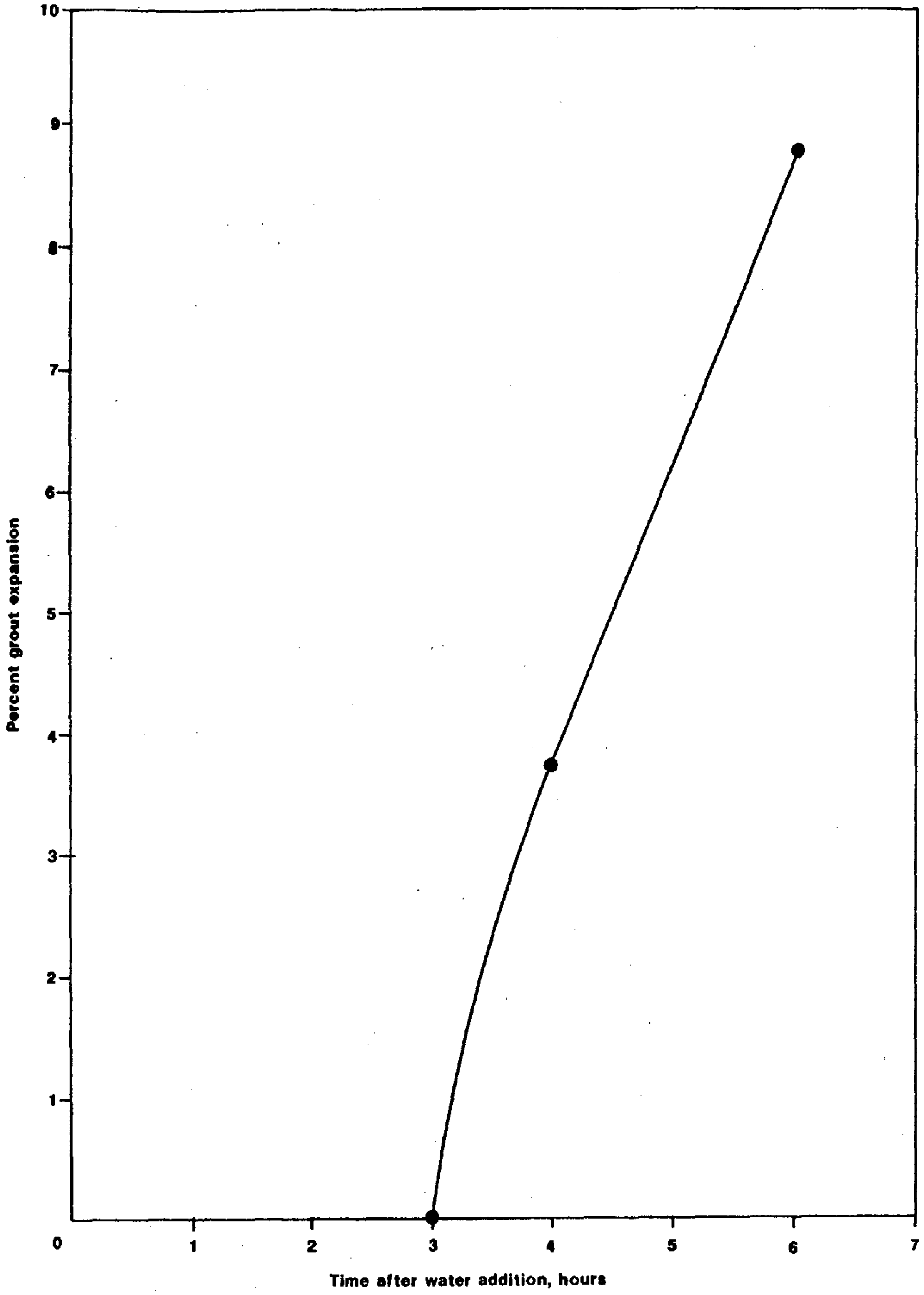


Figure 18. Expansion behavior (in the fresh state) of Grout 11L containing an anti-bleed additive, an HRWR, and Al powder at a water-cement ratio of 0.34.

Series 12 - Effect of Experimental Anti-Bleed Admixture on Grout Properties and Behavior

A number of anti-bleed/thickening admixtures were evaluated in the program. Following initial screening tests, most of the work was done on grouts containing a polysaccharide gum. The principal intended function of the gum was as an anti-bleed/anti-segregation additive. The ability of the gum to provide an anti-bleed/anti-segregation function (under pressure) is demonstrated in the data shown in table 25 and in figure 19.

Shown in table 25, the standard grout containing only cement and water at a water-cement ratio of 0.44, actually lost some water before any pressure was applied. With a 1.5-percent addition of a commercial anti-bleed additive (Conbex 209X), water was first lost from a grout with a water-cement ratio of 0.46 at 30 psi (207 kPa). Additions of the polysaccharide gum were made to the 20 percent silica fume grout (Grout No. 6D) at a rate of 0.05, 0.10, and 0.20 percent (based on cement weight). With no gum additive, a pressure of 20 psi (138 kPa) was required to initially force water from Grout 6D. At the 0.05-percent gum level, a 30-psi (207 kPa) pressure was required while at 0.10 and 0.20-percent gum addition, the pressure to remove water was increased to 50 and 70 psi (345 and 483 kPa) respectively.

The polysaccharide gum had the same water retention effect in a variety of grout compositions. Data reported in table 25 for a sanded grout (Grout No. 5-1) containing a silica sand, flyash, and an HRWR at a water to cement plus flyash ratio of 0.27. For this composition, the polysaccharide gum overcame any tendency of the silica sand to segregate and required a pressure of 50 psi (345 kPa) before water was removed from the grout.

Figure 19 shows the cumulative water loss in the pressure filtration test from grouts with and without anti-bleed additives. The polysaccharide gum not only increases the pressure required to first force water from the grout but also limits the total amount of water forced from the grout at the highest pressure (80 psi or 552 kPa). The best result was obtained using 0.20 percent of the gum in silica fume grout Composition 6D. Here, 70 psi (483 kPa) was required before any water was forced from the grout and at 80 psi (552 kPa) only 0.5 percent of the total water was removed from the grout.

At increasing levels of polysaccharide gum (to a maximum of 0.20 percent), the fluidity of the grout is adversely affected. However, at the highest addition rate (0.20 percent of cement weight), the grout is still pumpable.

TASK C - DESIGN AND CONDUCT LABORATORY TEST PROGRAM

In task A, the detailed test procedures of the ACTM were previously presented. In task C, the ACTM procedures were performed on seven different grouts. The detailed test procedures previously given in task A are the procedures proposed for the final ACTM tests. During task C, these procedures were modified from time to time as the testing progressed. Of significant importance is the casting procedure used. Throughout this section, specimens

Table 25. Pressure at which water is first lost from grouts subjected to elevated pressure in the pressure filtration funnel.

Grout Identification	Filtration Funnel Pressure at Which Water Loss Was First Effected in the Grouts, psi
"Standard" Grout No. 1 containing only cement and water (w/c = 0.44)	0
Grout No. 2-1 containing cement, water, and 1.5% (by cement weight) of a commercial anti-bleed additive (w/c = 0.46	30
Grout No. 6D, a silica fume/superplasticized grout (20% silica fume) having a water to cement + silica fume ratio of 0.365	20
Grout No. 6D containing 0.05% (by cement weight) of Welan Gum (a polysaccharide gum - Kelco Company - K1A96 - 47004A)	30
Grout No. 6D containing 0.1% Welan Gum (polysaccharide gum)	50
Grout No. 6D containing 0.2% Welan Gum (polysaccharide gum)	70
Sanded Grout No. 5-1 containing flyash (w/c = 0.351)	50

1 psi = 6.9 kPa

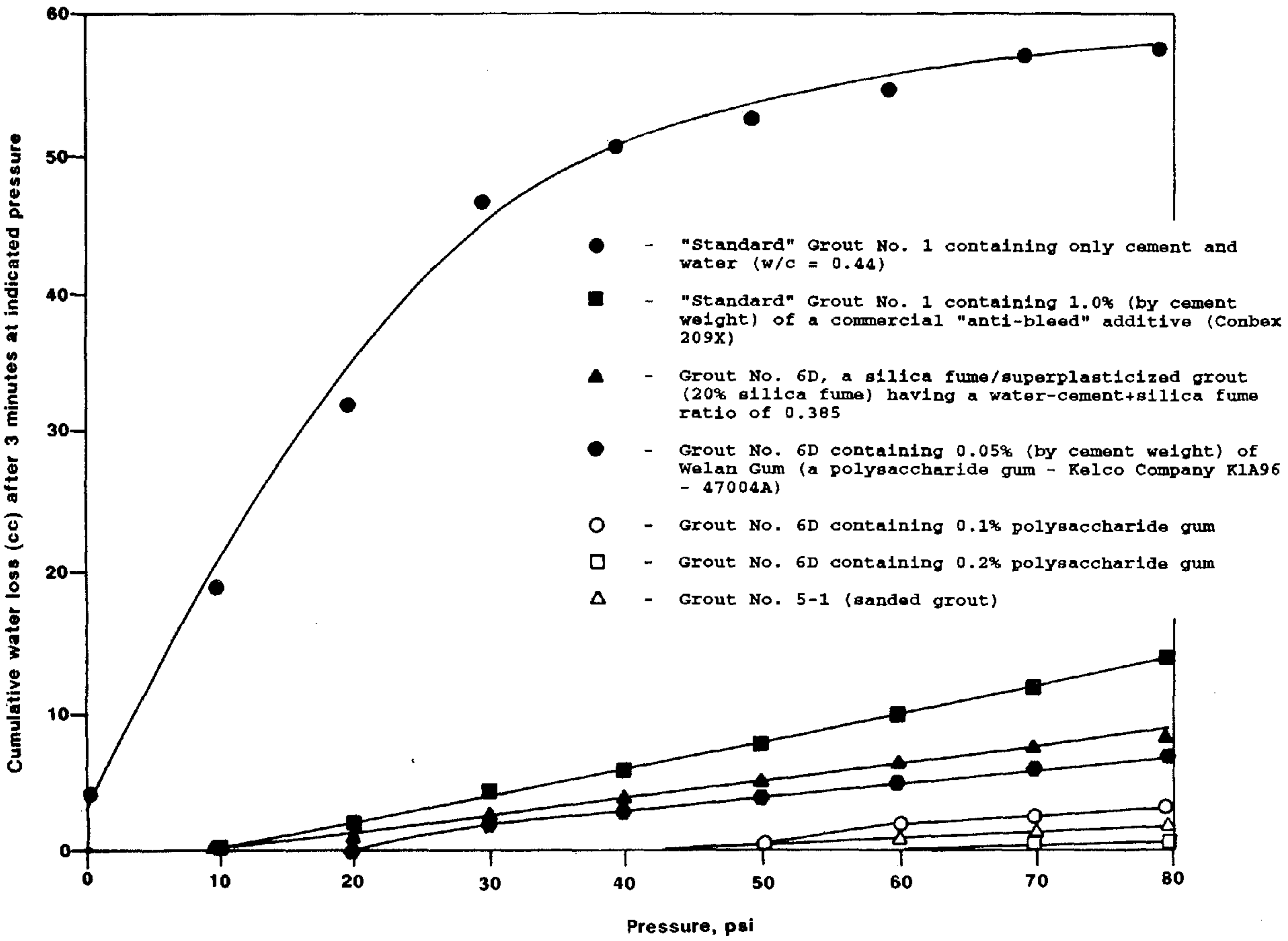


Figure 19.Cumulative water loss from indicated grouts (from 0 To 80 psi) using the Gelman pressure filtration funnel.

1 psi = 6.9 kPa

1 cm^3(cc) = 0.06 in^3

were prepared using the new casting procedure unless otherwise designated. The new casting procedures are those described in the procedures given in task A. The original casting procedures were much more complicated and were aimed at filling the grouted specimen from the bottom to attempt to prevent air voids from forming. The much more complicated procedures ended up producing more voids than the simplified procedures described in task A. It should be noted that a void-free and crack-free specimen is mandatory prior to testing.

An additional change was made to the ACTM as described in task A. The ACTM was to include a minimum cover grout specimen produced by dipping the steel tendon specimen into the grout and pulling the steel specimen out allowing the grout to freely drip off. It was extremely difficult to achieve any consistency in specimen preparation. The initial data produced using the dipped specimens indicated that, in most instances, corrosion was initiated immediately such that differentiation between specimens was difficult, if not impossible, to make. Therefore, it was decided to delete the dipped specimens from the testing procedures.

The grouts tested in task C were selected based on the physical and mechanical property data generated in task B. The following is a list of the grouts examined utilizing the ACTM in this task:

1. Grout No. 1 - Standard grout, Type II portland cement and water (w/c = 0.44).

2. Grout No. 1B - Standard Grout with high water-cement ratio (w/c = 0.65).

3. Grout No. 5-1 - HRWR (40 oz/cwt or 26 ml/kg) plus 14 percent flyash and 23 percent sand (w/c + f = 0.32).

4. Grout No. 6B - HRWR (24 oz/cwt or 15.6 ml/kg) plus 10 percent silica fume (w/c + sf = 0.365).

5. Grout No. 8-1 - HRWR (15 oz/cwt or 9.7 ml/kg) plus 22 percent SBR latex modifier (w/c = 0.29).

6. Grout No. 10-1 - Standard grout with calcium nitrite inhibitor (6 gallons/yd^3 or 30 l/m^3 of grout).

7. Grout No. 11L - HRWR (32 oz/cwt or 20.8 ml/kg) plus 0.0075 part by weight aluminum powder and 0.01 part by weight polysaccharide gum (w/c = 0.338).

Grout No. 1 - Standard Grout

As previously mentioned, the ACTM was performed initially using what has been termed "original casting procedures." The original casting procedures gave less than satisfactory reproducibility of the specimens due to air void entrapments in the grout. Upon changing to the "new casting procedures", very few specimens were rejected due to air voids present in the grout cover. In the following sections, data is presented for the new casting procedures only.

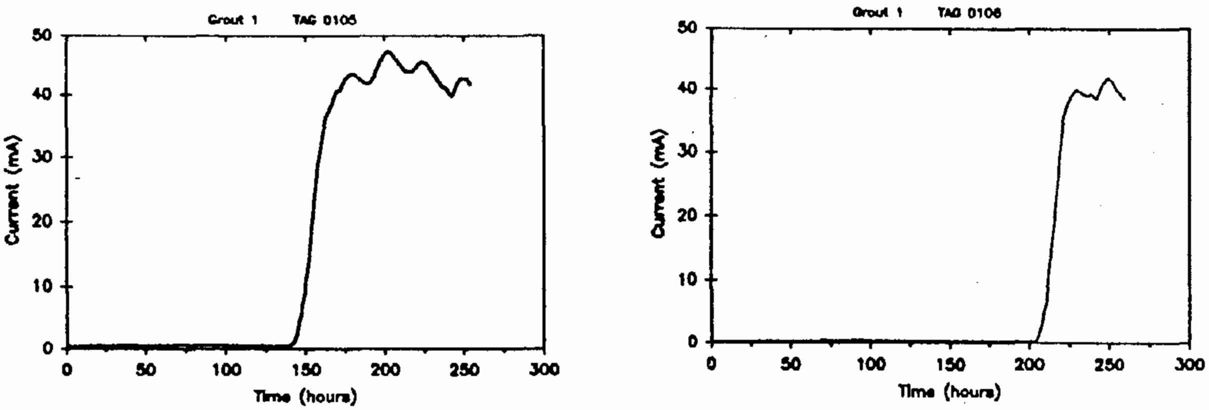
Figure 20 shows the results of the ACTM for Grout No. 1. The data are presented as current-time plots, where an increasing current signifies the initiation of corrosion. The important data selected from these plots are time to corrosion initiation and total current following initiation of corrosion. The data in figure 20 is for four replicate standard grout specimens. As seen in the figure, the current remains near zero for an initial period of time where the carbon steel is passive and Cl^- has not migrated to its surface. Following this initial period, for specimens prepared with Grout No. 1, there is a very sharp rise in current signifying the onset of corrosion. It is this time to corrosion initiation that is of most interest to this study.

