EVALUATION OF EMULSIFIABLE OILS FOR LUBRICATION AND TEMPORARY CORROSION PROTECTION OF SEVEN-WIRE STRAND

APPROVED:

John E. Breen

Karl H. Frank

To my twin brother, Whitaker

EVALUATION OF EMULSIFIABLE OILS FOR LUBRICATION AND TEMPORARY CORROSION PROTECTION OF SEVEN-WIRE STRAND

by

WILLIAM MARLEY KITTLEMAN, B.S.C.E.

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN ENGINEERING

THE UNIVERSITY OF TEXAS AT AUSTIN

December 1992

ACKNOWLEDGEMENTS

This research was performed at the Ferguson Structural Engineering Laboratory at The University of Texas at Austin. Funding was provided by the Texas Department of Transportation and the Federal Highway Administration. Private organizations that donated specific products and technical support were Viscosity Oil Company, Shell Oil Company, Unocal 76, Texaco, E.F. Houghton and Company, Nalco Chemical Company, The PQ Corporation, and the Wright Oil Company. Special thanks goes to Charles Novak (Viscosity Oil Co.), Jim Smit (Viscosity Oil Co.), Kevin Friday (Texaco), and Dr. Jerry Hollander (Unocal 76) for their technical advice and friendly attitudes.

At this time I would like to thank the individuals who made this thesis possible. First of all I want to think my supervising professors Dr. John Breen and Dr. Karl Frank. It's not often in life that you get the chance to work with two individuals of such high caliber. Their guidance and patience, especially in the early stages of this research were greatly appreciated. More importantly, I would like to thank both of them for their friendship during my work at The University of Texas at Austin.

The technical and administrative staffs at Ferguson Lab were instrumental in helping me adapt to my new surroundings two years ago. Thank you Wayne Fontenot, Wayne Little, Blake Stassney, Pat Ball, Jean Gherke, Laurie Golding, April Jenkins, and Sharon Cunningham.

The special friends I made during my work at Ferguson Lab deserve special recognition. In particular I would like to mention five individuals, Raoul Karp, Reed

Freeman, Trey Hamilton, Todd Helwig, and Bruce Russell. These individuals were great role models who were always there when I needed them. I only hope that I gave back to them what they gave to me.

Finally, I would like to thank my family for their continuous support during my graduate studies. I love you all.

William Kittleman

August 11, 1992
Austin, Texas

TABLE OF CONTENTS

CHAPTER 1
INTRODUCTION

1.1 General. The use of prestressed concrete has increased at a rapid rate since its introduction in 1928 by Eugene Freyssinet of France[1]. Today prestressed concrete is used in several types of structures including bridges, buildings, and parking garages. In the last thirty years the use of post-tensioned prestressed concrete in U.S. bridge construction has rapidly increased due to its versatility and favorable economics. Two of the most notable developments in which post-tensioned concrete and post-tensioning technology have been used include segmental and cable-stay bridge construction (Figures 1.1 and 1.2). In segmental construction precast or cast-in-place concrete bridge segments are post-tensioned together to form a continuous structure. In cable-stay construction steel girders or concrete segments for deck elements are combined with post-tensioning steel stay elements.

During the last twenty years over 100 large segmental bridge projects and 13 cable-stay bridges have been completed in the United States[2,4]. These bridges have provided excellent performance to date and are not expected to have any problems in the near or distant future. However, their have been a number of concerns associated with their construction. Two of these are friction reduction during stressing of post-tensioned tendons and temporary corrosion protection of both post-tensioned tendons and cable-stays after installation and before grouting.

1.2 Post-tensioned Concrete. In post-tensioned prestressed concrete, ducts are placed in the formwork before the concrete. After the concrete has cured, prestressing steel tendons are placed within the ducts. These tendons are then stressed by using a hydraulic ram which jacks the tendon against the end of the

Figure 1.1 The H-3 windward viaduct in Hawaii (Reference [2]).

Figure 1.2 Sunshine Skyway Bridge, Tampa, Florida (Reference [3]).

concrete member resulting in precompression of the member. At this stage there is no bond between tendon and concrete. When the tendon has been stressed to the desired force, the ram is released with the elongated tendons anchored by special anchorages at the ends of the member. The anchorages therefore hold the force of the tendon and continue the compressive force transfer into the concrete.

After anchoring the post-tensioned tendons, the duct may or may not be grouted. If the duct is grouted, the tendon is then bonded to the surrounding concrete by the grout. If the duct is not grouted, the tendon is then attached to the surrounding concrete only at the anchorages. Grouted tendons are referred to as bonded tendons while ungrouted tendons are referred to as unbonded tendons. Unbonded tendons may also be in the form of single strand tendons encased in grease-filled sheaths.

1.3 Post-tensioned Tendons.

1.3.1 Description. As shown in Figure 1.3 a bonded post-tensioned tendon consists of a tension element, duct, anchorages and grouting system. The tension element is often referred to as the tendon and may consist of high strength wires, bars, or strands. In the United States 0.5" diameter or 0.6" diameter seven-wire strands are the preferred types of prestressing steel. The duct usually consists of galvanized steel or high density polyethylene. Anchorages are always steel and vary depending on the type of prestressing steel used for the tendon. The grout usually consists of water, cement, and sometimes commercial admixtures.

1.3.2 Concerns.

1.3.2.1 Friction Reduction. During stressing of multi-strand tendons friction forces are encountered between the tendon and the duct as shown in Figure 1.4a. This friction can be divided into two types, friction due to curvature and friction due to wobble. The curvature of the duct results in direct contact between the tendon and the duct and also high normal forces between the tendon and the duct. These are accompanied by high friction forces. Wobble refers to the actual path of a straight duct in post-tensioned construction. In practice almost all straight ducts will have some amount of wobble due to their large lengths and/or "kinks" caused during the

Figure 1.3 Bonded post-tensioned tendon.

fabrication process. Accidental contact with the tendons in these wobble zones also produces friction but of considerably lower magnitude. In curved tendons both curvature and wobble are present.

Substantial research has been completed on friction during stressing of post-tensioned tendons[5,6] resulting in ranges of values for both curvature friction and wobble friction coefficients for different post-tensioning systems. From these values general estimates of the friction forces encountered during stressing can be determined. The values are usually expressed as ranges.

As shown in Figure 1.4b frictional forces encountered during stressing can result in a significant loss in the prestress force along the length of a post-tensioned tendon. In long continuous tendons this loss may be as much as 30 to 40%. Therefore, if the tendon is temporarily stressed at one end to 80% of its ultimate strength, which is the maximum allowed by current codes, then the stress in the tendon at the other end will be approximately 50% of ultimate. If the tendon is jacked from both ends, then frictional losses may be reduced. However, significant losses will still exist along the length of the tendon.

High frictional losses are undesirable for the following reasons:

(1) If the tendon strength cannot be fully utilized along its full length, then prestressing steel is being wasted which results in higher construction costs.

(2) Generally, the level of effective prestress governs tendon design. Additional tendons may be required to obtain the design prestress in the structure. Installation of additional tendons introduces additional costs and time delays in construction.

(3) The overall structural design changes when the required prestress cannot be achieved or additional tendons are used.

Due to the increasing complexity of tendon layouts for post-tensioned bridges, high frictional forces have become an increasing problem in recent years. In some cases the friction forces encountered in the field have been much larger than the calculated values. In other cases the field friction forces have agreed with the calculated values. In either case high friction losses are considered unacceptable. They have been offset by lubrication of the tendon. Historically, the lubricant of choice has been some type of emulsifiable oil. This type of lubricant has been claimed to provide good friction reduction in the field. However, there are numerous emulsifiable oils available and it is not known whether different oils will provide different amounts of friction reduction.

1.3.2.2 Temporary Corrosion Protection. Another concern during post-tensioned concrete construction is temporary corrosion protection of the tendons after installation in the duct and before grouting. In most cases tendons are installed, stressed, anchored, and grouted within a few days. However, in some staged construction as well as when long construction delays due to inclement weather or other unforeseen events occur, these tendons could be left ungrouted for several months. During this period humidity in the duct or corrosive agents from the ambient outdoor surroundings could lead to corrosion of the tendon.

Corrosion of post-tensioned tendons is a serious matter because tendons consist of small cross-sectional areas under high stresses. If corrosion occurs, then a reduction in strength or possible fracture of the tendon could occur leading to serious structural damage.

In order to protect post-tensioned tendons from corrosion prior to grouting, emulsifiable oils and vapor phase inhibitors have been used. Vapor phase inhibitors are in the form of fine crystals, which slowly sublime to create a vapor which acts in the presence of moisture and oxygen to prevent corrosion. These inhibitors tend to be preferred over emulsifiable oils for protection of the tendon after installation in the duct[7]. However, both vapor phase inhibitors and emulsifiable oils are used by strand manufacturers for protection of strand during long storage periods[8,9]. Again, there are numerous emulsifiable oils currently available but there is no test data comparing the corrosion protection offered by different oils.

1.4 Cable-Stays.

1.4.1 Description. Cable-stays are another form of a post-tensioned tendon. A cable-stay consists of a tension element anchored at both ends and usually grouted inside a duct. The most common tension elements are multiple wires, multiple bars, or multiple strands. In recent times, cable-stays have usually been grouted in order to provide permanent corrosion protection of the prestressing steel. The grout serves no direct structural purpose since the tendon is only attached to the structure at its ends. A cable-stay is therefore an unbonded post-tensioned tendon on a much larger scale. At the present time, concerns over corrosion protection are leading to the introduction of other cable stay systems with combinations of galvanized strand, epoxy-coated strand, grouting or other blocking agents such as waxes.

1.4.2 Temporary Corrosion Protection. The construction of a cable-stay bridge usually takes several years. During this time the stays are erected, but are often left ungrouted until the final stages of construction. Temporary corrosion protection of the stays during this time is of utmost concern since they are primary load carrying members.

Currently, there are no products marketed specifically for temporary corrosion protection of cable-stays. Since the same types of steels are used for both post-tensioned tendons and cable-stays, the same type of temporary corrosion inhibitors have been employed, namely emulsifiable oils. Vapor phase inhibitors are not usually used for temporary corrosion protection of cable-stays due to the length and inclination of the stays.

When emulsifiable oils are used for friction reduction or temporary corrosion protection in post-tensioned construction, water is usually pumped through the duct in an attempt to "flush" the oil off of the tendon before grouting. The efficiency of this flushing process is unknown. If the oil is not completely removed from the tendon, then the adhesion between the tendon and the grout may be incomplete leading to problems with serviceability or tendon ultimate strength. In cable-stay construction the stay is usually not flushed in order to prevent the introduction of water into the duct.

1.5 Problem Statement. Emulsifiable oils have been used for friction reduction in post-tensioned tendons and temporary corrosion protection of post-tensioned tendons and cable-stays. Currently, there are numerous emulsifiable oils manufactured, but none are marketed specifically for any or all of these applications. In order to compare the friction reduction and temporary corrosion protection performance of candidate emulsifiable oils, a lubricant evaluation should be performed.

1.6 Objectives. The objectives of this evaluation were to:

1. Identify emulsifiable oils that could be effectively used for lubrication and/or temporary corrosion protection of seven-wire strand.

2. Evaluate the performance of these oils in small-scale corrosion and adhesion tests. These tests should also study the effect of flushing on the corrosion and adhesion properties of lubricated seven-wire strands.

3. Provide recommendations for use of the selected oils in post-tensioning or cable-stay applications.

1.7 Scope. In the following chapters an evaluation of eleven candidate lubricants is presented. Of these eleven lubricants, ten are emulsifiable oils and one is a sodium silicate solution. The eleven candidate lubricants were selected after performing an extensive literature review and an informal phone survey of users and manufacturers of emulsifiable oils. Findings of the literature review and phone survey are presented in Chapter 2. Results of small-scale friction tests performed by Hamilton and Davis as part of this overall project are also presented in Chapter 2 since these results are incorporated into the overall lubricant evaluation.

Accelerated wire corrosion tests are described in Chapter 3. These tests used a reference electrode and visual observations to compare the corrosion protection offered by the eleven lubricants in deionized water and 3.5% NaCl solution.

Chapter 4 presents exposure tests in which lubricated unflushed and lubricated then flushed strands were subjected to a daily wetting cycle in outdoor ambient conditions. Small lubricated wires were also tested to compare the performances of the lubricants in the exposure tests and the accelerated wire corrosion tests reported in Chapter 3.

Chapter 5 describes pull-out tests that were performed to compare the effects of the different lubricants on the adhesion between seven-wire strand and cement grout before and after flushing. Additional pull-out tests performed in Chapter 6 were used to determine the relative effects of restricting twist on the behavior of bare, lubricated, and lubricated, then flushed strands.

Chapter 7 reports the overall lubricant evaluation that was used to select the best four lubricants for use in large-scale friction tests that were part of this overall project. In Chapter 8 the findings are summarized, conclusions are drawn, recommendations concerning the use of these eleven products, and recommendations for further research are given.

CHAPTER 2

STATE-OF-THE-ART

2.1 Introduction. This chapter presents the findings from the literature review and phone survey that were completed to determine the state-of-the-art in lubricated tendon utilization. From these findings it became apparent that no product is currently marketed specifically for lubrication or temporary corrosion protection of multistrand post-tensioning tendons. An emulsifiable oil that had been previously marketed for temporary corrosion protection of post-tensioned tendons before grouting was identified. However, this oil is no longer manufactured. It is interesting to note that this product was originally designed for use as a coolant-lubricant in metalworking operations and that its formulation was only changed slightly before being marketed for use in post-tensioned concrete construction. This formula change involved the removal of chlorides from the oil[10].

Related research that was identified in the literature review included a previous evaluation of temporary corrosion inhibitors, studies of various temporary corrosion protection techniques, and friction tests using emulsifiable oils.

The informal phone survey identified four emulsifiable oils that have been used for temporary corrosion protection or friction reduction of post-tensioned tendons. Six other products were recommended by three different manufacturers of emulsifiable oils.

After reviewing the literature and completing the phone survey eleven candidate products were selected for possible use in lubrication or temporary corrosion protection of prestressing steel. These eleven products were compared using small-scale corrosion tests, pull-out tests, and small-scale friction tests. The corrosion and pull-out tests are presented in their entirety in this thesis, while only the procedures and results of the small-scale friction tests are presented in this chapter. These latter tests were designed and performed by Trey Hamilton and Rodney Davis as part of this overall project.

2.2 Background on Emulsifiable Oils. Historically, emulsifiable oils have been the most common products used for friction reduction of post-tensioned tendons. Since this thesis concentrated primarily on emulsifiable oils, background information on these types of lubricants will be presented before the findings of the literature review and phone survey.

Emulsifiable oils are primarily designed for use as coolant-lubricants in metalworking operations. These oils, which are often described as "water soluble" oils, are designed to be mixed with water to form an emulsion, which can be pictured as tiny oil droplets surrounded by a thin film of emulsifier, which in turn is surrounded by water. The emulsifier is an additive in the oil that reduces the interfacial tension between the oil and the water. This allows the oil and water to mix[11]. Oil in water emulsions usually appear as a milky white solution similar to milk. However, different color emulsions can be encountered depending on the oil.

Table 2.1 shows additives that are commonly used in emulsifiable oils manufactured for metalworking operations. These additives are designed for several purposes including friction reduction between the cutting tool and the metal, rust prevention, odor control, and bacterial growth.

Since emulsifiable oils are usually used "straight" in post-tensioning operations, problems that are sometimes encountered with an oil in water emulsion are avoided. These problems include bacterial growth in the emulsion, maintaining the correct pH in the emulsion, and checking the type of water used to make the emulsion. One problem that may arise with the use of

Table 2.1 Additives commonly used in emulsifiable oils (From reference [11]).

an emulsifiable oil in post-tensioned construction is separation of the oil's constituents. If an emulsifiable oil is subjected to sub-freezing conditions during storage, then there is a possibility that the components of the oil will separate[11]. This separation could lead to reduced friction reduction or reduced corrosion protection offered by the oil.

To determine if separation of the oil's components has occurred, a sample of the oil should be drawn from the container and mixed with water. During mixing the oil should be added to the water not vice versa. If the oil forms an emulsion, then separation of the oil has not occurred. However, if the oil does not form an emulsion, then separation has occurred. The oil can usually be agitated to remix the ingredients. However, it is not advisable to store an oil under conditions which will cause separation of the oil's components[11].

2.3 Findings from Literature Review.

2.3.1 Evaluation of Temporary Corrosion Inhibitors. Previous research of temporary corrosion inhibitors recommended the use of a vapor phase inhibitor or a sodium silicate-sodium nitrite solution for temporary corrosion protection of prestressing steel[12]. In that research five products were tested for possible use in temporary corrosion protection of prestressing steel. These products were evaluated based on their performance in small-scale corrosion tests and small-scale bond tests.

The products studied in that research were a sodium silicate-sodium nitrite solution, an emulsifiable oil, two organic corrosion inhibitors, and a vapor phase inhibitor. The emulsifiable oil and the organic corrosion inhibitors provided better corrosion protection than the sodium silicate-sodium nitrite solution, but their adverse effects on bond prevented their recommended use in prestressed concrete. The sodium silicate-sodium nitrite solution and vapor phase inhibitor essentially had no affect on bond.

The sodium silicate-sodium nitrite solution consisted of a product called sodium silicate "N", sodium nitrite, and water. The emulsifiable oil was Shell Dromus B and the two organic corrosion inhibitors were Trachem Drycoat and Trachem Lubecoat. Shell VPI No. 250 was the vapor phase inhibitor.

Sodium silicate "N" is a multi-purpose product that can be used for corrosion protection of metals. This product is manufactured by The PQ Corporation of South Gate, California.

Shell Dromus B is a general purpose emulsifiable oil marketed for use as a coolant-lubricant in metalworking operations. Shell Dromus B is manufactured by the Shell Oil Company.

Trachem Drycoat was an organic corrosion inhibitor that dried rapidly to form a clear, non-tacky film after application. Trachem Lubecoat was an organic, water-displacing corrosion inhibitor which remained soft and tacky after application. Both of these products were manufactured by Tracor, Inc. of Austin, Texas. Neither of these products are currently manufactured[13].

Shell VPI No. 250 is currently manufactured by the Olin Chemical Company of Stamford, Connecticut under the name Dichan 100[14]. This inhibitor is in the form of fine crystals. These crystals slowly sublime to create a vapor that prevents corrosion.

Corrosion tests using 2.5" long, 0.25" diameter prestressing wires were used to compare the corrosion protection offered by the sodium silicate-sodium nitrite solution, the emulsifiable oil, and the two organic corrosion inhibitors. A separate corrosion test was performed for the vapor phase inhibitor due to its physical characteristics. The vapor phase inhibitor is in the form of fine crystals. Therefore, it could not be used to coat wire specimens.

In the wire corrosion tests the 2.5" wire specimens were coated with the corrosion inhibitors for one-half of their length. These wire specimens were then hung on racks and placed in a desiccator containing water in the bottom. Every forty-eight hours the racks were taken out of the desiccator, placed in a refrigerator for one hour, and then placed back into the desiccator. This cooling cycle and insertion back into the desiccator caused water to condense on the wire specimens creating a corrosive environment. Visual observations were recorded at regular intervals to determine the length of corrosion protection offered by the different inhibitors.

Two modified versions of this corrosion test were also performed. The first version dipped the coated wires in distilled water before the cooling cycle. The second version dipped the coated wires in 3.5% NaCl solution before the cooling cycle.

In the original version of this test all four of the corrosion inhibitors prevented corrosion for more than 1100 hours, or approximately 46 days. When the coated wires were dipped in distilled water before cooling the organic corrosion inhibitors provided the best corrosion protection. Each of these inhibitors prevented corrosion for more than 1100 hours. Shell Dromus B prevented corrosion for 720 hours and the sodium silicate-sodium nitrite solution prevented corrosion for 360 hours.

When the coated wires were dipped in the 3.5% NaCl solution the organic corrosion inhibitors again provided the best corrosion protection. Trachem Drycoat prevented corrosion for 640 hours and Trachem Lubecoat prevented corrosion for 450 hours. Shell Dromus B prevented corrosion for 240 hours and the sodium silicate-sodium nitrite solution prevented corrosion for 75 hours.

During the wire corrosion tests performed in that study a white precipitate was observed on the wires coated with the sodium silicate-sodium nitrite solution. According to the study the precipitate was probably SiO_2 caused by the reaction between the sodium silicate film and the CO_2 in the atmosphere.

Corrosion tests for the vapor phase inhibitor used 0.25" diameter prestressing wire specimens enclosed in Pyrex tubes. The tubes were inclined at 5 on a flat surface and contained 20 mL of water at the lower end of the tube. Before sealing the tube, five grams of Shell VPI 250 were sprinkled onto the wire at the top end. After 50 days of exposure, corrosion spots extended from the bottom of the wire to within 1" of the VPI crystals. No tests were performed using a 3.5% NaCl solution and the vapor phase inhibitor.

The small-scale bond tests completed in that study used single 0.25" diameter prestressing wire specimens and single 0.5" diameter seven-wire strand specimens surrounded by a sand-cement mortar. A complete set of test results was presented for the strand specimens, but not for the wire specimens.

In the tests using the strand specimens two strands were coated with each corrosion inhibitor and then rinsed with distilled water to simulate flushing of a post-tensioned tendon. Each rinsed strand was then placed in the fixture shown in Figure 2.1 and stressed to 7000 lbs. using a testing machine. After stressing, the load in the strand was transferred to the fixture by tightening the 1" nuts on the two threaded rods. The fixture was then removed from the testing machine and a sand-cement mortar was placed around the center section of the strand while the strand was still in the fixture. The dimensions of the mortar block were 2.5" x 2.5" x 5".

The specimen shown in Figure 2.1 actually shows a prestressing wire surrounded by the sand-cement mortar. However, the same size mortar block was used for both the 0.25" diameter wires and the 0.5" diameter strands.

