Improved Grouts for Bonded Tendons in Posttensioned Bridge Structures

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A serious problem in the United States and elsewhere is the deterioration of concrete bridges as a result of 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 posttensioned 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. In bonded posttensioned construction, grout is the final line of defense against corrosion of the uncoated steel tendon. The purpose of this research was to develop and test new mixture designs for grouts, develop and perform accelerated corrosion test methods on the new grouts, and compare the corrosion performance of the new grouts with the standard grouts. A variety of modifiers and additives for grouts were examined, including high-range water reducers, fly ash, silica fume, latex polymer modifier, expansive agents, antibleed additives, and corrosion inhibitors. It was shown that these additives can favorably influence grout fluidity, open time, bleeding and segregation, Cl^- permeability, mechanical properties, and the resistance to corrosion of steel tendons embedded in the grout. Several experimental grouts were designed that provided improved properties compared with the grouts used currently.

A detailed literature review was included in the research to determine the state-of-the-art of grouting materials and grouting technology for bonded posttensioned tendons. The results of this literature review are presented in FHWA Report FHWA-RD-90-102 (*1,2*).

In general, the performance of posttensioned concrete structures in the United States is good. Although several investigations have been performed, few examples of bonded posttensioned structures in which corrosion of the prestressed tendons has occurred are documented (*3–8*). 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 imbedded strands in a posttensioned 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 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 its practices. Available technology could improve performance significantly if 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 posttensioned 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 state-of-the-art technology. Up to now, the majority of grouts used in bonded posttensioned concrete structures have 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 nonbleeding additives sometimes specified.

EXPERIMENTAL

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 or admixture modifier category was represented by only one material. The following materials were selected for use in this study:

- Type II portland cement,
- Type F high-range water-reducing admixture (ASTM C494),
- Silica fume (also called microsilica),
- Class F fly ash (ASTM C618),
- A styrene-butadiene polymer modifier (supplied as a liquid with a solids content around 48 percent),
- Calcium nitrite corrosion inhibitor,
- Aluminum powder expansion agent,
- Polysaccharide gum antibleed agent,
- Celbex 209X commercial grout admixture (blend of superplasticizer, thickener, and controlled expansion agent), and
- Silica sand (maximum particle size 50 mesh).

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

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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. After mixing of the grout, specimens were prepared for measuring various physical and chemical properties.

Grout Properties in the Fresh State

Two or more grout batches were required to prepare enough material for all of the measurements. In a number of instances, replicate batches were prepared to establish the precision of the tests.

Grout Unit Weight

Unit weight is the density of the grout in the fresh state. 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 the Standard Test Method For Time of Setting of Grouts For Preplaced Aggregate Concrete in the Laboratory (ASTM C953-87). 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 the Standard Test Method For Flow of Grout (Flow Cone Method) (ASTM C939-87). 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. 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.

A few of the grouts developed a thixotropic behavior immediately after mixing 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 the Standard Specification For Flow Table For Use in Tests of Hydraulic Cement (ASTM C230-90). In this investigation, the initial fluidity of the grout was measured as the efflux time after a 1-min wait. Efflux times were then measured periodically (every 20 to 30 min) until the grout would no longer flow in a continuous stream through the cone. At that point, fluidity measurements were continued using the flow table. 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 value (from flow table) greater than 100 percent.

Expansion and Bleeding

Expansion and bleeding of the fresh grouts was measured using the procedure of the Standard Test Method For Expansion and Bleeding of Freshly Mixed Grouts (ASTM C940-87). The expansion of the grout mixture and its bleeding are expressed as percentages of the initial volume of the grout.

Bleeding and Segregation Under Pressure

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 severe 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 (Gelman Science, Inc., Ann Arbor, Michigan). 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 increments (552 kPa in 68.9 kPa increments).

Grout Properties in the Hardened State

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 in which the grouts exhibit expansion before initial set, the test procedure provides for the placement of a plate over the cube mold to ensure that expansion is confined. In this investigation, compressive strength was measured at intervals of 1 day, 7 days, 28 days, and 90 days.