A second parameter of interest is the current following breakdown of corrosion. This current is measured 24 to 48 hours following breakdown of corrosion. Table 26 summarizes the data for these tests. It is seen that the mean value for the time to failure for Grout No. 1 is 164 hours with the standard deviation of 40 hours. The mean current following breakdown is 41 mA with a standard deviation of 3 mA. These data become the baseline information by which all of the other grouts examined in this study are compared.

Figure 21 shows data for the ACTM performed on specimens prepared using Grout No. 1 which were precracked prior to testing. The data for these specimens are summarized in table 26. The mean value for the time to failure was 89 hours for the precracked specimens with a standard deviation of 61 hours. The large standard deviation indicates a significant variation in the data from specimen to specimen. This greater variation for the precracked specimens was expected since the procedures for producing the cracks cannot produce reproducible cracking from one specimen to the next. Also seen in figure 21 is that the current following breakdown for these specimens are continuing to increase even after 24 to 48 hours. Although the data shown in table 26 indicates only a slight increase in current following breakdown between the standard specimens and the precracked specimens, a comparison of figure 20 to figure 21 show that the current following breakdown for the precracked specimens was continuing to increase even after the ACTM was terminated. As seen in table 26, the time to failure was greatly decreased for the precracked specimens versus the standard (uncracked) specimens.

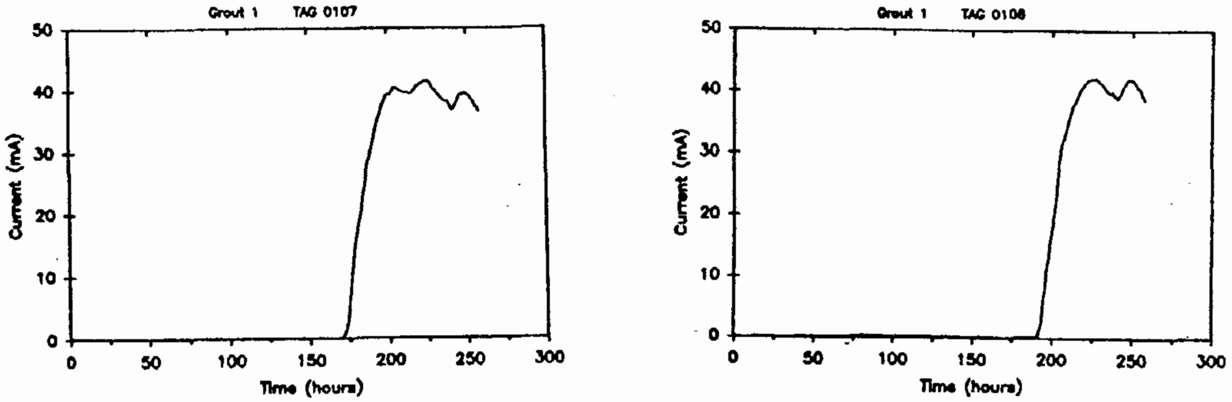
Grout No. 1B - Standard Grout With High Water To Cement Ratio

The grout was prepared with a relatively high water-cement ratio (w/c = 0.65) to determine whether the ACTM would detect a "poor standard grout". Grout No. 1B is exactly the same as Grout No. 1 with a higher water to cement ratio. Figure 22 shows the ACTM results for standard specimens prepared with Grout No. 1B. These data are summarized in table 27. The mean time to failure for specimens prepared with Grout No. 1B is 30 h with the standard deviation of 13 h. This was the lowest mean time to failure observed and much lower than for Grout No. 1. Therefore, the ACTM can easily detect the difference between a poor grout with a high water to cement ratio and an improved grout with a lower water to cement ratio.



a. Specimen No. 0105

b. Specimen No. 0106



c. Specimen No. 0107

d. Specimen No. 0108

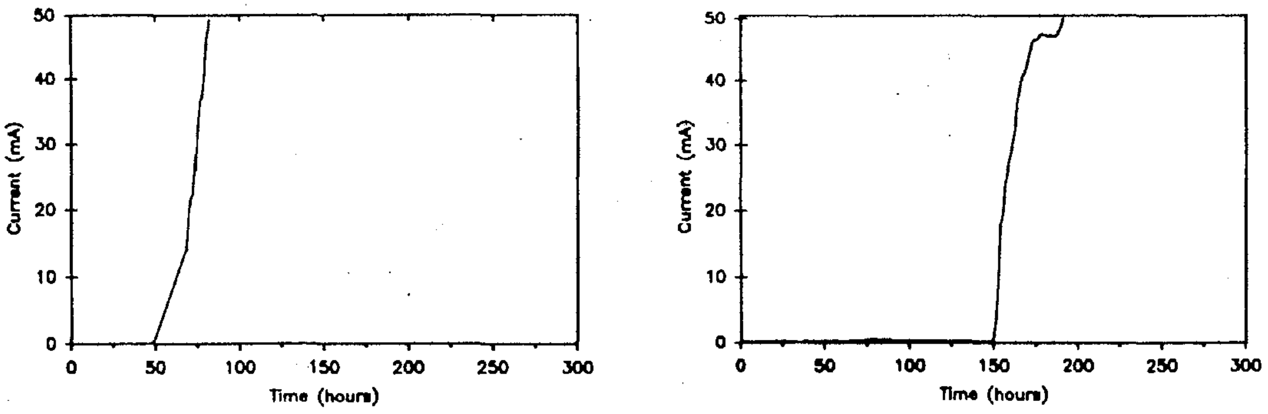
Figure 20.ACTM current-time data for replicate standard specimens for Grout No. 1 - standard grout.

Table 26. Summary of ACTM data for Grout No. 1 - standard grout.

Specimen Type	Specimen No.	Time To Failure, Hours	Current Following Breakdown,[a] mA
Standard	#0105	140	45
Standard	#0106	205	40
Standard	#0107	120	38
Standard	#0108	190	40
Mean Value		164	41
Std. Dev.		40	3
Precracked	#0109	50	50[b]
Precracked	#0110	150	48[b]
Precracked	#0111	25	50[b]
Precracked	#0112	130	34[b]
Mean Value		89	45
Std. Dev.		61	8

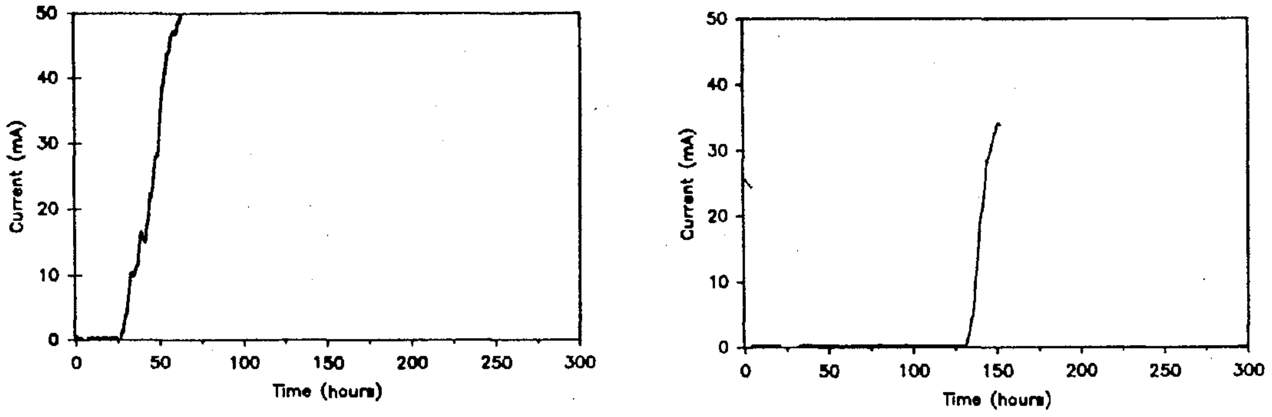
(a) Measured 24 to 48 h following breakdown (initiation of corrosion).

(b) Current continuing to increase.



a. Specimen No. 0109

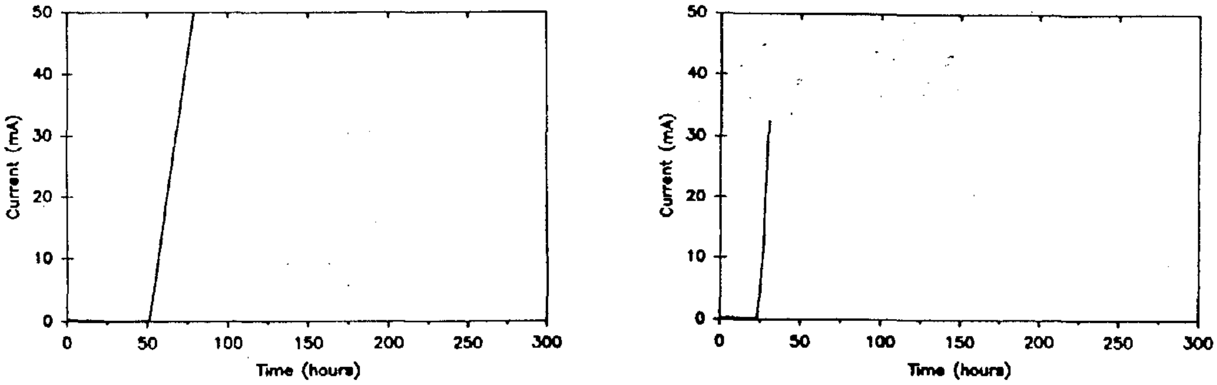
b. Specimen No. 0110



c. Specimen No. 0111

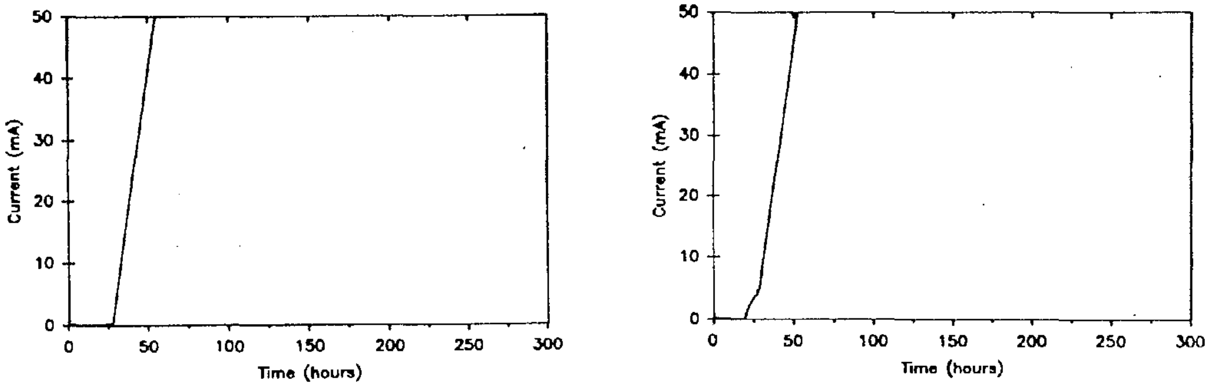
d. Specimen No. 0112

Figure 21. ACTM current-time data for replicate precracked specimens for Grout No. 1 - standard grout.



a. Specimen No. 0171

b. Specimen No. 0174



c. Specimen No. D

d. Specimen No. C

Figure 22. Modified ACTM (using 0.0 V, SCE, polarization) current-time data for replicate standard specimens for Grout No. 1B - standard grout with high w/c.

Table 27. Summary of ACTM data for Grout No. 1B - standard grout with high w/c.

Specimen Type	Specimen No.	Time To Failure, Hours	Current Following Breakdown,[a] mA
Standard	#0171	50	50[b]
Standard	#0174	25	32[b,c]
Standard	#D	27	50[b,c]
Standard	#C	20	50[b]
Mean Value		30	46
Std. Dev.		13	9

(a) Measured 24 to 48 h following breakdown (initiation of corrosion).
(b) Current continuing to increase.
(c) Data collection discontinued prior to 24 h following breakdown.

Grout No. 5-1 - HRWR Plus Flyash and Sand

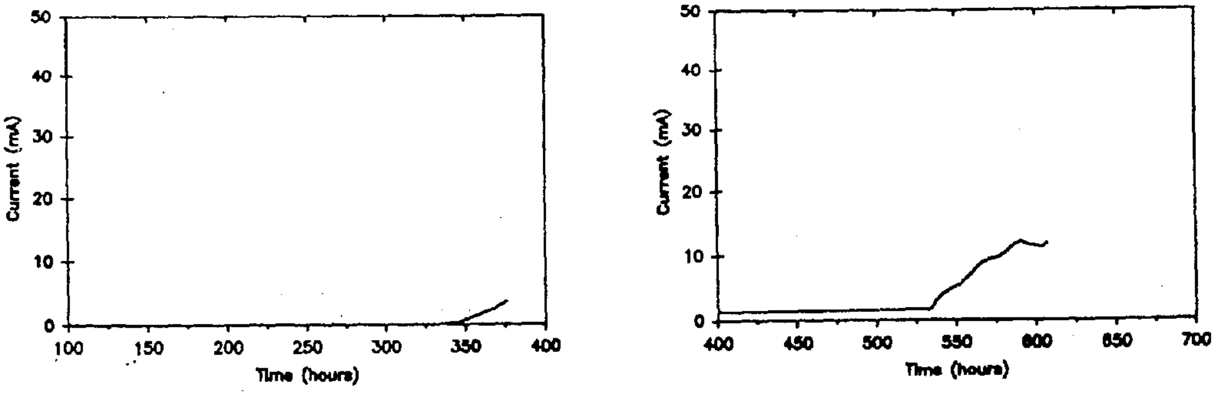
Figure 23 shows the ACTM results for the standard grout specimens cast with Grout No. 5-1. Table 28 summarizes the data for Grout No. 5-1. It is seen that the time to failure for the standard specimens is significantly greater for Grout No. 5-1 than for Grout No. 1. In addition, the current following breakdown, although slowly increasing with time is significantly lower than that observed for the standard grout. Therefore, significant improvement in the ability to resist corrosion of the steel tendon was achieved utilizing Grout No. 5-1.

Figure 24 gives the results of the ACTM for the precracked specimens cast with Grout 5-1. Data for the three replicate precracked specimens are summarized in table 28. The time to failure for the precracked specimens for Grout No. 5-1 is significantly lower than that observed for the precracked specimens cast with the standard grout. In fact, two of the three specimens initiated corrosion immediately upon beginning the ACTM.