After the mortar block had cured the fixture was placed back into the testing machine. The strand was then loaded until the 1" nuts could just be loosened transferring the load from the fixture to the testing machine. The test procedure consisted of unloading the strand in 200 lb. increments. At the conclusion of each load increment the strain in the mortar block and the load in the strand were recorded.

Figure 2.1 Fixture used for small-scale bond tests (From reference [12]).

The strain in the mortar block was measured using a strain gauge epoxied to the outer surface of the block. Load in the strand was indicated from the testing machine. By comparing the strain in the mortar block with the load in the strand, the bond-slippage load could be determined. Figure 2.2 shows the results for two uncoated strands and one coated, but then rinsed strand. The coated strand was coated with Shell Dromus B before rinsing. One of the uncoated strands was grit-blasted before testing, while the other uncoated strand was not treated before testing.

Points marked "A" in Figure 2.2 indicate where the outer wires of the strand began to slip through the mortar block. Points marked "B" indicate where the bond began to pick-up due to mechanical interlock between the strand and the mortar. For the bare, uncoated strand with smooth wires the bond-slip load was approximately 2400 lbs. compared to a bond-slip load of approximately 400 lbs. for the rinsed strand originally coated with Dromus B. The grit blasted strand had a much higher bond-slip load of approximately 7900 lbs.

The average bond release load for the bare strand specimens that were not grit blasted was 2330 lbs. For the strands coated with the sodium silicate-sodium nitrite solution the average slip load was 2150 lbs., which was 10% less than the bare strand. The organic coatings and the emulsifiable oil caused major reductions in bond. Average slip loads for Trachem Drycoat and Trachem Lubecoat were 1100 lbs. and 900 lbs. respectively. The average slip load for Dromus B was 300 lbs. These slip loads represented a 60% reduction in bond caused by the organic corrosion inhibitors and a 90% reduction in bond caused by the emulsifiable oil.

2.3.2 Other Temporary Corrosion Protection Methods.

Figure 2.2 Typical results from small-scale bond tests (From reference [12]).

2.3.2.1 Alkali-polymer Coating. An alkali-resistant polymer coating was mentioned in the literature as a possible temporary corrosion inhibitor for prestressing steel[15]. Exposure tests using this coating on mild steel reinforcing bars showed it to provide excellent corrosion protection in outdoor ambient conditions[16]. The exposure tests were performed in a South London urban atmosphere for 12 months. After 12 months, bars coated with the polymer coating were virtually unaffected, while uncoated bars were severely corroded. The polymer coating appeared to be flexible after drying and had little effect on the bond between reinforcing bars and concrete. Accelerated corrosion tests also showed this coating to provide excellent corrosion protection after the bar is surrounded by concrete. No methods for removing this coating were studied.

The alkali-polymer coating is similar in appearance to a conventional paint and can be applied by brushing, dipping, or spraying.

2.3.2.2 Corrosion Inhibitor Solution. A patented corrosion inhibitor solution has been tested for possible use in temporary corrosion protection of post-tensioned tendons. This passivating, alkaline solution was designed to fill ducts containing ungrouted tendons[17]. The solution is flushed out of the ducts before grouting.

Small-scale corrosion tests performed with four different corrosion inhibitor solutions showed the patented solution to provide the best corrosion protection. The solutions tested were the patented solution, a lime solution, cement extract, a carbonate solution, and a hydroxide solution. Anodic polarization measurements, peak potential measurements, immersion studies, and stress corrosion cracking studies were completed in the research. These tests involved small prestressing steel specimens. No full-scale tests using ducts filled with the different solutions were performed.

2.3.2.3 Swedish National Road Administration Study. A study conducted by the Swedish National Road Administration investigated five methods of temporary corrosion protection for post-tensioned tendons[15]. The tendons examined during their test were left ungrouted for three years. Twenty-six tendons, located in three different locations in Sweden, were used in this investigation. The corrosion protection methods were:

1. Careful sealing of the ducts combined with drain pipes at the duct low points.

2. Continuous flowing of predried air through the ducts.

3. Depositing a vapor phase inhibitor in the ducts.

4. Eliminating oxygen from the steel environment by filling the ducts with nitrogen. This method was not practical due to problems with gas tube connections and gas leakage.

5. Applying an emulsifiable oil on the tendons.

After three years of exposure no major differences in the corrosion protection methods were observed. The prestressing steel in all of the ducts at all three sites was in good condition. Tensile, fatigue, bend and stress-corrosion tests performed at the conclusion of the test also showed no variations in the prestressing steel from the different sites.

2.3.3 Small-scale Friction Tests using Emulsifiable Oils. Small-scale friction tests performed by Owens and Moore showed no reductions in friction when an emulsifiable oil was used to lubricate a single strand tendon[9]. This study used the test setup shown in Figure 2.3 to investigate the effect of different surface conditions on friction in post-tensioned tendons. Four tendon

sizes and three surface conditions were investigated in this study. The single tendons consisted of 7 mm wire, 12.7 mm drawn strand, 15.2 mm round wire strand, and 18 mm drawn strand. The surface conditions were clean, rusty, and oiled.

Table 2.2 shows the results from their tests. For the 15.2 mm round wire strand there was essentially no difference between the friction coefficients for the clean strands and the friction coefficients for the oiled strands. Results from this table also showed a significant increase in the friction coefficient caused by the presence of rust on the tendon before testing. This increase varied between factors of 1.5 and 2.5.

The test procedure used for these friction tests consisted of loading each single wire or single strand tendon up to 80% of its ultimate breaking load and then unloading it back to zero. Ten to fifteen load increments were used during loading and unloading the tendons.

In a related study, five post-tensioned beams containing clean and lubricated post-tensioning bars were tested[9]. These tests showed no difference in the cracking and deflection behavior of beams containing a "clean" bar and beams containing a lubricated bar that was flushed before grouting.

Figure 2.4 shows the test setup that was used for the beam tests. In this test each of the beams were loaded at quarter points and deflection was measured at midspan. The conditions of the post-tensioning bar for each of the five beams is shown below.

Beam Number	Conditions of post-tensioning bar
1,2	Clean, grouted post-tensioning bar
3,4	Lubricated, then flushed and grouted post-tensioning bar
5	Lubricated, ungrouted post-tensioning bar

Each beam contained a single 20 mm diameter Macalloy post-tensioning bar inside a 30 mm diameter flexible steel duct. The Macalloy bar was stressed to 227.5 kN four weeks after casting the beams. The beams were grouted immediately after stressing and tested three weeks later. A neat cement grout having a water to cement ratio of 0.45 was used to grout the ducts in four of the five beams. The duct in the fifth beam was left ungrouted.

The lubricated bars were lubricated with Shell Dromus B. According to their study some prestressing steel suppliers have used Shell Dromus B, Caltex Soluble RGBF, or Mobil Solvag 1535 for temporary corrosion protection of prestressing steel during storage. These products were shown to provide good corrosion protection in normal storage conditions. All three of these products are emulsifiable oils.

Figure 2.5 shows the moment-deflection results from the beam tests. The results for the beams containing the "clean" bars (beams 1 and 2) were noticeably different with beam 2 appearing to yield at a much lower load than beam 1. Due to the difference in results for beams 1 and 2 it was difficult to determine the effect of the flushed lubricant on the flexural behavior of the beams. Crack patterns and crack widths were similar for all four of the bonded beams (beams 1, 2, 3, and 4).

The behavior of the unbonded beam (beam 5) was quite different than the behavior of the bonded beams. The unbonded beam had less than half the number of cracks as the bonded beams and also had one crack that opened very quickly to 2 mm before loading was removed.

2.3.4 Large-scale Friction Tests using Emulsifiable Oils.

2.3.4.1 Large-scale Friction Tests Performed by the California Department of Transportation. Large-scale friction tests conducted on a concrete box girder bridge using an emulsifiable oil reduced the friction in a post-tensioned tendon

by approximately 15%[18]. In these tests four tendons, described in Table 2.3, were tested before and after lubrication to determine the effectiveness of an emulsifiable oil in reducing friction.

Two test procedures were used. The first jacked the tendons from both ends simultaneously and the second jacked the tendons from one end. In both tests load cells at both ends of the tendons and strain gages along the lengths of the tendons were used to determine friction losses along the tendon length.

Each of the four tendons were tested at least three times in a "dry" condition and then lubricated and tested at least two more times. The lubrication process consisted of pouring an emulsifiable oil directly into the ducts. Due to the fairly steep longitudinal grade of the bridge, the oil eventually ran through the ducts. The oil could not be pumped into the duct since there was no way of creating a tight seal at the end of the duct.

After the tendons were lubricated the friction was reduced by approximately 15% for the wire tendons. No reductions in friction were observed for the strand tendons after lubrication. Grout leaks and damaged ducts may have contributed to the lack of friction reduction in the strand tendons. The four lubricated tendons were flushed with water after testing and before grouting. The brand of the lubricant used to lubricate the tendons was not mentioned in the report.

2.3.4.2 Large-Scale Friction Studies Performed by Dywidag Systems International and the California Department of Transportation. Dywidag Systems International in cooperation with the California Department of Transportation performed large-scale friction tests on an actual structure to compare two different lubricating agents for use in post-tensioned tendons[19]. These tests showed a biodegradable soap to provide slightly better friction reduction than an emulsifiable oil. The soap reduced the friction by approximately 55% while the emulsifiable oil reduced the friction by 40 - 45%.

The structure used in these tests was a three cell concrete box girder bridge. Friction tests were performed on six tendons, all of which were located in the two inner webs of the box. Four of the tendons were stressed "dry" and two of the tendons were stressed after lubrication. The friction reduction offered by the two lubricants was determined by comparing the measured elongations and the forces reaching the far anchorages for both of the lubricated tendons.

Each of the six tendons consisted of 29, 1/2" diameter strands having an ultimate strength of 270 ksi. The sheathing was a semi-rigid corrugated galvanized

Table 2.3 Lubricated tendons tested in reference [18].

steel duct having an inner diameter of 100 mm. All of the tendons were draped following the same parabolic curve.

One of the two lubricated tendons was lubricated with a solution of Aqualube MX, while the other tendon was lubricated with a solution of Dromus B. Each solution was formulated by mixing one part soap, or one part oil, with one part water. Lubrication of the tendons was completed by pumping approximately 50 gallons of solution into the duct. Compressed air was used to drive the solution through the duct. Both ducts containing the lubricated tendons were flushed with water after testing and before grouting.

2.4 Summary of Findings from Literature Review. Three emulsifiable oils were mentioned in the literature review for use in lubrication or temporary corrosion protection of prestressing steel. These oils were Shell Dromus B, CalTex Soluble RGBF, and Mobil Solvag 1535. Shell Dromus B was used in both lubrication and corrosion protection studies. The other two oils (CalTex Soluble RGBF and Mobil Solvag 1535) have both been used for temporary corrosion protection of prestressing steel in storage. However, no controlled test data was presented which showed the actual amount of corrosion protection that could be expected from these two oils. A biodegradable soap (Aqualube MX) was also identified as a possible lubricant for use in friction reduction in multi-strand tendons.

The test data identified in the literature for Shell Dromus B showed this oil to provide good temporary corrosion protection[12]. When emulsifiable oils were used for friction reduction the reported data was conflicting. The reported data showed an emulsifiable oil to have no effect on friction[9], reduce friction by 15%[18], and reduce friction by 40 - 45%[19]. Shell Dromus B was the emulsifiable oil used in the first and third studies. The emulsifiable oil used in the second study was not identified.

Results showing the effect of an emulsifiable oil on adhesion after flushing were also conflicting. One study showed Shell Dromus B to essentially destroy the adhesion between a flushed seven-wire strand and cement grout[12]. Another study showed Shell Dromus B to have no effect on the cracking and deflection behavior of a post-tensioned beam containing a lubricated then flushed post-tensioning bar[9].

Due to these conflicting results in friction reduction, effect on adhesion, and the lack of test data comparing the corrosion protection of different emulsifiable oils a comparison of candidate oils was in order. This comparison, which is provided in this thesis, will serve as a base study that directly compares the friction reduction, effect on adhesion, and corrosion protection of several different emulsifiable oils. It also gives some insight into the chemical composition of emulsifiable oils in general.

2.5 Findings from Informal Phone Survey. The informal phone survey was designed to obtain information on products that are currently being used for lubrication and\or temporary corrosion protection of prestressing steel. In this survey four bridge contractors, four state highway departments, and six manufacturers of emulsifiable oils were contacted. Information was also obtained from the Federal Highway Administration and the Post-Tensioning Institute.

The primary questions asked during the phone survey were:

1. What products are currently being used to reduce friction in post-tensioned tendons?
2. What products are currently being used for temporary corrosion protection of post-tensioned tendons and/or cable-stays?
3. How are these products being applied to post-tensioned tendons or cable-stays?
4. How are these products being removed from post-tensioned tendons or cable-stays?

According to the sources contacted in this phone survey, emulsifiable oils are the most common products used for friction reduction in post-tensioned tendons. These oils are usually applied by one of the five methods shown below.

1. Spraying the tendon with oil as the tendon is entering the duct.
2. Pouring oil over the tendon as the tendon is entering the duct.
3. Pulling the tendon through a bath of the oil as the tendon is entering the duct.
4. Pumping oil into the duct after the tendon has been installed.
5. Pouring oil through grout ports as the tendon is entering the duct.

Removal of emulsifiable oils after stressing and before grouting is usually accomplished by pumping water through the duct. This "flushing" procedure is usually continued until the water exiting the duct is free of oil. One of the sources also mentioned the use of limewater to flush the oil off the tendon.

Graphite powder was mentioned by three of the sources for possible use as a friction reducer. This powder is smeared onto the tendon as the tendon is entering the duct.

Emulsifiable oils have also been used for temporary corrosion protection of post-tensioned tendons and cable-stays. In cable-stay construction the oil may not be flushed from the tendon in order to prevent the introduction of water into the duct. In post-tensioned tendons the oil is usually flushed from the tendon before grouting by pumping water through the duct. These oils can be applied in the same manner when used for friction reduction or temporary corrosion protection.

The use of a vapor phase inhibitor for temporary corrosion protection of post-tensioned tendons was also mentioned. This inhibitor is in the form of fine crystals and can be blown into the duct after the tendon has been installed. Flushing of a vapor phase inhibitor or graphite powder was not cited by any of the sources, but is probably performed before grouting.

2.6 Candidate Lubricants Selected for Evaluation. Table 2.4 shows the eleven products that were selected as possible candidates for temporary corrosion protection and/or lubrication of prestressing steel. These products were selected after reviewing the literature and completing the informal phone survey. Of these eleven products nine are emulsifiable oils, one is an emulsifiable oil-free fluid, and one is a sodium silicate solution. The sodium silicate solution is not designed for use as a lubricant, but will be referred to as a lubricant in this study. The sodium silicate solution was selected because it was used in previous research concerning temporary corrosion protection of prestressing steel.

Four of the eleven lubricants described in Table 2.4 have been used for temporary corrosion protection and/or friction reduction of post-tensioned tendons. One of these four lubricants has also been used in previous research studying corrosion protection and friction reduction in post-tensioned tendons.

Four other lubricants, Aqualube MX, Caltex Soluble RGBF, Mobil Solvag 1535, and Rust-veto 2212 were identified after this research had been completed. Aqualube MX has been used for friction reduction, while the other three lubricants have been used for temporary corrosion protection of prestressing steel during storage[19,9,8]. None of these lubricants were used in this study, but may be used in future tests.

2.7 Friction Tests. As part of the overall lubricant evaluation small-scale friction tests were performed to compare the relative lubrication properties of the eleven products studied in this thesis. In these tests static friction reduction and dynamic friction reduction were studied. Static friction was considered to be the friction that exists between the tendon and the duct before the tendon begins to move during stressing. Dynamic friction was considered to be the friction that exists between the tendon and the duct after the tendon begins to move during stressing.

Table 2.4 Continued.

Table 2.4 Continued.

The small-scale friction tests were designed and completed as part of this overall project by Trey Hamilton and Rodney Davis. This section presents the procedures and results from these tests.

2.7.1 Procedures. The test setup used for the small-scale friction tests is shown in Figure 2.6. In this setup a single 1/2" diameter seven-wire strand was positioned between two concrete blocks. Each concrete block contained a 1.25" x 12" strip of galvanized steel duct embedded in the surface facing the strand. The strand was therefore "sandwiched" between these two duct strips, which were embedded in the concrete blocks. A normal force of 1000 lbs. was applied to the top block by a 60 kip testing machine. This force was used to simulate normal forces encountered around duct bends in the field.

Two pairs of blocks were constructed for each of the eleven lubricants. For each pair of blocks the same test procedure was used. Initially, a bare strand was placed between the blocks and pulled two times. Next, this strand was lubricated with a candidate lubricant and pulled two more times. This procedure resulted in four sets of test data for each pair of blocks, two data sets for the bare strand and two data sets for the lubricated strand.

From the four data sets an average static friction factor and an average dynamic friction factor were determined for bare strand and for lubricated strand. The amount of friction reduction provided by the different lubricants was determined by comparing the average friction factors for the bare and lubricated strands.

An additional pair of blocks was also constructed to determine the sensitivity of the test results to dramatic changes in surface conditions on the duct strips. In these tests 1.25" x 12" strips of Teflon were placed between a bare strand and the duct strips that were embedded in the concrete blocks. The bare strand was then pulled two times to determine the static and dynamic friction factors provided by the Teflon.

Lubrication of the strand specimens was performed as shown in Figures 2.7 and 2.8. During this process approximately 30 mL of the lubricant was poured over the strand as it was resting on one of the blocks. Another 30 mL of lubricant was also poured over the duct on the other block. The blocks were then "sandwiched" together with the strand specimen between them and positioned in the testing machine.

After the first pull of each lubricated strand, the normal force on the blocks was removed. This allowed the top block to be removed so the strand specimen could be "rolled" in the duct of the bottom block. By "rolling" the strand in the duct of the bottom block the lubricant could be redistributed over the surface of the strand before being pulled for the second time.

2.7.2 Results. Figure 2.9 shows typical results for one pair of blocks. The top two curves represent the data for two pulls of the same bare strand. The bottom two curves represent the data for two pulls of the same bare strand, after the strand had been lubricated with Lubricant L8. The average load at

Figure 2.7 Lubrication of strand for small-scale friciton tests.

Figure 2.8 Lubrication of strand for small-scale friction tests.

which the bare strands began to pull through the blocks was 250 lbs. The average load at which the lubricated strands began to pull through the blocks was 180 lbs. These average loads were divided by 1000 lbs., which was the normal force on the blocks, to obtain an average static friction factor of 0.25 for the bare strand and an average static friction factor of 0.18 for the lubricated strand for this pair of blocks. Therefore, the static friction reduction for this lubricant for this pair of blocks was (1 - 0.18/0.25) x 100 or 28%. The same process was used to determine the static friction reduction for the second pair of blocks.

Determination of the loads for calculating the dynamic friction factors was quite subjective. As indicated by the data in Figure 2.9 several "dips" occurred in the load-slip data during testing. These "dips" were a result of the loading system used in the tests. During the tests a manual pump was used to jack the hydraulic ram. Every time the pump was stroked the load would suddenly increase at the beginning of the stroke and suddenly decrease at the conclusion of the stroke.

The "dynamic" load for each pull was obtained by using the loads at the first three "peaks" after the strand began to pull through the blocks. Typical "peaks" are marked with circles in Figure 2.9. An average "dynamic" load for each pull was determined by calculating the average of the three "peak" loads. This average "dynamic" load was then divided by 1000 lbs., which was the normal force, to obtain a dynamic friction factor for each pull. The dynamic friction reduction was then determined by comparing the dynamic friction factors for the bare strand and the lubricated strand.

Tables 2.5 and 2.6 show the average static and dynamic friction factors for the bare and lubricated strands for each lubricant and each pair of blocks. The lubricants are in descending order according to their average friction

reduction with the exception of L10 and Teflon which are not water soluble lubricants.

As indicated by Tables 2.5 and 2.6 the amount of friction reduction varied depending on the lubricant. For static friction the reductions varied from 27% to 0%. For dynamic friction the reductions varied from 14% to 2%. Three of the lubricants (L6, L7, and L10) actually increased the friction. The 30% increases in static and dynamic friction caused by Lubricant L10 were due to the nature of this lubricant. L10 is a sodium silicate solution that dries quickly to form a clear, glassy film. During the friction tests this lubricant became "tacky" and restricted movement of the strand through the blocks. The increase in friction caused by Lubricants L6 and L7 could not be explained. When Teflon was placed between a bare strand and the duct strips, both the static and dynamic friction were reduced by approximately 60%.

The results of the small-scale friction tests performed by Hamilton and Davis contradicted previous results reported by Owens and Moore, which showed no reductions in friction when an emulsifiable oil was used to lubricate a single strand tendon. However, the tests performed by Hamilton and Davis did agree somewhat with preliminary findings from large-scale friction tests performed by Tran at the University of Texas at Austin[20]. Tran's preliminary results showed average friction reductions of 10%, 16%, 18%, and 23% for L2, L8, L5, and L11 respectively. The 80' lubricated tendons used in Tran's tests consisted of seven, 1/2" diameter seven-wire strands in a 2" diameter corrugated galvanized steel duct.

The average static and dynamic friction reductions shown in Tables 2.5 and 2.6 for each of the eleven lubricants were used in the overall lubricant evaluation reported in Chapter 7.

CHAPTER 3

ACCELERATED WIRE CORROSION TESTS

3.1 Introduction. The purpose of the accelerated wire corrosion tests was to compare the length of corrosion protection offered by the eleven lubricants in two accelerated corrosive environments. In these tests small prestressing wire specimens were coated with each of the eleven lubricants and immersed for three days in either 750 mL of deionized water or 3.5% NaCl solution. The three day test period was selected after preliminary tests showed corrosion covering approximately 50% of bare wire specimens after three days in deionized water. It was decided that a good corrosion inhibitor should prevent corrosion during three days of immersion. Therefore, a three day test period was selected.

During this period potential difference readings between the wire specimens and a reference electrode were recorded. Visual observations were also recorded every twenty-four hours to record the appearance or increase in corrosion on the wire specimens.

