CORROSIVE BLEED WATER IN POST-TENSIONED TENDONS

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ABSTRACT

Bleeding of grouts used in post-tensioned construction is problematic because the water tends to migrate to the tendon high points and form a void. The water may be reabsorbed by the grout, evaporate, or remain in place. In any case, a void is formed in the duct where the tendon is susceptible to corrosion. The assumption traditionally has been that bleed water remaining in the duct will, like the grout, provide a protective environment for the steel unless chlorides enter the system. Recent examples of corroded bridge tendons in the absence of chlorides have led to speculation about the mechanism of corrosion in this system. This paper describes a study investigating the possibility of corrosive bleed water with certain cement-admixture combinations. Preliminary findings show significant corrosion in many of the specimens. Recommendations for avoiding this type of corrosion are presented.

Keywords: Grout, Post-tensioning, Bleed, Durability, Corrosion, Anchorage.

INTRODUCTION

Post-tensioned concrete bridge construction has been widely employed with much success in the United States and around the world. As used today, post-tensioning is a relatively new structural form, being first employed in the United States about fifty years ago.[1] The durability performance of post-tensioned concrete bridges has been excellent to this point, although assessment of the condition of the post-tensioned reinforcement is often very difficult. In recent years, durability problems have been discovered in several post-tensioned concrete structures, prompting the post-tensioning industry to take steps to improve various aspects of post-tensioned concrete design and construction.[2]

The durability concerns with post-tensioned concrete structures have primarily focused on the corrosion of the high-strength prestressing steel. Corrosion of the steel strands is caused by the presence of chloride ions, moisture, and oxygen at the steel surface. Corrosion protection of the strands involves preventing these constituents, especially the chloride ions, from reaching the steel surface.[3] In post-tensioned structures, the corrosion of the steel is a particularly serious problem, as the integrity of the structure is dependent on the large tensile load carried by the tendon. Failure of the tendon, due to corrosion of the strands, could result in the sudden failure of the entire structure. Corrosion protection for the strands is usually provided by a portland cement-based grout that is injected into the tendon duct after the strands have been tensioned. The grout is intended to provide an alkaline environment in which the steel can remain corrosion-free for the life of the structure. In addition, should the tendon duct or anchorage protection be breached, the grout should provide the final layer of protection for the steel against the ingress of chloride ions. The ideal grout will protect the strands from corrosion by filling the duct completely, having a highly alkaline nature, and possessing low permeability characteristics. Additionally, the freshly mixed grout should possess adequate fluidity and open time to facilitate pumping the grout into the tendon duct, and sufficient resistance to segregation to prevent the formation of bleed voids.[4]

BACKGROUND

Traditionally, the grout used in bonded post-tensioned concrete construction has been a simple water and cement mixture with a specified water-cement ratio in the range of 0.44 to 0.50.[1] In some cases, chemical admixtures, such as expansive agents or water reducers, were added in an attempt to improve certain grout properties. Many research programs were undertaken that attempted to identify a grout formulation with superior corrosion protection properties.[4,5,6,7,8] This research, generally, was conducted using a large number of desirable fresh and hardened grout properties, and various understandings of the means by which the grout provides corrosion protection for the post-tensioning system. Desirable fresh grout properties include fluidity, bleed resistance, appropriate set time, and controlled expansion. Additionally, the hardened grout should possess adequate strength, high electrical resistivity, and low chloride permeability. Some researchers focused on the corrosion protection capability of the hardened grout,[4,5,6] while others were primarily concerned with the ability of the fresh grout to completely fill the tendon duct and encapsulate the tendon.[7,8] Ideally, the fresh grout will completely fill the tendon duct, and the hardened grout will possess superior corrosion protection characteristics. Recommended grouts, typically, included a pozzolanic mineral additive and some type of chemical admixture. Mineral additives, such as silica fume or fly ash, tend to improve grout bleed resistance, lower chloride permeability, and increase electrical resistivity. Recommended chemical admixtures were superplasticizers, which lower water requirements, and gelling agents, which improve grout bleed resistance. These improved grout formulations were often not successfully implemented due to difficulties associated with handling and mixing ingredients, variations in cement and other constituents, and the lack of quality control and inspection in the field.[6,8] As corrosion problems due to poor quality grout have been discovered in recent years, the post-tensioning industry has turned to the use of prepackaged proprietary grouts for many projects. These prepackaged grouts are a blend of cement and other additives that require only the addition of water, and are formulated by the manufacturer to produce a high quality grout with low permeability, excellent bleed resistance, high strength, and suitable fluidity. Most of these prepackaged grouts are thixotropic in nature. Freshly mixed thixotropic grouts are gel-like at rest and quickly regain fluidity when agitated.[9]