Grout No. 6B - HRWR Plus Silica Fume

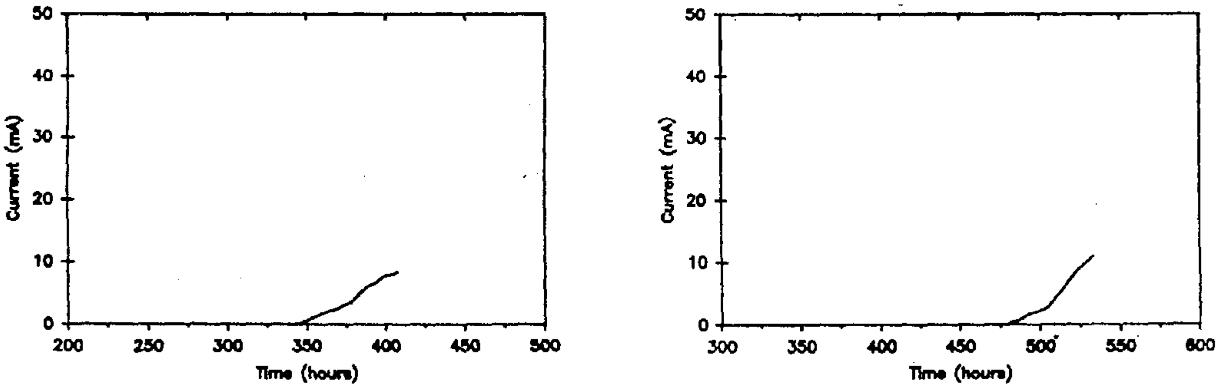
Figure 25 shows four replicate standard specimens for Grout No. 6B. The data is summarized in table 29. The time to failure data for the standard specimen gives a mean value of 295 h with the standard deviation of 242 h. The large standard deviation indicates a significant variation in time to failure data from specimen to specimen. This large variation is also observed in the data for the current following breakdown. As seen in Figure 25 and in table 29, the specimens with the short time to failure also had significantly higher current following breakdown. This is possibly due to a crack or void in the specimen which was present, but went undetected during the visual examination of the specimens prior to utilizing the specimen for testing. This indicates the need to perform additional tests, when a large variation is observed, to establish whether the specimens with the short time to failure and high current following breakdown are outlyers or are typical for the particular grout formulation. It is possible that this particular grout formulation had physical properties which make it difficult to prepare specimens without the presence of air voids. Even with these problems, the time to failure and the current following breakdown is a significant improvement over the specimens prepared using Grout No. 1.

Figure 26 presents two replicate precracked specimens prepared with Grout No. 6B. The data for the precracked specimens are also summarized in table 29. The data for time to failure for the precracked specimens are either zero or near zero depending on where the initiation point is selected. This data for the precracked specimens for Grout No. 6B are similar to that for Grout No. 5-1.



a. Specimen No. 0130

b. Specimen No. 0131



c. Specimen No. 0132

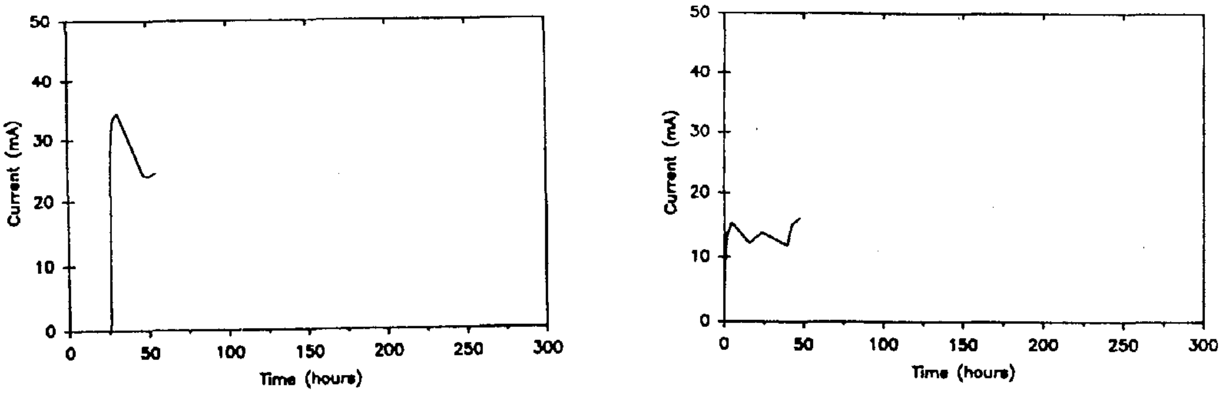
d. Specimen No. 0133

Figure 23. ACTM current-time data for replicate standard specimens for Grout No. 5-1 - HRWR plus flyash and sand.

Table 28. Summary of ACTM data for Grout No. 5-1 - HRWR plus flyash and sand.

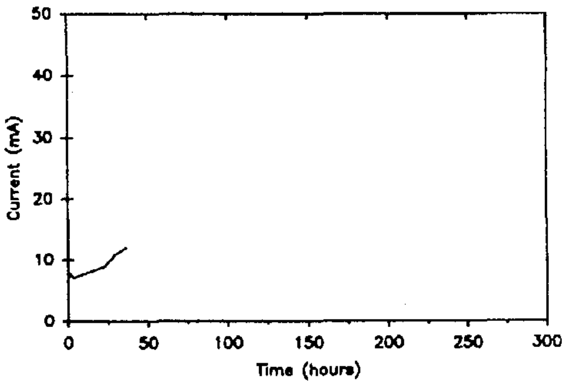
Specimen Type	Specimen No.	Time To Failure, Hours	Current Following Breakdown,[a] mA
Standard	#0130	335	5[b]
Standard	#0131	535	10[b]
Standard	#0132	350	7[b]
Standard	#0133	450	8[b]
Mean Value		418	8
Std. Dev.		93	2
Precracked	#E	25	24
Precracked	#F	0	13
Precracked	#G	0	10[b]
Mean Value		8	16
Std. Dev.		14	7

(a) Measured 24 to 48 h following breakdown (initiation of corrosion).
(b) Current continuing to increase.



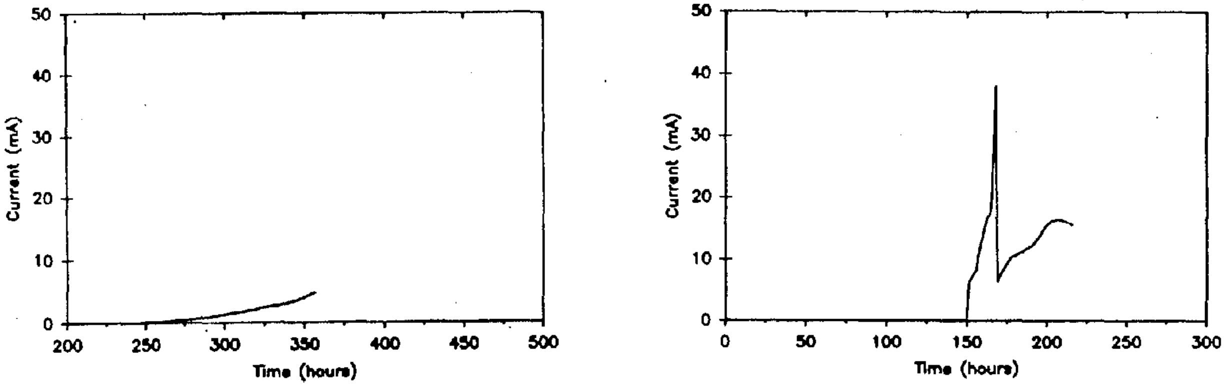
a. Specimen No. E

b. Specimen No. F



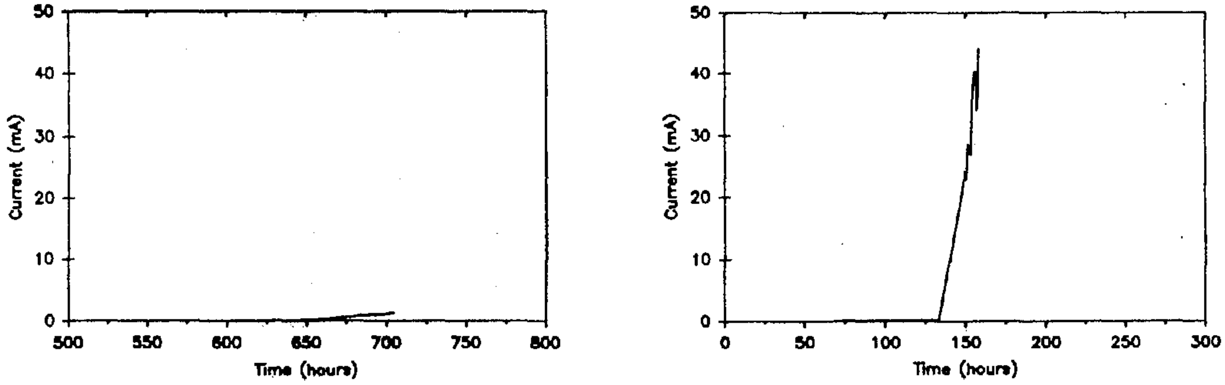
c. Specimen No. G

Figure 24. ACTM current-time data for replicate precracked specimens for Grout No. 5-1 - HRWR plus flyash and sand.



a. Specimen No. 0126

b. Specimen No. 0127



c. Specimen No. 0128

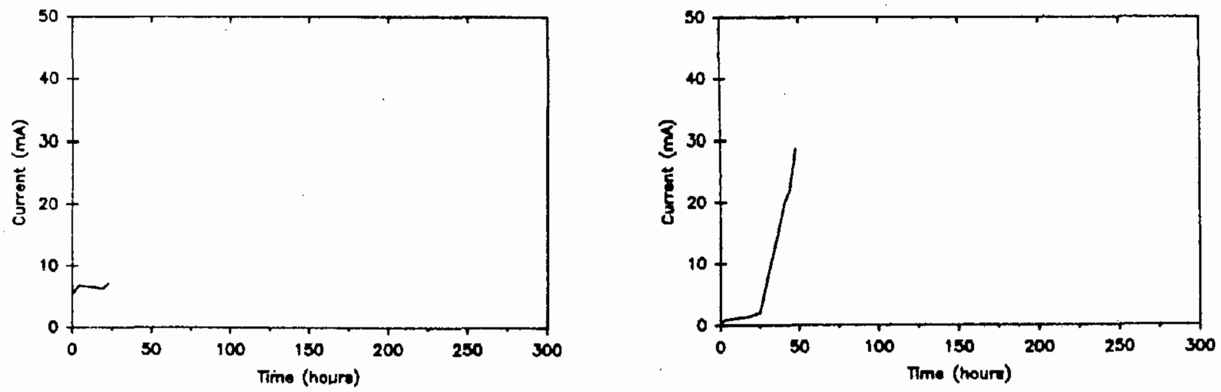
d. Specimen No. 0129

Figure 25. ACTM current-time data for replicate standard specimens for Grout No. 6B - HRWR plus silica fume.

Table 29. Summary of ACTM data for Grout No. 6B - HRWR plus silica fume.

Specimen Type	Specimen No.	Time To Failure, Hours	Current Following Breakdown,[a] mA
Standard	#0126	245	2[b]
Standard	#0127	150	11
Standard	#0128	650	2
Standard	#0129	135	40[b]
Mean Value		295	14
Std. Dev.		242	18
Precracked	#H	0	7
Precracked	#I	25	24[b]
Mean Value		12	16
Std. Dev.		18	12

(a) Measured 24 to 48 h following breakdown (initiation of corrosion).
(b) Current continuing to increase.



a. Specimen No. H

b. Specimen No. I

Figure 26.ACTM current-time data for replicate precracked specimens for Grout No. 6B - HRWR plus silica fume.

Grout No. 8-1 - HRWR Plus Latex Modifier

Figure 27 shows the ACTM data for the standard specimens prepared using Grout No. 8-1. The data selected from these curves are summarized in table 30. Six replicate specimens were tested for the standard specimen for Grout No. 8-1. The data is a mean value for time to failure of 237 h with the standard deviation of 105 h. Standard specimen no. 0140 gave the shortest time to failure and indicated a very rapid rise in current following breakdown which was uncommon of most of the other specimens. However, standard specimen no. 0180, which had the longest time to failure, also gave an uncharacteristically high current following breakdown. Both the time to failure and the current following breakdown provide a significant improvement over Grout No. 1.

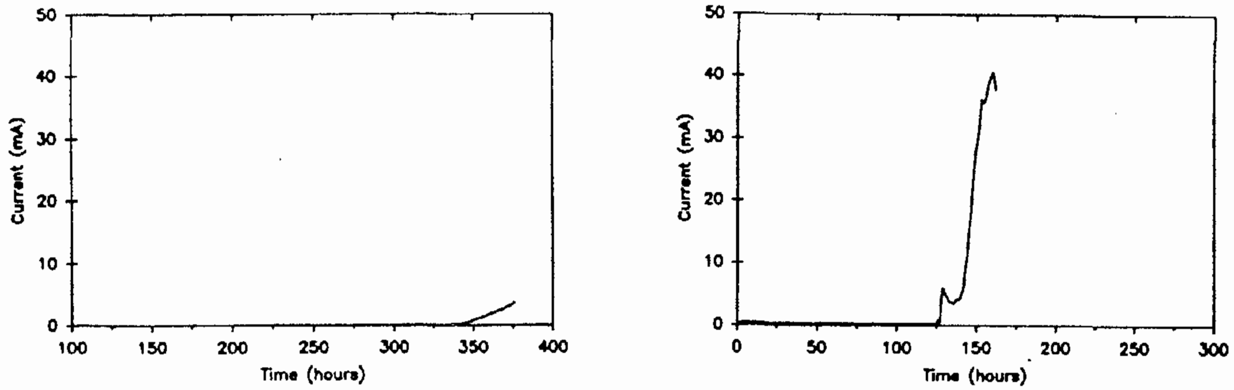
The precracked specimens were tested only for the original casting procedures. The data for the precracked specimens using the original casting procedures are summarized in table 30. The data for the precracked specimens for Grout 8-1 are similar to those previously described for Grouts No. 6B and 5-1. That is, several of the specimens initiated corrosion immediately upon immersion with one specimen showing a breakdown after 90 h. The data indicates a very small mean value for time to breakdown with a very high standard deviation. In general, the current following breakdown is greater than that observed for the standard specimens. It should be recalled, however, that the information for the precracked specimens are for the original casting procedures.

Grout No. 10-1 - Standard Grout With Inhibitor

Figure 28 presents data for standard specimens prepared using Grout No. 10-1. The important parameters for these data are summarized in table 31. The mean value for the time to failure is 129 h with a standard deviation of 50 h. This mean time to failure is slightly less than that determined for Grout No. 1. Although the current following breakdown is relatively high, it is somewhat less than that observed for Grout No. 1. For the current following breakdown, it should be noted that two of the test specimens were not permitted to corrode for the 24 to 48 hours recommended in the ACTM (due to data acquisition problems).