Permeability

The permeability of the grouts was measured using the Rapid Determination of the Chloride Permeability of Concrete procedure (AASHTO T277-83). This test measures the total electrical charge passed through a specimen 2 in. (5.08 cm) thick 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 hr. 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 hr. This procedure accomplished the objective of minimizing the temperature rise in the specimen during the test.

Accelerated Corrosion Test Method

The accelerated corrosion test method (ACTM) was designed based on the results of the preliminary experiments and consideration of several variables, including freeze-thaw cycles, wet-dry cycles, temperature, acceleration of Cl^- migration, specimen loading, types of ducts, types of prestressing steel, grout cover, and grout curing. These variables are discussed elsewhere (*10*).

The focus of 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, duct, and concrete cover.

Figure 1 shows the as-cast specimen and the specimen ready for testing. A primary focus of the as-cast specimen is the rigid, air-tight mold (PVC tube) used for casting and curing the specimen. After curing (minimum of 28 days), a gauge section of the PVC tube is removed to expose the grout specimen. This simulates a significant breach in the duct wall. The specimen is tested within 24 hr and is kept immersed in a saturated calcium hydroxide solution before testing. Maintaining moist conditions on the exposed gauge section is critical to prevent microcracking.

The following procedure is used to perform ACTM:

1. Set up the test cell arrangement as shown in Figure 2 with the grouted test specimen immersed in a 5 percent NaCl solution.
2. Use a potentiostat to polarize the grouted test specimen.
3. Set the potentiostat to apply +0.6 V (SCE).
4. Within 5 to 10 min of immersion, apply the +0.6 V (SCE) by switching the potentiostat from the "isolate" or "disable" mode to the "run" mode.
5. Record current and potential periodically during the test (every 10 to 30 min is sufficient).

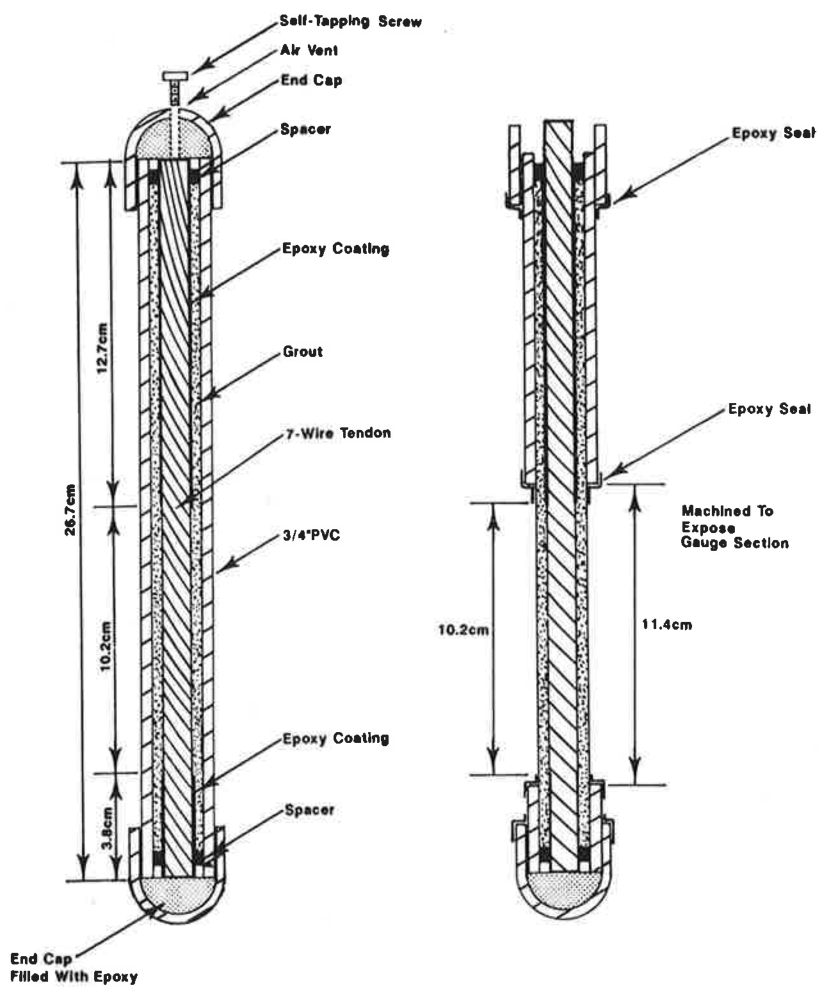


FIGURE 1 Diagrams of grouted pipe specimen: before cutting gauge section (*left*) and ready for testing (*right*).