It was anticipated that the length of corrosion protection offered by the different lubricants could be determined by comparing the visual observations with the potential difference data. However, the potential difference results were quite scattered and were not always consistent with visual observations. Therefore, the corrosion protection offered by the different lubricants was evaluated based on visual estimates of percent corrosion on the wire specimens after three days in each environment.

3.2 Background. Corrosion of steel in water or saltwater is an electrochemical process[21]. In this process iron from the steel is oxidized to ferrous ions:

$\mathrm{Fe} \qquad \mathrm{Fe}^{2+} + 2e-$(Oxidation of iron)

While oxygen is reduced to hydroxyl ions:

$\mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} + 4e- \qquad 4\mathrm{OH}-$ (Reduction of oxygen)

The ferrous ions react with the hydroxyl ions to form ferrous hydroxide, $Fe(OH)_2$:

$$2Fe^{2+} + 4OH- \qquad 2Fe(OH)_2$$

However, ferrous hydroxide is unstable in oxygenated solutions and is oxidized further to form rust, or $Fe(OH)_3$:

$$2Fe(OH)_2 + H_2O + (1/2)O_2 \qquad 2Fe(OH)_3$$

The oxidation and reduction reactions for iron and oxygen are known as half-reactions. At standard conditions half-reactions have known potentials with respect to the standard hydrogen electrode. For example, $Fe \quad Fe^{2+} + 2e-$ has a potential of -0.44 V with respect to the standard hydrogen electrode, while $O_2 + 2H_2O + 4e- \quad 4OH-$ has a potential of 0.40 V with respect to the standard hydrogen electrode. Since different half-reactions have different potentials, a reference electrode can be used to indicate when new half-reactions begin, such as $Fe \quad Fe^{2+} + 2e-$.

If a reference electrode is connected to a prestressing wire as shown in Figure 3.1, then the potential difference between the reference electrode and the wire can be measured. Since the reference electrode is at equilibrium any changes that occur in the potential difference between the wire and the electrode are due to changes that occur on the wire surface or in the corrosive environment. If no changes occur on the wire surface or in the corrosive environment, then the potential difference between the wire and the electrode will remain constant.

If a bare wire is connected to the reference electrode and deionized water is used for the corrosive environment, then the potential difference readings between the bare wire and the reference electrode will begin to

decrease immediately as shown in Figure 3.2. This decrease in potential difference is due to corrosion occurring on the wire immediately after the wire is immersed in the water.

If a lubricated wire is now connected to the reference electrode, then the time at which corrosion begins on the wire surface may or may not be indicated by changes in the potential difference. Figure 3.3 shows an idealized plot of potential difference data along with visual observations for this type of test setup. Initially, the lubricant prevents any activity on the wire resulting in a constant potential for the first twenty-four hours. However, at twenty-four hours a sharp decrease in the potential difference occurs indicating a change on the wire surface. At forty-eight hours corrosion was visually observed on the wire. Based on this idealized data, t_{corr}, the length of corrosion protection offered by the lubricant, would be twenty-four hours. If different wire specimens are lubricated with different lubricants, then the length of

Figure 3.2 Potential difference data for bare wire immersed in deionized water.

Figure 3.3 Idealized results for lubricated wire immersed in deionized water.

corrosion protection offered by these lubricants could be compared by using their t_{corr} values from this test.

The test setup shown in Figure 3.1 is a mixed-potential test setup because the reference electrode is connected to two or more oxidation-reduction systems. These systems can include, but are not limited to, iron, Fe^{2+}, Fe^{3+}, oxygen, and water. The potential difference between the electrode and the wire is defined as E_{corr} (corrosion voltage) and equals the potential that exists where the total rate of oxidation equals the total rate of reduction. For a more detailed discussion of mixed-potential theory see Reference 21.

This study recognizes that mixed-potential data is usually not used in this manner. However, E_{corr}, between a lubricated wire and a reference electrode is easily measured and does indicate changes on the wire surface or in the corrosive environment. Also, there is currently no corrosion measurement technique available for lubricated wires, other than visual methods.

3.3 Experiment Design. Forty-eight wire specimens, as shown in Table 3.1, were tested using the setup shown in Figure 3.1. These wires consisted of two wires for each of the eleven lubricants in both environments and two bare wires in both environments. Four additional wires, as shown in Table 3.2, were tested later to study the effect of changes in the test setup on the potential difference data and to compare the performance of bare wires obtained from a second reel of strand.

3.4 Materials.

3.4.1 Prestressing Wire. Seven-inch prestressing wire specimens with a diameter of 0.156" were used in the accelerated wire corrosion tests. These wires were outside wires obtained by untwisting 7" strand samples cut from two reels of 1/2" diameter, Grade 270 low-relaxation strand. The strand properties that were reported by the strand manufacturer are shown in Table 3.3. These strand reels are referred to as R1 and R2 in the remainder of this thesis. All of the wires tested in the accelerated wire corrosion tests were from R1 except for the two 7" wires shown in Table 3.2, which were from R2.

The strand from R2 had a noticeable white coating on its surface that was not present on the strand from R1. According to the strand manufacturer this white coating was due to a stearate soap that was used in the strand drawing process. This white coating is often present in varying amounts, but is not expected to provide any corrosion protection[8]. It should also be mentioned that the strand from R1 was approximately two years old, from the time of manufacture, when the accelerated wire corrosion tests were performed. The strand from R2 was approximately three months old, from the time of manufacture, when the accelerated wire corrosion tests were performed. All of the wire specimens were in good condition and were corrosion free before

Table 3.1 Wire specimens tested in accelerated wire corrosion tests.

Table 3.2 Additional wires tested in accelerated wire corrosion tests.

Table 3.3 Strand properties reported by manufacturer.

testing.

3.4.2 Five-minute Epoxy. A two-part, five-minute epoxy was used to "cap" the ends of the wire specimens before lubrication to prevent galvanic corrosion at the ends. In preliminary tests several specimens were immersed without these caps resulting in heavy corrosion at the immersed cut end and virtually no corrosion along the length of the wires. The ends of the wires were ground lightly to form a uniform surface before applying the epoxy "caps".

3.4.3 Deionized Water. Deionized water was used by itself to form one of the two corrosive environments.

3.4.4 Sodium Chloride Crystals. Sodium chloride crystals were mixed with deionized water to formulate the 3.5% NaCl solution. This solution was made in 2.5 liter increments.

3.5 Specimen Preparation. Lubrication of the wire specimens was performed by dipping the wires into a tube of the lubricant as shown in Figure 3.4. After lubrication the wires were left undisturbed for twenty-four hours on a "drying rack" as shown in Figure 3.5 before immersion into the corrosive environment. Twenty-four hours was selected to allow the lubricants time to adhere to the wire surface and "cure" before immersion into the corrosive environment.

3.6 Test Setup. The overall test setup is shown in Figures 3.6 and 3.7. Eight wire specimens were tested at a time. The individual test setup for each of the wires was shown in Figure 3.1. Each individual setup consisted of a corrosive environment, reference electrode, wire specimen, and c-clamp.

The c-clamp as shown in Figure 3.8 was used to clamp the lead wire from the datalogger to the wire specimen. Small neoprene pads were attached to the clamp areas in contact with the wire specimen to isolate the connection from the clamp.

In all of the tests approximately 3.5" of the 7" length of the wire specimens were immersed into the corrosive environment. The wires were positioned approximately 1/2" away from the tip of the reference electrode.

3.7 Instrumentation.

3.7.1 Reference Electrodes. A saturated calomel reference electrode as shown in Figure 3.9 was used to measure E_{corr}. This electrode, which has a

Figure 3.4 Lubrication of wire specimens.

Figure 3.5 "Drying rack" used for lubricated wires.

Figure 3.6 Test setup used for accelerated wire corrosion tests.

potential of -0.241 V with respect to the standard hydrogen electrode, consists of a mercury/mercury chloride element surrounded by a saturated potassium chloride gel.

3.7.2 Datalogger. E_{corr} measurements were recorded by a datalogger, as shown in Figure 3.10, and then downloaded to a personal computer for analysis.

3.8 Test Procedure. The test procedure consisted of immersing the bare andlubricated wire specimens into the corrosive environments and recording visual observations and potential difference readings during the next three days.

3.8.1 Scan Rate. E_{corr} readings were taken every minute for the first five minutes and then switched to sixty minute intervals for the remainder of the test. This scan rate resulted in seventy-seven data points over the three day test period. When analyzing this data it became apparent that this number of points was not needed. Also the data was more difficult to present when every point was plotted. Therefore, the data that was actually used consisted of the readings taken at 0, 1, 3, 5, and 60 minutes followed by readings at 120 minute

Figure 3.8 C-clamp.

Figure 3.9 Saturated calomel reference electrode.

Figure 3.10 Datalogger.

intervals. The shorter scan rates at the beginning of the test were used to show any large changes that might occur in E_{corr} after the lubricant on the wires came into contact with the corrosive environment.

3.8.2 Visual Observations. Visual observations were taken immediately after immersion and at twenty-four hour intervals. Observations consisted of water color, type of corrosion, and amount of corrosion. Painted wires as shown in Figure 3.11 were used as visual references to estimate the amount of corrosion present on the wire specimens. The painted areas indicate 50, 40, 30, 20, and 10% corrosion of the surface area below the waterline, respectively.

3.9 Results. Figure 3.12 shows the five patterns of corrosion that were observed during the accelerated wire corrosion tests. These corrosion patterns included corrosion spots, vertical corrosion streaks, spiral corrosion streaks, corrosion at the epoxy interface, and corrosion at the waterline. The corrosion spots or corrosion streaks may be better indicators of the corrosion protection offered by the different lubricants. Corrosion at the waterline was partially due to evaporation of the water, while corrosion at the epoxy interface was possibly due to the presence of the epoxy,

Figure 3.11 Painted wires used to estimate percent corrosion on wire specimens.

which increased the chance of crevice corrosion at this location.

The spiral corrosion streak was unique because it seemed to follow a path that was identical to the contact area between the outside wire and the center wire of the strand. This corrosion pattern was observed on one lubricated wire during the accelerated wire corrosion tests and three bare wires during preliminary corrosion tests using distilled water.

The labelling system used for the wire specimens included the lubricant number, if a lubricant was used , the specimen number, and the type of corrosive environment. This system is shown below.

Labelling System for Wire Specimens used in Accelerated Wire Corrosion Tests.

L# = Lubricant number (if a lubricant was used)
BW = Bare wire
1,2 = Specimen number
DW = Deionized water
SW = 3.5% NaCl solution

Examples of this labelling system are L1-1DW and BW-2SW.   L1-1DW was the

first wire specimen lubricated with L1 and immersed in deionized water. BW-2SW was the second bare wire specimen tested in 3.5% NaCl solution. All of the wires were obtained from strand from R1 (Reel 1) except for two wires which are discussed in section 3.10. These wires were obtained from R2 (Reel 2).

Table 3.4 shows an example of visual observations for two lubricated wire specimens. These observations were for wire specimens lubricated with Lubricant L2 and immersed in deionized water for three days. Visual observations for all of the wire specimens are shown in Tables A.1 through A.4 in Appendix A.

Figure 3.13 shows typical E_{corr} data for bare wire specimens immersed in deionized water and 3.5% NaCl solution. Notice how E_{corr} decreased immediately upon immersion for both wires. The E_{corr} data for the bare wire specimen in the saltwater solution began at a more negative potential due to the presence of the chloride ions in the solution. Corrosion was present on both wires after twenty-four hours. This corrosion increased gradually over the next forty-eight hours to cover approximately 50% of each wire at seventy-two hours.

During immersion the corrosion present on both wires was a bright orange color. After the wires were removed from their corrosive environments the corrosion on the saltwater specimen gradually changed to a dark reddish-brown. Corrosion on the deionized water specimen remained bright orange after removal from the deionized water. When lubricated wires were removed from their respective saltwater environments the corrosion also changed from a bright orange to a dark reddish-brown. The corrosion on the lubricated wires tested in deionized water remained bright orange after removal from the water.

Figure 3.14 shows the E_{corr} data and visual observations for L8-1DW

Table 3.4 Typical visual observations for wire specimens in accelerated wire corrosion tests.

Figure 3.13 Typical E_{corr} data for bare wire specimens.

Figure 3.14 E_{corr} data and visual observations for L8-1DW.

which exhibited a well defined t_{corr} (length of corrosion protection) value. As shown by the visual observations no corrosion was present on this wire after twenty-four hours. However, at forty-eight hours a spiral corrosion streak covering 10% of the surface area was observed. The appearance of this corrosion streak was preceded by a decrease in E_{corr} of approximately 160 mV between thirty-six and forty-eight hours. Since the E_{corr} data decreased sharply at thirty-six hours and since corrosion appeared immediately after this decrease t_{corr}, or the length of corrosion protection offered by Lubricant L8 on this wire, was defined to be 36 hours.

After the drop in E_{corr} at thirty-six hours the E_{corr} readings continued to change noticeably, which agreed with the noticeable increase in corrosion at seventy-two hours. At seventy-two hours E_{corr} was also approaching the average E_{corr} data for the bare wire specimens indicating that the E_{corr} data may show when a lubricated wire starts to behave like a bare wire. The change in E_{corr} for L8-1DW between two and ten hours cannot be explained entirely, but may have been due to some type of "stepped" breakdown of the lubricant on the wire surface.

Typical E_{corr} data for lubricated wires in both environments are shown in Figures 3.15 through 3.18. These figures include data where t_{corr} (the length of corrosion protection for the lubricants) could be determined and results where t_{corr} could not be determined. Average E_{corr} data for the bare wire specimens in deionized water and 3.5% NaCl solution are also included in these figures to show the general protection offered by the lubricants. This protection is indicated by the more positive E_{corr} data for the lubricated wires.

Figure 3.15 shows typical E_{corr} data for lubricated wires in deionized water where t_{corr} values could be defined. These t_{corr} values were determined by comparing the visual observations and E_{corr} readings for these wires. For

each wire, corrosion was observed after the E_{corr} readings began to decrease. Therefore, t_{corr} was defined to be the time at which the decrease in E_{corr} began. E_{corr} data for all of the wire specimens are shown in Figures A.1 through A.24 in Appendix A.

Figure 3.16 shows E_{corr} data for lubricated wires in deionized water in which t_{corr} values could not be defined. For L4-1DW and L8-2DW no corrosion appeared on the wires during the three day test period. For L3-1DW a corrosion streak covering 10% of the surface area was observed at twenty-four hours. T_{corr} could not be determined for this wire since the E_{corr} data did not show a change from inactive behavior to active behavior. However, this data did indicate that sharp decreases in E_{corr} will occur when significant corrosion appears in a short time frame.

The "dips" in the data for L8-2DW could not be explained. Similar "dips" were observed in the data for L7-1DW, L7-2DW, L9-1DW, and L9-2DW as shown in Figures A.8 and A.10 in Appendix A.

E_{corr} results were noticeably different when the 3.5% NaCl solution was used for the corrosive environment. Figures 3.17 and 3.18 show typical E_{corr} results for lubricated wires where t_{corr} values could and could not be defined. In general, the E_{corr} readings for the saltwater specimens always began to decrease immediately upon immersion or soon after immersion. Where t_{corr} values could be determined they were always less than fourteen hours.

T_{corr} values could not be determined for all of the wire specimens tested in the accelerated wire corrosion tests. Also, when a t_{corr} value was determined it did not always seem to be a fair measurement of the corrosion protection offered by the different lubricants. For example the t_{corr} value for L4-1DW was thirty-four hours. The amount of corrosion present on this wire after three days of immersion was approximately 1%. The t_{corr} value for L8-1DW was thirty-six hours. The amount of corrosion present on this wire after three days of immersion was 20%. Therefore, for similar t_{corr} values the amounts of corrosion varied by a factor of twenty. Due to these inconsistencies and the lack of t_{corr} values for several of the wire specimens it was decided to use the average percent corrosion present on the wire specimens after three days to compare the corrosion protection offered by the different lubricants. These average corrosion values were also used in the lubricant evaluation performed in Chapter 7.

Tables 3.5 and 3.6 show the percent corrosion on all of the wire specimens after three days of immersion in both environments. The lubricants are placed in order of decreasing corrosion protection based on their average corrosion allowed during the three day tests. T_{corr} values are also included where they could be determined. In some cases a t_{corr} value is given, but the percent corrosion is 0%. In these cases a noticeable decrease occurred in the E_{corr} data, but only a very slight corrosion appeared after this change. This corrosion covered less than 1% of the surface area and was considered to be negligible.

In both the deionized water and the 3.5% NaCl solution the lubricants can be divided into three groups based on their average amounts of corrosion. Lubricants that allowed 3.5% average corrosion or less were considered to provide excellent corrosion protection. Lubricants that allowed corrosion between 3.5% and 15% were considered to provide good corrosion protection and lubricants that allowed 15% or more corrosion were considered to provide poor corrosion protection.

Figure 3.19 shows wire specimens from each of these three groups as well as bare wire specimens from both environments. These pictures show the lengths of the wires that were below the waterline with the epoxy interface at

the bottom of the pictures. The estimated amounts of corrosion for each of these wires is given below the pictures. From these pictures the excellent corrosion protection offered by L5 in deionized water and L9 in the 3.5% NaCl solution can be seen. The poor corrosion protection offered by L1 in both environments is also illustrated.

The poor performance of L1 was surprising since this lubricant has been used for temporary corrosion protection of prestressing steel in post-tensioned construction. However according to its former manufacturer the sample of L1 used in this thesis did not contain any emulsifiers, which assist in holding the lubricant in place on the surface of the wire. If the emulsifiers are not present, then the water will displace the lubricant eliminating the coating from the wire[22].

As indicated in Tables 3.5 and 3.6 Lubricant L10 also provided poor corrosion protection during the accelerated wire corrosion tests. This poor corrosion protection was probably due to the nature of this lubricant, which is a sodium silicate solution that dries to form a clear, glass-like film. The corrosion observed on the wires lubricated with L10 was different than the corrosion observed on other lubricated wires. For the L10 wires tested in deionized water, dark orange corrosion spots appeared underneath the glass-like film after one day. This corrosion may have occurred because the protective coating did not cover the entire wire and left small unprotected areas on the wires' surface.

When wire specimens were lubricated with L10 and immersed in the 3.5% NaCl solution no corrosion was visible on the wires. Instead, white streaks similar in size and shape to corrosion streaks on other wires appeared after one day of immersion and gradually increased over the next two days. These white streaks appeared to be a result of the saltwater solution dissolving the protective film on the wire. After the wires were removed from the saltwater solution, corrosion, which covered the same area as the white streaks, was observed underneath the white streaks indicating that corrosion probably began immediately after the white streaks appeared. After these wires were removed from the saltwater solution a flaky white film appeared on the wire surfaces that were above the waterline during the immersion tests. This film was probably a result of some type of silicate precipitating onto the wire surface. A similar white precipitate was observed on prestressing wire specimens in previous research using a sodium silicate-sodium nitrite solution[12].

Figure 3.20 compares the corrosion protection offered by the different lubricants in the deionized water and the 3.5% NaCl solution. As indicated by this figure all of the lubricants performed worse in the 3.5% NaCl solution except for L3 which actually performed better in the saltwater solution than in the deionized water. The important points to note from Figure 3.20 are that L10 and L11 performed significantly worse in the saltwater solution than in the deionized water. Also, the performance of L1 in both environments was significantly worse than all of the lubricants except for L10 in the 3.5% NaCl solution. The average corrosion on the L4, L5, L6, and L9 wires in deionized water was either very small or nonexistent. L9 also prevented any corrosion on wires immersed in the 3.5% NaCl solution. None of the lubricants decreased the corrosion resistance of the bare wire specimens.

3.10 Comparison of Wires from Different Reels. For the two additional tests that used bare wire specimens from R2 (Reel 2), seven-inch bare wire specimens were immersed in 750 mL of 3.5% NaCl solution for three days. These tests, which used the test setup shown in Figure 3.1, were performed to determine the affect of a stearate soap on the corrosion properties of bare wires. After three days the bare wire specimens from R2 had corrosion covering 50% and 40% of their surface areas. This amount of corrosion was less than the corrosion observed on the wires from R1 (Reel 1), which had 50% and 70% corrosion after three days in 3.5% NaCl solution. However, it is difficult to conclude from this small number of tests whether the stearate

Figure 3.20 Lubricant performances in deionized water and 3.5% NaCl solution.

soap actually provided any additional corrosion resistance. More tests would have to be completed to determine the effect of the stearate soap on the corrosion resistance of the strand.

3.11 Discussion of Test Setup. The test setup that was used in the accelerated wire corrosion tests was designed for relative comparisons between lubricants. This test setup provided reasonable results and was considered to be a fair test for all of the lubricants involved. However, it was felt that some changes could be made that could possibly improve the results of this test.

The accelerated wire corrosion tests consisted of wire specimens with half of the wire above the waterline and half of the wire below the waterline. This test should probably be performed with the wire specimen totally submersed in the corrosive environment so the wire is only in one environment. To determine if this change in setup would affect the E_{corr} readings an additional test using a 3.5" wire specimen was performed. This specimen, which was lubricated with L4, was totally submersed in 750 mL of deionized water for three days. The lubrication process used for this wire was the same process that was used for the other lubricated wires tested in this chapter. The 3.5" length was equivalent to the length of wire that was immersed for the 7" long specimens. As shown in Figure 3.21 the E_{corr} data for the 3.5" specimen was similar to the E_{corr} data for the 7" specimen with both sets of data showing very little change during the three day test. Also, no corrosion occurred on either specimen during their respective three day tests. Based on these results it appears that partial submersion of the wire does not significantly affect the E_{corr} data or the corrosion protection offered by the lubricant. Lubricant L4 was used for this test and the test described in the following paragraphs since its behavior and physical characteristics were typical of the eleven lubricants.

Another concern was that the lubricant from the lubricated wire specimens was mixing with the water. In the deionized water tests this situation occurred with seven of the eleven lubricants. After the wires were immersed in the water, the lubricant from the wires mixed with the water giving the water a white tint. The concern was that the lubricant changes the solubility of oxygen in the water and therefore, changes the corrosivity of the environment. In the tests using a 3.5% NaCl solution this problem did not arise.