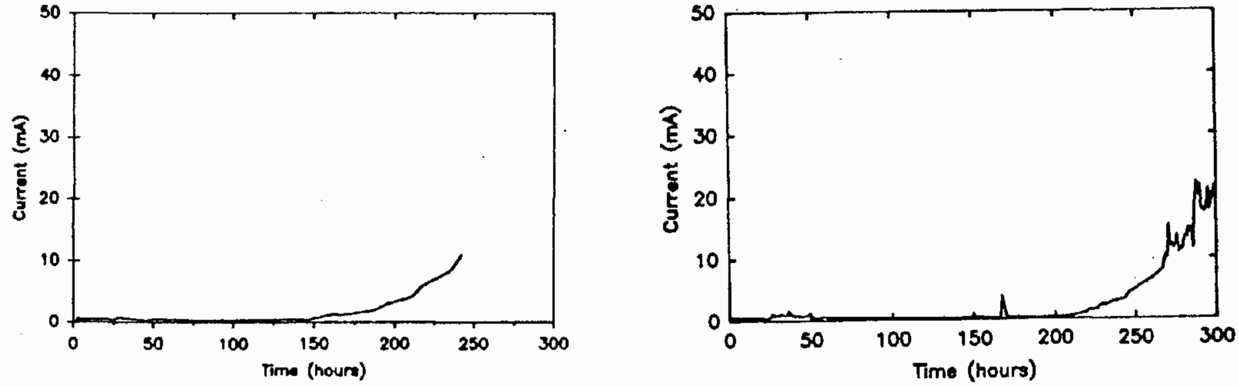
Figure 29 shows data for two replicate precracked specimens prepared using Grout No. 10-1. The data is summarized in table 31. The mean value for the time to failure is 48 h and the mean value for the current following breakdown is 49 mA. The value for the mean time to failure is somewhat less than that observed for Grout No. 1, but is much greater than that observed for Grout Nos. 8-1, 6B, and 5-1.

Grout No. 10-1 was exactly the same grout as Grout No. 1 with the exception that inhibitor was added. The data summarized in table 31 when compared to the data for Grout No. 1, which was summarized in table 26 indicates that a shorter time to failure for both the standard specimens and the precracked specimens is observed with an inhibitor added to Grout No. 1.



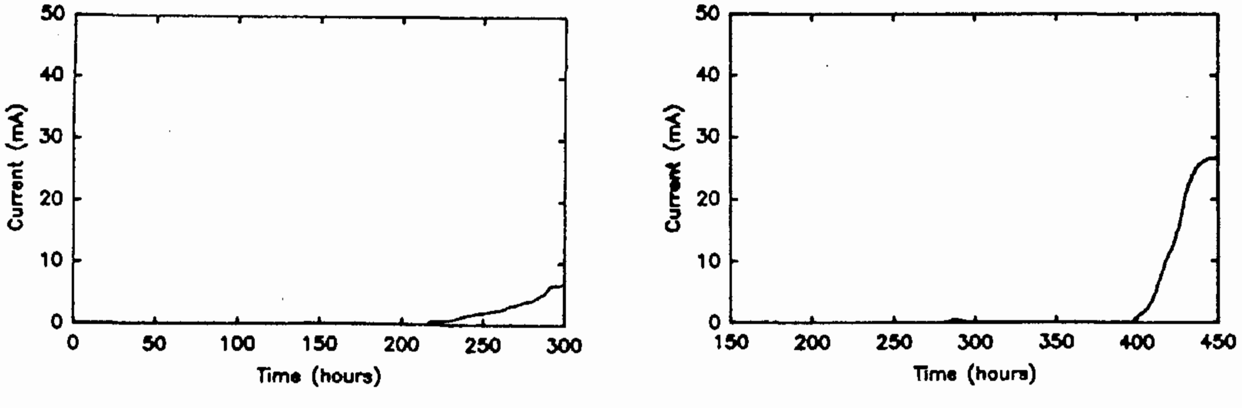
a. Specimen No. 0138

b. Specimen No. 0140



c. Specimen No. 0168

d. Specimen No. 0178



e. Specimen No. 0179

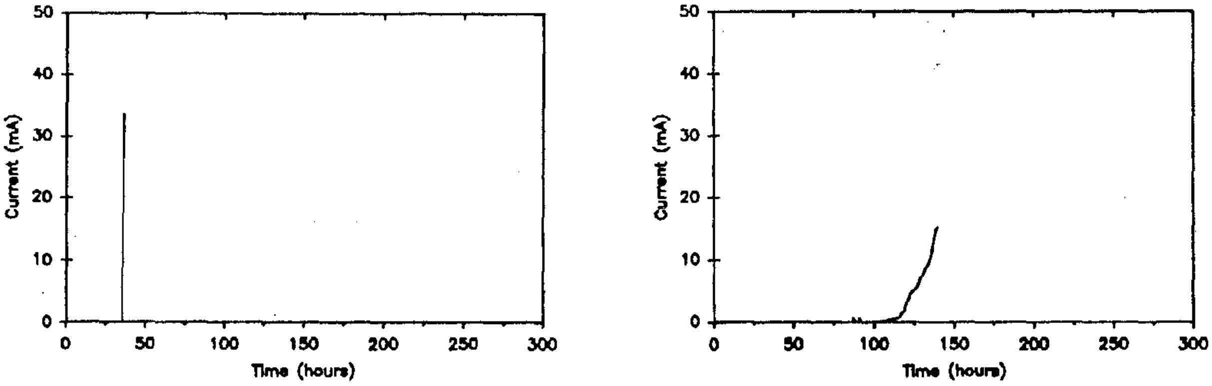
f. Specimen No. 0180

Figure 27.ACTM current-time data for replicate standard specimens for Grout No. 8-1 - HRWR plus latex modifier.

Table 30. Summary of ACTM data for Grout No. 8-1 - HRWR plus latex modifier.

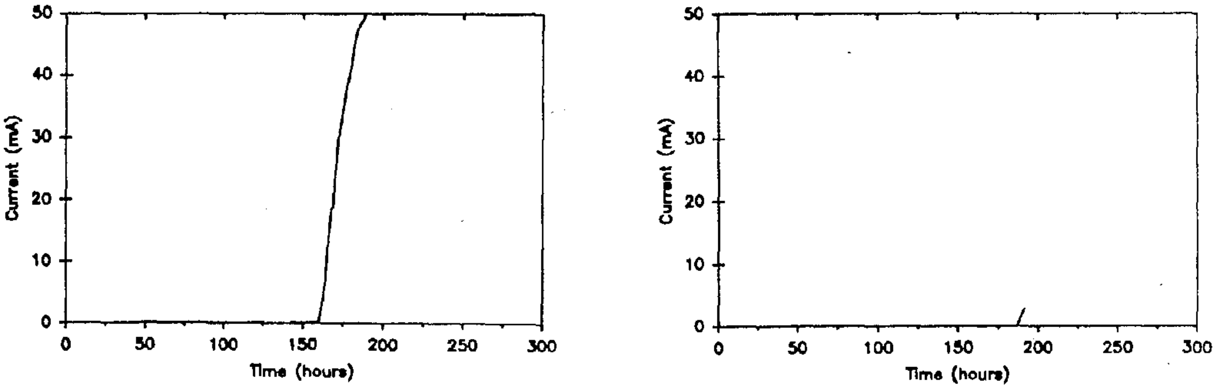
Specimen Type	Specimen No.	Time To Failure, Hours	Current Following Breakdown,[a] mA
Standard	#0138	335	4[b]
Standard	#0140	125	39
Standard	#0168	150	4[b]
Standard	#0178	200	5[b]
Standard	#0179	220	3[b]
Standard	#0180	390	27
Mean Value		237	14
Std. Dev.		105	15
Precracked	#0040[c]	90	31
Precracked	#0041[c]	0	15
Precracked	#0042[c]	0	16[b]
Precracked	#0043[c]	0	25
Mean Value		18	22
Std. Dev.		40	8

(a) Measured 24 to 48 h following breakdown (initiation of corrosion).
(b) Current continuing to increase.
(c) Original casting procedures.



a. Specimen No. 0122

b. Specimen No. 0123



c. Specimen No. 0124

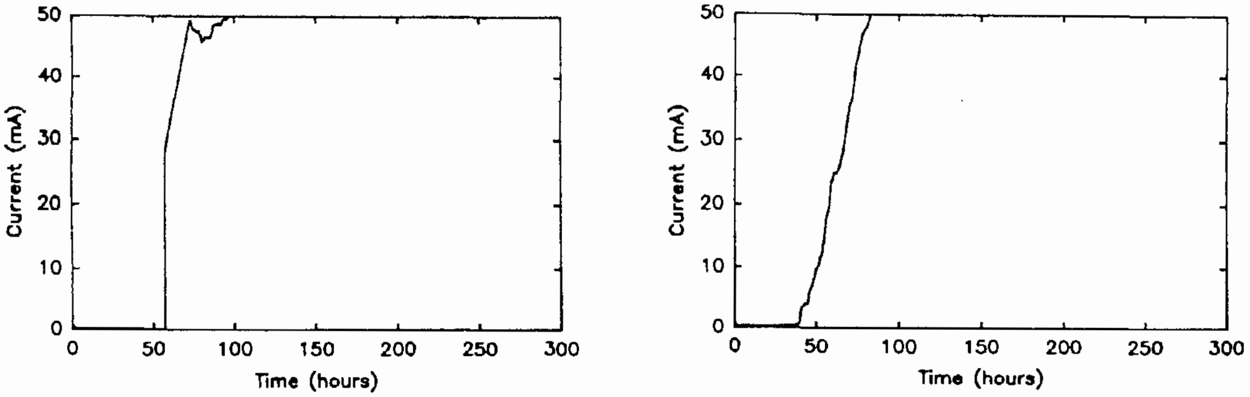
d. Specimen No. 0125

Figure 28. ACTM current-time data for replicate standard specimens for Grout No. 10-1 - standard grout with inhibitor.

Table 31. Summary of ACTM data for Grout No. 10-1 - standard grout with inhibitor.

Specimen Type	Specimen No.	Time To Failure, Hours	Current Following Breakdown,[a] mA
Standard	#0122	70	35[b,c]
Standard	#0123	105	15[b]
Standard	#0124	160	50[b]
Standard	#0125	180	3[b,c]
Mean Value		129	26
Std. Dev.		50	21
Precracked	#0183	55	48
Precracked	#0184	40	50[b]
Mean Value		48	49
Std. Dev.		11	1

(a) Measured 24 to 48h following breakdown (initiation of corrosion).
(b) Current continuing to increase.
(c) Data collection discontinued prior to 24 hr following breakdown.



a. Specimen No. 0183

b. Specimen No. 0184

Figure 29. ACTM current-time data for replicate precracked specimens for Grout No. 10-1 - standard grout with inhibitor.

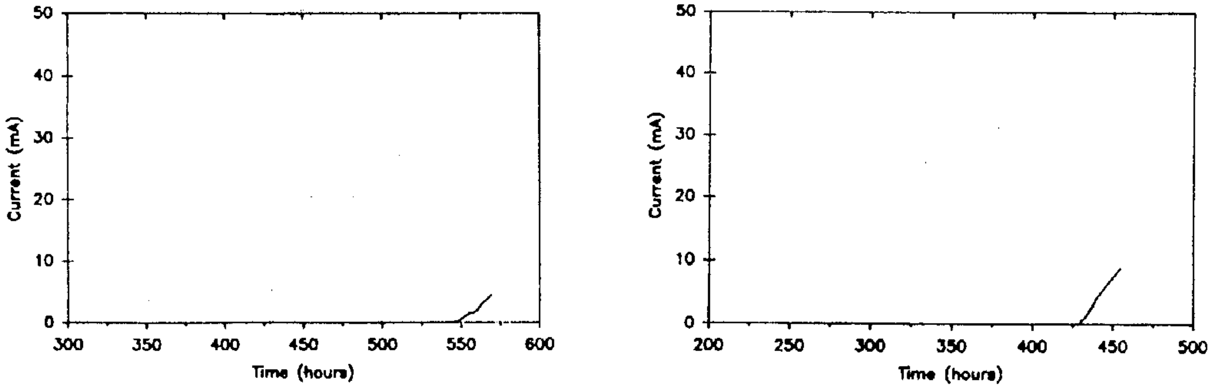
It is believed that this data is not reflective of the actual corrosion behavior of the grout with inhibitor added. This is likely due to the level of polarization applied to this test specimen (0.6V, SCE) which is above the breakdown potential for the inhibitor in the presence of Cl^-. Therefore, a modified ACTM test was performed using a polarization level of 0.0V (SCE) in place of the standard 0.6V (SCE) specified in the ACTM.

Figure 30 shows data for the standard specimens for Grout No. 10-1, utilizing the modified ACTM. Figure 31 shows the data for the standard specimen for Grout No. 1 utilizing the modified ACTM. Comparison of these data will provide a better indication of the benefits of inhibitor than the specified ACTM. The data from figures 30 and 31 are summarized in table 32. The mean time to failure or the specimens prepared with Grout No. 10-1 (with inhibitor) was 713 h. Two replicate specimens were tested with Grout No. 1 (no inhibitor added) and the mean time to failure was 177 h. The mean time to failure for specimens prepared with Grout No. 1 was very similar for the specified ACTM and the modified ACTM. Because only two specimens were tested with the modified ACTM for Grout No. 1 and the time to failure values were significantly different (290 h and 65 h), it is difficult to make a comparison with a high level of confidence. The time to failure would be expected to be the same only if no enhanced migration of Cl^- is produced by the applied potential. As seen in table 32, a significant benefit is now observed in the time to corrosion failure for Grout No. 10-1 with inhibitor added. This shows the importance of utilizing the modified ACTM when examining grouts with inhibitors added. It should also be noted that the current following breakdown for specimens both with Grout 10-1 and No. 1 were similar and much lower than the current following breakdown for the specified ACTM (0.6V, SCE polarized potential) performed for Grout No. 1. This difference between the specified ACTM and the modified ACTM and current following breakdown is easily explained by the difference in polarized potential.

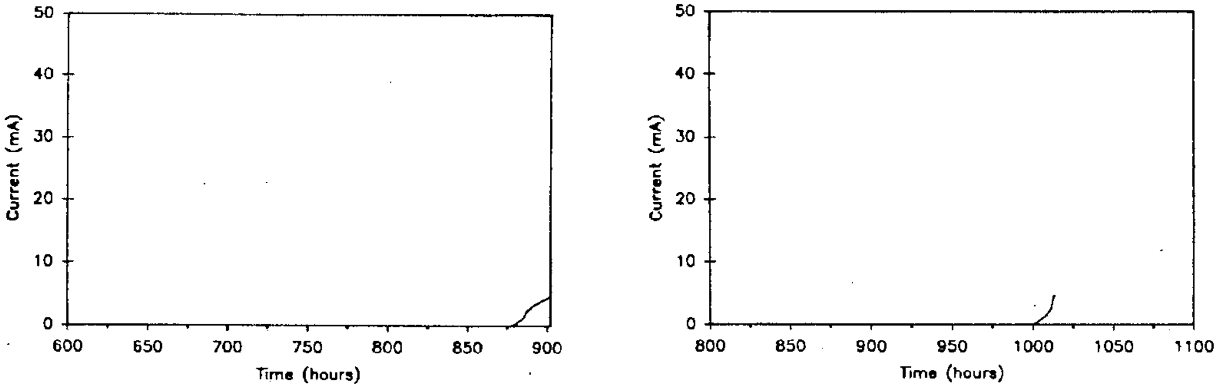
Grout No. 11L - HRWR Plus Aluminum Powder and Polysaccharide Gum

Figure 32 shows the ACTM data for standard specimens of grout prepared with Grout No. 11L. The data for these curves are summarized in table 33. The mean value for the time to failure for the standard specimens tested in Grout No. 11L is 168 h with a standard deviation of 32 h. The mean data is very similar to that obtained for Grout No. 1.

ACTM data for the precracked specimens prepared with Grout No. 11L are shown in figure 33. These data are summarized in table 33. The time to failure for the precracked specimens was quite low. These data are much lower values than observed for Grout No. 1. The current following breakdown for both the standard and the precracked conditions are relatively high and are similar to those values for Grout No. 1.