Resistance to segregation or bleed has been recognized as a key property of high performance grouts. Segregation of the grout takes place when the mix water and the cement particles separate due to sedimentation or high pressures. This problem is exaggerated where the post-tensioning tendon consists of seven-wire steel strands. The seven-wire strands contain six outer wires wound about a central wire. The mix water is able to seep into the interstitial voids between wires and is then driven upward by the pressure head of the surrounding grout.[10] Bleeding of grouts used in post-tensioned construction is particularly problematic because the water is trapped in the duct. The bleed water tends to migrate to the high points of the tendon and form a bleed void, as depicted in Fig.1. The water may be reabsorbed by the grout, evaporate, or remain in place for a long time. In either situation, a grout void is formed in the duct where the tendon is susceptible to corrosion. Typical void locations are the tendon anchorages, and any intermediate tendon high points. Grouts that resist bleeding have been formulated. These grouts are considered bleed resistant, and are often thixotropic in nature. Bleed resistance is usually achieved with the addition of a gelling agent, similar to the admixture developed by Schupack.[8]

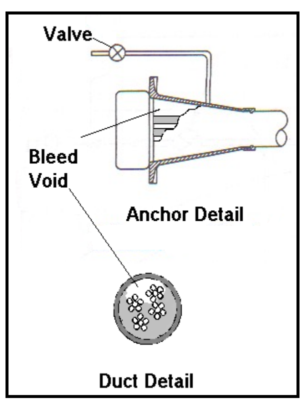

Figure 1: Grout Bleed Void Details.

Surveys of post-tensioned and post-tensioned segmental concrete bridges in the United States have found these structures to be quite durable.[11,12,13] There have been a few post-tensioned structures where corrosion of poorly grouted and detailed tendons has decreased the service life of the structure, but there have been no failures of post-tensioned structures in the United States due to corrosion of the tendons.[2] The collapse of two post-tensioned bridges in the United Kingdom and a third in Belgium led to a ban on post-tensioned bridge construction in the United Kingdom from 1992 to 1996. The moratorium was lifted after the publication of Concrete Society Technical Report No. 47 "Durable Post-Tensioned Bridges." This document included design and construction recommendations for producing very durable post-tensioned bridges. In addition, it showed that the collapses were a result of poor design details and mistakes made during construction, rather than an inherently flawed construction form.[14]

In the spring of 1999, the first of four cases of grouting related corrosion problems in post-tensioned bridges in Florida was discovered on the Niles Channel Bridge.[15] The structure is a low-level post-tensioned segmental concrete bridge over seawater. One of the external post-tensioning tendons failed at the anchorage due to corrosion. Additionally, two strands of a tendon in the opposite web of the same span had failed at the tendon anchorage. The initial corrosion has been attributed to grout bleed water in a void at the anchorage, and additional corrosion is thought to have occurred when the void was recharged with chloride-laden deck runoff that leaked through the expansion joint. On a similar bridge, the MidBay Bridge, two tendon failures were discovered during a routine inspection.[16] One had completely failed at the anchorage, and the other had partially failed in the free length of the tendon. Subsequent inspection of the entire post-tensioning system of the structure resulted in the replacement of nine more tendons due to corrosion at grout bleed voids at the anchorages. Ten of the eleven tendons replaced due to corrosion were located at expansion joints. These corrosion problems have been blamed on grout subsidence, bleed water, and possible recharge of the resultant voids with seawater before casting of the anchorage pour-backs. Severe corrosion damage to vertical looped tendons on a pier of the Sunshine Skyway was discovered in September 2000.[17] Piers on the bridge were known to be partially filled with seawater, and the grout was found to contain high chloride-ion concentrations. The final case involved the I-75/I-595 Sawgrass Interchange. Tendons were discovered during the repair of some joints and anchor blocks that had been left completely ungrouted.[2]

PROBLEM STATEMENT

It has been shown that grout segregation and the resulting bleed water voids lead to decreased protection from corrosion due to chloride ingress at the void location. The investigation of some corroded tendons on the post-tensioned segmental concrete bridges in Florida showed no indication of chloride ingress. This led to speculation about the possibility of corrosion initiation by the grout bleed water in the tendon.[16] The research program described herein investigates the potential for corrosion of isolated prestressing strand in bleed water without the presence of chlorides.