To determine the affect of the lubricants on the corrosivity of the deionized water environment another 3.5" wire specimen lubricated with L4 was tested. This wire was also submersed in 750 mL of deionized water for three days. However, in this test air was bubbled into the water to keep the solubility of oxygen constant in the corrosive environment. This air kept the water from turning a white color even though the lubricant from the wire had mixed with the water. After three days no corrosion was visible on this specimen indicating that the corrosivity of the environment was

Figure 3.22 E_{corr} data for lubricated wires with and without air.

Figure 3.21 E_{corr} data for 3.5" and 7" specimens.

probably not affected by the presence of lubricant in the water.

Figure 3.22 shows the E_{corr} data for this test along with the data from the 3.5" lubricated wire, which did not have air bubbled into its environment. As shown in Figure 3.22 the presence of air in the deionized water slightly increased the E_{corr} data for some unknown reason. However, these two sets of data were well within the scatter observed for the other wire specimens shown in Appendix A.

3.12 Conclusions. The accelerated wire corrosion tests showed that some differences in the corrosion protection offered by the eleven lubricants could be determined after three days of immersion in two accelerated corrosive environments. These tests showed eight lubricants to provide from good to excellent corrosion protection in both environments and two lubricants to provide poor corrosion protection in both environments. The other lubricant, L8, provided good protection in the deionized water, but poor protection in the 3.5% NaCl solution.

Even though the E_{corr} results from the accelerated wire corrosion tests could not be used for evaluating the corrosion protection offered by the different lubricants they did show that sharp changes in potential difference may precede the appearance of corrosion on a lubricated wire. This type of corrosion measurement technique seemed to work best when relatively large amounts of corrosion suddenly appeared on a wire as indicated by the data for L8-1DW in Figure 3.14. When smaller amounts of corrosion appeared the changes in E_{corr} tended to be gradual over time preventing the determination of a definite t_{corr} value.

In order to improve the test setup used for the accelerated wire corrosion tests the wire specimens should be totally submersed in the corrosive environment to insure that the specimen is only exposed to one environment. Another type of capping system at the bottom of the wire specimen also needs to be used to reduce the chance of crevice corrosion at the epoxy interface. Finally, air or oxygen should be bubbled into the corrosive environment to keep the solubility of oxygen constant during the test.

CHAPTER 4

EXPOSURE TESTS

4.1 Introduction. During post-tensioned and cable-stay construction emulsifiable oils have been used to protect the tendon or stay from corrosion between the time the strand is inserted into the duct and the time at which the duct is grouted. In post-tensioned construction the oil is usually flushed from the strands before grouting. However, there are no current guidelines regarding the time limit between flushing and grouting. In cable-stay construction the oil is usually not flushed from the stay in order to prevent the introduction of water into the duct. The purpose of the exposure tests was to compare the corrosion protection of the different lubricants in ambient outdoor conditions as well as to see whether some corrosion protection remained after normal flushing.

4.2 Experiment Design. The exposure tests studied the behavior of three types of specimens for each of the eleven lubricants. These specimens were a lubricated strand, a lubricated then flushed strand, and four lubricated wires. Two bare strand specimens and four bare wire specimens were also tested to serve as controls for the exposure tests.

All of the strand and wire specimens were placed outside the Ferguson Structural Engineering Laboratory in Austin, Texas for forty-six days and subjected to a daily wetting cycle. Visual observations were recorded twice a week until all of the specimens began to corrode. Inner strand protection, outer strand protection and corrosion rate were used to compare the corrosion protection of the eleven lubricants.

The length of corrosion protection offered by the different lubricants on the lubricated wire specimens was used to compare the lubricant performances in the exposure tests with the lubricant performances in the accelerated wire corrosion tests.

A separate exposure test was performed for Lubricant L11. This lubricant has been used in the field for friction reduction in post-tensioned tendons. A sample of

Lubricant L11 was not obtained until after the original exposure test had started.

The separate exposure test consisted of four strand specimens and eight wire specimens. The four strand specimens consisted of one strand lubricated with L1; one strand lubricated with L1, but then flushed; one strand lubricated with L11; and one strand lubricated with L11, but then flushed. The eight wire specimens consisted of four wires lubricated with L1 and four wires lubricated with L11. The relative performance of L11 was compared to the other lubricants by first comparing it to the performance of L1 in the separate exposure test.

A daily wetting cycle was used for both exposure tests. The original exposure test lasted 46 days. The separate exposure test lasted 68 days. The separate exposure test was longer since the ambient conditions were less severe during this period.

4.3 Materials. Fifteen inch long strand specimens and 3.5" long wire specimens were used in the exposure tests. The fifteen inch strand length was selected because this is equal to the length required for two full wraps of the outer wire around the center wire. The 3.5" wire length corresponded to the length of wire that was submersed in the corrosive environments in the accelerated wire corrosion tests.

The strand specimens were cut directly from R1 (Reel 1) while the wire specimens were obtained by untwisting a 3.5" length of strand from R1. The strand properties for strand from R1 are shown in Table 3.3. After the strand and wire specimens were cut to length five-minute epoxy was used to form an epoxy "cap" at the ends of the specimens to prevent galvanic corrosion at these locations. The five-minute epoxy was described in section 3.4.2.

4.4 Specimen Preparation.

4.4.1 Lubrication. Strand and wire specimens were lubricated by dipping the specimen into a tube containing approximately 225 mL of the lubricant as shown in Figures 4.1 and 3.4 respectively. Each lubricant had its own tube to prevent contamination of the lubricant sample. After lubrication the wires and strands were placed horizontally on wood racks that supported them throughout the exposure test. All of the specimens remained indoors for twenty-four hours after lubrication before they were moved to the outdoor ambient conditions.

4.4.2 Flushing. One of the two lubricated strands for each lubricant was flushed by using a garden hose as shown in Figure 4.2. During the flushing process the lubricated strand was held in an upright position and rotated as the hose was moved in an up and down motion for two minutes. All of the specimens were setup outside immediately after the flushing process.

This flushing procedure is not considered to be representative of flushing

Figure 4.1 Lubrication of strand specimens.

procedures in the field where a stream of water is pumped through the duct. Instead, this procedure was felt to be more likely to flush off the lubricants and was used to determine if the lubricants could be removed from the strand by a direct flushing and how much corrosion protection could be expected after this vigorous type of flushing.

4.5 Test Setup. Figure 4.3 shows the test setup for the exposure tests. All of the specimens were supported horizontally on wood racks. The specimens were placed in an East-West direction outside the Ferguson Structural Engineering Laboratory.

4.6 Test Procedure. The exposure specimens were left unprotected in ambient outdoor conditions and were also subjected to a daily wetting cycle Monday through Friday to increase the possibility of corrosion on the specimens.

4.6.1 Ambient Conditions. During the forty-six days of the original exposure test, six inches of rain were recorded. The temperature during this period varied from 70 F to 102 F with 85 F being the average daily temperature. During the sixty-eight days of the separate exposure test, five inches of rain were recorded. The temperature during this period varied from 47 F to 98 F with 77 F being the average daily temperature[23].

4.6.2 Wetting Cycle. A garden hose, as shown in Figure 4.4, was used to wet each of the strand and wire specimens. The hose was moved along the full length of the specimen to wet the entire top surface. This cycle lasted

Figure 4.2 Flushing of lubricated strand specimen for exposure tests.

Figure 4.3 Test setup for exposure tests.

approximately five seconds for each strand specimen and two seconds for each wire specimen. The wetting cycle took place between 8:00 a.m. and 9:00 a.m. each day Monday through Friday.

Originally, the wetting cycle was twice a week. However, it was changed after two weeks to a five day cycle Monday through Friday to increase the possibility of corrosion on the specimens. The same wetting schedule was used for the separate exposure test.

4.6.3 Visual Observations. The exposure specimens were inspected daily, but visual observations were only recorded twice a week (Mondays and Thursdays). These observations recorded the appearance of new corrosion, increases in existing corrosion, and an estimate of the existing corrosion on the specimen.

Figure 4.4 Wetting of strand specimen for exposure tests.

4.7 Results. Dark, reddish-brown corrosion spots appeared on the bare strand specimens after four days of exposure. These spots were approximately 1/16" in diameter. After seven days of exposure corrosion appeared in the interstices between the outside wires of the bare strand specimens. Both the corrosion spots and the interstitial corrosion gradually increased during the exposure test to form a heavy, uniform corrosion that covered 100% of the bare strands at 26 days.

Corrosion was not observed on the bare wire specimens until eleven days after exposure. This delay in corrosion on the bare wire specimens may have been due to the size of these specimens. The wire specimens were only 3.5" long compared to the 15" long, strand specimens. The larger the surface area the greater the chance of corrosion. Also, after eleven days of exposure the corrosion on the bare strand specimens tended to be in the interstices of the strand with scattered corrosion spots along the length. The interstices provided areas for water to collect, which could lead to faster corrosion on the strand specimens.

For the unflushed strand specimens corrosion usually appeared as small corrosion spots on the top surface of the strands where the specimens were wetted. These corrosion spots were usually a dark reddish-brown, but a few bright orange corrosion spots were encountered on some of the specimens. The corrosion spots were usually about 1/16" in diameter. In most cases the underneath of the unflushed specimens remained in good condition throughout the test. For the bare strands, flushed strands, and unflushed wires corrosion occurred on both the top and bottom surfaces of the specimens.

The labelling system used for the exposure specimens is shown below. This labelling system includes the lubricant number, if a lubricant was used, and the type of specimen.

<u>Labelling System for Unflushed and Flushed Specimens.</u>

L# = Lubricant Number
UF = Unflushed strand
F = Flushed strand

UFW = Group of unflushed wires (Four wires in a group)

Labelling System for Bare Strand and Bare Wire Specimens.

BS = Bare strand

BW = Group of bare wire specimens (Four wires in a group)

Examples of this labelling system are L2-UF, L2-F, and L2-UFW These labels represent the unflushed strand, flushed strand, and unflushed wire specimens that were initially lubricated with lubricant material L2. BS-1, BS-2, and BW represent the first bare strand specimen, the second bare strand specimen, and the group of four bare wire specimens, respectively.

Table 4.1 shows a typical summary of visual observations for a strand specimen in the exposure tests. This strand was lubricated with Lubricant L3 before being exposed to the ambient outdoor conditions and the daily wetting cycle. Summaries of visual observations for all of the exposure specimens are shown in Tables B.1 through B.4 in Appendix B.

Before the results of the exposure tests are presented a few statements concerning the separate exposure test mentioned in section 4.3 will be made. In the separate exposure test four strand specimens and eight wire specimens were exposed to the ambient conditions and the daily wetting cycle. The four strand specimens consisted of one strand lubricated with L1, one strand lubricated with L1, but then flushed; one strand lubricated with L11; and one strand lubricated with L11, but then flushed. The eight wire specimens consisted of four wires lubricated with L1 and four wires lubricated with L11. None of the wire specimens were flushed.

In order to compare the corrosion protection of L11 with the corrosion protection of the other lubricants a "data transformation" was performed. For example, in the separate exposure test, Lubricant L11 prevented corrosion on the unflushed strand for 25 days. To transform this protection to an equivalent protection

Table 4.1 Example of summary of visual observations for one unflushed strand in exposure tests.

in the original exposure test, 25 days was multiplied by 39/64, to give an equivalent protection of 15 days. Thirty-nine days was the length of corrosion protection offered by L1 on an unflushed strand in the original exposure test. Sixty-four days was the length of corrosion protection offered by L1 on an unflushed strand in the separate exposure test. Similar calculations were performed for the inner strand protection, the corrosion rate, and the protection of unflushed wires associated with Lubricant L11.

The length of corrosion protection offered by the unflushed and flushed lubricants on the strand specimens is shown in Figure 4.5. This length of protection represented the day at which corrosion was first observed on the strands. For the unflushed strands the length of protection varied from fifteen to thirty-nine days. For the flushed strands the length of protection was four days for all of the specimens except for L10-F, which did not have visual corrosion until twenty days. The days where precipitation occurred[23] are marked with a "P". This precipitation varied from trace amounts at 1, 12, 17, 18, and 22 days to heavy thunderstorms at 19, 37, and 38 days. As indicated by Figure 4.5 seven of the eleven lubricants allowed corrosion to occur on the unflushed strands at twenty days. This corrosion may or may not have been a result of the heavy thunderstorm that occurred at 19 days. In any event the

Figure 4.5 Length of corrosion protection offered by unflushed and flushed lubricants.

corrosion behavior of these seven unflushed strands varied noticeably after twenty days. Therefore, a corrosion rate calculation was performed for all of the strand specimens after first corrosion occurred. This corrosion rate is discussed in more detail later in this section.

The corrosion protection provided by L10 after flushing (Figure 4.5) was probably due to the nature of this lubricant. L10 is a sodium silicate solution that dries to form a clear, glassy film. This film was probably dry before flushing was carried out. Therefore, none of the lubricant was removed by the flushing procedure. All of the other lubricants were essentially removed by the flushing procedure used in these tests.

It should also be mentioned that the behavior of the unflushed strand lubricated with L10 was similar to the behavior of the flushed strand lubricated with L10. Both of these strands began to corrode at twenty days. This corrosion increased gradually to form a moderate, uniform corrosion covering 90% and 95% of the surface areas at forty-six days for L10-F and L10-UF respectively. Both of these strands also had a white, flaky film along their length after two days of exposure. This film seemed to break down over time and leave a white substance in the interstices of both the unflushed and flushed strands as shown in Figure 4.6, which shows L10-F after forty-six days of exposure.

The white film on the L10 strand specimens was similar to the white film observed on the L10 wire specimens after removal from the 3.5% NaCl solution in the accelerated wire corrosion tests. The unflushed wires originally lubricated with L10 in the exposure tests also had a white film on their surfaces after two days, which disappeared gradually over time.

Figure 4.6 L10-F at conclusion of exposure tests.

Corrosion rates after initial corrosion appeared for the unflushed and flushed strands are shown in Tables 4.2 and 4.3 along with the time of initial corrosion and the percent corrosion present at forty-six days. The corrosion rate after appearance of corrosion was calculated by dividing the percent corrosion present at forty-six days by the time difference between forty-six days and the time when initial corrosion was noted. Where two values are present for the time of initial corrosion the first value indicates the day at which first corrosion was observed on the specimen. The second value indicates the day at which additional corrosion was observed. After this second value corrosion on the specimen grew at a gradual rate until the conclusion of the test. Since additional corrosion did not occur until after the second value and since the corrosion present at the first value was always very small, the use of the second value in the corrosion rates seemed to be a more fair indication of the corrosion protection offered by the different lubricants. The primary reasons for this type of corrosion rate calculation were the performances of L3-UF, L4-UF, L5-UF, L6-UF, L7-UF and L8-UF all of which had very small corrosion spots at twenty days. However, for L3-UF, L4-UF, L5-UF, and L6-UF additional corrosion did not appear until eight or fifteen days later, whereas the corrosion of L7-UF and L8-UF was increasing considerably during this time. This method of corrosion rate computation indicates these differences in corrosion protection. For example the corrosion rate of L7-UF is twice that of L3-UF even though time of first corrosion was the same for both specimens. The corrosion rate calculations for L7-UF and L8-UF used 35 and 43 days, respectively, instead of 46 days since 100% corrosion was present on both of these specimens at these times.

The corrosion rate for L11-UF was determined from a data transformation using the corrosion rates from the unflushed strands in the separate exposure test. In this test the corrosion rate for L1 was 3.75% / day, while the corrosion rate for L11 was 2.00% / day. The corrosion rate of L11-UF in Table 4.2 was equal to (2.00/3.75) x 2.14, where 2.14 was the corrosion rate for L1-UF in the original exposure test. Similar calculations were used to determine the corrosion rate for L11-F shown in Table 4.3.

Table 4.2 Corrosion rate data for bare and unflushed strands.

Corrosion protection of the inner strand was evaluated by cutting a 3" length of strand from each unflushed, flushed, and bare strand specimen. The 3" strand specimen was then opened and examined for corrosion. As shown in Table 4.4 seven of the eleven lubricants provided excellent corrosion protection of the inner strand when they were not flushed from the strand. These lubricants allowed less than 15%

Table 4.3 Corrosion rate data for bare and flushed strands.

corrosion of the inner strand after 46 days of exposure. Lubricant L8 provided moderate corrosion protection of the inner strand. L1, L7, and L10 provided little corrosion protection of the inner strand. The amount of corrosion on the inner bare strands was slightly less than the corrosion amounts on L1-UF and L10-UF, but was more severe. The inner strand surface consisted of the complete center wire and the insides of the outer wires.

Table 4.5 shows the inner strand protection provided by the lubricants after

Table 4.4 Inner strand corrosion for bare and unflushed strands.

flushing. Only one of the lubricants provided complete corrosion protection of the inner strand. This lubricant was L9, which is a very thick emulsifiable oil. Inner strands associated with the other ten lubricants were covered with 70% to 100% corrosion after forty-six days of exposure. The amount of corrosion present on the inner bare strands was less than the corrosion present on eight of the flushed inner strands. However, the corrosion on the bare inner strands was more severe.

The length of corrosion protection offered by the different lubricants on the unflushed wire specimens is shown in Table 4.6. This table also shows the results

Table 4.5 Inner strand corrosion for bare and flushed strands.

from the accelerated wire corrosion tests reported in Chapter 3. The results from these two types of tests agree in some respects and differ in others. In both tests Lubricant L9 provided excellent corrosion protection of the wire specimens. Also, the performances of L2, L3, L4, L5, L6, , and L7 were relatively similar in each of the three environments. In the exposure tests these seven lubricants prevented corrosion for 14 to 18 days. In the accelerated wire corrosion tests these lubricants allowed less than 10% corrosion after three days in both environments.

L10 provided relatively poor corrosion protection of the wire specimens in all

Table 4.6 Results for unflushed wires in exposure tests and accelerated wire corrosion tests.

three environments. In the exposure tests this lubricant allowed corrosion on the unflushed wires after eleven days. In the accelerated wire corrosion tests this lubricant allowed 15% corrosion after three days in deionized water and 32.5% corrosion after three days in 3.5% NaCl solution.

The performance of L1 in the exposure tests and the accelerated wire corrosion tests was contradictory. In the exposure tests this lubricant provided good corrosion protection of the unflushed wires and excellent corrosion protection of the unflushed strand. However, in the accelerated wire corrosion tests this lubricant provided minimal corrosion protection. As discussed in section 3.9 this poor corrosion protection in the accelerated wire corrosion tests was probably due to the lack of emulsifiers in this oil sample. In the exposure tests this oil probably provided better corrosion protection since large amounts of water were not present which would displace the lubricant on the specimen surface. Also, the specimens in the exposure tests were in a horizontal position, which may have assisted in keeping the oil on the top surface of the specimens. As indicated in Table 4.6 and Figure 4.5 the lubricants provided better corrosion protection on the unflushed strand specimens than on the unflushed wire specimens. The only exception was L9, which provided 39 days of corrosion protection on both types of specimens. The lower protection values for the unflushed wires was probably due to the wetting of the specimens. During the wetting cycle the flow rate of the water was the same for both the strand specimens and the wire specimens even though the strand specimens have a much higher surface area. This flow rate probably had more effect on the lubricants coating the smaller wire specimens than the lubricants coating the larger strand specimens. L9 is a very thick emulsifiable oil and therefore was affected less than the other lubricants on the unflushed wires.

4.8 Conclusions. The results from the exposure tests indicated that not all emulsifiable oils provide the same amount of corrosion protection when exposed to ambient outdoor conditions and a daily wetting cycle. As shown in Figure 4.5 the amount of corrosion protection offered by the eleven lubricants before flushing varied from fifteen days to thirty-nine days. The thirty-nine day protection was considered to be good corrosion protection especially when compared to the bare strands, which began to corrode at four days. This length of protection would probably be acceptable for most post-tensioned concrete projects where the tendons are left ungrouted after installation in the ducts.

Figure 4.7 shows the amounts of corrosion present on the unflushed strand specimens at the conclusion of the test. Based on these amounts of corrosion the lubricants can be more or less divided into three groups. The first group, which only allowed 15% corrosion after forty-six days, consisted of L1 and L9. The second group, which allowed from 35% to 60% corrosion, consisted of L2, L3, L4, L5, L6, and L11. Group three was made up of the remaining three lubricants L7, L8, and L10, all three of which provided poor corrosion protection and had results similar to bare strand over the forty-six day test period. Figures 4.8 through 4.12 show bare strand specimens before and after the exposure tests and typical unflushed specimens from each of the three groups mentioned above.

The strands from Groups 1 and 2 were in much better condition than both the bare strand specimen shown in Figure 4.9 and the unflushed Group 3 specimen shown in Figure 4.12. For L9-UF (Figure 4.10) the corrosion is not quite as obvious due to the nature of this lubricant, which caused the strand to have a "dirty" brown appearance. When corrosion appeared on this strand at 39 days it appeared as dark, reddish-black spots along the length of the strand. This corrosion increased gradually to cover 15% of the surface area at 46 days. Corrosion on L2-UF (Figure 4.11) was a light-moderate, uniform corrosion that covered 50% of the surface area at 46 days, while corrosion on L7-UF (Figure 4.12) was a heavy, uniform corrosion that covered 100% of the surface area at 35 days.

As indicated in Figure 4.5 only one of the lubricants provided any corrosion protection after flushing. This lubricant was L10, which is a sodium silicate solution. Figures 4.13 and 4.14 show L10-F and L2-F after forty-six days of exposure. L10-F

Figure 4.7 Percent corrosion on unflushed strands.

had a moderate-uniform corrosion covering 90% of its surface area at forty-six days. L2-F had a heavy, uniform corrosion covering 100% of its surface area after twenty-six days. L2-F was typical of the flushed strands, except for L10-F.