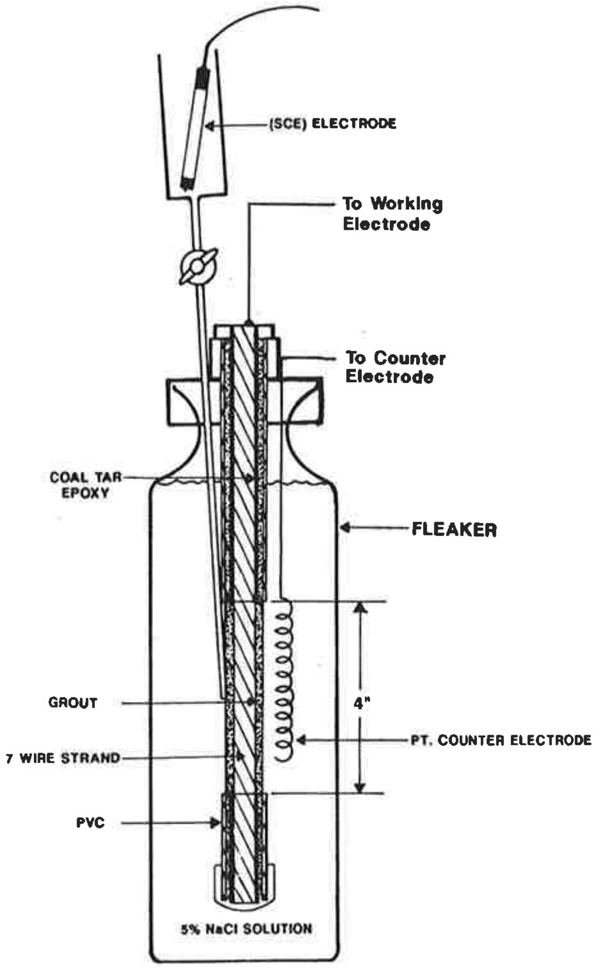


FIGURE 2 Diagram of ACTM test cell arrangement.

6. Plot current versus time until a rapid current increase. This signifies the initiation of corrosion.
7. Allow tests to continue for 48 hr after initiation of corrosion.

RESULTS AND DISCUSSION

Physical and Mechanical Properties

Nine different grout series were evaluated in this program. The distinction between the various series was made on the basis of grout additives. Brief descriptions of the series examined follow.

1. Series 1, standard grout: The standard grout was chosen to be representative of grouts that have been used for many years in the United States. It is a simple mixture of Type II portland cement and water with a water/cement ratio of 0.44.
2. Series 2, commercial antibleed admixtures: This grout also has a normal water/cement ratio (0.45) but contains a commercially available antibleed admixture that has been fairly widely used in recent years (Celtite Inc.'s Celbex 209X).
3. Series 3, high-range water reducer (HRWR): 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 composition.
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, HRWR plus fly ash 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, HRWR 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, HRWR plus latex: There is little information 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 11, HRWR plus expansive agent plus antibleed additive: This series was evaluated to learn the effect of the expansive additive on the performance of Grout Series 3 and 12.
9. Series 12, antibleed additive: In this grout series, a water soluble, polysaccharide gum, providing superior antibleed behavior, was evaluated.

Actual components of the grout mixtures used in this study are given in Table 1. Measured properties for several grout mixtures are given in Tables 2–5.

Series 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. 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 sec. The grout poured uniformly with no disruption or tearing of the grout stream. The standard grout showed 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 more than 3 hr at 73°F (23°C). The standard grout showed good strength gain behavior with a 7-day compressive strength of 6,000 psi (41,370 kPa) and a 90-day compressive strength of almost 10,000 psi (68,950 kPa). Tested at 30 V, the standard grout showed a rapid permeability test current flow of 2400 coulombs in 6 hr.