COMPLETED RESEARCH PROGRAM

Chemical admixtures are commonly added to grout mixes to improve properties such as fluidity, bleed resistance, and corrosion protection.[4,5,6,7,8] Common admixtures include superplasticizers, antibleed admixtures, expansive agents, and corrosion inhibitors. The bleed water, as it separates from the freshly mixed grout, also contains these chemicals. A preliminary investigation of the corrosive nature of bleed water from grout mixes containing several admixtures was performed. The results showed increased corrosion levels with the use of some admixtures.[18]

The first phase of the program used small-scale strand corrosion testing to evaluate the corrosive characteristics of grout bleed water collected from the freshly mixed grouts. Grout mix designs were selected that included common chemical admixtures and admixture combinations. In addition, available prepackaged proprietary grouts were included in the testing. The grouts included in this phase of the program are listed in Table 1.

Table 1: Grout Mix Designs Tested.

Grout Mix	Cement Type	Description
PL-I	Type I	0.45 w:c Plain Grout
PL-II	Type II	
SP-I	Type I	0.35 w:c Grout with Superplasticizer
SP-II	Type II	
AB-I	Type I	0.42 w:c Grout with Antibleed Admixture
AB-II	Type II	
IC-I	Type I	0.45 w:c Grout with Inorganic Calcium Nitrite Corrosion Inhibitor
IC-II	Type II	
OC-I	Type I	0.45 w:c Grout with Organic Corrosion Inhibitor
OC-II	Type II	
EX-I	Type I	0.42 w:c Grout with Expansive Admixture
EX-II	Type II	
IX-I	Type I	0.44 w:c Grout with Calcium Nitrite Corrosion Inhibitor and Expansive Admixture
IX-II	Type II	
OX-I	Type I	0.44 w:c Grout with Organic Corrosion Inhibitor and Expansive Admixture
OX-II	Type II	
PA	---	0.23 w:c Prepackaged Grout

Each grout was mixed using both Type I/II and Type II cement to investigate cement-admixture interactions and two specimens were made for each mix. Admixture dosages were made according to the recommendations of the manufacturer. The water-cement ratios of the grout mixes were adjusted in order to achieve a target fluidity of 11-30 seconds in the ASTM C939 Flow Cone Test[19] in accordance with the recommendations of the PTI Guide Specification for Grouting of Post-Tensioned Structures.[9] The freshly mixed grouts were also subjected to the Schupack Pressure Bleed Test as a measure of bleed resistance. The bleed water was collected from the freshly mixed grout with the Schupack Pressure Filter, shown in Fig.2. This test was developed to model the pressures and filtering effects experienced by grout in a post-tensioned tendon.[8,19] The pH of the grout bleed water was also measured as an indication of its potential corrosion protection capability.

The test specimens, as shown in Fig.3, consisted of a length of seven-wire prestressing strand placed in a 100 mL graduated cylinder containing 50 mL of bleed water. The strand surface was cleaned with acetone and the strands were weighed beforehand. All strands were taken from the same spool for consistency between specimens. The specimens were covered and sealed in an attempt to prevent evaporation and simulate the environment inside of a sealed post-tensioning duct. The strands were exposed to the bleed water in the sealed system for a period of six months.

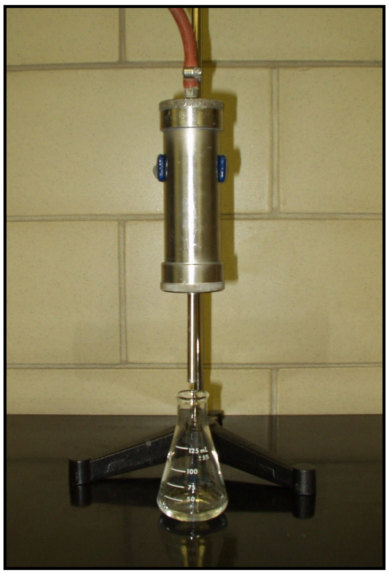

Figure 2: Schupack Pressure Filter.

Figure 3: Test Specimen.