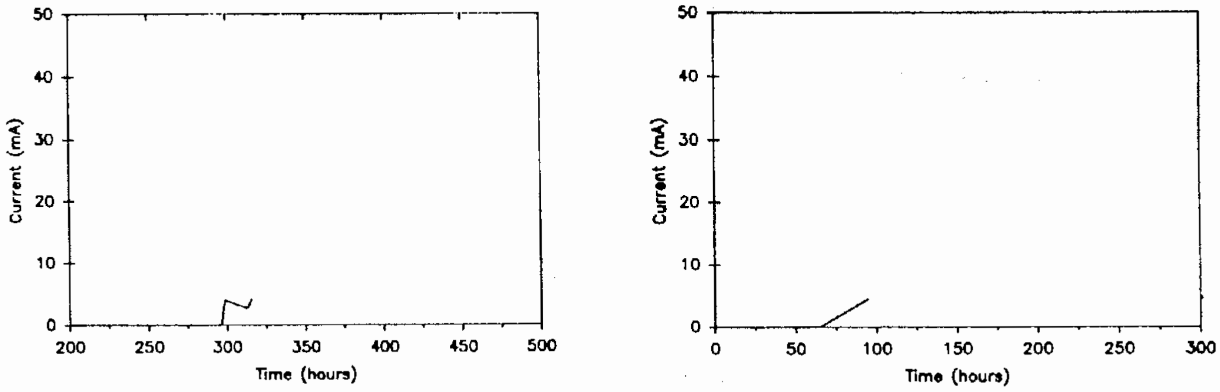


a. Specimen No. 0186 & 0197 b. Specimen No. 0191



c. Specimen No. 0192 d. Specimen No. 0193

Figure 30. Modified ACTM (using 0.0 V, SCE, polarization) current-time data for replicate standard specimens for Grout No. 10-1 - standard grout with inhibitor.



a. Specimen No. 0187

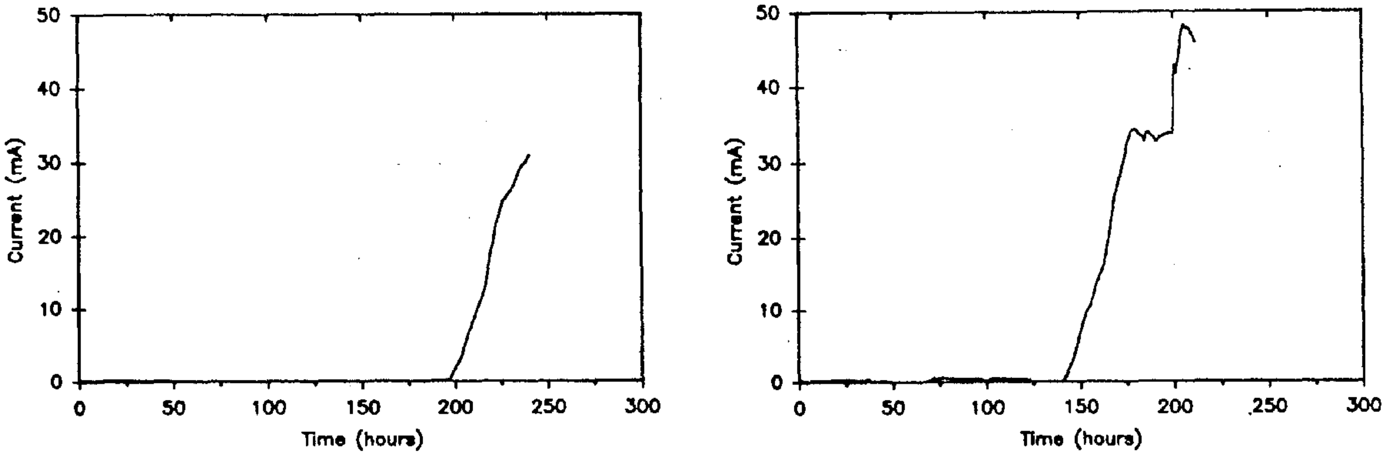
b. Specimen No. 0195

Figure 31. Modified ACTM (using 0.0 V, SCE, polarization) current-time data for replicate standard specimens for Grout No. 1 - standard grout.

Table 32. Summary of modified (using 0.0 V, SCE, polarization) ACTM data for Grouts No. 10-1 - standard grout with inhibitor and No. 1 - standard grout.

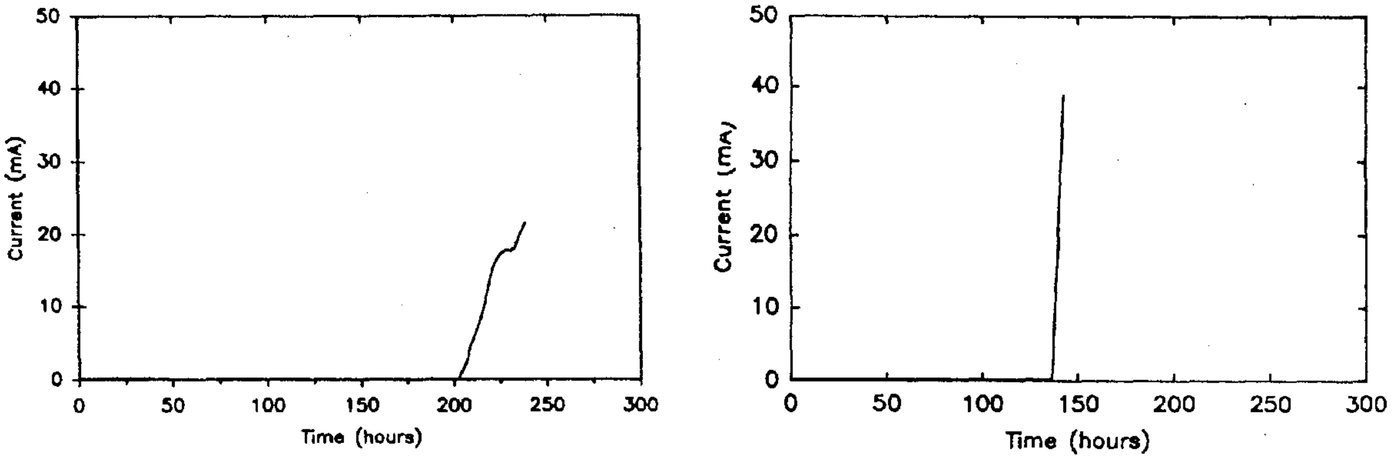
Grout	Specimen No.	Time To Failure, Hours	Current Following Breakdown,[a] mA
No. 10-1	#0186	546	5[b]
No. 10-1	#0191	430	10[b]
No. 10-1	#0192	875	5[b]
No. 10-1	#0193	1,000	5[b]
Mean Value		713	6
Std. Dev.		269	2
No. 1	#0187	290	4
No. 1	#0195	65	5[b]
Mean Value		177	4
Std. Dev.		159	1

(a) Measured 24 to 48 h following breakdown (initiation of corrosion).
(b) Current continuing to increase.



a. Specimen No. 0114

b. Specimen No. 0116



c. Specimen No. 0117

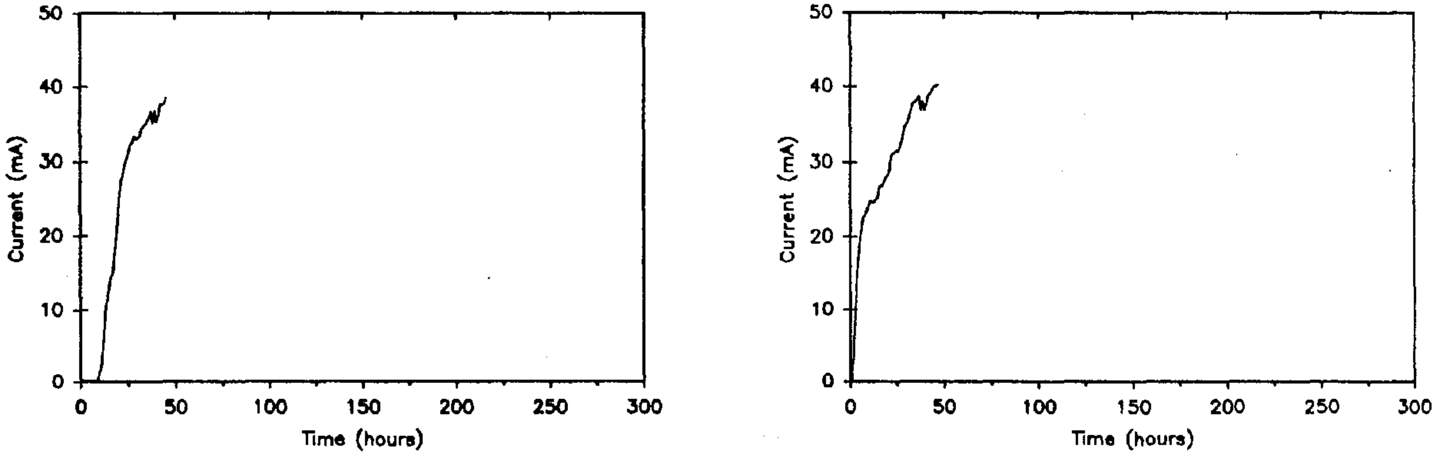
d. Specimen No. 0181

Figure 32. Modified ACTM (using 0.0 V, SCE, polarization) current-time data for replicate standard specimens for Grout No. 11L - HRWR plus Al powder and gum.

Table 33. Summary of ACTM data for Grout No. 11L - HRWR plus Al powder and gum.

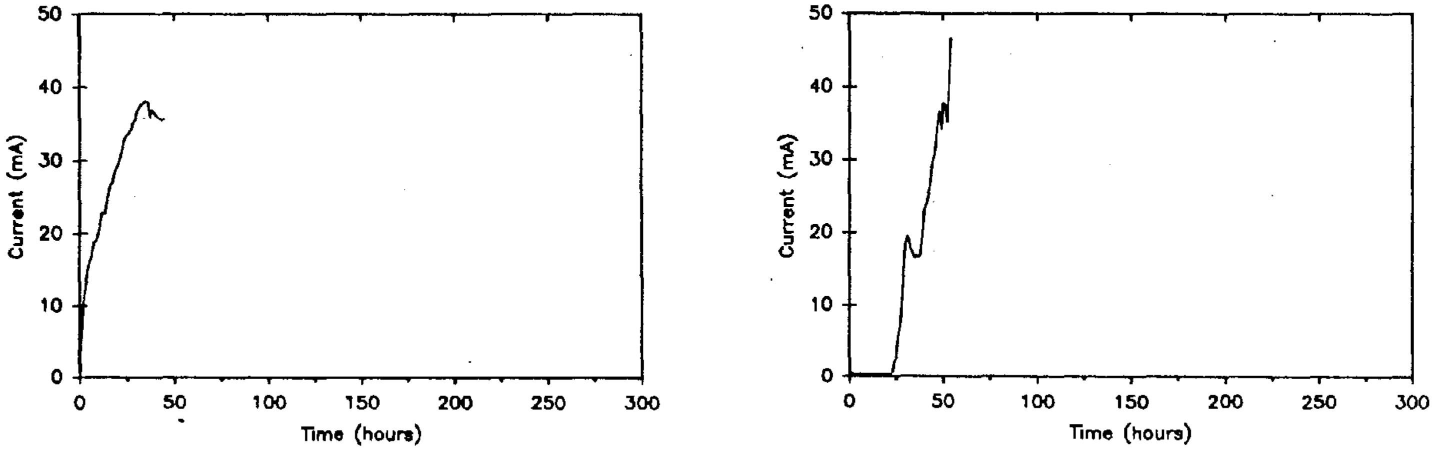
Specimen Type	Specimen No.	Time To Failure, Hours	Current Following Breakdown,[a] mA
Standard	#0114	190	30[b]
Standard	#0116	140	35[b]
Standard	#0117	200	22[b]
Standard	#0181	140	40[b,c]
Mean Value		168	32
Std. Dev.		32	8
Precracked	#0118	10	38[b]
Precracked	#0119	2	38
Precracked	#0120	0	36
Precracked	#0121	20	47[b]
Mean Value		8	40
Std. Dev.		9	5

(a) Measured 24 to 48 h following breakdown (initiation of corrosion).
(b) Current continuing to increase.
(c) Data collection discontinued prior to 24 h following breakdown.



a. Specimen No. 0118

b. Specimen No. 0119



c. Specimen No. 0120

d. Specimen No. 0121

Figure 33. Modified ACTM (using 0.0 V, SCE, polarization) current-time data for replicate precracked specimens for Grout No. 11L - HRWR plus Al powder and gum.

Summary Of ACTM Results

Table 34 summarizes the ACTM results for all of the grouts tested. First, it is important to note that a "poor" grout with a high water-to-cement ratio (w/c = 0.65) gave by far, the worst results; indicating the ACTM can differentiate "good" from "poor" grout. The addition of HRWR (and corresponding decreases in water-to-cement ratio), flyash and sand, silica fume, and latex modifier all improved the corrosion performance over Grout No. 1. Grout No. 5-1 containing the HRWR, sand, and flyash provided the longest time to failure. The increase in corrosion performance for these grouts correlates to a decrease in Cl^- permeability (see task D for discussion).

Using the specified ACTM test, Grout No. 10-1, which was the same as Grout No. 1 but with an inhibitor added, indicated a decrease in corrosion performance when compared to Grout No. 1. This was due to the 0.6V (SCE) applied polarization exceeding the breakdown potential for the inhibitor. Upon modifying the ACTM to use a 0.0 (SCE) applied polarization, the inhibitor indicated (based on limited data) a significant improvement in corrosion performance. Therefore, when an inhibitor is added, the modified ACTM must be utilized.

An extremely large variation is observed in the data for the precracked specimens. This is because it was difficult to reproduce the cracking in the grouted specimens. It is questionable whether the precracked specimen data are worthwhile based on the limited data available.

TASK D - SPECIFICATION FOR GROUT MIXTURES

In the early years of bonded, post-tensioned concrete construction in the United States, grout was a simple mixture of portland cement and water and it is likely that the majority of grout material currently in place is comprised of these two ingredients. The use of flyash, other pozzolans, and fine aggregates in these grouts appears to be quite limited. However, as the technology advanced, various additive and admixtures were used in small quantities (typically less than 1 percent of cement weight) to favorably modify various properties.

Currently, the proportioning and engineering property requirements for grouts in bonded, post-tensioned construction include the following specifications(10) (also see Appendix A in this report):

1. The type and amount of portland cement.

2. The maximum water-cement ratio.

3. The type and amount of pozzolans or fine aggregate that can be used.

4. The type and amount of admixtures that can be used.

Table 34. Summary of ACTM results.

Grout Identification	Standard Specimens, (0.6V, SCE, Polarized) Time-To-Failure, Hours	Standard Specimens, (0.6V, SCE, Polarized) Current Following Failure, mA	Standard Specimens, (0.0V, SCE, Polarized) Time-To-Failure, Hours	Precracked Specimens, (0.6V, SCE, Polarized) Time-To-Failure, Hours
No. 1 Standard	164	41	177	89
No. 1B Standard/ High w/c	30	46	-	-
No. 10-1 Standard/Inhibitor	129	26	713	48
No. 5-1 HRWR/ Flyash/Sand	418	8	-	8
No. 6B HRWR/ Silica Fume	295	18	-	12
No. 8-1 HRWR/ Latex Mod.	237	14	-	18
No. 11L HRWR/ Expansive/Anti-Bleed	168	32	-	8

5. Grout fluidity.

6. Grout strength.

The current specifications encompass the following three main categories of grout technology:

1. Mix design of the grout.

2. Properties of the grout in the fresh state.

3. Properties of the grout in the hardened state.

The current specifications are deficient in a number of areas including the following:

1. Although "allowable" grout constituents are identified, the engineer is given very little guidance as to what constitutes the "best" mix design for an application.