Series 2: Effect of Commercial Antibleed Admixture on Grout Properties and Behavior

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

TABLE 1 Compositions of Grout Mixtures

Component	Grout Series									
	1	2-1	3	4-1	5-1	6B	6D	8	10-1	11
Type II, Portland Cement, parts by weight	100	100	100	100	100	100	100	100	100	100
Water, parts by weight	44	46	36	34.7	40.8	39.6	43.2	12	42.7	32.7
Conbex 209X, % (based on cement weight)		1.5								
HRWR, fl oz per 100 lb cement			15	15	40	24	55	15		32
Calcium Nitrite, gal/yd^3				6					6	
Flyash, parts by weight					33					
Silica Sand, parts by weight					52					
Gum, parts by weight					0.05					0.01
Silica Fume, parts by weight						11	25			
Latex Modifier, parts by weight								31.4		
Al Powder, parts by weight										0.0075

TABLE 2 Physical Properties: Flow and Bleeding Characteristics

Grout Series	Unit Weight, lb/ft^3	Initial Flow Cone Efflux Time[a], sec.	Bleeding[b] Percent	Expansion[b] Percent	Bleeding Under Pressure[c]	
					Pressure, psi at which water loss first effected	Percent of Total Water Removed at 80 psi
1	118	18	0.1	0	0	48
2-1	115	59	0	1.3	30	5
3	120	19	0.15	0	10	38
4-1	121	22	0.60	0	0	44
5-1	128.6	86	0	0	40	5
6B	116	28	0	0	10	16
6D	117	27	0	0	30	6
8	117	16	0	0	50	1
11	126	57	0	0	30	7

[a] ASTM C939
[b] ASTM C940
[c] Gelman pressure filtration procedure

TABLE 3 Physical Properties: Open and Setting Time and Heat Evolution

Grout Series	Grout Open Time, Hr: Min (Estimated Time Grout Remains Pumpable at 74F)	Setting Time[a]		Heat Evolution Behavior	
		Initial Hr:Min	Final Hr:Min	Maximum Temperature, F	Time to Reach Maximum Temperature Hr:Min
1	3:20	5:15	7:00	150	9:50
2-1	8:00	14:00	23:30	155	11
3	4:20	8:06	10:00	180	12:00
4-1	3:15	6:50	8:45	157	13:00
5-1	5:00	16:10	18:45	132	24:00
6B	1:53	6:50	9:00	170	11:00
6D	6:00	10:23	12:00	150	15:00
8	5:20	9:57	11:15	155	16:00
11	7:30	13:00	13:50	ND	ND

[a] ASTM C953
ND - No Data

TABLE 4 Mechanical Properties

Grout Series	Compressive Strength,[a] psi			
	1d	7d	28d	90d
1	2700	5960	7840	9860
2-1	155	3410	5580	6530
3	4170	8000	9530	10,980
4-1	1700	6225	8740	9710
5-1	900	6450	8400	13,385
6B	3310	7130	10,030	11,620
6D	1930	6760	8830	9340
8	1775	5710	7150	9190
11	1850	4810	5440	6225

[a] ASTM C942.

TABLE 5 Rapid Permeability Data[a]

Grout	Coulombs	
	60 V	30 V
1	33,000 (36,000)[b]	2,400
2-1	59,000	14,500
3	24,000	4,300
4-1	32,000	4,000
5-1	6,960	370 (140)[b]
6B	270	1,000 (910)[b]
6D	590	150
8-1	15,000	1,600
11L	ND	7,200

[a] AASHTO Designation T277-83.
[b] Duplicate specimens.
ND - No Data.