PRELIMINARY RESULTS AND DISCUSSION

Corrosion products were typically seen forming on the seven-wire prestressing strands within one to two weeks after the strand was inserted in the bleed water. The corrosion activity was usually concentrated near the bleed water/air interface, but also occurred on the exposed and submerged portions of some strands. Upon removal of the strands from the bleed water, the corrosion product was removed with a wire brush, and the strands were cleaned with a Scotch™ pad.[21] The strands were then reweighed to determine the total amount of metal loss. Total weight loss of the individual strands due to corrosion varied from 0.9 to 2.0 percent. This measure of corrosion activity was valuable, but the presence and severity of corrosion pits was deemed a more appropriate measure of corrosion severity. This intense, localized pitting corrosion was commonly observed. The nature and severity of the pitting corrosion was recorded, including the number of wires with pits, total number of pits, largest pit depth, and other corrosion effects for each strand. Greater than fifty percent of the strands tested developed corrosion pits at least 1/32" in depth. Pitting on this scale would result in a significant reduction in the ultimate strength of the strand. Fatigue effects due to localized stress concentrations may also be a concern when pits are present on the strand surface.[23] Less severe surface and crevice corrosion effects were observed on some strands. Corrosion rate measurements from the testing would be helpful, but the random nature of the observed pitting corrosion prevents the accurate determination of the corrosion rate based on the strand weight loss values. Calculation of the corrosion rate, based on weight loss, is highly dependent on the surface area assumed to be corroding. For example, the corrosion rate based on the portion of the strand surface area exposed to the bleed water (i.e. uniform corrosion) would grossly underestimate the local corrosion rate at the individual corrosion pits. The average total weight loss and maximum corrosion pit depth for each grout mixture is given in Table 2. Details of typical strand corrosion patterns are shown in Fig.4.

Table 2: Average Total Weight Loss and Maximum Pit Depth.

Grout Mix	Avg. Weight Loss (%)	Max. Pit Depth (in.)
PL-I	1.62	1/32
PL-II	1.77	1/32
SP-I	1.44	1/16
SP-II	1.50	1/32
AB-I	1.05	3/64
AB-II	1.21	1/32
IC-I	1.14	1/64
IC-II	1.54	1/64
OC-I	1.73	1/32
OC-II	1.18	1/32
EX-I	0.99	1/128
EX-II	1.53	1/64
IX-I	1.90	1/64
IX-II	1.31	1/32
OX-I	1.35	3/64
OX-II	1.73	1/16
PA	1.20	1/32

The pH of the bleed water in which the strands had been inserted was measured. Initial measurements of bleed water pH were all between 12.5 and 13.0. The traditional assumption has been that the highly alkaline bleed water passivates the steel surface and prevents corrosion initiation.[5] The initially high pH of the grout bleed water was not able to prevent the initiation of intense localized strand corrosion or the subsequent formation of severe corrosion pits. Measurements taken after the strands were removed were between 9.5 and 10.5. As the corrosion progressed the grout bleed water became more acidic in nature. There has been some discussion as to the possibility of the formation of localized regions of low pH due to interaction with atmospheric carbon dioxide near the grout/void interface at voided post-tensioning tendon anchorages.[24] Further investigation is needed to determine if a similar mechanism allowed the initiation of the corrosion observed in these tests.

The cement type used in the grout mixtures did not noticeably affect the grout properties or the corrosive characteristics of the extracted bleed water. Bleed water from grouts dosed with the same admixture and different cements displayed similar corrosive characteristics. The corrosion caused by the bleed water from these grouts was comparable in nature and severity. The observed corrosion products and progress were also very much alike. Combinations of common grouting admixtures are often used in particular mix designs. In two cases (IX-I and OX-II), the combination of a corrosion inhibitor and an expansive admixture resulted in a grout with bleed water that was more corrosive than mixes containing each admixture individually. This indicates possible admixture interaction effects. Such effects may be quite severe, and are not readily predicted. This could be a concern with a prepackaged grout, if the product was not tested for these effects.