The relatively short lengths of corrosion protection for L11 shown in Figure 4.5 and Table 4.6 for an unflushed strand and the unflushed wires was probably due to the method of data transformation between the original and separate exposure tests. It is likely that if lubricant L11 had been tested in the original exposure test, then its length of corrosion protection would likely have been around twenty days and eighteen days for the unflushed strand and unflushed wire specimens respectively. This assumption was based on the performances of L11 in the accelerated wire corrosion tests and its similar physical characteristics with other lubricants that provided twenty and fourteen days of protection in the ambient outdoor conditions.

In general, eight of the eleven lubricants provided from good to excellent corrosion protection in a corrosive environment that was more severe than most environments encountered by unprotected seven-wire strand before grouting. Results from the unflushed strand specimens were the best indicators of corrosion protection offered by the different lubricants. These results showed corrosion protection varying from 15 days to 39 days depending on the lubricant. However, results from both the flushed strand and unflushed wires will be used in the overall lubricant evaluation in Chapter 7 in order to give some credit to the performances of L10 after flushing and to L9 for its protection of unflushed wires.

Figure 4.13 L10-F at conclusion of exposure tests.

Figure 4.14 L2-F at conclusion of exposure tests.

CHAPTER 5

PULL-OUT TESTS

5.1 Introduction. In order to compare the relative effect of the eleven different lubricants on the adhesion between seven-wire strand and cement grout a small-scale test was desired. The test specimen needed to simulate a post-tensioned concrete member and be constructed using lubrication and flushing procedures that were representative of those used in post-tensioned construction.

An 8" x 8" x 12" pull-out specimen containing a single seven-wire strand grouted inside a steel duct was designed. Three conditions of strand were tested, bare strand, lubricated strand, and lubricated then flushed strand. The specimens were lubricated, flushed, and grouted using techniques that are similar to those encountered in the field.

Due to the large number of tests involved, two groups of specimens were constructed. The first group consisted of bare strand and unflushed specimens, while the second group consisted of bare strand and flushed specimens. Both groups used the same concrete mix and the same grout mix. All specimens were tested seven days after grouting.

5.2 Purpose. The purpose of the pull-out tests was to compare the effect of the different lubricants on the adhesion between seven-wire strand and cement grout before and after flushing.

5.3 Experiment Design. Pull-out specimens as shown in Figure 5.1 were used to compare the effect of the different lubricants on the adhesion between seven-wire strand and cement grout. Each specimen consisted of a single seven-wire strand grouted inside a galvanized steel duct, which was surrounded by concrete. Outside

Figure 5.1 Pull-out specimen for small-scale pull-out tests.

dimensions of the surrounding concrete were 8" x 8" x 12". The actual adhesion length between the strand and the grout was 10.5" due to the use of grout plugs at the ends of the duct during specimen construction.

Fifty-four specimens were tested, two unflushed specimens for each of the eleven lubricants, two flushed specimens for each of the eleven lubricants, eight bare strand specimens, and two additional unflushed specimens. The eight bare strand specimens consisted of three specimens from R1 (Reel 1) and five strand specimens from R2 (Reel 2). The latter strand reel had a noticeable white coating on the strand surface, which according to the strand manufacturer, was caused by a stearate soap that is used during the strand drawing process. This white coating is often present in varying amounts, but disappears over time and should not affect the adhesion between the strand and grout[8]. The additional unflushed specimens were used to correlate data between the two groups of specimens.

A 60-kip testing machine was used to pull the strands from the specimens. The average pull-out loads for the unflushed and flushed specimens were used in the overall lubricant evaluation reported in Chapter 7.

5.4 Materials.

5.4.1 Concrete. Concrete for the pull-out specimens consisted of 3/4" crushed limestone aggregate, Colorado River sand, Type II Portland cement, and water. No admixtures were used in the concrete. The 28-day compressive strength of the concrete was 6480 psi. for the first group of specimens and 8390 psi. for the second group of specimens.

5.4.2 Cement Grout. Cement grout having a water-cement ratio of 0.44 was used for both groups of specimens. This w\c ratio was slightly less than the maximum ratio of 0.45 allowed by section 3.3.5 of the PTI Post-tensioning Manual. The grout, which was mixed with a hand drill and mixing attachment, was made from Type II Portland cement and water. Mix quantities, seven day, and twenty-eight day cube strengths for the grout are shown in Tables 5.1 and 5.2.

5.4.3 Prestressing Strand. One-half inch diameter, Grade 270 low-relaxation strand was used in the pull-out specimens. This strand was obtained from two different reels of strand having the strand properties shown in Table 3.3. All of the specimens used strand from R2 except for three bare strand specimens that used strand from R1.

5.4.4 Duct. Corrugated, galvanized steel duct having an inner diameter of 2" was used in the pull-out specimens. This duct is typical of duct used in post-tensioned concrete construction.

Table 5.1 Mix quantities for grout.

Figure 5.2 Gangform used for construction of pull-out specimens.

Table 5.2 7-day and 28-day cube strengths for grout.

5.4.5 Grout Hose. Three quarter inch diameter grout hose was used for flushing and grouting the pull-out specimens. This grout hose is typical of grout hose used in post-tensioned concrete construction.

5.4.6 Grout Plugs. Wood grout plugs were used to center the seven-wire strand in the duct after lubrication and also to provide a water-tight duct that could be flushed and grouted.

5.5 Construction.

5.5.1 Formwork. A gangform as shown in Figure 5.2 was used for specimen construction. Twelve-inch steel ducts were placed in the forms before placing concrete.

5.5.2 Batching. Concrete was batched using a 6 ft^3. mixer. Both groups of specimens required three separate casts. Each cell of the gangform was vibrated during casting.

5.5.3 Curing. Curing consisted of covering the concrete with wet burlap and plastic sheeting for two days. Forms were removed after three days.

5.6 Lubrication. The lubrication process consisted of dipping the strands into a tube containing approximately 225 mL of lubricant as shown in Figure 4.1. After the strands were lubricated they were inserted into the ducts of their respective pull-out specimens. Wood grout plugs were used to center the strands in the ducts. Grout hoses were inserted into each grout plug and silicone caulking was used to seal the plugs and hoses for each specimen. The grout hoses and silicon caulking provided a water-tight specimen that could be flushed and grouted easily. The specimens were left undisturbed for twenty-four hours after the strands were inserted into the ducts.

5.7 Flushing. Flushing was carried out as shown in Figure 5.3. During this process the specimen was always positioned so that water was sprayed through a grout hose that was above the strand and exited through a grout hose that was below the strand. This hose positioning forced the water to flow over the strand before it exited the duct. Each specimen was flushed for thirty seconds through each end at a rate of 0.4 ft.^{3}/min. for a total flushing time of one minute.

During the flushing process oil was observed in the exiting water during the first five to ten seconds, but after this time the water was clear. It was felt that a longer flushing period would not remove additional oil since the amount of water which flowed through the ducts during the total one minute flush was twenty times the volume of the sealed duct. The volume of water that flowed through the duct was approximately 0.4 ft.^{3} or 3 gallons. The volume of the sealed duct was 0.019 ft.^{3} or 0.14 gallons.

5.8 Grouting. A hand grout pump as shown in Figure 5.4 was used to grout the specimens. The cement grout was pumped through a plastic tube running from the grout pump to the grout hose which entered the specimen below the strand. During grouting the grout hose which exited the duct at the other end above the strand, was held in a vertical position. After the grout began to flow freely from this hose, it was plugged with a rubber plug. The grout in the duct was then slightly pressurized by providing an additional stroke of the grout pump.

5.9 Test Setup. The test setup for the pull-out tests is shown in Figure 5.5. In this setup a 60 kip testing machine was used to pull the strands out of the specimens. The strand was gripped by a prestressing chuck above the top crosshead and then pulled out of the specimen. During this process the top crosshead moved up, while the middle crosshead remained stationary. The potentiometer attached to the unloaded end of the strand measured slip of the strand through the specimen.

A hard rubber pad was placed directly on top of the pull-out specimen and a steel plate was placed on top of the pad. The plate and pad distributed the load from the crosshead over the specimen.

5.10 Instrumentation. Instrumentation for the pull-out tests consisted of a potentiometer, power source for the potentiometer, and an X-Y plotter. The

Figure 5.3 Flushing of pull-out specimen.

Figure 5.4 Hand grout pump used to grout pull-out specimens.

potentiometer was clamped to the unloaded end of the strand to determine when the strand began to pull through the specimen. The deformation signal from the potentiometer and the load signal from the testing machine were plotted by the X-Y plotter.

5.11 Test Procedure. The test procedure consisted of seating the prestressing chuck and pulling the strand out of the specimen. Each specimen was loaded at approximately 1.5 k/min. and the slip load was read directly from the testing machine.

5.11.1 Initial Seating. After the specimen was inserted into the testing machine the strand was gripped above the top crosshead with a standard prestressing chuck. The specimen was allowed to hang unsupported from the chuck and the teeth were seated by tapping them lightly with a hammer. After seating the chuck the bottom crosshead was lowered until it contacted the steel plate above the specimen.

5.11.2 Potentiometer Setup. The potentiometer was attached to the unloaded end of the strand after the initial seating.

5.11.3 Loading Rate. A loading rate of approximately 1.5 k/min. was used to pull the strands from the specimens.

5.11.4 Slip Load Reading. The slip load for each specimen was read directly from the testing machine when the data from the potentiometer indicated initial slip of the strand on the X-Y plotter. This load was read to the nearest 5 lbs.

5.12 Test Results. The labelling system used for the pull-out specimens is shown below. This system used the lubricant number, the type of specimen, and the number of the specimen. For the bare strand specimens the Reel Numbers (R1 or R2) were used instead of the lubricant number.

<u>Labelling System for Pull-out Specimens:</u>

L# = Lubricant Number
UF = Unflushed Specimen

F = Flushed Specimen
R1 = Bare Strand from Reel 1
R2 = Bare Strand from Reel 2

Examples of the labelling system are L1-UF1 and R2-2. L1-UF1 corresponds to the first unflushed specimen that was lubricated with Lubricant L1. R2-2 corresponds to the second bare strand specimen from R2 (Reel 2). All of the unflushed and flushed specimens used strand from R2.

Typical results for bare, flushed, and unflushed specimens are shown in Figure 5.6. For these specimens the strand began to pull through the specimen at 2950, 540, and 260 lb., respectively. These loads are referred to as "slip loads" and include the self-weight of the specimen as well as the weights of the steel plate and rubber pad that were positioned on top of the specimens before testing.

Figure 5.7 shows the slip loads for the eight bare strand specimens. These loads varied from 1360 lb. for R2-1 to 4040 lb. for R1-1. The overall average was 3260 lb. and the standard deviation was 850 lb. The average slip load for the strands from R1 was 3640 lb. For strands from R2 the average slip load was 3020 lb. when all five specimens were included and 3330 lb. when the lowest and highest slip load values were excluded. With the exception of outlier R2-1, the bare strand slip load can be taken as greater than 3000 lb.

Slip loads for the unflushed and flushed specimens are shown in Figures 5.8 and 5.9 along with the average slip load for the bare strands from R2. The average slip loads for the unflushed and flushed specimens were 350 lb. and 750 lb., respectively.

5.13 Discussion of Test Results and Conclusions. All of the strands in the pull-

Figure 5.6 Typical results from small-scale pull-out tests.

Figure 5.7 Slip loads for bare strand specimens.

Figure 5.8 Slip loads for unflushed pull-out specimens.

Figure 5.9 Slip loads for flushed pull-out specimens.

out specimens pulled out of the specimen in a twisting motion with virtually no cracking or spalling of the surrounding grout at the ends of the specimens.

Based on the average slip loads for the bare strand specimens Figure 5.7 indicates that the stearate soap present on the strands from R2 does not appearto have a significant effect on the adhesive properties of the strand. The difference in average slip loads for the two reels of strand was less than 10% when the high and low values for the strands from R2 were excluded. This difference in average values is acceptable for this type of test considering the number of specimens involved. It indicates that the stearate soap present on the surfaces of the strand does not significantly effect the adhesion properties of the strand.

Figure 5.8 clearly indicates that for the unflushed specimens the presence of the lubricants on the strand almost totally destroyed the adhesion between strand and grout. In the unflushed specimens the average slip load was 350 lb. when L10 was included and 260 lb. when L10 was not included. Both of these average slip loads are only 10% of the average slip load for the bare strand specimen which was 3020 lb. Only Lubricant L10 had values greater than 33% of the slip load for bare strands.

Figure 5.9 indicates that flushing the lubricants was ineffective since for the flushed specimens the average slip load was 750 lb. when L10 was included and 520 lb. when L10 was not included. These average slip loads are only 25% and 17%, respectively, of the average slip load for the bare strand specimens. After flushing Lubricant L10 was the only lubricant in the range of the bare strand. These results were similar to the results of previous research which showed a sodium silicate-sodium nitrite solution to have little effect on bond after flushing. That research also showed flushed strand specimens previously coated with an emulsifiable oil to have a bond-slip load that was only 10% of the bond-slip load for bare strand[12].

In several cases the lubricants destroyed virtually all adhesion between strand

and grout. For L8-UF2, L9-UF1, L9-UF2, L9-F1, and L9-F2 the strands pulled out under the weight of the specimen, which was 69 lbs. For L8-UF1 and L7-F2 the strands pulled out under the weight of the block, rubber pad, and steel plate, which was a combined load of 86 lbs.

Figure 5.10 shows the average slip loads for the unflushed lubricants in descending order along with the average slip load for the bare strand specimens from R2. As indicated by this figure L10 performed considerably better than the other lubricants followed by L11 and L3. L1, L2, L4, L5, L6, and L7 were similar while L8 and L9 were the worst. The performance of L10 was atypical due to the nature of this lubricant, which is not an emulsifiable oil. L10 dries to form a clear, glassy film that bonds to the grout better than the oily film left by the other lubricants.

Average slip loads for the flushed lubricants are shown in Figure 5.11. Again the performance of the lubricants varied noticeably. After flushing, L10 was almost identical to the bare strand specimens, while the other lubricants still reduced the adhesion by more than 2/3 even though ample flushing water was provided. The increase of the slip load for L10 after flushing was surprising since this lubricant dries within a few hours to form a hard glassy film. Either this film was not completely dry and the flushing removed some of the lubricant or the wetting of the dry film increased the adhesive properties of the lubricated strand.

The two additional unflushed specimens that were constructed in the second group of specimens showed that the general effect of grouting were the same for both groups of specimens. These additional specimens used L8 to lubricate the strands. Slip loads for L8-UF1 and L8-UF2 were 86 lbs. and 69

Figure 5.10 Average slip loads for unflushed specimens.

Figure 5.11 Average slip loads for flushed specimens.

lbs., respectively. For L8-UF1 the strand began to pull through the specimen after it was positioned in the testing machine. At this point the load on the specimen included its self-weight plus the weight of the rubber pad and steel plate. Before the pad and plate were positioned on L8-UF2 this specimen was suspended by its strand to determine if the strand would pull out under the weight of the specimen without the rubber pad and steel plate, which it did. Therefore, L8-UF2 had a slip load of 69 lbs.

In the second group of specimens the same procedures were used for the two unflushed specimens lubricated with L8. For these specimens the strand began to pull through the specimen at 86 lbs. and 69 lbs., respectively, which indicated that the general effects of grouting in both groups of specimens were the same or very similar.

Figure 5.12 compares the effects of the different lubricants on the adhesion before and after flushing. Based on these results the flushing process slightly increased the adhesive strength of the lubricated strands. However, the slip loads after flushing were still 2/3 less than the slip loads for the bare strand specimens.

The pull-out tests performed in this research showed that the presence of a lubricant on the strand before grouting significantly reduces the adhesion between strand and grout. These tests also indicated that the lubricants could not be removed using the flushing procedures utilized in this study which are similar to those that are used in the field.

The pull-out tests performed in this research provided good, relative results that were used to compare the eleven lubricants. However, there were two concerns with these tests. One that the strands twisted out of the specimens during testing. Two that no admixtures were used in the grout.

In post-tensioned members, strands are anchored at both ends so they are not allowed to undergo significant twisting. It was felt that restricting twist of the strands may increase their adhesion strength. Therefore additional pull-out tests were performed with bare strands, lubricated strands, and lubricated then flushed strands that were all restricted from twisting. These tests are presented in Chapter 6.

Commercial admixtures are sometimes used in grouts employed in post-tensioned construction. These admixtures can be used to cause the grout to flow better or to cause the grout to expand during curing. The grout used in the pull-out specimens in this chapter did not use any admixtures in order to reduce the number of variables in the tests. However some preliminary tests were performed using the 8" x 8" x 12" pull-out specimen.

These preliminary specimens used bare strand and a grout containing an expansive admixture. The average slip loads for these specimens was 6420 lb., which was twice the average slip load for the bare strand specimens tested in this chapter. This increase in slip load may or may not occur for unflushed or flushed strands.

Figure 5.12 Comparison of unflushed and flushed lubricants.

CHAPTER 6

ANCHORED PULL-OUT TESTS

6.1 Introduction. The pull-out tests performed in Chapter 5 were used to determine the relative effect of different lubricants on the adhesion between seven-wire strand and cement grout before and after flushing. From these tests it was shown that all of the lubricants significantly reduced or totally prevented adhesion between the strand and grout when the lubricants were not flushed. Results were generally similar for the flushed specimens which had improved but still greatly reduced adhesion except for those which had used L10. L10 was shown to have little effect on the adhesion between strand and grout after the flushing process.

As indicated in the discussion of results in Chapter 5 the strands twisted while being pulled out so it was decided to perform additional pull-out tests to determine the effect of restricting the twist on the adhesion between seven-wire strand and cement grout when the strand specimen is bare, lubricated, and lubricated then flushed respectively. In these tests Lubricant L5 was used to lubricate the lubricated and flushed strands, since this lubricant performed the best in the overall lubricant evaluation reported in Chapter 7.

6.2 Experiment Design. A rectangular concrete specimen, as shown in Figure 6.1, was used for the anchored pull-out tests. This specimen, which was constructed and tested outside the Ferguson Structural Engineering Laboratory in Austin, Texas, contained six bare strands, two lubricated strands, and two lubricated and then flushed strands. Each strand was grouted inside a 2" diameter, 6' long steel duct, except for the two bare strands in the middle of the specimen, which were left ungrouted. As shown in Figure 6.1, eight of the strands were anchored at the dead end of the specimen and two of the strands

were unanchored at both ends of the specimen. The anchored strands consisted of two bare, grouted strands; two bare, ungrouted strands; two lubricated, grouted strands; and two lubricated, flushed and grouted strands. Both unanchored strands were bare and grouted.

The testing procedure consisted of jacking the strands at the live end of the specimen with a hydraulic ram and measuring the elongation of the strand at the loaded end. By comparing the load-elongation data for the anchored strands as shown hypothetically in Figure 6.2, the load at which the adhesion between the strands and grout had been destroyed could be determined. These "pull-out" loads were the loads at which the grouted strands would start to behave like the bare, ungrouted strands since at this point the adhesion between the strand and grout had been completely destroyed. By comparing these "pull-out loads" the relative effect of either unflushed or flushed lubricants on the adhesion between seven-wire strand and cement grout when the strands are restricted from twist could be determined.

For the bare, unanchored strands the slip of the strand at the dead end of the

Figure 6.2 Hypothetical results from anchored pull-out tests.

specimen was used to determine when the adhesion between the bare strand and grout had been destroyed. This load was compared to the "pull-out" load for the bare, anchored strands to determine the effect of restricting twist on the pull-out loads for bare strands grouted inside a steel duct.

Originally, all of the strands were to be tested seven days after grouting, which was the same time period used for the pull-out specimens tested in Chapter 5. However, only a single test on the two bare, ungrouted strands and the first unflushed strand were completed at seven days due to time constraints. Two additional tests on each bare, ungrouted strand and a single test on each of the remaining unflushed, flushed, and bare strands were completed seven days later, or fourteen days after grouting.

6.3 Materials.

6.3.1 Concrete. Concrete for the anchored pull-out specimen consisted of 3/4" limestone aggregate, sand, water, Type I Portland cement, and Rheobuild superplasticizer. The twenty-eight day compressive strength of the concrete was 7770 psi.

6.3.2 Steel Reinforcement. Grade 60, #3 reinforcing bars were used to reinforce the anchored pull-out specimen to allow handling and movement after testing.

6.3.3 Grout. Cement grout with a w/c ratio of 0.44 was made from Type II Portland cement and water. The grout was mixed using an electric hand drill with a mixing attachment. Mix quantities, seven day, and twenty-eight day cube strengths for the grout are shown in Tables 6.1 and 6.2. The w/c ratio of 0.44 was the same ratio that was used in the grout for the pull-out specimens tested in Chapter 5.

6.3.4 Prestressing Strand. One-half inch diameter, Grade 270 low-relaxation strand from R2 (Reel 2) was used for the strand specimens in the anchored pull-out

Table 6.1 Mix quantities for grout.

Table 6.2 7-day and 28-day cube strengths for grout.

tests. The properties for this strand are shown in Table 3.3.

6.3.5 Duct. Corrugated, galvanized steel duct with a 2" inner diameter was used in the anchored pull-out specimen. This duct, which was also used in the pull-out specimens constructed in Chapter 5, is representative of duct used in post-tensioned concrete construction.

6.3.6 Anchorages. Anchorages as shown in Figure 6.3 were fabricated by welding standard prestressing chucks to 5/8" thick steel plate. Strands were seated in the anchorages with a preload of 4 kips by using a 60 kip testing machine. It was felt that a seating load of 4 kips, which is approximately 10% of the ultimate strand load, would be suitable to prevent twisting of the strands during testing.

6.4 Construction.

6.4.1 Formwork. The formwork for the anchored pull-out specimen is shown in Figure 6.4. A steel cage made from number three reinforcing bars was included in the formwork to resist forces that might occur during movement of the specimen after testing.

Steel ducts and 1/2" diameter clear plastic tubing were also positioned in the formwork before the concrete was placed. The plastic tubing, which was removed with the formwork, provided openings underneath the fabricated anchorages at the dead end of the specimen for flushing and grouting the ducts.