2. With regard to fluidity, the only property currently specified is the initial fluidity expressed as an efflux time value through the flow cone. A major shortcoming here is that the flow cone test cannot be used in grouts that contain admixtures imparting thixotropic behavior and no guidance is given with regard to how long this fluidity should be maintained or as to how this property should be measured.

3. No requirement is currently given for an acceptable grout consistency to minimize the potential for bleeding, segregation, and the creation of water lenses or voids. Of particular concern here is the tendency for grouts to segregate under pressure when stranded tendons are used in vertical placements.

4. No requirement is currently given regarding the ability of the grout to protect the embedded tendon from corrosion.

5. Although frequently specified for grouts in bonded, post-tensioned applications, additives that cause expansions of the grout in the fresh state have not been examined thoroughly to determine whether they represent a liability or an asset with respect to grout performance. This work suggests that the use of these additives should be reconsidered (see Specification Issue 3).

The next generation of grout specifications for bonded, post-tensioned concrete applications should take all of these factors into account. All of these issues are addressed in this section and are offered as the first step toward the development of an improved specification guideline for the formulation, testing, and qualification of grouts for this application.

Specification Issue 1: Achievement and Maintenance of Suitable Grout Fluidity

Proper emplacement of a grout in bonded, post-tensioned work can only occur if the grout is of a "suitable" initial fluidity and maintains its ability to be pumped throughout the entire length of the duct. Currently, there is no concensus for a:

1. Measurement technique for grout fluidity.
2. Specification for initial grout fluidity.
3. Specification for a time-dependent requirement for grout fluidity.

Fluidity Measurement Technique

The measurement and the specification of grout fluidity is made difficult by the fact that the rheological properties of grouts that can be satisfactorily emplaced using conventional pumping equipment can vary widely. For pourable grouts, the flow cone (ASTM C939) is frequently used to measure a property (efflux time) related to grout fluidity. However, specifying only an acceptable efflux time range does not solve the problem for thixotropic grouts which can be satisfactorily pumped with conventional equipment but may not pass through the flow cone.(11)

Fluidity measurements can be made on thixotropic grouts using the flow table (ASTM C230). However, no correlations exist between flow table values and flow cone efflux times.

Also, no precise correlation has been established between these measurements of fluidity (flow table, flow cone) and the pumpability of a grout. It is recommended that ultimately the specification for grout fluidity will include a requirement for the following:

1. Initial grout fluidity (measurement within minutes after mixing the grout).
2. Changes in grout fluidity as a function of time.
3. Temperature dependency of (1) and (2).

The fluidity measurement technique for a specific grout will be cognizant of the rheological properties of the grout. It is expected that at least three categories of grouts from the rheological viewpoint will be encountered including:

1. Grouts that remain pourable throughout the specified time period.
2. Grouts that are not pourable at any time during the specified time period (thixotropic).

3. Grouts that are initially pourable, remain so for a period of time but lose this characteristic prior to completion of the specified open time.

Because a single device does not presently exist that can be used to measure the fluidity of all three grout categories, it is recommended that different fluidity measurement devices be employed initially for this measurement.

For example, for category 1 grouts, the flow cone (ASTM C939) should prove satisfactory for use. For category 2 grouts, the flow table (ASTM C230) should prove satisfactory. For category 3 grouts, it will be necessary to use a combination of the flow cone (for initial measurements) and the flow table (used after the grout is no longer pourable).

Ultimately, it is desired that a single measurement device/technique be developed that will work satisfactorily with grouts having a wide range of rheological properties. A procedure that has been used successfully by one of the authors for this purpose is a standard ASTM C939 flow cone that is subjected to vibration during the efflux time measurement period.

Specification For Initial Grout Fluidity

Until such time as a correlation is established between flow cone efflux time (or another measurement of fluidity) and the pumpability of a grout, it will not be possible to develop a rational specification for initial grout fluidity.

For most of the simple cement/water grouts placed to date (with water-cement ratios around 0.45), an efflux time range specified by state highway departments falls within the range of 11 to 20 seconds.(10) However, in the present program, grouts were developed having water-cement ratios in the range of 0.29 to 0.37 with unit weight values as high as 130 lb/ft^3 (2082 kg/m^3 (the standard grout is 118 lb/ft^3 or 1890 kg/m^3) that were pourable but had initial flow cone efflux times ranging from 20 seconds to 90 seconds. Grouts having efflux times in the range of 70 to 90 seconds are extremely viscous but it is quite likely that they can be successfully emplaced using conventional pumping equipment and procedures.

Therefore, it is likely that in the future, an acceptable grout fluidity range should be based on the rheological properties and characteristics of the grout to be emplaced. This will, of course, necessitate establishing a correlation between the fluidity range (efflux time or other measurement) and the grout pumpability. Once this is established, it should be possible to specify a fairly narrow fluidity range (efflux time) to define an "acceptable" initial fluidity value. It is likely that a range will need to be given in which both the maximum and minimum fluidity value are specified.

The specification for initial grout fluidity should also include a requirement for the ambient and material temperature of the fluidity measurement test. This temperature requirement will take into account the expected ambient temperature conditions at the time the project under consideration is initiated.

Specification For Grout Open Time

"Open time" is defined here as the time period during which the grout retains the ability to be emplaced by the available pumping equipment under job conditions. The requirement here would be for a time period during which the grout stays within the specified fluidity range (efflux time or other measurement). Grouts would be qualified by measuring their fluidity as a function of time at a specified temperature. Between measurements, the grout would remain in a quiescent state.

The results obtained in the present program strongly suggest that a fairly tight range of fluidity can be specified to define an acceptable grout open time. Data shown in figure 16 show that a pourable silica fume grout was produced that maintained an efflux time of 15 to 20 seconds for over 8 hours. This stable fluidity was achieved through the use of high dosage rates of the HRWR (up to 55 oz/cwt or 35.8 ml/kg).

Specification Issue 2: Measurement and Maintenance of Grout Consistency

One of the problems encountered in grouting post-tensioned tendons is the segregation of water from the grout mixture (termed "bleeding"). Normally, bleeding occurs simply as a result of sedimentation of cement and aggregate particles in the grout prior to hardening, with free water rising to the surface. However, when strand tendons are used, a bleeding phenomenon can also occur because of the filtering action of the void spaces between the strands.(12) Pressure from the grouting operation forces the grout against the strands and water passes through the interstices between the outer strand and the center wire with the solid particles in the grout left behind. This filtering action can be a special problem in strand tendons with a high vertical rise where bleeding can amount to up to 20 percent of the height of the vertical rise.

Despite its importance, none of the State DOT's contacted in a recent survey had a requirement for bleeding in grouts intended for use in post-tensioned concrete work.(10) However, a number of State highway departments do specify or allow the use of additives that provide an anti-bleed function. Although some agencies have recognized the influence of bleeding on the quality of the in-place grout and a number of proprietary anti-bleed additives are available, there has been very little research conducted to address this problem in grouts for bonded, post-tensioned construction.

The phenomenon of pressure-induced bleeding was examined in the present investigation. An existing technique for studying the phenomenon was used and was found to give satisfactory results.

Measurement of Pressure Induced Bleeding

The test procedure/equipment used to study pressure induced bleeding involves the placement of a fluid grout mixture into a small pressure vessel having a filter on one end. Pressure is applied to the top end of the pressure vessel with water forced from the grout through the filter which retains 99.7 percent of all particles greater than 0.3 microns. The pressure at which water loss first occurs is measured as well as the total water lost at pressures up to 80 psi (552 kPa). The procedure and equipment was described in some detail in the approach section of this report. The pressure at which water loss first occurs can be equated to an equivalent height of strand tendon in a vertical duct placement of grout as shown in figure 34.

Factors Controlling Pressure Induced Bleeding in Grouts

Table 35 summarizes pressure filtration funnel results for grouts evaluated in the present investigation. The standard cement/water grout (Series No. 1) at a water-cement ratio of 0.44 and containing no additives, showed some water loss at 0 psi (0 kPa) (would bleed under normal ambient conditions) and lost almost half of its total water at a pressure of 80 psi (552 kPa). This grout would obviously be quite vulnerable to pressure induced bleeding in stranded tendon applications. Variables examined with respect to their influence on pressure induced bleeding included water-cement ratio, silica fume, polymer modifiers, and anti-bleed admixtures.

Water-cement ratio. A reduction in water-cement ratio alone (from 0.44 to 0.365) had only a marginal beneficial effect on pressure induced bleeding (Grout 3-1) with first water loss occurring at 10 psi (69 kPa) with a total of 38 percent of the water lost at 80 psi (552 kPa).

Silica fume. The use of silica fume, combined with a low water-cement ratio, did have a significant beneficial effect on pressure induced bleeding. At a 10 percent silica fume addition (Grout 6B - table 35), first water loss still occurred at 10 psi (69 kPa) but only 16 percent of the water was lost at 80 psi (552 kPa). At a silica fume addition of 20 percent (Grout 6D - table 35), first water loss did not occur until 30 psi (207 kPa) and only 6 percent of the water was lost at 80 psi (552 kPa).

SBR latex. The use of SBR latex polymer modifier at a relatively high dosage rate (15 percent of cement weight) produced a significant reduction in pressure induced bleeding with first water loss occurring at 50 psi (345 kPa) and only 1 percent of the total water removed at 80 psi (552 kPa) (Grout 8-1 - table 35).

Anti-bleed admixtures. Anti-bleed admitures are very effective in reducing the amount of pressure induced bleeding in grouts.

A commercial grout used at a rate of 1.5 percent of cement weight (Grout No. 2-1 - table 35) limited water lost at 80 psi to 5 percent of the total with a pressure of 30 psi (207 kPa) being required to effect the first loss of water.

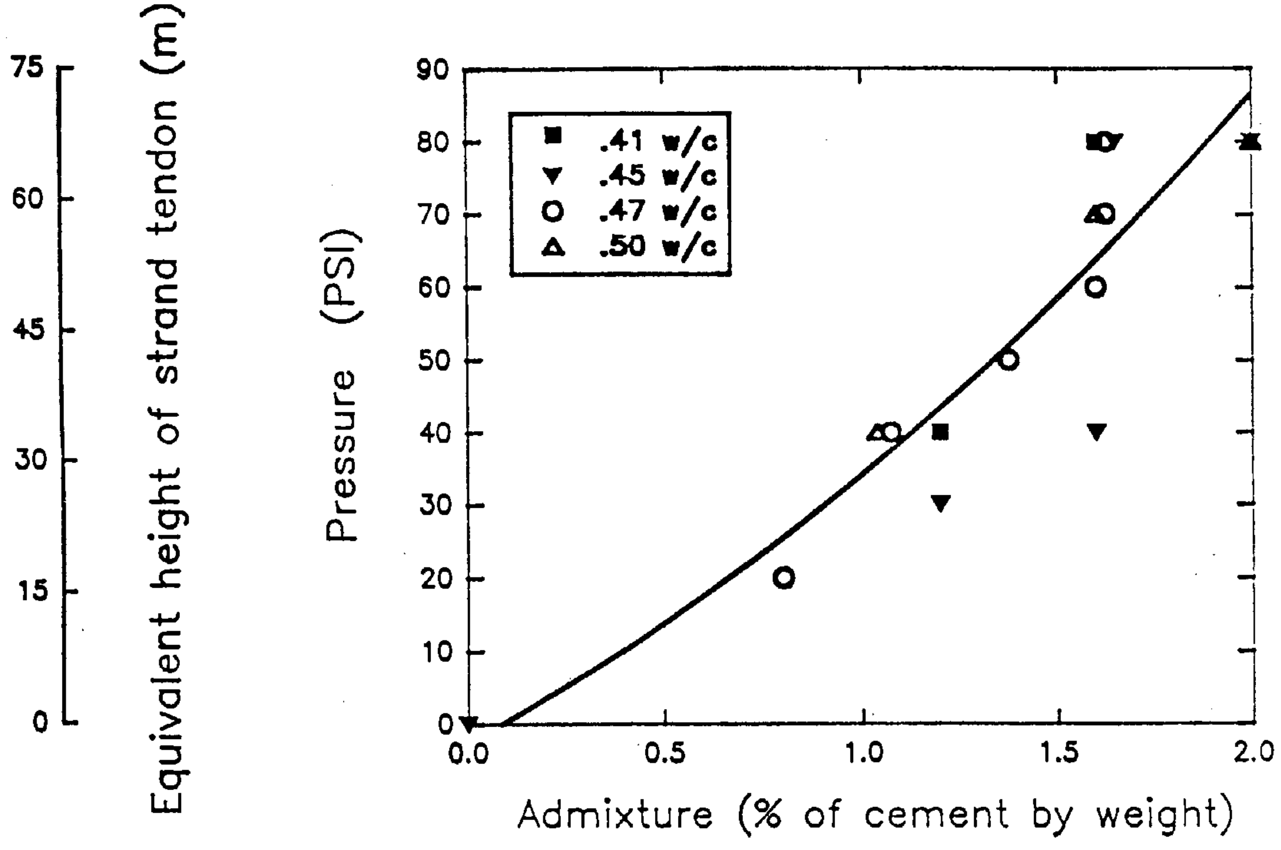


Figure 34. Equivalent tendons height and pressure at which bleeding begins versus the amount of water retentive admixture in grouts.

1 psi = 6.9 kPa

Table 35. Pressure induced bleeding behavior of various grouts grouts investigated in the present program.

Grout Identification	Pressure at Which Water Loss Was First Effected in the Grouts, psi	Percent of Total Water Removed at 80 psi
"Standard" Grout No. 1 containing only cement and water (w/c = 0.44)	0	48
Grout No. 3 containing cement, water and a HRWR (w/c = 0.365)	10	38
Grout No. 6B containing cement, water, HRWR, and silica fume (10% silica fume) - (w/c = 0.365)	10	16
Grout No. 6D containing cement, water, HRWR, and silica fume (20% silica fume) - (w/c = 0.365)	30	6
Grout No. 6D-2 containing cement, water, HRWR, and silica fume (20% silica fume), and 0.1% (by cement weight) of polysaccharide gum (w/c = 0.365)	50	3
Grout No. 6D-3 containing cement, water, HRWR, and silica fume (20% silica fume), and 0.2% (by cement weight) of polysaccharide gum (w/c = 0.365)	70	0.5
Grout No. 2-1 containing cement, water, and 1.0% (by cement weight) of a commercial anti-bleed additive (w/c = 0.46)	30	5
Grout No. 8-1 containing cement, water, HRWR, and SBR latex additive (15% of cement weight) - (w/c = 0.29)	50	1

1 psi = 6.9 kPa

The combination of anti-bleed admixtures with low water-cement ratio and silica fume provided the best overall results relative to minimizing the effects of pressure induced bleeding. Grout 6D-3, containing 20-percent silica fume and 0.2-percent polysaccharide gum, lost only 0.5 percent of its total water at 80 psi (552 kPa) with a pressure of 70 psi (483 kPa) being required before any water loss at all occurred.