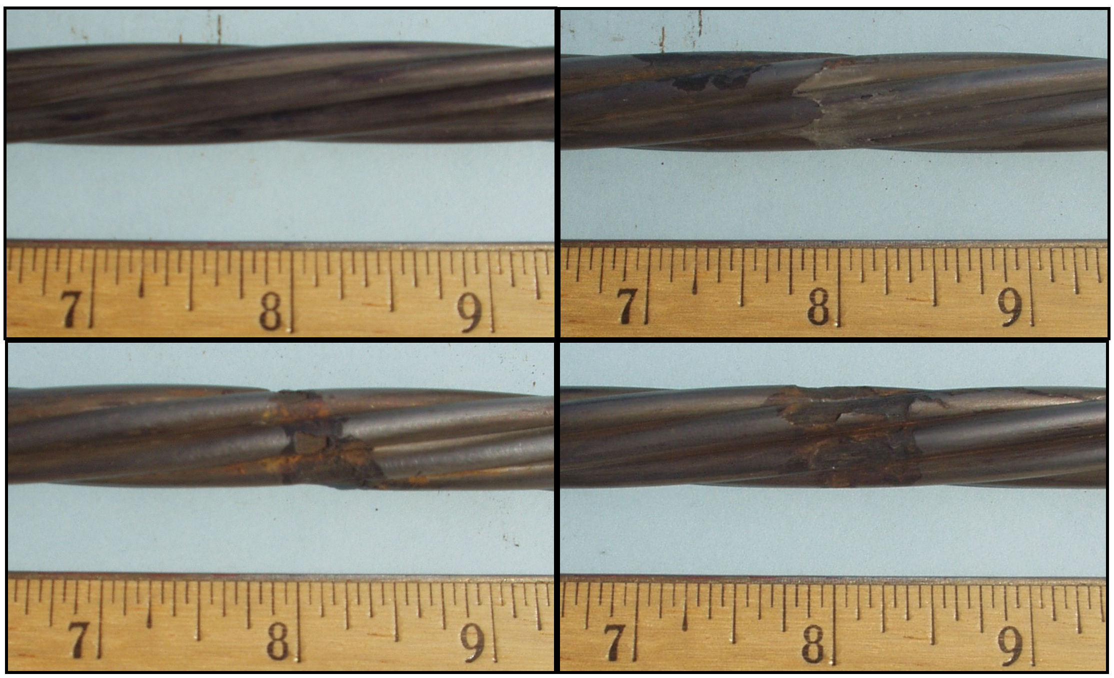

Figure 4: Details of (clockwise from top left) strands with no corrosion, light surface corrosion, and heavy pitting corrosion (2).

CONCLUSIONS

Several conclusions can be drawn from the results of the small-scale strand corrosion testing.

1. Seven-wire, high-strength steel prestressing strands may experience severe corrosive attack, particularly corrosion pitting, in the presence of grout bleed water.
2. The corrosion occurs despite the high pH of the grout bleed water and the absence of chlorides in the system. The corrosion also takes place without galvanic corrosion effects, since the strand specimen is isolated from dissimilar metals.

3. The chemical admixtures used in a particular grout mixture influence the nature and severity of the corrosion caused by the grout bleed water. Admixture interactions can also occur, and may amplify the corrosive effects of the grout bleed water.

RECOMMENDATIONS

The following recommendations can be offered based on the results of this research:

1. Antibleed grouts should be used in post-tensioned construction to insure tendon durability. The motivation for using bleed resistant grouts has previously focused on grout bleed voids as potential locations for chloride ingress and subsequent corrosion initiation. The presented research indicates that even the presence of grout bleed water in the tendon can initiate corrosion in the absence of chlorides.
2. Chemical admixtures should be used sparingly in grouts for post-tensioned construction. The specific ingredients and mechanisms responsible for the observed severe strand pitting are not yet understood. Thus, some reservations should be held concerning their use, unless it has been proven that they will not further aggravate corrosion if bleed occurs.

FUTURE RESEARCH

Planned large-scale testing will be performed on those mixes showing the most severe corrosive characteristics in the small-scale tests. This testing will attempt to more closely model the actual conditions inside a post-tensioning tendon, and to verify the results of the small-scale tests. The large-scale test specimens will consist of 5.00m long, 65mm diameter, clear plastic tubing containing 11 prestressing strands. These tubes will be inclined at 30 degrees from horizontal and pumped full of grout. A pocket of bleed water and air will be allowed to form at the top of the tube, and sealed in place for a period of time. A similar test is often used to determine the bleed properties and stability of a grout mix at near full scale and including the filtering effect of the tendon strands.[14] The resulting corrosion activity will be compared to that observed in the small-scale tests. In addition the corrosion rate will be measured Chemical analyses of bleed water collected from these grout mixes will be performed in an attempt to isolate specific corrosive agents.

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