6.4.2 Curing. Curing consisted of covering the concrete with plastic sheeting for four days. Both the formwork and the plastic sheeting were removed four days after placing the concrete.

6.4.3 Installation of Strands. A compressed air sprayer, as shown in Figure 6.5, was used to lubricate the strands as they were inserted into the ducts. Figure 6.6 shows the stream of lubricant produced from the sprayer that covered the strand as it was inserted into the duct. This lubrication method is similar to lubrication methods used in post-tensioned concrete construction. The bare strand specimens were not lubricated as they were inserted into the specimen.

After the strands were installed, the anchorages were epoxied to the dead end of the specimen using a two-part epoxy. This epoxy is used between precast bridge segments in segmental bridge construction.

6.4.4 Grout Plugs and Grout Hoses. Two-inch diameter wood grout plugs and 3/4" diameter grout hose were used to create water-tight ducts that could be flushed and grouted easily. Both the grout plugs and the grout hose were described previously in sections 5.4.5 and 5.4.6.

6.4.5 Flushing. Flushing was accomplished, as shown in Figure 6.7, by using a garden hose with a spray nozzle. During this process water was sprayed

Figure 6.3 Fabricated anchorages.

Figure 6.4 Formwork for anchored pull-out specimen.

Figure 6.5 Compressed air sprayer.

Figure 6.6 Lubrication of unflushed and flushed strands.

through the grout hose at the live end of the specimen at a rate of 0.5 $ft.^3$/min. for two minutes. Figure 6.8 shows the flow of water from the dead end of the specimen during flushing.

The flushing procedure shown in Figure 6.7 was considered to be representative of flushing techniques used in the field. During the flushing process oil was observed in the water exiting the duct during the first 45 seconds. After this time the water appeared free of oil.

6.4.6 Temporary Post-tensioning. To remove slack in the strands after flushing and before grouting a temporary post-tensioning force was applied to the strands. Each strand that was to be grouted was stressed to approximately 480 lbs. using a hydraulic ram. Standard prestressing chucks and wood shims, as shown in Figure 6.9, were used to hold the strands in place after stressing the strands. The wood shims and chucks were removed seven days after grouting.

6.4.7 Grouting. A hand grout pump as shown in Figure 6.10 was used to grout eight of the ducts. After grout began to flow freely from the grout openings below the anchorages at the dead end of the specimen this end was plugged with a rubber plug and grouting was continued until the duct was full. The two middle ducts, which contained bare, anchored strands were left ungrouted.

6.5 Test Equipment. The test equipment and instrumentation for the anchored pull-out tests are shown in Figure 6.11

6.5.1 Prestressing Chair. The prestressing chair used in the anchored pull-out tests had been used in previous research at the Ferguson Structural Engineering Laboratory and consisted of four, Grade 60, #7 reinforcing bars and 1" thick steel plate. The reinforcing bars were 6" long and the dimensions of the steel plate were 4" x 6".

6.5.2 Load Cell. A 50-kip load cell was used to measure the jacking load

Figure 6.7 Flushing of ducts.

Figure 6.8 Exiting water at dead end of specimen during flushing process.

Figure 6.9 Temporary post-tensioning of strands before grouting.

Figure 6.10 Grout pump used to grout anchored pull-out specimen.

during testing.

6.5.3 Hydraulic Ram. The hydraulic ram used to jack the strands in the anchored pull-out tests had two ports and an 80 kip capacity. This ram, along with the hoses, manifold, and pressure gauge were calibrated before testing to provide a check on the load cell readings.

6.5.4 Prestressing Chuck. A standard prestressing chuck was used to grip the strands at the live end of the specimen during testing.

6.5.5 Shims. One-half inch thick, slotted, steel shims with a diameter of 1 1/2" were placed between the hydraulic ram and the prestressing chuck at the live end of the specimen to enhance chuck removal after testing.

6.5.6 Pump. A dual port, manual pump was used to operate the hydraulic ram during testing.

6.5.7 Potentiometer. A potentiometer with a maximum displacement of 2" was used to measure elongation of the strand at the live end of the specimen for the anchored strands and slip of the strand at the dead end of the specimen for the unanchored strands. For the anchored strands the potentiometer was attached to the prestressing chair as shown in Figure 6.12. The potentiometer measured the movement of the 1/2" thick aluminum plate that was attached to the strand. For the bare, unanchored strands the potentiometer was attached directly to the strand at the dead end of the specimen.

6.6 Instrumentation. Instrumentation for the anchored pull-out tests consisted of an electrical box, power supply/amplifier, two voltmeters, and an X-Y plotter. The two voltmeters were used to display the load and elongation signals from the potentiometer and load cell, while the X-Y plotter was used to plot the load-elongation signals from the power supply/amplifier during testing.

6.7 Test Procedure. The test procedure consisted of gripping the strand at the live

Figure 6.12 Prestressing chair with potentiometer attachment.

end with a prestressing chuck, providing a small initial load to stabilize the hydraulic ram and load cell, then loading the strand until the adhesion between strand and grout was destroyed. Each of the bare, ungrouted strands, which were anchored at one end, were tested three times. All of the other strands were tested once. The same test procedure was used for all of the strands.

6.7.1 Initial Loading. An initial loading of approximately 200 lb. was applied to the strands to stabilize the hydraulic ram and load cell. This initial loading varied from strand to strand due to the sensitivity of the hand pump used in the tests.

6.7.2 Load Increments. The load increments used in the anchored pull-out tests varied depending on the type of strand specimen being tested. For the bare, ungrouted strands load increments of 2 kips were used in the first and second tests. In the third tests 2 kip load increments were used initially, but were changed to 4 kips after a load of 10 kips had been reached.

For the unflushed and flushed strands the load increments were usually 1 kip, but 0.25 and 0.5 kips were used in the initial stages of testing to facilitate the determination of pull-out loads that might occur at very low loads. The loading rate for all of the tests was approximately the same. However, the length of the stroke varied depending on the load increment.

6.7.3 Data Acquisition. Load and elongation readings were recorded manually from the voltmeters and were also plotted during testing using an X-Y plotter. Pressure readings from the pressure gauge on the manifold were also recorded manually to serve as a check on the load cell readings.

6.8 Test Results. The labelling system used for the different strand specimens consisted of five descriptors as shown in Table 6.3. These descriptors included the surface condition of the strand, anchorage condition, bond condition, specimen number, and test number.

An example of this labelling system is BAUG23, which was the third test of the second ungrouted, anchored, bare strand. FAG21 was the first test of the second flushed strand that was anchored and grouted. All strand specimens were tested once, except for the bare, anchored, ungrouted strands, which were both tested three times. In order to simplify the discussion of results the bare, anchored, ungrouted strands will often be referred to as unbonded strands, since these strands were not bonded to the anchored pull-out specimen.

Load-elongation results for the second and third tests of the unbonded strands are shown in Figures 6.13 and 6.14. Results for the first tests of the unbonded strands were not presented due to problems with the test setup during testing. For BAUG11 the strand was stressed to approximately 12 kips. However, the potentiometer was incorrectly positioned in the setup. Therefore, this test had to be terminated. For BAUG21 the strand was stressed to approximately 8 kips, but the hydraulic ram was

Table 6.3 Labelling system used for strands in anchored pull-out tests.

out of stroke at this point. Therefore, this test also had to be terminated.

As shown in Figures 6.13 and 6.14 stiffness values (K) were calculated for each unbonded strand in each test to serve as a check on the test setup. These values were based on the data points marked with arrowheads since these points seemed to best indicate the elastic behavior of the strand. The lengths of strand from the tip of the potentiometer to the tip of the jaws in the fabricated anchorages at the dead end of the specimen were used to determine the change in strain between the marked data points for each set of data. These strand lengths were determined after the tests had been completed by knowing all of the dimensions of the test setup including the initial displacement of the potentiometer before each test began.

The calculated stiffness values for the two unbonded strands were noticeably different as indicated in Figures 6.13 and 6.14. In both tests BAUG1 had stiffness values significantly lower than those for BAUG2. This difference in stiffness may have been due to set or slip of the prestresing chucks used in

Figure 6.13 Results from second testing of unbonded strands.

Figure 6.14 Results from third testing of unbonded strands.

the anchorages at the dead end of the specimen, since the chucks were the only difference between the first and second strands and since movement of the jaws was not measured. The same test equipment and test procedures were used for both strands in both tests.

The average stiffness value from the second and third tests of the unbonded strands was 22,500 ksi. with a standard deviation of 1190 ksi. This stiffness was 20% less than the modulus of elasticity value that was reported by the strand manufacturer for this strand. The purpose of this test was not to measure the modulus of elasticity for the strand. However, it was felt that the average stiffness value for the unbonded strands should be closer than 20% to the modulus value reported by the strand manufacturer. Therefore, three types of losses were investigated. These losses were elastic shortening of the prestressing chair, elastic shortening of the concrete, and anchorage takeup in the fabricated anchorages at the dead end of the specimen. The first two losses were quickly ruled out since the combined shortening of the prestressing chair and concrete was less than 0.001" at a load of 30 kips. The most probable cause for the low stiffness value was anchorage takeup in the prestressing chuck at the dead end of the specimen. In fact during the third testing of the unbonded strands both strands were observed to pull in to the anchorages approximately 1/8". This pull-in was measured using a steel tape with divisions of 1/32". Pull-in was not examined during the first and second tests of the unbonded strands.

In order to address the possible anchorage takeup, the elongation results for the unbonded strands were recalculated assuming a gradual anchorage takeup of 0.1" during the test. The amount of anchorage takeup varies depending on the type of prestressing chuck used. According to Lin and Burns a reasonable estimate is 0.1"[24].

The adjusted results for the unbonded strands are shown in Figures 6.15

through 6.18. These figures show the original and adjusted data for the second and third tests of each unbonded strand. Based on this adjusted data the new average stiffness for the unbonded strands was 27,600 ksi. with a standard deviation of 1800 ksi. This stiffness is within 5% of the modulus supplied by the strand manufacturer and is reasonable for the test setup used in the anchored pull-out tests. Even though it appears that anchorage takeup did occur during testing of the unbonded strands the original average stiffness value of 22,500 ksi. was used when analyzing the data for the unflushed and flushed strands since the same test setup was used for all of the strands.

Figures 6.19 through 6.21 show the results for the bare, unflushed, and flushed strands, all of which were anchored at one end and therefore, restricted from twisting out of the specimen. For each strand a pull-out load is indicated where the adhesion between the strand and grout was destroyed. Ideally, this load was to be determined graphically where the data for the bare, unflushed, and flushed strands intersected the average data for the unbonded strands. However, the bare, unflushed, and flushed strands pulled through the anchorages at the dead end of the specimen after the adhesion between the strand and grout had been destroyed. Therefore, this graphical method could not be used. Instead, the pull-out loads were determined by observing when the strands began to pull through the anchorages at the dead end of the specimen. This pull through was determined by measuring the length of the strand exiting the anchorage after each load increment. The load at which the strand began to pull through the anchorage was considered to be the pull-out load for this strand since at this load the adhesion between the strand and grout had obviously been destroyed.

The movement of the strand was measured with a steel tape having

Figure 6.15 Original and adjusted data for BAUG12.

Figure 6.16 Original and adjusted data for BAUG22.

Figure 6.17 Original and adjusted data for BAUG13.

Figure 6.18 Original and adjusted data for BAUG23.

Figure 6.19 Results for bare, anchored strands.

Figure 6.20 Results for unflushed, anchored strands.

Figure 6.21 Results for flushed, anchored strands.

divisions of 1/32". It should be mentioned that the strand was not twisting as it was pulling through the anchorage and that it only pulled through the anchorage in extremely small increments.

For BAG11 the pull-out load, as shown in Figure 6.19, was 20.3 kips. At this load the strand had just pulled through the anchorage at the dead end of the specimen approximately 1/16". For BAG21 only the total pull-through of the strand at the dead end of the specimen was measured during the test. Therefore, the approximate load at which the strand began to pull through the anchorage was unknown. However, the data for BAG21 definitely seems to indicate pull through of the strand at 18.0 kips. Therefore, this load was defined as the pull-out load for this specimen.

For the unflushed strands the pull-out loads were 7.25 and 8.57 kips for UFAG11 and UFAG21, respectively. Pull-out loads for the flushed strands were 6.89 kips and 6.60 kips for FAG11 and FAG21, respectively. The results for the unflushed and flushed strands were somewhat contradictory, but were about the same.

The reason for the strand pull-through at the anchorages at the dead end of the specimen for the bare, unflushed, and flushed grouted strands was probably due to the low seating force that was used to seat the strands in the anchorages before the strands were inserted into the ducts. During seating, the jaws in the anchorage must move a small distance while they are biting into the strand. If a force of 4 kips is applied to the strand, then the jaws will move a certain distance in the anchorage. However, if a force greater than 4 kips is applied to the strand, then the jaws will need to move a little further to continue to bite into the strand.

After the anchorages were attached to the pull-out specimen and the ducts were grouted, the grout in the duct prevented the jaws from moving with the strand after the adhesion between strand and grout had been destroyed. The result was pull-through of the strand at the dead end of the specimen after the adhesion between strand and grout had been destroyed.

Figure 6.22 shows the results for the bare anchored and bare unanchored strands tested in this test series. For the unanchored strands, slip of the strands at the dead end of the specimen was measured instead of elongation of the strands at the live end of the specimen. The slip loads for the unanchored strands were 14.8 kips and 15.8 kips for BUAG11 and BUAG21, respectively. The pull-out loads for the bare, anchored strands were 20.3 kips and 18.0 kips for BAG11 and BAG21, respectively.

6.9 Conclusions. Due to the pull-through of the strands at the dead end of the specimen, the pull-out loads for the anchored strands could not be determined graphically as explained in section 6.2. Instead, the load at which the strands were observed to pull through the anchorages at the dead end of the specimen were considered to be the pull-out loads. However, as indicated by the data for the unflushed and flushed strands (Figures 6.20 and 6.21), the pull-out loads for these

Figure 6.22 Results for bare, anchored and bare, unanchored strands.

strands occurred very close to the average data for the unbonded strands. This agreement between the intersection of the data and the observed pull-through of the strands indicated that the data obtained from this test setup was probably accurate even though some type of losses seemed to occur in the system during testing.

As indicated by the average pull-out loads in Table 6.4 the presence of both the unflushed lubricant and the flushed lubricant significantly reduced the adhesion between the seven-wire strand and cement grout. This reduction was approximately 60% for the unflushed lubricant and 65% for the flushed lubricant. These reductions were less than the reductions observed in the small-scale pull-out tests performed in Chapter 5, which showed average reductions in adhesion strength of 90% when L5 was used to lubricate the unflushed and flushed strands.

Table 6.4 Results of anchored pull-out tests.

The pull-out loads for the bare, unanchored strands and bare, anchored strands shown in Table 6.5 allowed a direct comparison between the adhesion strength of bare strands that are free to twist and bare strands that are not free to twist. As shown by the average pull-out loads for these two types of specimens it appears that restricting twist of a bare strand may increase the adhesion strength by approximately 20%. This increase in adhesion strength agreed somewhat with the 30% increase observed for the unflushed and flushed strands that were restricted from twisting. The values for the pull-out load per foot for the unanchored strands shown in Table 6.5 agreed somewhat with the 3.45 k/ft. value determined for the bare strand specimens from R2 in Chapter 5. These values differed by approximately 30%, which is acceptable for these types of

Table 6.5 Comparison of bare anchored and bare unanchored strands.

tests and the size differences between the two types of specimens.

Results from the anchored pull-out tests indicated that restricting twist of bare, unflushed, and flushed strands may increase the adhesion strength between these strands and cement grout. However, this increase is only around 20-30%, which means that the presence of an unflushed or flushed lubricant on a seven-wire strand that is restricted from twist still reduces the adhesion strength between strand and grout by about 60%. These findings reinforce the findings of Chapter 5, which were (1) the presence of a lubricant on a seven-wire strand significantly reduces the adhesion between the strand and cement grout and (2) a lubricant cannot be removed from the strand surface by the flushing techniques used in this research, which are similar to those used in post-tensioned concrete construction.

CHAPTER 7

LUBRICANT EVALUATION

7.1 Introduction. The purpose of this chapter is to evaluate the overall performance of the eleven lubricants and recommend the best four for use in large-scale friction tests. A Matrix Priority Rating System was selected for this evaluation because it can use several criterion of different importances to evaluate several alternatives. In this study the alternatives were the ten emulsifiable oils, a sodium silicate solution, and bare strand. The criteria were friction reduction, effect on adhesion, temporary corrosion protection, safety hazards, lubricant cost, and difficulty of use. An importance factor is selected for each criterion as a percentage of 100 points. The system works by rating the lubricants based on their performance under each criterion and multiplying this rating by the importance of the criterion to obtain a score for that lubricant. The total score for the lubricant is obtained by summing the scores under each criterion. The alternative having the highest total score is considered the best solution.

7.2 Matrix Priority Rating System

7.2.1 Background. The Matrix Priority Rating System was developed by Robert R. Dunford of the Business Research Division of Dow Corning Corporation in 1974. Two assumptions were made when designing this system. One, that a variety of criteria are usually used to judge the success or efficacy of a decision's outcome. Two, that some criteria are more important than others[25].

This system is similar to methods used by businesses when evaluating new products or new investments. The advantages of this system are its speed and simplicity. Its only disadvantage is that it does not include probabilities, which does not affect this application which evaluated the observed behavior of the alternatives rather than predicting the probable behavior of the alternatives.

7.2.2 Alternatives. The twelve alternatives were the eleven lubricants that were shown previously in Table 2.4 and bare strand. Each of these alternatives is described in Table 7.1.

7.2.3 Criteria. A variety of criteria must be used in order to prevent implicit weighting of a criterion category. For this evaluation six different criteria were selected as shown in Table 7.2. These criteria were selected based on the demands of lubricants and the concerns associated with their use. Friction reduction, effect on adhesion, temporary corrosion protection, and safety hazards were broken down further as shown in Table 7.3 to account for more specialized criterion. The large number of corrosion criteria did not cause an implicit weighting problem because three types of specimens and three types of environments were considered. Also, the total importance of the corrosion criteria was assigned first and then divided among the more specialized criterion. Descriptions of each criterion are discussed in detail in the following sections.

7.2.3.1 Friction Reduction. Friction reduction is the primary reason for using lubricants in the field. This criterion was divided to include static friction reduction and dynamic friction reduction since both types of friction are present during stressing operations.

7.2.3.2 Effect on Adhesion. The effect of the lubricant on the adhesion between strand and grout is a major concern. Two cases were considered, unflushed and flushed specimens. The unflushed case showed the effect of the lubricant on grout adhesion, while the flushed case indicated the flushability of the lubricant.

7.2.3.3 Temporary Corrosion Protection. A secondary use of lubricants in the field is to provide temporary corrosion protection. This criteria was also

included to insure that the alternative lubricants did not decrease the corrosion resistance of bare strand. The corrosion criteria was divided into three groups; unflushed strands, flushed strands, and unflushed wires. The strand criteria was broken down further into outer strand protection, inner strand protection, and corrosion rate. The unflushed wire criteria was broken down into ambient, deionized water, and 3.5% NaCl solution.

For the unflushed and flushed strands outer strand protection was used to indicate the length of time of protection offered by the different lubricants to the outside of the strands. Inner strand protection judged the ability of the lubricants to enter the interstices of the strand and remain there for corrosion protection and corrosion rate showed the performance of the lubricants over time.

For the unflushed wires ambient conditions showed the performance of the lubricants in simulated field conditions while the differences between deionized water and 3.5% NaCl solution indicated the corrosion protection offered in accelerated corrosive environments.

7.2.3.4 Safety Hazards. In order to account for the safety risks associated with handling these lubricants three different safety hazards were considered. These hazards were health, flammability, and reactivity.

7.2.3.5 Lubricant Cost. Lubricant cost refers to the cost/gallon of the lubricant when the lubricant is purchased in approximately fifty-five gallon drums.

7.2.3.6 Difficulty of Use. Difficulty of use takes into account the application and cleanup procedures that are required for each lubricant.

7.2.4 Importance Factors. Importance factors indicate the relative importance of the criteria. For this evaluation one hundred points was distributed among the criteria to indicate their importances. This number of points could be any convenient number such as 50, 500 or 1000 since the importances are relative.

The distribution of points is shown in Table 7.4 directly below the criteria. Of the one hundred points, forty points were given to friction reduction, twenty-five for effect on adhesion, twenty for temporary corrosion protection, six for safety hazards, five for lubricant cost, and four for difficulty of use. Importance factors for each criterion are discussed in detail in the following sections.

7.2.4.1 Friction Reduction. Friction reduction was given the most importance since it is the primary reason for the use of lubricants in the field. Both static and dynamic friction are present during stressing operations. Therefore, both of these criterion were considered equally important and given importance factors of twenty.

7.2.4.2 Effect on Adhesion. Effect on adhesion was considered second in importance. While the primary reason for this evaluation was to determine the lubrication properties of the different lubricants there is concern over possible reduction in bond affecting ultimate strength. Weighting factors of 12.5 were given to the unflushed and the flushed criterion. These criterion were considered equally important to give equal credit to lubricants that do not effect the adhesion and to lubricants that can be totally removed by flushing.

7.2.4.3 Temporary Corrosion Protection. Corrosion protection was considered to be half as important as friction reduction since corrosion protection is a secondary reason for lubricated tendons. Twenty points were distributed among nine criterion with ten going to protection of unflushed strands, five for flushed strands, and five for unflushed wires.

For the unflushed strands importance factors for outer strand protection, inner strand protection, and corrosion rate were six, two, and two respectively. Outer strand protection was given the highest weighting since corrosion usually begins on the outer strand first. Inner strand protection was of less importance because it was based on smaller specimens and because it was only measured at the conclusion of the exposure tests. Corrosion rate was also of less importance since it dealt with the performance of the lubricants after corrosion began.

Corrosion protection of flushed strands was considered half as important as corrosion protection of unflushed strands since these lubricants are not expected to provide protection after flushing. However, corrosion protection after flushing is definitely a plus. Therefore, lubricants were credited for this characteristic. The importance factors for outer strand protection, inner strand protection, and corrosion rate were three, one, and one respectively.