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 3: Effect of HRWR on Grout Properties and Behavior

The use of an HRWR provided for the maintenance of adequate fluidity and working time in the grouts at up to a 20 percent reduction in water content. Relative to the standard grout, the grouts 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 4 and 10: Effect of Calcium Nitrite Corrosion Inhibitor on Grout Properties and Behavior

Grouts containing the calcium nitrite corrosion inhibitor were prepared at water/cement ratios of 0.365 (Grout No. 4-1) and 0.44 (Grout No. 10-1). No property data were 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 ensure that the inhibitor had no adverse effect on the properties of the grout in the fresh and hardened state while providing the desired corrosion inhibiting function in the hardened grout. A comparison of the grouts with (Grout 4-1) and without (Grout 3) the corrosion inhibiting admixture confirms this desired result. The only exception is a lower 1 day compressive strength for the grout containing the corrosion inhibitor. This was an unexpected result because 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 5: Effect of Fine Aggregate (Sand) Additions on Grout Properties and Behavior

Sanded grouts containing up to 28 percent sand were prepared with ratios of water/cement and fly ash between 0.27 and 0.32. These grouts had a pourable fluidity and maintained their pumpability for up to 5 hr. Although initially pourable, these grouts were quite viscous; Grout 5-1 showed an initial flow cone efflux time of 86 sec at a water/cement and fly ash ratio of 0.32.

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 posttensioning 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). The overall pumpability of these relatively viscous, high unit weight grouts remains to be determined.

Series 6: Effect of Silica Fume on Grout Properties and Behavior

Grout compositions were studied that 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. Two of the silica fume grout compositions that were studied most extensively in the present investigation were Composition 6B (10 percent silica fume) and Composition 6D (20 percent silica fume).

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 3 for a 10-percent silica fume grout (Grout 6B). At the 10 percent silica fume addition, the open time of the grout varied from 1½ hr to 8 hr when the HRWR was increased from 25 oz/cwt (16.2 ml/kg) to 55 oz/cwt (35.8 ml/kg).

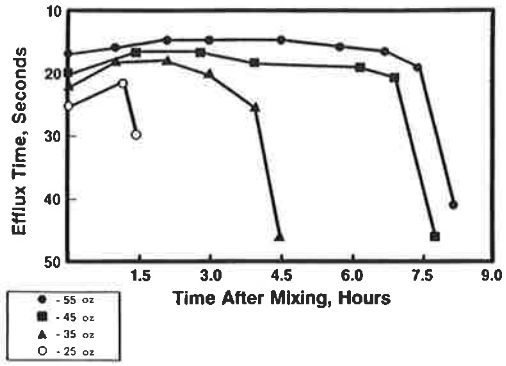


FIGURE 3 Initial and time-dependent efflux time of Grout 6B (90 percent Type II portland cement, 10 percent silica fume grout) as affected by superplasticizer (M150) (water/cement and silica fume ratio = 0.365).

Relative to the standard grout, the use of silica fume (10 and 20 percent cement replacement) in conjunction with an 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 8: Effect of Latex Polymer Modifier on Grout Properties and Behavior

Acrylic and SBR latex polymer modifiers were evaluated. The SBR latex modifier provided the most stable grout and the most consistent properties. The latex addition was 15 percent (percent of cement weight based on dry latex solids). The use of an SBR latex in conjunction with an 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 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).

Series 11: Effect of Expansive Additive on Grout Properties and Behavior

Opinion is divided on the merit of incorporating an expansion-causing additive in grouts for bonded, posttensioned construction. In this program, a grout composition (Composition 11L) was developed to study this variable.

The performance of Composition 11L somewhat paralleled the performance of the grout containing the commercial antibleed 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. One interesting and unexpected phenomenon associated with Composition 11L was the nature of the expansion caused by the aluminum powder. In simple cement and water systems, a powdered aluminum additive typically provides some expansion within 15 to 60 min after the contact time between water and cement. For Grout 11L, no expansion occurred in the grout for up to 3 hr after mixing. At that point (3 hr) the grout began to expand and showed a final expansion value of 9 percent after 6 hr.

Series 12: Effect of Experimental Antibleed Admixture on Grout Properties and Behavior

A number of antibleed and thickening admixtures were evaluated in the program. After 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 antibleed/antisegregation additive. The cumulative water loss in the pressure filtration test from grouts with and without antibleed additives is shown in Figure 4. 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.