Specifications For Bleeding in Grouts

Bleeding in grouts, and especially pressure induced bleeding, has been shown to be a significant variable controlling the in-place quality of the grout. A specification for bleeding should be a requirement of grouts for bonded, post-tensioned construction. Several means of achieving an "acceptable" level of bleeding in grouts are available including the use of:

1. Silica fume in conjunction with reduced water-cement ratios (requires the use of a high range water reducer).
2. Polymer modifiers.
3. Anti-bleed admixtures.

It is expected that the requirements for bleeding behavior will vary depending upon the particular bonded, post-tensioned construction job at hand. In applications involving only horizontal placements with solid tendons, the requirements will obviously be much less stringent than for applications involving significant vertical rises which include the use of stranded tendons.

Specification Issue 3: Expansion Requirement for Grouts

A desired feature of grouts is that they not experience a reduction in volume at any time either in the wet state, the plastic state, or after hardening. Such grouts are accurately referred to as "non-shrink" grouts. In fact, the use of the term "non-shrink" may not strictly apply to many grouts for which such claim is made and there are those that maintain that there is no such thing as a "non-shrink" grout based on portland cement.

Most workers agree that a slight expansion in grouts is preferred to shrinkage. However, the mere accomplishment of expansion is not sufficient. The expansion must be uniform and controlled and should occur at the "right time" during the hydration reaction. In grouts in which the expansive function is provided by gas formers (aluminum, coke), gas forms and expansion occurs only when the grout is in the fluid or plastic state. Once the grout has hardened, the gas formation can no longer contribute to expansion. After hardening, these grouts may then be subject to conventional drying shrinkage strains which may cause an overall reduction in volume.

Currently, there is no concensus among workers in the grout field regarding the need for expansive additives in grouts intended for post-tensioned concrete construction. Some agencies have specified an expansive additive (aluminum powder) for many years. One result of a 1977 evaluation of a variety of post-tensioned concrete structures in California was a conclusion that the elimination of expansive admixture had no apparent effect on the quality of the grout.(13)

The Case For the Use of an Expansive Additive

It appears that the principal motive for the recommendation/use of an expansive additive is the expectation that such use will, in fact, aid in eliminating void volumes in the ducts. A search of the literature and discussions with knowledgable individuals in the grouting field failed to turn up a single instance where a direct verification could be made of the fact that the use of an expansive additive (typically in the form of aluminum powder or coke breeze) prevented the formation of a void in the duct of a bonded, post-tensioned structure.

The Case Against the Use of Expansive Additives

Information was developed in the present investigation on the addition of expansive additives for grouts intended for use in bonded, post-tensioned construction applications and the following observations were made:

1. There is no hard evidence to substantiate the view that the expansive additives do indeed perform their intended function of eliminating voids in ducts.
2. Expansive additives have an adverse effect on the compressive strength of grouts, reducing strength values by 30 to 40 percent (relative to grouts not containing the additive).
3. The expansive additive has a significant adverse effect on chloride ion permeability.
4. The grout producer has very little control over the time at which the gas-forming reactions occur. It is quite possible that in some instances the reactions have occurred prior to placement of the grout in the ducts.

Based on the above results, the user may want to reconsider the use of additives that cause an expansion in the grout as a consequence of gas-forming reactions prior to hardening of the grout.

Specification Issue 4: Requirement for Corrosion Protection Offered by the Grout

In most reinforced concrete highway structures, the principal factor promoting the corrosion of reinforcing steel is the ingress of chloride ions (derived from deicing salts, saltwater, and other sources) to the depth of the reinforcing steel. In bonded, post-tensioned concrete structures, such an event requires that the duct surrounding the tendon be breached so that chloride ion migrating through the duct grout can reach the prestressing tendons. To date, such events have been very infrequent but they have occurred.

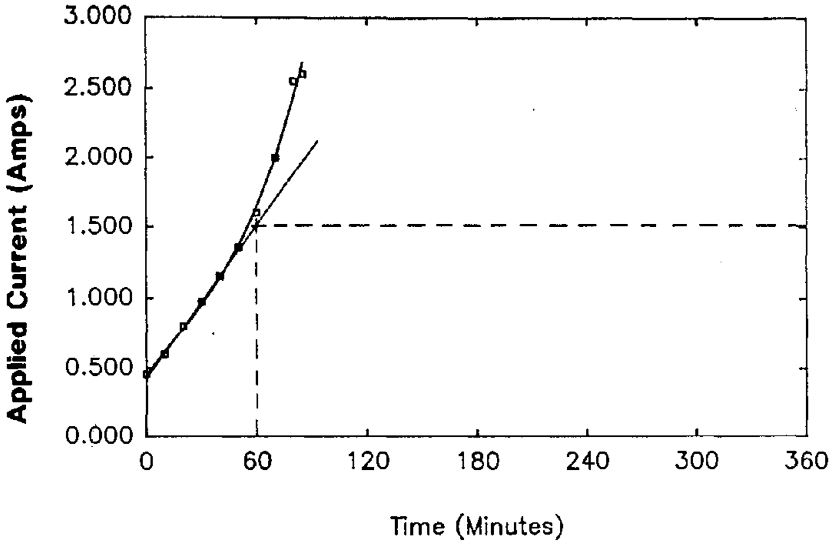
It is recommended that future specifications contain a requirement for grouts regarding their ability to protect prestressing steel in the event that the duct is breached. In the present investigation, this protective function was sought through changes in the grout composition/micro-structure that resulted in a reduction of the permeability of the grout to chloride ion movement and through the use of inhibitors. The chloride ion permeability of grouts was measured using the conventional AASHTO T277-83, the rapid permeability test, and using a new test (ACTM) developed in this program specifically for this purpose. The AASHTO permeability test uses a 4-in (10.16 cm) diameter, 2 in (5.08 cm) long plug of grout while the new accelerated corrosion tests (ACTM) simulates conditions of a bonded, prestressing tendon in service.

Comparison Of ACTM And Rapid Cl^- Permeability

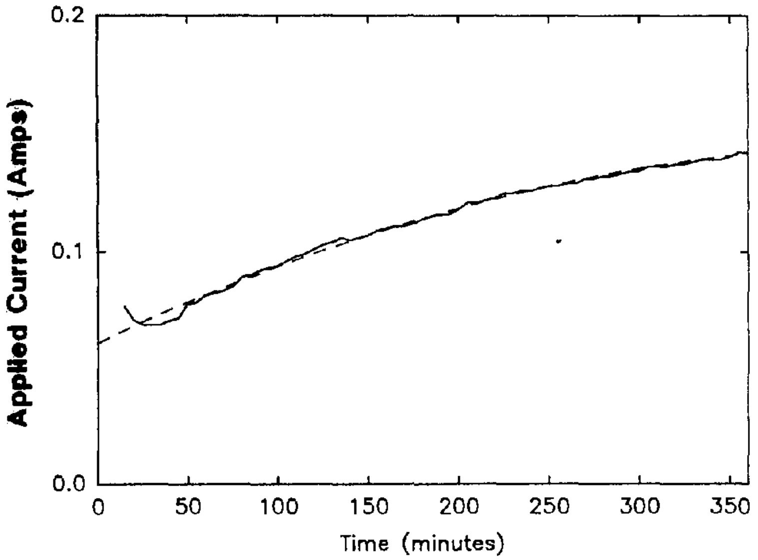
The ACTM was specifically designed to simulate conditions of a bonded prestressing steel tendon in service and to permit its use as a standard performance test by testing laboratories. The ACTM provides corrosion performance data which would be used in conjunction with other physical and mechanical grout property tests to evaluate candidate grout materials.

The rapid permeability test was modified by reducing the 60 V applied voltage down to a 30 V applied voltage. This was necessary to prevent severe overheating of the grout during the 60 V tests. Figure 35 shows typical current - time plots for the rapid Cl^- permeability tests. When a 60 V applied voltage was used overheating occurred and extrapolation of the data was required. In a few instances the overheating resulted in cracking of the grout specimen. Table 36 shows a comparison of rapid Cl^- permeability results for the 60 V and 30 V applied voltage. The only discrepancy in the data is with grout 6B. The 30 V tests were repeated and it is believed that these data are correct which indicates that the 60 V data is incorrect.

Table 37 compares the ACTM results and the AASHTO rapid Cl^- permeability results for several grouts. For the five grouts for which both data are available, there is a reasonable correlation between the two sets of data; as permeability increases, the time to corrosion initiation decreases. This correlation suggests that if Cl^- permeation is the major contributor to corrosion initiation, the rapid Cl^- permeability test may be sufficient to characterize a grout's corrosion performance. Therefore, in the absence of inhibitors, a specification of corrosion performance may include only the rapid Cl^- permeability test. However, initial test results using a modified (0.0V, SCE, polarized) ACTM indicates that the addition of inhibitor significantly increases the time for corrosion initiation. Furthermore, it is expected (although tests were not performed) that the rapid Cl^- permeability would have indicated just the opposite results. Therefore, when an inhibitor is incorporated in the grout, the modified ACTM test is required to



a. 60 V applied voltage.



b. 30 V applied voltage.

Figure 35. Rapid Cl^- permeability test results for Grout No. 1 for a 60 V and 30 V applied voltage.

Table 36. Rapid permeability test results for 60 V and 30 V applied voltage.

Grout	Coulombs	
	60V	30V
1	33,000 (36,000)	2,400
2-1	59,000	14,500
3	24,000	4,300
4-1	32,000	4,000
5-1	6,900	370 (140)[a]
6B	270	1,000 (910)[a]
6D	590	150
8-1	15,000	1,600
11L	-	7,200

[a] Duplicate specimens.

Table 37. Comparison of ACTM results (0.6 V , SCE, polarization) with the AASHTO rapid Cl^- permeability test.

Grout Identification	ACTM (0.6V, SCE, Polarized), hours	AASHTO Rapid Permeability Test (6h at 30V), coulombs
No. 1 Standard (w/c = 0.44)	164	2,400
No. 11L HRWR/ Expansive/Anti-Bleed	168	7,200
No. 8-1 HRWR/Latex Mod.	237	1,600
No. 6B HRWR/Silica Fume	295	1,000 (910)[a]
No. 5-1 HRWR/Flyash/Sand	418	370 (140)[a]

[a] Duplicate Specimens

characterize the corrosion performance. Also, the ACTM provides an indication of the rate of corrosion following corrosion initiation. The test data in task C indicated that not only did the use of additives (HRWR, flyash, silica fume, and/or latex) all tend to increase time to initiation (also indicated as a decrease in Cl^- permeability) the ACTM indicated that a significant decrease in current (corrosion rate) following breakdown resulted when these additives were used. Therefore, the ACTM provides additional information on rates of corrosion following breakdown which the rapid Cl^- permeability test does not.

Therefore, both the rapid Cl^- permeability test and the newly developed ACTM are important in characterizing corrosion performance. For examining grouts, a modification to the rapid Cl^- permeability test (30 V instead of 60 V) will minimize heating of the cell. It was shown in this study, that the rapid Cl^- permeability test provides a good ranking of grouts with respect to time to corrosion initiation in the absence of an inhibitor. If any type of inhibitor is added such that corrosion initiation is affected by mechanisms other than Cl^- permeation, the ACTM is required to characterize corrosion performance.

Specification Issue 5: General Performance Specification or Material Specification

It is obvious that the performance requirements for grouts used in bonded, post-tensioned construction can vary widely depending upon the job conditions. Consideration should be given to the creation of performance specifications for grouts for these applications to reflect the specific requirements of each job.

The performance specifications should include the following requirements:

1. Initial grout fluidity.
2. Grout fluidity as a function of time and temperature.
3. Maximum tolerable values for pressure induced bleeding.
4. Maximum tolerable value for chloride ion permeability.
5. Minimum value for compressive strength and rate of compressive strength development.

The tailoring of grouts for a specific post-tensioned job application will dictate the choice of materials to achieve the desired performance variables. It is envisioned that the material specification will require attention given to the following material variables.

1. Type and amount of portland cement.
2. Allowable water-cement ratio.

3. Type and amount of additive to achieve the pressure induced bleeding requirement.

4. Type and amount of additive to achieve the corrosion protection requirement.

5. Type and amount of additive to achieve the initial fluidity requirement.

6. Type and amount of additive to achieve the open time requirement.

Table 38. Estimated cost per cubic foot of experimental grouts evaluated in the present program relative to a standard grout containing Type II Portland cement and water having no admixtures and a water-cement ratio of 0.44.

Grout Number	Grout Description	Relative Cost, $/Ft^3 of Grout
1	Standard Grout No Admixtures w/c = 0.44	1.0[(a)]
2-1	Anti-Bleed Admixture w/c = 0.46	2.2
3	Superplasticizer w/c = 0.365	1.4
4-1	Superplasticizer Corrosion Inhibitor w/c = 0.365	1.6
5-1	Superplasticizer Flyash/Sand w/c = 0.32	1.9
6B	10% Silica Fume Superplasticizer w/c = 0.365	1.7
6D	20% Silica Fume Superplasticizer w/c = 0.365	2.5
8-1	Latex Additive Superplasticizer w/c = 0.29	8.3
11L	Superplasticizer/gum Aluminum Powder w/c = 0.338	1.7

(a) Actual cost of Grout No. 1 = \$2.96/ft^3.

1 ft^3 = 0.028 m^3

CHAPTER 5

CONCLUSIONS

The results presented in chapter 4 successfully accomplish the objectives set out at the beginning of the program. The objectives were: (1) to develop and test new mixture designs for grout used in ducts so that the grout may provide long-term corrosion protection for the prestressing steel in post-tensioned concrete bridge structures, and (2) to develop and perform accelerated corrosion test methods on the new grout mixtures to predict their performance over the design life of the bridge. The following conclusions are based on the results presented in this report and in the previously issued topical report no. FHWA-RD-90-102.(10)

1. In general, bonded post-tension concrete structures have given excellent performance based on investigations to date. However, in at least one instance, corrosion of the duct material and subsequent corrosion and failure of individual strands of a tendon have been reported.

2. Present specifications are inadequate for insuring optimum corrosion performance of the prestressing steel based on state-of-the-art grout technology.

3. It is possible to achieve and control a specified level of grout fluidity and acceptable open time through the use of high dosage rates of HRWR admixture.

4. Use of modifiers and additives provided improved resistance to pressure induced grout bleeding:

   - Reduction in water-to-cement ratio had a marginal beneficial effect.

   - Silica fume combined with low water-to-cement ratio had a significant beneficial effect.

   - SBR latex polymer modifier produced a significant reduction in pressure induced bleeding.

   - Anti-bleeding admixtures were very effective in reducing pressure induced bleeding.

5. Based on the present investigation, the use of expansive additives for grouts designed for bonded, post-tensioned construction should be reconsidered.

6. A test protocol (ACTM) was developed that provides a relatively fast evaluation of the corrosion performance of grouts and which simulates bonded post-tensioned bridge exposures while accelerating the corrosion process.

7. Evaluation of corrosion performance is accomplished by two performance tests:

   - The ACTM developed in this study.

   - Modified AASHTO rapid Cl^- permeability test method (30 V applied voltage).

8. Rapid Cl^- permeability test gives similar ranking of grout performance as ACTM when Cl^- permeability is the primary mechanism controlling corrosion initiation. ACTM provides more detailed information (time to corrosion initiation and current following initiation) than rapid Cl^- permeability test.

9. A modified version of the ACTM must be used when inhibitors are added to the grout and in these cases the ACTM is the only method for evaluating corrosion performance.