Unflushed wires had relatively low importance factors since they were smaller than the strand specimens. Wires in the ambient conditions were slightly more important than those in the controlled environments because the ambient conditions were more closely related to field conditions. The importance factors were 2, 1.5, and 1.5 for ambient, deionized water, and 3.5% NaCl solution respectively.

7.2.4.4 Safety Hazards. Each safety hazard was assigned a weighting of two. These importance factors were relatively low since no unusual precautions are necessary when using these lubricants.

7.2.4.5 Lubricant Cost. Lubricant cost was given an importance of five. This importance was based on the fact that the cost of lubricants is almost negligible when compared to the cost of a typical project requiring lubricated tendons.

7.2.4.6 Difficulty of Use. For this evaluation difficulty of use was given an importance of four. This relatively low importance factor was selected because this evaluation was more concerned with the properties of the lubricants after they were applied to seven-wire strand.

7.2.5 Scales for Rating of Criteria. The scales used for rating the criteria are the most important element of the Matrix Priority Rating System because they must separate good performances from bad and also give similar ratings to similar performances. Ideally, the scales should be designed before any tests are completed. However, this is hard to do if there is little idea of the ranges of results that will be encountered. For example, how long should an emulsifiable oil provide temporary corrosion protection? In this thesis some data was referenced to provide a fair rating system. This data was only used to design upper and lower limits for the ratings and not to give preferential treatment to any of the lubricants.

Table 7.5 shows the rating systems that were used for the different criterion. Ratings varied linearly from zero to ten with ten being the best. This linear relationship can be seen in the rating system for outer strand protection of unflushed strands where a rating of ten was given to lubricants providing corrosion protection for forty days and a rating of zero was given to lubricants providing corrosion protection for zero days. If a lubricant protected the strand for twenty days, then it would be given a rating of 20 x (10/40), or 5.

Care must be exercised when designing the upper and lower limits for the rating systems to prevent lubricants from being credited or penalized too much. Table 7.6 shows the ratings of the lubricants when different lower limits were used for static friction reduction. The amount of friction reduction provided by each lubricant is shown in the second column. The third column of the table shows the ratings for the lubricants based on the rating system for static friction reduction shown in Table 7.5. In this rating system a rating of zero was given to lubricants increasing friction by 10% or more. Originally, a rating of zero was given to lubricants increasing friction by 33% or more to

Table 7.6 Comparison of rating systems for static friction reduction.

account for L10, which increased friction by 31%. The ratings using the 33% lower limit are shown in the fourth column of the table. This lower limit caused the ratings for the lubricants that reduced friction to be closer together and gave a significant credit of 73 points (3.65 x 20) to L7, which increased friction by 9%. When the lower limit of 10% was used L7 was only credited with 4.6 points (0.23 x 20) and the lubricants that reduced friction were spread out more giving a better representation of their different performances.

7.2.5.1 Friction Reduction. In order to design the upper and lower limits for the friction rating the test data was referenced to get an idea of the amount of friction reduction that was possible. L5 reduced the static friction by 27% and teflon reduced the static friction by 61%. It was felt that a reduction of 33% would be a practical ideal, therefore, a rating of ten was given to any lubricants reducing friction by 33% or more. This was a significant decrease since only about 10% reduction is usually expected in the field when frictional problems are encountered.

The lower limit accounted for any lubricants that increased the frictional resistance. Again, the test data was referenced to get an idea of the amount of frictional increase possible. The two lubricants that increased the static friction were L7 and L10. The increases were 9% and 31% respectively. In order to appropriately penalize these lubricants a rating of zero was given to lubricants that increased the friction by 10% or more.

The same rating system was used for dynamic friction reduction since both types of friction were considered equally important.

7.2.5.2 Effect on Adhesion. According to ACI Building Code Section 12.9.1 the development length of 1/2" diameter Gr. 270 low-relaxation strand is 135" assuming a maximum nominal stress of 270 ksi. and no prestress losses. This correlates to a force of 41.3 kips over 135". Assuming the relationship between force and bond length is linear then the maximum force in bare strand with a bond length of 10.5" is approximately 3.2 kips. The bond length of the small-scale pull-out specimens was 10.5". Therefore, a rating of ten was given to any lubricant with a slip load of 3.2 kips or more. A rating of zero was given to any lubricant having a slip load of 100 lbs. or less, which essentially corresponded to total loss of bond since the weight of the pull-out specimen with bearing pad and plate was 86 lbs. The same rating system was used for the unflushed and the flushed cases since they were of equal importance.

7.2.5.3 Temporary Corrosion Protection. The same rating systems were used for the unflushed and flushed strands to make a direct comparison between the performances of the lubricants with and without flushing.

For outer strand protection a rating of ten was given to lubricants preventing corrosion for forty days or more and a rating of zero was given to lubricants allowing corrosion after zero days. These limits were selected as being appropriate for construction sequences between placement of strands and grouting. They did reference the visual observations for the exposure tests which showed protection of unflushed specimens varying from fifteen days to thirty-nine days. Strand that was not lubricated began to corrode after four days.

For inner strand protection a rating of ten was given to lubricants that allowed 0% corrosion of the inner strand after forty-six days. If 100% of the inner strand was corroded after forty-six days, then the lubricant was given a rating of zero. The only problem with this rating system was that it did not account for severity of corrosion or when corrosion began. For example, 90% of the unflushed strand lubricated with L1 was covered with a light, uniform corrosion , while 85% of the unflushed strand lubricated with L7 was covered with a heavy, uniform corrosion. However, the L7 strand received a slightly higher rating since it had slightly less corrosion.

A rating of ten was given to lubricants allowing a corrosion rate of 0%/day, while a rating of zero was given to lubricants allowing a corrosion rate greater than or equal to 10%/day. This rating system was chosen after noticing that the corrosion rates of the unflushed strands varied from 1.5%/day to 6.7%/day. It was felt that a maximum rate of 10%/day would be fair to all of the lubricants.

For the unflushed wires in the ambient conditions a rating of ten was given to lubricants that prevented corrosion for forty days and a rating of zero was given to lubricants that allowed corrosion after zero days. This is the same rating system that was used for the outer strand protection since the strands and wires were both in the same environment.

For the unflushed wires in deionized water and 3.5% NaCl solution a rating of ten was given to lubricants that allowed 0% corrosion after three days, while a rating of zero was given to lubricants that allowed 100% corrosion after three days.

7.2.5.4 Safety Hazards. Material Safety Data Sheets were referenced for information concerning the health, flammability, and reactivity hazards of each lubricant. For all ten emulsifiable oils NFPA (National Fire Protection Association) and/or HMIS (Hazardous Material Information Systems) hazard ratings were available. These ratings were not applicable to L10 so personal judgement was used when rating this product for safety.

The NFPA and HMIS ratings range from zero to four with zero being an insignificant hazard and four being an extreme hazard. These ratings were modified to be consistent with the rating systems used for the other criteria in the decision matrix. Table 7.7 shows the NFPA, HMIS and modified rating systems.

All of the lubricants posed insignificant to slight hazards to health, flammability, and reactivity except for L10, which was considered to pose moderate health and reactivity hazards. L10 dries to form a glassy film that can easily cut skin and its decomposition or prolonged contact with certain metals can produce flammable Hydrogen gas[26].

7.2.5.5 Lubricant Cost. Lubricants that cost \$2/gallon or less were given a rating of ten. Lubricants that cost \$20/gallon or more were given a rating of zero. The range of costs for the lubricants as shown in Table 7.8 varied from \$3.16/gallon to \$14.38/gallon when purchased in approximately fifty-five gallon drums. L1 is no longer manufactured, but the price quoted in the table is an approximate cost based on information from its former manufacturer.

Table 7.7 Rating systems for safety criteria.

7.2.5.6 Difficulty of Use. This rating system was based on application and cleanup procedures associated with lubricated tendons. For this rating system the normal application procedures were considered to be dipping the tendon or spraying the tendon as it is entering the duct. Both of these methods are considered to be moderately difficult, but can be performed in reasonable time frames. Cleanup procedures refer to removal of lubricant from skin and clothing of employees and equipment involved in the lubrication or stressing operations. In this rating system normal cleanup procedures were assumed to use water and soap to remove the lubricant from skin, clothes, and equipment.

A rating of ten was given to lubricants that were very simple to use and require no application time and no cleanup. The only alternative that fit this description was bare strand. A rating of five was given to lubricants that were moderately difficult to use. Lubricants that were very difficult to use were given a rating of zero.

All of the alternatives were given a rating of five except L9, L10, and bare strand. L9 was given a score of two because it is very thick and could not be sprayed onto a tendon. It is also very messy and hard to remove from skin or clothing. L10 was given a score of zero because it dries quickly and is hard to remove from equipment. Bare strand was given a score of ten because it does not require any application or cleanup procedures.

7.2.6 Evaluation Process. The matrix setup, which is shown in Table 7.9, lists the alternatives in the first column and the criteria across the top. Importance factors for the criteria are shown in the first row of the table. The matrix works by rating each alternative based on its performance with respect to each criterion. The rating ranges from 0 to 10 with 10 being the best. This rating is then entered in the top box for the lubricant under that particular criterion. For example, L1 was given a rating of 6.28 for its performance in reduction of static friction. This rating is multiplied by the importance of the criterion to give a score for that lubricant. For L1 the rating of 6.28

Table 7.8 Costs of lubricants.

was multiplied by the importance factor of 20 to get a score of 126. This process is repeated for each lubricant and each criterion. The total score for the alternative lubricant is obtained by summing the scores from the lubricant's performance with respect to each criterion. For L1 its total score was 454. The solution with the highest total score is the best alternative. A perfect solution would have a score of 1000 points.

7.2.7 Matrix Evaluation of Candidate Lubricants. The final matrix evaluation is shown in Table 7.10. The alternatives were placed in descending order according to their total scores. The best alternative was L5 with a total score of 529, while the worst alternative was L7 with a score of 219. Bare strand was considered the third best alternative with a total score of 516. These results are interesting because they indicate that only two lubricants were better than bare strand when looking at the advantages and disadvantages of the lubricants studied in this thesis.

Matrix ratings for bare strand differed under the adhesion criterion due to the construction sequence of the pull-out specimens. As mentioned in section 5.1, the pull-out specimens were constructed in two groups. The first group consisted of bare and unflushed strand specimens. The second group

consisted of bare and flushed strand specimens. Ratings for the bare strand alternative under the unflushed and flushed adhesion criteria are based on the pull-out loads for bare strand in these two groups of specimens. In the first group of specimens the average pull-out load for bare strand was 2560 lbs. which corresponded to a matrix rating of 7.94. In the second group of specimens the average pull-out load for bare strand was 3330 lbs., which corresponded to a matrix rating of 10.0. It was felt that both average pull-out loads should be used since two groups of specimens were tested.

In order to show the relative performances of these lubricants during the evaluation process their cumulative scores were plotted versus the criterion. Figure 7.1 shows the curves for the eleven lubricants, bare strand, and the ideal lubricant, which was given a rating of ten under each criterion.

In general the curves for the alternative lubricants were similar in shape. The curves increased with the addition of the friction scores and then flattened out due to the low adhesion scores before increasing gradually with the addition of the remaining criterion scores. The biggest difference between the ideal curve and the alternative curves occurred above the adhesion criteria. All of the lubricants reduced the adhesion strength by approximately 90% except for L10, which reduced the adhesion by 50% for the unflushed case and 10% for the flushed case.

The lubricants were divided into four groups based on the curves shown in Figure 7.1. These groups are shown in Figures 7.2 through 7.5 along with the ideal lubricant. The first group consisted of L5 and L11. Group two consisted of L1, L2, L3, L4, and L8. L6, L7, L9, and L10 made up the third group. The fourth group consisted of bare strand. Lubricants in groups one and two were considered acceptable lubricants, while lubricants in group three were considered unacceptable lubricants.

L5 and L11 performed well under all of the criteria except for adhesion, where they significantly reduced the adhesion. Lubricants in the second group were not quite as good in friction reduction, but were similar under all of the remaining criteria. Lubricants in the third group behaved in various manners. L9 slightly reduced friction and was an excellent corrosion inhibitor, but had a disastrous effect on adhesion. This lubricant is also expensive and difficult to use. All of these characteristics are shown in the curve for L9 in Figure 7.4. L10 had less effect on the adhesion than the other lubricants, was the best corrosion inhibitor after flushing and relatively inexpensive. However, its low scores in friction reduction, safety and difficulty of use kept it from being an acceptable lubricant. L6 had very little effect on friction reduction and significantly reduced the adhesion strength. In the remaining criteria its performance was acceptable. L7 performed poorly in the friction, adhesion, and corrosion tests resulting in a weak overall performance. L7 is also relatively expensive. Its only favorable characteristic was its safety.

Figure 7.5 shows the performance of bare strand during the evaluation. Bare strand was credited in the friction criteria because two of the lubricants actually increased friction. It was close to ideal for adhesion and was ideal with respect to safety, cost, and difficulty of use. Its major drawback was its low corrosion resistance which is shown by the flat region of the curve above the corrosion criteria.

7.3 Recommendations. Table 7.11 shows the four lubricants that were recommended for use in the large-scale friction tests that were a part of this overall project. The top four alternatives from the matrix evaluation were L5, L11, bare strand, and L2. Their respective scores were 529, 518, 516, and 475. However, bare strand is not a viable candidate for friction reduction. Therefore, it was replaced with another lubricant. The fifth, sixth, and seventh place candidates were L3, L1, and L8 with scores of 465, 454, and 451 respectively. L8 was selected as the fourth candidate

Table 7.11 Top four lubricants.

for the large-scale friction tests because L3 changed its formulation within the last year and L1 is no longer manufactured. Both L3 and L4 changed from a parathenic base oil to a napthenic base oil, but the other ingredients of these oils remained the same. This change in base oils could cause a slight decrease in the friction reduction properties of L3 and L4 when it is used straight, but not when it is mixed with water. A parathenic base oil is composed of straight chain hydrocarbons that lie down better on a surface than the branch chain hydrocarbons of a napthenic base oil. This difference in lubrication properties could only be measured with very precise equipment[27] and would more than likely go unnoticed in post-tensioning operations. None of the other lubricant formulations have changed during this research.

It is interesting to note that the top four lubricants from the matrix evaluation were the lubricants that provided the best friction reduction as shown in Tables 2.4 and 2.5. These lubricants reduced static friction by 18% to 27% and dynamic friction by 6% to 14%. These lubricants all provided from good to excellent corrosion protection except for Lubricant L8. This lubricant provided less corrosion protection than the other three lubricants in the accelerated wire corrosion tests and the exposure tests as shown in Table 3.5, Table 3.6, and Figure 4.7.

CHAPTER 8

SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

8.1 Summary. The use of post-tensioned concrete and post-tensioning technology in U.S. bridge structures has increased rapidly in the last twenty years. During this period over 100 large, post-tensioned segmental bridge projects and 13 cable-stay bridges have been completed. These bridges have provided excellent performance to date and are not expected to have any problems in the near or distant future. However, there have been a number of concerns associated with their construction. Two of these are friction reduction during stressing of post-tensioned tendons and temporary corrosion protection of both post-tensioned tendons and cable-stays after installation and before grouting.

During the stressing of multi-strand post-tensioned tendons large frictional losses can be encountered between the tendon and the duct. These losses can be a significant concern since large losses can appreciably reduce the efficiency of the post-tensioning process. In effect prestressing steel is being wasted since the effective prestress allowed by codes and standards cannot be totally developed at all sections along the tendon length.

Temporary corrosion protection of post-tensioned tendons and cable-stays after installation and before grouting is another concern. Both the tendons and the stays consist of tension elements that are under very high stresses. Failure of one of these elements due to corrosion could cause severe structural damage. Failure of several might cause collapse of a structure.

Historically, the solution to both of these concerns has been the application of emulsifiable oils to the surface of the tendon or stay. However, there are numerous oils available and there is very little test data providing the amount of friction reduction or corrosion protection that can be expected from different oils. There is also no test data comparing the effect of different oils on the adhesion between seven-wire strand and cement grout before and after flushing. Therefore, an extensive lubricant evaluation was performed. This evaluation included an extensive search for emulsifiable oils that could be used for lubrication and/or temporary corrosion protection of multi-strand tendons. Eleven lubricants were identified. Of these eleven lubricants, ten were emulsifiable oils and one was a sodium silicate solution.

In order to evaluate the eleven lubricants, small-scale corrosion and adhesion tests were performed. Small-scale friction tests performed by Hamilton and Davis as part of the overall project were also incorporated into the evaluation. The corrosion tests compared the corrosion protection offered by the different lubricants in three environments. These environments were deionized water, 3.5% NaCl solution, and ambient outdoor conditions. Small lubricated wire specimens were used in the deionized water and the 3.5% NaCl solution. In the ambient outdoor conditions, lubricated wires, lubricated strands, and lubricated then flushed strands were all exposed to ambient outdoor conditions as well as a daily wetting cycle. In the deionized water and 3.5% NaCl solution a reference electrode and visual observations were used to determine the length of corrosion protection offered by the different lubricants. In the ambient outdoor conditions visual observations were used to compare the corrosion protection offered by the different lubricants.

The adhesion tests used single bare, lubricated, and lubricated then flushed strands grouted inside steel ducts to determine the effect of the different lubricants on the adhesion between seven-wire strand and cement grout before and after flushing by pulling the strand out of the specimen. Additional pull-out tests, which prevented the strands from twisting were also performed to determine if restricting twist would increase the adhesive strength of bare, lubricated, and lubricated then flushed strands.

In these additional tests, which were referred to as anchored pull-out tests, the strand specimens were also grouted inside steel ducts.

The overall performance of the different lubricants was determined by using a Matrix Priority Rating System. This system was selected since it can use several criterion of different importances to evaluate several alternatives. Based on the results of these rankings four lubricants were recommended for use in large-scale friction tests that were part of this overall project.

8.2 Findings. This section presents the findings from each of the small-scale tests as well as the results from the matrix evaluation of the different lubricants.

8.2.1 Small-scale Friction Tests. Eight of the eleven lubricants reduced friction while three of the lubricants increased friction. The reductions in friction varied between 2% and 30% while the increases varied between 5% and 30%. The 30% increase was caused by the sodium silicate solution which dried during testing and prevented movement of the strand specimen during the test. The increase caused by the other two lubricants was between 5% and 10%.

8.2.2 Accelerated Wire Corrosion Tests in Deionized Water and 3.5% NaCl Solution..

(a) The length of corrosion protection offered by the different lubricants could not be determined by using a reference electrode. However, sharp changes in potential difference data did precede the appearance of visual corrosion in several cases.

(b) Eight of the eleven lubricants provided from good to excellent corrosion protection in both the deionized water and the 3.5% NaCl solution. Two lubricants provided poor corrosion protection in both environments. One lubricant provided good corrosion protection in deionized water and poor corrosion protection in the 3.5% NaCl solution.

(c) Similar amounts of corrosion were observed on bare wires tested in deionized water and 3.5% NaCl solution. The corrosion on the saltwater specimens changed from a bright orange color to a dark reddish-brown after the wires were removed from the saltwater environment.

8.2.3 Exposure Tests in Ambient Outdoor Conditions.

(a) Bare stand specimens began to corrode after four days of exposure.

(b.) The length of corrosion protection offered by the eleven lubricants varied from fifteen to thirty-nine days on lubricated strands.

(c) A sodium silicate solution was the only lubricant that provided any corrosion protection after flushing. This lubricant prevented corrosion for twenty days after flushing.

(d) There was some correlation between the length of corrosion protection provided by the lubricants on the lubricated wires in the exposure tests and the percent corrosion present on the lubricated wires in the accelerated wire corrosion tests. In general, emulsifiable oils that provided corrosion protection for fourteen to eighteen days in the exposure tests allowed 10% or less corrosion in the accelerated wire corrosion tests.

8.2.4 Small-scale Adhesion Tests.

(a) Pull out results from the grouted specimens showed that all of the lubricants essentially destroyed the adhesion between a single seven-wire strand and the hardened cement grout. On average the reduction in adhesion was 90%. Results were similar for pull-out tests using lubricated strands which had been generously flushed. For the flushed specimens the average reduction in adhesion was still approximately 75%. The only exception was the sodium silicate solution which reduced adhesion by 50% before flushing and 10% after flushing.

(b) The adhesion properties of seven-wire strand with a stearate soap on its surface were the same as those of seven-wire strand without a stearate soap.

8.2.5 Anchored Pull-out Tests. Restricting twist of bare, lubricated, and lubricated then flushed strands slightly increased the adhesion strength of these strands. This increase was approximately 30% for all three types of strands. There was essentially no difference in the behavior of the lubricated strands and the lubricated then flushed strands..

8.3 Recommendations. Four lubricants are recommended for use in full-scale tests for the effectiveness of lubrication of multi-strand tendons. These lubricants were L2, L5, L8, and L11. Based on the results of the small-scale friction tests these four lubricants can be expected to reduce friction during stressing by 10 to 20%. These four lubricants also provided the best overall performance with respect to the criteria used in this evaluation. These criteria were friction reduction, effect on adhesion, corrosion protection, safety, cost, and difficulty of use.

Five lubricants are recommended for temporary corrosion protection of prestressing steel. These lubricants are L2, L3, L4, L5, and L6. All five of these lubricants provided from good to excellent corrosion protection in the accelerated wire corrosion tests and the exposure tests. Based on the tests reported in this thesis, it is difficult to determine the length of corrosion protection that could be expected from these five lubricants when applied to tendons in ungrouted ducts. However, it is felt that all five of these lubricants could easily provide excellent corrosion protection of ungrouted tendons for at least one to two months in a sealed duct.

Different emulsifiable oils provide different amounts of friction reduction and different amounts of corrosion protection. Therefore, before other emulsifiable oils are used their lubrication and/or corrosion protection properties should be evaluated. In order to evaluate these properties small-scale friction tests and small-scale corrosion tests similar to those presented in this thesis could be used. Small-scale adhesion tests may also be useful even though it appears that all emulsifiable oils will essentially destroy the adhesion between strand and grout before and after flushing.