Accelerated Corrosion Test Method

Typical results from ACTM are shown in Figure 5, and results for all of the grouts tested are summarized in Table 6. More detailed data are found in FHWA Report FHWA-RD-91-092 (*1,2*). It is important to note that a poor grout with a high water/cement ratio (0.65) gave, by far, the worst results, which indicates that ACTM can differentiate good from poor grout. The addition of HRWR (and corresponding decreases in water/cement ratio), fly ash and sand, silica fume, and latex modifier all improved the corrosion performance over Grout 1. Grout 5-1, containing the HRWR, sand, and fly ash, provided the longest time to failure.

Using the specified ACTM test, Grout 10-1, which was the same as Grout 1 with the addition of an inhibitor, indicated a decrease in corrosion performance when compared with Grout 1. This was unexpected; these results were further examined. It is believed that ACTM is too severe for evaluating inhibitor performance and that the 0.6 V (SCE) applied potential exceeds the breakdown potential for steel in an inhibited grout. Therefore, the ACTM masked the inhibiting ability of the grout. To examine this problem, ACTM was modified to use an applied potential of 0.0 V (SCE). The 0.0 V potential is sufficient to accelerate corrosion once Cl^- reaches the steel surface, but will not unrealistically break down protection provided by an inhibitor of the type utilized in this study. The data presented in Table 6 show the results for the modified ACTM for Grout 1 (standard) and Grout 10-1 (standard plus inhibitor). The time to failure for Grout 1 is similar for both