10. Based on the ACTM results, additives and modifiers which significantly reduce Cl^- permeation also significantly improve corrosion performance.

11. Grout No. 5-1 containing 33 percent (cement weight) flyash provided a 3-fold increase in time to corrosion initiation relative to the standard grout.

12. Grout No. 6B containing 10 percent (cement weight) silica fume addition provided a 2-fold increase in time to corrosion initiation relative to the standard grout.

13. Based on limited comparison data from the modified ACTM, the calcium nitrite corrosion inhibitor provided improvement in corrosion performance.

CHAPTER 6

RECOMMENDATIONS

One of the principal accomplishments of the present study has been the development of grouts having improved performance relative to the historical standard cement/water grout used in bonded post-tensioned concrete applications. These improvements are in (1) the control of the initial fluidity and the maintenance of fluidity in the grouts, (2) the minimization or elimination of pressure-induced bleeding in the grouts, and (3) the ability of the grout to prolong the time to corrosion of embedded prestressing steel. Another major accomplishment of the present study is the development of a test protocol for evaluating the ability of grouts to provide corrosion protection for embedded prestressing steel.

Before the improved grouts can be recommended for implementation in practice, additional work will be required to address the following issues:

- The current specifications for grouts for bonded post-tensioned concrete applications are inadequate, in that (1) they do not address all of the significant performance/property requirements for grouts and (2) in some cases, test procedures/equipment have not been identified for quantifying these variables.
- Large-scale field trials will be required to verify that the new grouts can be successfully emplaced under field conditions.

SPECIFICATIONS FOR GROUTS FOR BONDED POST-TENSIONED CONCRETE APPLICATIONS

Even for the grouts currently in use in post-tensioned concrete applications, the present specifications fail to address major performance issues. The optimum grout for a particular application can only be identified if acceptable property and performance criteria are identified and if test procedures/equipment are developed to quantify the variables. The proper/performance variables at issue here include:

- The initial fluidity of the grout.
- The time period during which the grout maintains a desired level of fluidity (open time).
- The consistency of the grout, particularly as related to the pressure-induced bleeding phenomenon.
- Expansion requirements for the grout.
- The ability of the grout to delay the onset of corrosion in embedded prestressing steel (corrosion protection).

Before meaningful specifications can be written for initial grout fluidity and for grout open time, it will be necessary to establish a correlation between new and existing fluidity measurements and the ability of the grout to be pumped using field equipment. This study would be part of the large-scale field tests and would encompass a wide range of grout formulations.

Regarding the pressure-induced bleeding of grouts in these applications, additional work is needed in the following areas:

- Development of a standard procedure for measuring this property.
- The establishment of meaningful limits on pressure-induced bleeding as related to the requirements of a particular job.
- The development of a standard procedure to identify the most cost/effective means of minimizing or eliminating pressure-induced bleeding in grouts.

In the present study, a case was made for eliminating the use of additives that cause expansion of the grout prior to hardening. However, there is not yet sufficient information in hand to assess the advisability of using expansive cements or additives that cause expansion to occur in grouts in the hardened state. Inasmuch as grout shrinkage is highly undesirable, this issue should be carefully reviewed and test procedures developed or modified to appropriately study this variable as related to the bonded post-tensioned concrete application.

The present research established a test protocol for characterizing the ability of a grout to protect prestressing steel against corrosion. However, a statistically significant data base is lacking at present especially as regards the effects of corrosion inhibitors on grout performance. Additional work is required to establish this data base by performing the accelerated corrosion test method (ACTM) on a broader range of grout formulations and by conducting a suitably large number of tests for each formulation. With regard to the effect of corrosion inhibitors on the corrosion protection offered by grouts, several concerns remain:

- The comparison data base for this conclusion is small and must be increased to increase the confidence level in the data.
- The corrosion inhibitor was examined only in conjunction with a simple cement/water grout. What is the effect when adding an inhibitor with other additives?
- Over what period of time does the corrosion inhibitor remain effective and how is this effectiveness influenced by other additives?

Chapter 4 of the present report reviewed the considerations for general performance and material specifications for grouts used in bonded post-tensioned concrete construction. Additional work is required to expand these specifications once the above-described issues have been addressed. Also, the cost/effectiveness of the improved grouts needs to be assessed in view of the higher material costs and any unique handling or construction costs associated with their use. With this information in hand, the bridge engineer would have at his disposal performance and material specifications for specifying grouts for bonded post-tensioned concrete construction which would provide maximum corrosion protection for the embedded prestressing steel.

FIELD TESTING

Large-scale trials will have to be conducted in conjunction with the investigation of the grout specification issues just discussed. The specific issues addressed in this work should include:

- The correlation of grout fluidity measurements with pumpability.
- The formation of voids in the grouting ducts.
- The ability of grouts to penetrate the interstices of stranded tendons.
- The pumpability of sanded grouts and of grouts having higher density/viscosity relative to the standard cement/water grout.
- The evaluation of new/improved techniques for emplacement of the new grouts.

These field tests will be the final stage in qualifying the improved grouts for construction and will provide the necessary information for writing an initial new specification for grouts that address all of the relevant property and performance variables for this application.

APPENDIX A

STATE HIGHWAY AND TRANSPORTATION AGENCY SPECIFICATIONS FOR GROUTS FOR BONDED POST-TENSIONED CONSTRUCTIONS

Table 39. Material and proportioning specifications for grout.

Grout Specification No.	Specified By (Ref.)	Binder Type	Binder Part By Wt. Of Cement	Water/ Cement	Aggregate Type	Aggregate Part By Wt. Of Cement	Additive Type	Additive Part By Wt. Of Cement
1	Va. DOT 220.03-(c) Cement Grout (14)	Hydraulic Cement AASHTO M240,M85	1(wt.)	As Need For Free Flowing	Fine Grade A Or C	2(wt)	As Needed; Section 217 Of Road & Bridge Spec; 3-7% Air.	As Needed
2	Va. DOT 220.03-(d) High Strength Grout (14)	Prepackaged Non-Shrink Hydraulic Cement Mixture	NS	As Need For Free Flowing	NS	NS	NS	NS
3	Post-Tensioning Institute (15)	Portland Cement ASTM C150 Type I, II, or III, no lumps	1(wt.)	0.45(a) (water must be clean & free of harmful substances)	NS	NS	Al powder or other that causes 5 to 10% unrestrained expansion. Cl ≤ 0.5% by weight	As Needed
4	Inryco, Inc. (15)	Portland Cement ASTM C150 Type I	1(wt.)	0.44	NS	NS	Inland-Ryerson	0.011
5	Washington St. DOT (Standard Spec. for Road, Bridge, & Municipal Construction (16)	Portland Cement Type II	1(wt.)	0.49	NS	NS	Sika Intraplast-N	0.004 (6 oz/bag)
6	Florida DOT (Road & Bridge Spec.) (17)	Portland Cement (plus flyash)	1(wt.) (plus 0.25 flyash)	0.35 to 0.53	Sand	0.75	Plasticizing additive approved by engineer	As approved by engineer
7	Industry Representative (18)	Portland Cement Type II	1(wt.)	0.4 to 0.5	None	0	Intrusion Aid	0.011

NS: Not specified by reference material.

Table 39. Material and proportioning specifications for grout (continued).

Grout Specification No.	Specified By (Ref.)	Binder Type	Binder Part By Wt.	Water/ Cement	Aggregate Type	Aggregate Part By Wt.	Additive Type	Additive Part By Wt.
8	Oregon DOT (19, 20)	Portland Cement Type II	1(wt.)	≤0.44	NS	NS	Approved that gives 5-10% unrestrained expansion. Cl ≤0.25% by wt.	As needed
9	California DOT (21, 22, 29, 30)	Portland Cement (Section 90-2.01) Type II Modified. No lumps.	1(wt.)	≤0.44	NS	NS	Approved that gives 5-10% unrestrained expansion. Cl ≤0.25% by wt.	As needed
10	Kentucky Transportation Cabinet (23, 24, 25)	Approved non-shrink grout with hydraulic cement or prepackaged product.	1(wt.)	≤0.44	Mortar Sand (Optional)	2	Approved non-ferrous expansive admixture	As needed
11	Tennessee DOT (26, 27)	Portland Cement Type I or II Section 901.01.	1(wt.)	≤0.45	NS	NS	Approved that has Cl <0.5% by wt. of admixture. No fluorides, sulphites or nitrates.	As needed
12	AASHTO (28, 29)	Portland Cement Type I, II or III, AASHTO M85	1(wt.)	≤0.45(a)	NS	NS	Approved that gives (approx. 5-10% unrestrained expansion. Cl ≤0.5% by wt. of admixture.	As needed (approx. 0.011)

(a) Water/cement ratio to be established for Type III cement based on tests.

NS: Not specified by reference material.

Table 40. Performance specifications for grouts.

Grout Specification No.	Compressive Strength psi	Bond Strength, psi	Fluidity	Open Time	Cure Time	Freeze-Thaw Performance	Bleeding Characteristics	Other
1	NS	NS	NS	NS	NS	DF>60 WL<7 ASTM C666-A w/2% NaCl	NS	Meets requirements when mixed w/oil. (Mixtures made w/1.8% oil.)
2	4,000 psi 7 Days ASTM C109 Cubes	1000 psi 7 days VTM-41 Slant Shear	NS	NS	NS	DF>60 WL<7 SR>3 ASTM C666-A w/2% NaCl	NS	
3	4,000 psi 28 Days	NS	≥ 11 sec. Efflux Time By CRD-C79	NS	NS	NS	≤ 2% by vol. 3 hrs. and ≤ 4% total. Separated water absorbed ≤ 24 hrs.	Efflux time not applied when thixotropic additive used. Additives not required for horizontal tendons.
4	NS	NS	NS	NS	NS	NS	NS	
5	NS	NS	15-20 sec. Efflux Time ASTM C939	NS	Concrete temp. ≥ 35°F until 2" cube has 800 psi comp strength	NS	NS	Flyash (complies w/9-23.9) may replace up to 20% of cement. Other expansion agents may be used if not corrosive to steel. Pump grout w/in 30 min. of adding Intraplast-N.
6	NS	NS	Equal To That Of Heavy Paint	NS	NS	NS	NS	Flyash shall have carbon content ≤5%. Sand screened & washed & 100% passing No. 16 sieve & ≤5% retained on No. 30 30 sieve.
7	NS	NS	NS	NS	NS	NS	NS	

NS: Not specified by reference material.

1 psi = 6.9 kPa
5(F-32)/9 = C

Table 40. Performance specifications for grouts (continued).

Grout Specification No.	Compressive Strength, psi	Bond Strength psi	Fluidity	Open Time	Cure Time	Freeze-Thaw Performance	Bleeding Characteristics	Other
8	NS	NS	≥ 11 Sec. ≤ 19 Sec. Efflux Time.	NS	Concrete Temp. ≥ 35°F until 2" Cube has 800 psi	NS	NS	Pump grout between 35 & 90°F. @ Grout 150 psi & must pass 0.125 in screen.
9	NS	NS	≥ 11 Sec. Efflux Time Cal. Test 541, CRD C79-58	NS	NS	NS	NS	Grout must pass 0.07 in screen. Pump @ ≤90°F. Additional requirements for efflux time.
10	3000 min. @ 7 days; 4500 min. @ 7 days for approval on non-shrink grout.	NS	≥ 11 Sec. Efflux Time By CRD-C79	Initial Set ≤ 45 min. (ASTM C191 or C403)	0.0% to 1.5% Expansion (CRD-C621)	NS	NS	Non-shrink grout may be an approved mixture of hydraulic cement, water F.A., & additive or an approved commercial product.
11	NS	NS	≥ 11 Sec. Efflux Time By CRD-C79	NS	Conc. Temp. ≥ 35°F until 2" Cubes have 800 psi.	NS	NS	Admixtures approved include Sika Intraplast N or C. Grouts approved include Masterflow 814 Cable Grout (Master Bldgrs.). Grout must pass 0.125 in screen.
12	NS	NS	≥ 11 Sec. Efflux Time By CRD-C79	NS	Conc. Temp. ≥ 35°F Until 2" Cubes Have 800 psi	NS	NS	

NS: Not specified by reference material.

1 psi = 6.9 kPa
5(F-32)/9 = C

Table 41. Grout mixtures that have been used in bonded post-tensioned constructions.

Grout Mixture No.	Specified By	Binder Type	Binder Part By Wt. Of Cement	Water/ Cement	Aggregate Type	Additive Type	Additive Part By Wt. Of Cement	User	Notes
1	Va. DOT (18, 30)	Type II Portland Cement (ASTM C150)	1 (wt)	0.42	None	Conbex 208 By Celtite (Celbex)	0.012	Va. Dot-I295 0095-020-101, B610, B611 Chesterfield, VA	Vertical Tendons On I295 Bridge
2	Va. DOT (18, 30)	Type II Portland Cement (ASTM C150)	1 (wt)	0.42	None	Intraplast N by Sika	0.010	Va. DOT-I295 0095- 020-101, B610, B611, Chesterfield, Va.	Longitudinal Tendons On I295 Bridge
3	Va. DOT (18, 30)	Type II Portland Cement (ASTM C150)	1 (wt)	0.42-0.43	None	Combex 208 By Celtite	0.007-0.015	Va. DOT-I295 0095-020-101, B610, B611 Chesterfield, VA	Cable stays on I295 Bridge. Must pass thru 0.0787" screen. Mixture does not meet 5-9% expansion criteria.
4	In. DOH (28, 29, 31)	Type I, II or III Portland Cement (ASTM C150)	1 (wt)	≤ 0.45	None	Al powder or other gas evolving material	0.011	In. DOH Contract No. B-11000, Str. No.4499A 7/25/77	Additive shall produce 5-10% unrestrained expansion
5	Il. DOT (32)	Type I, II or III Modified Portland Cement (ASTM C150)	1 (wt)	≤ 0.45	None	Al powder or other gas evolving material	0.011	Il. DOT Spec for Rt. 408 Section (75, 86) -7B, Pike & Scot.	Additive shall produce 5-10% unrestrained expansion. Grout must pass thru 0.125 in. sieve

Table 41. Grout mixtures that have been used in bonded post-tensioned constructions (continued).

Grout Mixture No.	Specified By (Ref.)	Compressive Strength psi	Fluidity	Dimensional Stability	Other
1	Va. DOT Mixed w/0.8% oil (Viscono Rust 4171E oil) (18, 30)	3025 (4 day) 3794 (7 day) 5300 (28 day)	NP	NP	Cure at 30 F Until Compressive Strength Of 2 in. Cubes 800 psi
1	Va. DOT Mixed w/1.6% oil (Viscono Rust 4171E oil) (18, 30)	3000 (4 day) 3488 (7 day) 4987 (28 day)	NP	NP	Same as 1
1	VA. DOT No Oil (18, 30)	3356 (4 day) 4138 (7 day) 5682 (28 day)	NP	NP	Same as 1
2	Va. DOT (18, 30)	NP	≥11 Sec. (CRD-C79)	NP	Same as 1
3	Va. DOT (18, 30)	3000 Minimum	NP	≥5% ≤9% Expansion	Same as 1
4	In. DOH (31)	NP	NP	NP	
5	Il. DOT (32)	NP	≥11 sec (CRD-C611-80)	NP	Place at 50-90 F, cure at ≥50 F until comp. str. ≥ 500 psi.

NP: Not performed

1 psi = 6.9 kPa
5(F-32)/9 = C

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