8.4 Future Research. The search for a different type of lubricant needs to be continued. This lubricant needs to reduce friction by at least 10 - 20% yet have substantially less effect on the adhesion than the emulsifiable oils. One possible candidate is a biodegradable soap called Aqualube MX. This product has shown to provide slightly more friction reduction than Lubricant L2, but no adhesion tests have been performed with this lubricant. Another possible lubricant is graphite powder which has been used in the field for friction reduction with multi-strand tendons.

Small-scale beam tests using seven-wire strand need to be performed to determine the effect of a flushed lubricant on the flexural behavior of a post-tensioned member. Tests performed by Taylor indicated that a flushed lubricant will have little effect on the flexural behavior of a post-tensioned beam. However, the pull-out tests and anchored pull-out tests performed in this study indicated that the adhesion between the strand and the grout will be significantly reduced by an unflushed lubricant leading to unbonded behavior.

Corrosion tests using lubricated strands in vertical or inclined positions would be useful. In cable-stay bridges the stays are in an inclined position and it is felt that an emulsifiable oil may "drain" to the bottom of the stay over time. This "draining" of the oil may result in less corrosion protection on the upper portions of the stay.

APPENDIX A

VISUAL OBSERVATIONS AND TEST RESULTS FOR ACCELERATED WIRE CORROSION TESTS

This appendix contains the visual observations and E_{corr} data for all of the wire specimens tested in the accelerated wire corrosion tests. The labelling system for the wire specimens, which is shown below, included the lubricant number, if a lubricant was used, the specimen number, and the type of corrosive environment.

Labelling System for Wire Specimens used in Accelerated Wire Corrosion Tests

L# = Lubricant Number (if a lubricant was used)
BW = Bare Wire
1,2 = Specimen Number
DW = Deionized Water
SW = 3.5% NaCl Solution

Examples of the labelling system are L1-1DW and BW-2SW. L1-1DW was the first wire specimen lubricated with L1 and immersed in deionized water. BW-2SW was the second bare wire specimen tested in 3.5% NaCl solution.

Tables A.1 through A.4 contain the visual observations for each wire specimen. Figures A.1 through A.24 contain the E_{corr} data for each wire specimen.

Table A.1 - Visual observations for bare wire specimens immersed in deionized water for three days.

Specimen	24 Hours	48 Hours	72 Hours
BW-1DW	Several corrosion spots along length of wire.	Corrosion spots growing together or growing individually.	Slight increase in existing corrosion to cover 50% of surface area.
BW-2DW	Three vertical corrosion streaks along length of wire.	Slight increase in existing corrosion. Appearance of five small corrosion spots.	Increase in existing corrosion to cover 60% of surface area.

Table A.2 - Visual observations for lubricated wires immersed in deionized water for three days.

Specimen	24 Hours	48 Hours	72 Hours
L1-1DW	One corrosion streak and one corrosion spot covering a total of 15% of the surface area.	Slight increase in existing corrosion to cover 20% of the surface area.	Noticeable increase in existing corrosion. The corrosion streak and corrosion spot have grown together to cover 35% of the surface area.
L1-2DW	Three corrosion streaks covering a total of 15% of the surface area.	Slight increase in corrosion streaks to cover 20% of the surface area.	Slight increase in corrosion streaks to cover 25% of the surface area.
L2-1DW	No corrosion.	Very slight corrosion at epoxy interface.	Slight increase in existing corrosion at epoxy interface. Appearance of slight corrosion at waterline. Total corrosion covers less than 1% of the surface area.
L2-2DW	No corrosion.	Corrosion spot at waterline.	No change in existing corrosion at waterline. Appearance of corrosion streak at bottom of wire. Total corrosion

			covers 7% of surface area.
L3-1DW	Corrosion streak covering 10% of the surface area.	Slight increase in corrosion streak.	Slight increase in corrosion streak to cover 15% of the surface area.
L3-2DW	Small corrosion streak at bottom of wire covering less than 5% of the surface area.	Slight increase in corrosion streak to cover 5% of the surface area.	No change in existing corrosion.
L4-1DW	No corrosion.	Slight corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface to cover 1% of surface area.
L4-2DW	No corrosion.	No corrosion.	No corrosion.
L5-1DW	No corrosion.	No corrosion.	Corrosion spot at waterline covering less than 1% of the surface area.
L5-2DW	No corrosion.	No corrosion.	Slight corrosion at epoxy interface covering less than 1% of the surface area.
L6-1DW	No corrosion.	Very slight corrosion at epoxy interface.	No change in existing corrosion at epoxy interface. Corrosion covers 1% of surface area.
L6-2DW	No corrosion.	No corrosion.	No corrosion.
L7-1DW	No corrosion.	No corrosion.	Very slight

			corrosion at epoxy interface covering 1% of surface area.
L7-2DW	No corrosion.	No corrosion.	Corrosion at waterline covering 3% of the surface area.
L8-1DW	No corrosion.	Spiral corrosion streak covering 10% of the surface area. Slight corrosion at epoxy interface covering less than 1% of the surface area.	Noticeable increase in corrosion streak to 20% of surface area. Very slight increase in corrosion at epoxy interface. Corrosion at epoxy interface still covers less than 1% of the surface area.
L8-2DW	No corrosion.	No corrosion.	No corrosion.
L9-1DW	No corrosion. Thick , light blue film covering entire wire surface.	No corrosion. Light blue film on half of wire for entire length and dark green film on other half of wire for entire length.	No corrosion. Dark green film covering entire wire surface.
L9-2DW	No corrosion. Thick, light blue film covering entire wire surface.	No change in appearance of wire.	No change in appearance of wire.
L10-1DW	Dark orange corrosion spots covering 15% of	Slight increase in existing corrosion	Slight increase in existing corrosion spots to cover 20%

	the surface area.	spots.	of the surface area.
L10-2DW	Dark orange corrosion spots covering 5% of the surface area.	Slight increase in existing corrosion spots.	Slight increase in existing corrosion spots to cover 10% of the surface area.
L11-1DW	No corrosion.	No corrosion.	Corrosion spot at epoxy interface covering less than 1% of the surface area.
L11-2DW	No corrosion.	Very slight corrosion at epoxy interface.	No change in corrosion at epoxy interface. Corrosion covers 2% of surface area.

Table A.3 - Visual observations for bare wire specimens immersed in 3.5% NaCl solution for three days.

Specimen	24 Hours	48 Hours	72 Hours
BW-1SW	Corrosion streak covering 25% of surface area.	Slight increase in existing corrosion.	Noticeable increase in existing corrosion to cover 50% of surface area.
BW-2SW	Uniform corrosion covering 50% of surface area.	No observation recorded.	Increase in existing corrosion to cover 70% of surface area.

Table A.4 - Visual observations for lubricated wires immersed in 3.5% NaCl solution for three days.

Specimen	24 Hours	48 Hours	72 Hours
L1-1SW	Light, uniform corrosion near bottom of wire covering 10% of surface area.	Slight increase in existing corrosion. Appearance of corrosion spot slightly below waterline.	Increase in existing corrosion to cover 25% of surface area.
L1-2SW	Light, uniform corrosion covering 30% of surface area.	Slight increase in existing corrosion to cover 35% of surface area.	Slight increase in existing corrosion to cover 40% of surface area.
L2-1SW	Very slight corrosion at epoxy interface.	Very slight increase in existing corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface to cover 5% of surface area.
L2-2SW	Very slight corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface.	Increase in corrosion at epoxy interface to cover 10% of surface area.
L3-1SW	Very slight corrosion at epoxy interface.	No change in existing corrosion.	Slight increase in corrosion at epoxy interface to cover 1% of surface area.
L3-2SW	Very slight corrosion at epoxy interface.	No change in existing corrosion.	No change in existing corrosion. Total corrosion

			covers 1% of surface area.
L4-1SW	Slight corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface.	Increase in corrosion at epoxy interface. Corrosion spot slightly below waterline. Total corrosion covers 10% of surface area.
L4-2SW	Slight corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface to cover 2% of surface area.
L5-1SW	Slight corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface.	Slight increase in existing corrosion to cover 7% of surface area.
L5-2SW	Slight corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface.	Slight increase in existing corrosion at epoxy interface to cover 5% of surface area.
L6-1SW	Slight corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface.	Slight increase in existing corrosion at epoxy interface to cover 4% of surface area.
L6-2SW	Slight corrosion at epoxy interface.	No change in existing corrosion.	No change in existing corrosion. Corrosion covers 1% of surface area.

L7-1SW	Slight corrosion at epoxy interface.	Slight increase in corrosion at epoxy interface.	Slight increase in existing corrosion to cover 5% of surface area.
L7-2SW	Slight corrosion at epoxy interface.	No change in existing corrosion.	No change in existing corrosion. Corrosion covers 1% of surface area.
L8-1SW	Corrosion streak near bottom of wire covering 10% of surface area.	Slight increase in corrosion streak.	Increase in existing corrosion streak to cover 20% of surface area.
L8-2SW	Corrosion streak near bottom of wire covering 5% of surface area.	Slight increase in existing corrosion.	Slight increase in existing corrosion to cover 10% of surface area.
L9-1SW	Slight corrosion at epoxy interface covering less than 1% of surface area. Wire is covered by dark green film.	Slight increase in existing corrosion, but this corrosion still covers less than 1% of the surface area. Wire is still covered by dark green film.	No change in appearance of wire.
L9-2SW	No corrosion. Wire is covered by dark green film.	No change in appearance of wire.	No change in appearance of wire.
L10-1SW	White streak covering 20% of surface area.	Slight increase in white streak to cover 25% of surface area.	No change in appearance of wire.
L10-2SW	White streak covering 20% of	Slight increase in existing white	Increase in white streak to cover 40% of surface

	surface area.	streak.	area.
L11-1SW	Light, uniform corrosion near bottom of wire covering 10% of surface area.	Slight increase in existing corrosion.	Slight increase in existing corrosion to cover 15% of surface area.
L11-2SW	Light, uniform corrosion near bottom of wire covering 5% of surface area.	Slight increase in existing corrosion to cover 10% of surface area.	No change in existing corrosion.

APPENDIX B

VISUAL OBSERVATIONS FOR EXPOSURE TESTS

This appendix contains summaries of the visual observations for the exposure specimens in Chapter 4. The labelling systems used for these specimens are shown below.

Labelling System for Unflushed and Flushed Specimens:

Lubricant Number - Type of Specimen

L# = Lubricant Number
UF = Unflushed Strand
F = Flushed Strand
UFW = Group of unflushed wires (Four wires in a group)

Labelling System for Bare Strand and Bare Wire Specimens:

BS = Bare Strand
BW = Group of bare wires (Four wires in a group)

Examples of this labelling system are L2-UF, L2-F, and L2-UFW. These labels represent the unflushed strand, flushed strand and four unflushed wires lubricated with Lubricant L2. BS-1, BS-2, and BW represent the first bare strand specimen, the second bare strand specimen, and the group of bare wire specimens, respectively.

Table B.1 - Summary of visual observations for bare strand and bare wire specimens exposed to ambient conditions and daily wetting cycle.

Specimen	Observations
BS-1	Corrosion spots at 4 days. Corrosion in interstices at 7 days. Localized areas of uniform corrosion after 18 days. Gradual increase in corrosion to form a heavy, uniform corrosion that covered 100% of the surface area at 26 days.
BS-2	Corrosion spots at 4 days. Corrosion in interstices at 7 days. Localized areas of uniform corrosion after 18 days. Gradual increase in corrosion to form a heavy, uniform corrosion that covered 100% of the surface area at 26 days.
BW	Very light uniform corrosion along length of wires at 11 days. This corrosion gradually increased to a heavy, uniform corrosion that covered 100% of the surface area at 32 days.

Table B.2 - Summary of visual observations for unflushed strands exposed to ambient conditions and daily wetting cycle.

Specimen	Observations
L1-UF	Corrosion spots at 39 days that gradually increased to cover 15% of the surface area at 46 days. During testing the top surface of the strand was darker than the other lubricated specimens and the bottom surface was light brown in color.
L1-UF (Separate Exposure Test)	Strand was light brown in interstices at 38 days. Corrosion spots at 64 days that gradually increased to cover 15% of the surface area at 68 days.
L2-UF	Corrosion in interstices at 35 days. Corrosion spots at 39 days. Both the corrosion spots and interstitial corrosion gradually increased to form a light-moderate, uniform corrosion that covered 50% of the surface area at 46 days.
L3-UF	Corrosion spots appeared at 20 days, but did not change in size or number for the next 8 days. After 28 days additional corrosion spots and localized areas of light, uniform corrosion began to appear. The spots and uniform corrosion gradually increased to form a light-moderate, uniform corrosion that covered 60% of the surface area at 46 days.
L4-UF	Corrosion spots appeared at 20 days, but did not change in size or number for the next 8 days. After 28 days additional corrosion spots and localized areas of light, uniform corrosion began to appear. The spots and uniform corrosion gradually increased to form a light-moderate, uniform corrosion that covered 50% of the surface area at 46 days.
L5-UF	Three bright orange corrosion spots appeared at 20 days, but did not change in size or number for the next 8 days. After 28 days additional corrosion spots and localized corrosion in the interstices began to appear. The corrosion spots tended to be bright orange in

	color and gradually increased to form a light-moderate, uniform corrosion that covered 50% of the surface area at 46 days.
L6-UF	Corrosion spots appeared at 20 days, but did not change in size or number for the next 15 days. After 35 days additional corrosion spots appeared. These spots were bright orange in color and tended to be larger than corrosion spots on other lubricated strands. The corrosion spots gradually increased to form a light-moderate, uniform corrosion that covered 35% of the surface area at 46 days.
L7-UF	Corrosion spots at 20 days. Rapid increase in corrosion over next 23 days. During this time additional corrosion spots and areas of localized uniform corrosion appeared. The corrosion spots and uniform corrosion rapidly increased to form a moderate-heavy uniform corrosion covering 100% of the surface area at 35 days. This corrosion increased to a heavy, uniform corrosion covering the entire surface are at 43 days.
L8-UF	Corrosion spots at 20 days. Noticeable increase in number of corrosion spots over next 23 days. These spots rapidly increased to form a heavy, uniform corrosion that covered 100% of the surface area at 43 days.
L9-UF	Corrosion spots at 39 days. Strand had dark, oily appearance. Corrosion spots gradually increased to cover 15% of the surface area at 46 days.
L10-UF	White, flaky film at 2 days. Corrosion spots at 20 days. Rapid increase in corrosion over next 26 days. During this time additional corrosion spots and localized areas of light uniform corrosion appeared. Both the corrosion spots and uniform corrosion rapidly increased to form a light, uniform corrosion that covered 95% of the surface area at 46 days. At 46 days a white substance was also visible in the interstices of the strand.
L11-UF	Corrosion spots appeared at 25 days, but did not change for another 23 days. After 48 days additional corrosion spots and areas of localized uniform corrosion appeared. The corrosion spots and uniform corrosion gradually increased to cover 40% of the surface area at 68 days.

Table B.3 - Summary of visual observations for flushed strands exposed to ambient conditions and daily wetting cycle.

Specimen	Observations
L1-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L1-F (Separate Exposure Test)	Corrosion spots at 7 days that gradually increased to form a heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L2-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L3-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L4-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L5-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L6-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L7-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L8-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface

	area at 26 days.
L9-F	Corrosion spots at 4 days that gradually increased to form a moderate-heavy, uniform corrosion that covered 100% of the surface area at 26 days.
L10-F	White substance in interstices at 7 days. White, flaky film covering strand at 14 days. Corrosion spots at 20 days that gradually increased to form a light, uniform corrosion that covered 90% of the surface area at 46 days.
L11-F	Corrosion spots at 7 days that gradually increased to form a heavy, uniform corrosion that covered 100% of the surface area at 68 days.

Table B.4 - Summary of visual observations for unflushed wires exposed to ambient conditions and daily wetting cycle.

Specimen	Observations
L1-UFW	Corrosion spots on three of four wires at 18 days. Increase in corrosion spots to form a heavy, uniform corrosion that covered 100% of all four wires at 32 days.
L1-UFW (Separate Exposure Test)	Corrosion spots on one wire at 2 days. Other wires were corrosion free at 2 days. Light, uniform corrosion at third points of wires at 12 days increasing to heavy, uniform corrosion covering 100% of all four wires at 33 days.
L2-UFW	Corrosion spots at mid-length on bottom of wires at 14 days. Uniform corrosion along middle third of wires at 18 days increasing to a heavy, uniform corrosion covering 100% of all four wires at 32 days.
L3-UFW	Corrosion spots at mid-length on bottom and along top of wires at 14 days. Uniform corrosion along middle third of wires at 18 days increasing to heavy, uniform corrosion covering 100% of all four wires at 32 days.
L4-UFW	Corrosion spots on bottom and third points of wires at 18 days. Uniform corrosion at third points at 20 days increasing to heavy, uniform corrosion covering 100% of all four wires at 32 days.
L5-UFW	Corrosion spots at mid-length on bottom and along top of wires at 14 days. Uniform corrosion along middle third of wires at 18 days increasing to heavy, uniform corrosion covering 100% of all four wires at 32 days.
L6-UFW	Corrosion spots along length of wires at 18 days. Uniform corrosion at third points at 20 days gradually increasing to heavy uniform corrosion covering 100% of all four wires at 32 days.
L7-UFW	Corrosion spots at mid-length on bottom of wires and along top of wires at 14 days. Uniform corrosion along middle third of wires at

	18 days increasing to heavy uniform corrosion covering 100% of all four wires at 32 days.
L8-UFW	Corrosion spots at mid-length on bottom and along tops of wires at 14 days. Uniform corrosion along middle third of wires at 18 days increasing to heavy, uniform corrosion covering 100% of all four wires at 32 days.
L9-UFW	Corrosion spots along length of wires at 39 days. Wires are dirty black color. No noticeable increase in corrosion spots at 46 days.
L10-UFW	Flaky, white film covering wires at two days. Corrosion spots at 11 days. Uniform corrosion along middle third of wires at 18 days increasing to heavy, uniform corrosion covering 100% of all four wires at 32 days.
L11-UFW	Corrosion spots on all four wires at 2 days. Light, uniform corrosion covering approximately 70% of surface areas at 12 days increasing to heavy, uniform corrosion covering 100% of all four wires at 33 days.

REFERENCES

1. Podolny, W., and Muller, J., *Construction and Design of Prestressed Concrete Segmental Bridges*, John Wiley and Son's, Inc., 1982.

2. Freyermuth, C., "Building Better Bridges: Concrete vs. Steel," Civil Engineering, American Society of Civil Engineers, July 1992, pp. 66-71.

3. Breen, J., "Prestressed Concrete: The State of the Art in North America," Journal of Prestressed Concrete Institute, Vol. 35, No. 6, November/December 1990, pp 62-67.

4. Swait, W., and Funashi, M., "Corrosion Protection Systems for Bridge Stay Cables and Anchorages Volume 1: Final Report," Report No. FHWA/RD-91/050, May 1991, Federal Highway Administration, Washington D.C., 163 p.

5. Cooley, E., "Friction in Posttensioned Prestressing Systems," and "Estimation of Friction in Prestressed Concrete," Cement and Concrete Association, London, 1953.

6. Lin, T., "Cable Friction in Posttensioning," Journal of the Structural Division, American Society of Civil Engineers, November 1956.

7. Federation Internationale de la Precontrainte, "Corrosion Protection of Prestressing Steels," Joint Working Group on Corrosion Protection of Prestressing Steels, August 1990.

8. McCrossen, Robert, Florida Wire and Cable. Phone interview. 9 July 1992.

9. "Prestressed Concrete - Friction Losses During Stressing," Construction Industry Research and Information Association. Report 74. 1978. 53 pp. (Summaries of results from studies completed by A. Owens, D. Moore, and H. Taylor)

10. Novak, Charles, Viscosity Oil Company. Phone interview. 9 July 1992.

11. "Role of Cutting Fluids," Special Technical Publication, Texaco Library of Technical Aids for Industry. December 31, 1971.

12. Moore, D., Klodt, D., and Henson, R., "Protection of Steel in Prestressed Concrete Bridges." National Cooperative Research Program - Report 90 (1970) 86 pp.

13. Kelley, Marion, Tracor Inc. Phone interview. 7 July 1992.

14. Wagner, John, Shell Oil Company. Phone interview. 7 July 1992.

15. Perenchio, W., Franszok, J., and Pfeifer, D., "Corrosion Protection of Prestressing Systems in Concrete Bridges." National Cooperative Highway Research Program - Report 313 (1989) 25 pp.

16. Cork, H., "Coating Treatment for Reinforcing Steel," Concrete, January 1977, pp 31-33.

17. Vedalakshmi, R., Rengaswamy, N., and Baludriwshnan, K., "Temporary Protection of Prestressing Steels Lying in Cable Ducts," Transactions of the SAEST,

Vol. 23, No. 2-3, 1988, pp 257-262.

18. Bezouska, T., "Friction Loss in Post-tensioned Prestressing Steel Units," California Department of Transportation. Report SSR 3-66. 34 pp.

19. "Methods for Reducing Friction in Post-tensioning Tendons," Field Test Results. Dywidag Systems International. February 1988. 13 pp.

20. Tran, T. Current research at The University of Texas at Austin. To be published in Master's thesis.

21. Fontana, M., *Corrosion Engineering*, McGraw-Hill, 1986.

22. Smit, Jim, Viscosity Oil Company. Phone interview. 9 June 1992.

23. Monthly summary of local climatological data. National Oceanic and Atmospheric Administration. July through October 1991.

24. Lin, T., and Burns, N., *Design of Prestressed Concrete Structures*, John Wiley and Son's, Inc., 1981.

25. Dunford, R., "Decisions, Decisions," Industrial Research, July 1974, pp 27-30.

26. Material Safety Data Sheet, Sodium silicate "N", PQ Corporation, 1991.

27. Hollander, J., Union 76. Phone interview. 5 February 1992.