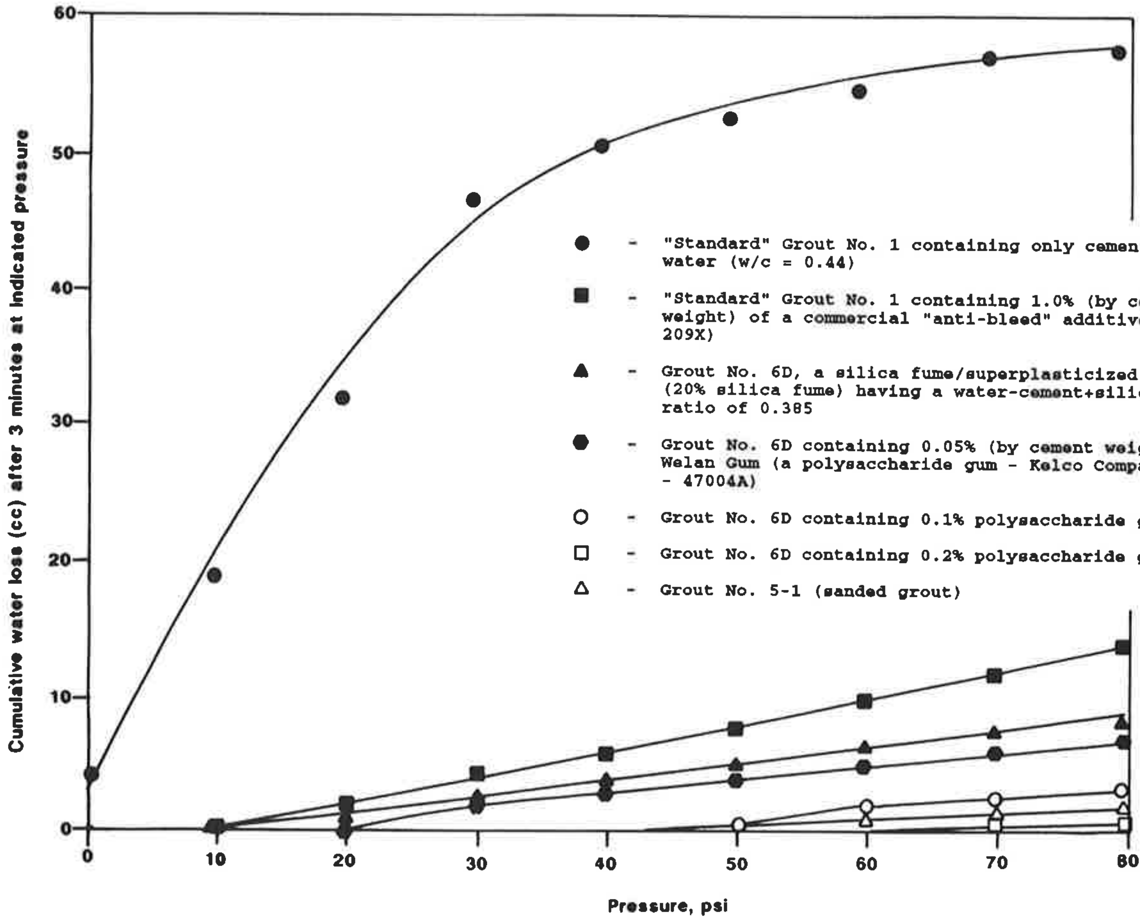


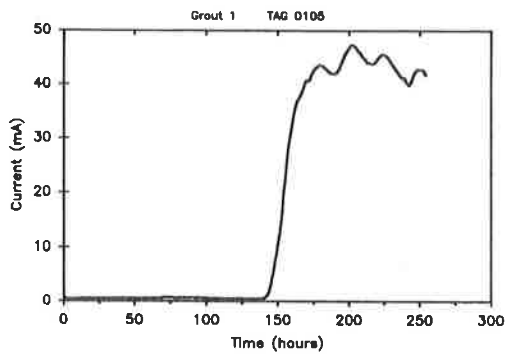
FIGURE 4 Cumulative water loss from indicated grouts (from 0 to 80 psi) using Gelman pressure filtration funnel.

the 0.6 V applied ACTM and the modified 0.0 V applied ACTM. This indicates that the modified ACTM is adequate to examine corrosion performance. A significant improvement in the corrosion performance was realized when an inhibitor was added to the grout (time to failure increased from 177 up to 713 hr) based on the modified ACTM results. Although the data are limited, the improvement in corrosion performance is significant. Therefore, when an inhibitor is added, the modified ACTM must be used. Typical plots for current and time for the rapid Cl^- permeability tests are shown in Figure 6. 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. A comparison of rapid Cl^- permeability results for the 60 V and 30 V applied voltage is presented in Table 5. The only discrepancy in the data is with Grout 6B. The 30 V tests were repeated; it is believed that these data are correct, which indicates that the 60 V data may be in error.

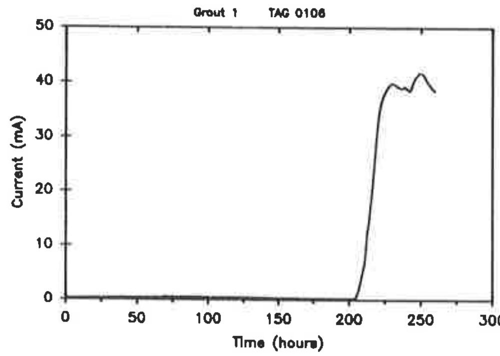
The ACTM results and the AASHTO rapid Cl^- permeability results for several grouts are compared in Table 7. For the five grouts for which both sets of data are available, there is a reasonable correlation between the two sets of data. As permeability increases, the time to corrosion initiation decreases. 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 time to corrosion initiation may include only the rapid Cl^- permeability test. However, initial test results using a modified (0.0 V, SCE, polarized) ACTM indicates that the addition of an inhibitor significantly increases the time for corrosion initiation. It was not expected that the rapid Cl^- permeability would have indicated this result. Therefore, when an inhibitor is incorporated in the grout, the modified ACTM test is required to characterize the corrosion performance. It should also be recalled that ACTM provides an indication of the rate of corrosion following corrosion initiation.

CONCLUSIONS

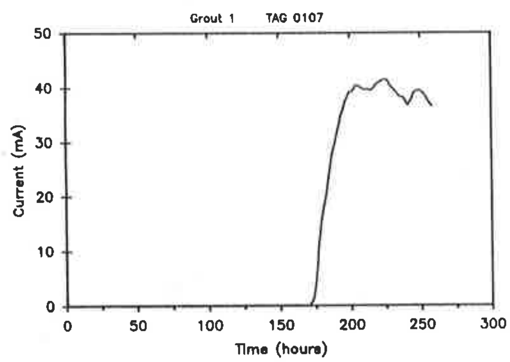
1. The results of investigations to date indicate that, in general, bonded posttension concrete structures exhibit excellent performance. However, in at least one instance, corrosion of the duct material and subsequent corrosion and failure of individual strands of a tendon have been reported.
2. Present specifications are inadequate for ensuring optimum corrosion protection 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 controlled dosage rates of HRWR.



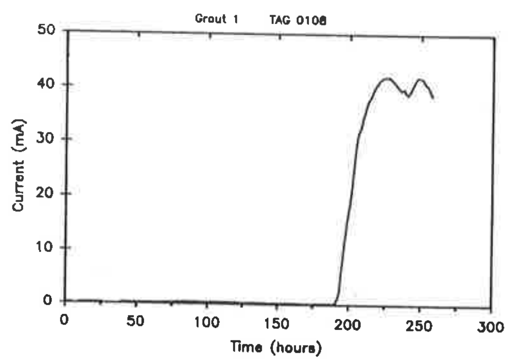
a. Specimen No. 0105



b. Specimen No. 0106



c. Specimen No. 0107



d. Specimen No. 0108

FIGURE 5 ACTM current-time data for replicate standard specimens for Grout 1 (standard grout).

TABLE 6 Summary of ACTM Results

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

[a] Mean Value

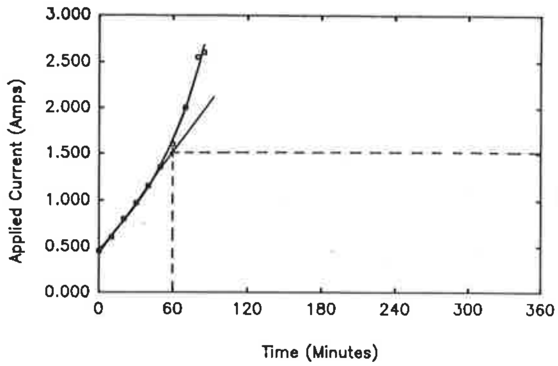
4. Use of modifiers and additives provided improved resistance to pressure-induced grout bleeding:

- Reduction in water/cement ratio had a marginal beneficial effect,
- Silica fume combined with low water/cement ratio had a significant beneficial effect,
- SBR latex polymer modifier produced a significant reduction in pressure-induced bleeding, and
- Antibleeding admixtures were effective in reducing pressure-induced bleeding.

5. On the basis of results from this 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 ability of grouts to delay the onset of corrosion in prestressing steel, which simulates bonded posttensioned bridge exposures while accelerating the corrosion process.

7. Evaluation of corrosion performance is accomplished by two performance tests: the ACTM developed in this study and the modified AASHTO rapid Cl^- permeability test method (30 V applied voltage).



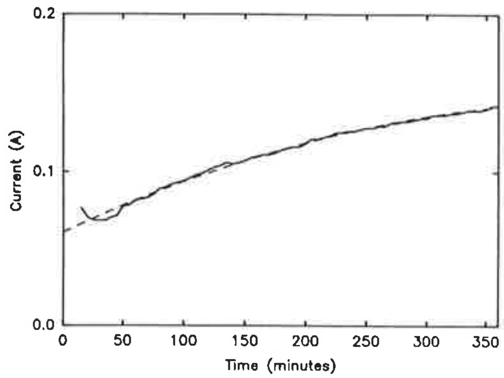


FIGURE 6 Rapid Cl⁻ permeability test results for Grout 1 for 60 V (*top*) and 30 V (*bottom*) applied voltage.

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 ACTM must be used when inhibitors are added to the grout, and in these cases ACTM may be the only method for evaluating corrosion performance.

10. On the basis of ACTM results, grout additives and modifiers that significantly reduce Cl⁻ permeation also significantly increase the time to corrosion of embedded steel tendons.

11. Grout 5-1, containing 33 percent (cement weight) fly ash, provided a threefold increase in the time to corrosion relative to the standard grout.

12. Grout 6B, containing 10 percent (cement weight) silica fume addition, provided a twofold increase in the time to corrosion 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.

TABLE 7 Comparison of ACTM Results (0.6 V, SCE, Polarization) with 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

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Publication of this paper sponsored by Committee on Corrosion.