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16. Abstract

In the construction of post-tensioned bridges, the increased use of precast technology has resulted in somewhat tighter radii of curvature and greater total angle changes. Both factors make friction losses during stressing higher and somewhat less predictable. In both cast-in-situ and precast post-tensioned bridges, as well as cable stays, there is often a need for temporary corrosion protection agents between installation and before grouting.

Historically, the solution to both the friction reduction and the temporary corrosion protection problem has been use of a single agent, often an emulsifiable oil applied to the surface of the tendon or stay. The agent is usually flushed immediately before grouting. Particularly in bonded post-tensioned girders, it is essential that any residues of these agents not diminish the bond between the strand and the grout.

There are numerous oils available, as well as several other agents often used in these applications. There is very little in terms of prior data indicating the amount of friction reduction or corrsoion protection that can be expected from different oils or agents. In this study, thirteen agents were identified as practical candidates for tendon lubrication and/or temporary corrosion protection. Ten were emulsifiable oils, one was a sodium silicate solution, one was a soap and one was powdered granite.

A series of small-scale corrosion, friction and adhesion tests were conducted to evaluate the candidate materials and compare their behavior with that of bare or unprotected prestressing strand. In the corrosion tests, the corrosion protection offered by the eleven corrosion protection agents was compared by accelerated testing in deionized water, 3.5% NaCl solution and ambient outdoor exposure. The adhesion tests used grouted single-strand pullout tests to indicate bonding. Test conditions before grouting included bare strands, lubricated strands and lubricated but then thoroughly flushed strands. The small-scale friction tests involved comparison of the static and dynamic coefficients of friction of a single strand being pulled through a segment of galvanized post-tensioning duct with a constant normal force applied. Test conditions included both bare and lubricated strands.

Comparative data for all tests are provided, and the overall performance of the different agents was compared by using a Matrix Priority Rating System. Based on these results, four lubricants were selected for use in later large-scale girder friction tests with multi-strand tendons, which are a part of the overall project and will be reported in CTR Report 1264-2.

17. Key Words

post-tensioned, bridges, precast technology, friction losses, cable stays, corrosion protection agents, friction reduction, tendons, strands, girders, grouting, emulsifiable oil, adhesion

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EVALUATION OF AGENTS FOR LUBRICATION AND TEMPORARY CORROSION PROTECTION OF POST-TENSION TENDONS

by

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Research Report Number 1264-1

Research Project 0-1264

"CORROSION PROTECTION FOR POST-TENSION TENDONS AND CABLE STAY SYSTEMS"

Conducted for the

Texas Department of Transportation

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Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

AUGUST 1993

IMPLEMENTATION

This report provides a detailed description of an experimental program to determine the actual performance of thirteen agents which have been indicated as good candidates for either friction reduction or temporary corrosion protection, or both, in post-tensioned girders. These agents have typically been recommended when tight or extensive curvatures exist in a medium- or long-span bridge girder, when checks during stressing indicate high friction losses and/or insufficient elongations of the tendons, or when there will be a time delay between installation of the tendons in ducts and subsequent cement grouting. While such agents have been used under such special circumstances and are generally permitted or encouraged under existing design and construction guidelines, there has not been any systematic study of their effects or side effects.

In the current studies several agents were identified as having very good temporary corrosion protection ability. Use of such agents would greatly enhance long-term life of post-tensioned bridges when there is need for delay between tendon installation and grouting. Several agents were also identified as having good, but not great, lubrication properties. Use of such agents could substantially (20-30%) reduce friction losses and in this way contribute 5-6% to increased efficiency of the post-tensioning strand. This could result in some cost savings. Unfortunately, the comparative bond tests indicated that all of the emulsifiable oils had a serious side effect. Even when thoroughly flushed with substantial amounts of water, enough residue of the oil was present to practically destroy bond between the strand and the grout. Thus the study showed it would be dangerous to use these agents whenever a bonded design was being used. In such cases, the development of the strand could be substantially reduced which could reduce the ultimate capacity of the girder. Fortunately the study identified two agents which provide acceptable lubrication and do not significantly harm the bond between strand and grout after they are flushed. Unfortunately, neither of these agents is designed for corrosion protection.

The results reported herein are of direct interest to those selecting agents for temporary corrosion protection and for lubrication of tendons to reduce friction losses. Combined with the large-scale friction tests to be reported in CTR Report 1264-2, they should result in more efficient use of post-tensioning steel as well as safer structures.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

NOT INTENDED FOR CONSTRUCTION,
BIDDING, OR PERMIT PURPOSES

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SUMMARY

In the construction of post-tensioned bridges, the increased use of precast technology has resulted in somewhat tighter radii of curvature and greater total angle changes. Both factors make friction losses during stressing higher and somewhat less predictable. In both cast-in-situ and precast post-tensioned bridges, as well as cable stays, there is often a need for temporary corrosion protection agents between installation and before grouting.

Historically, the solution to both the friction reduction and the temporary corrosion protection problem has been use of a single agent, often an emulsifiable oil applied to the surface of the tendon or stay. The agent is usually flushed immediately before grouting. Particularly in bonded post-tensioned girders, it is essential that any residues of these agents not diminish the bond between the strand and the grout.

There are numerous oils available, as well as several other agents often used in these applications. There is very little prior data indicating the amount of friction reduction or corrosion protection that can be expected from different oils or agents. In this study thirteen agents were identified as practical candidate for tendon lubrication and/or temporary corrosion protection. Ten were emulsifiable oils, one was a sodium silicate solution, one was a soap and one was powdered graphite.

A series of small-scale corrosion, friction and adhesion tests were conducted to evaluate the candidate materials and compare their behavior with that of bare or unprotected prestressing strand. In the corrosion tests, the corrosion protection offered by the eleven corrosion protection agents was compared by accelerated testing in deionized water, 3.5% NaCl solution and ambient outdoor exposure. The adhesion tests used grouted single-strand pullout tests to indicate bonding. Test conditions before grouting included bare strands, lubricated strands and lubricated but then thoroughly flushed strands. The small-scale friction tests involved comparison of the static and dynamic coefficients of friction of a single strand being pulled through a segment of galvanized post-tensioning duct with a constant normal force applied. Test conditions included both bare and lubricated strands.

Comparative data for all tests is provided and the overall performance of the different agents was compared by using a Matrix Priority Rating System. Based on these results, four lubricants were selected for use in later large-scale girder friction tests with multi-strand tendons, which are a part of the overall project and will be reported in CTR Report 1264-2.

CHAPTER 1
INTRODUCTION

1.1 General.

During the last twenty years over 100 large segmental bridge projects and 13 cable-stay bridges have been completed in the United States [1,2]. 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. After anchoring the post-tensioned tendons, the duct may or may not be grouted. With internal tendons, 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. With external tendons and in cable stay applications, the strands are often grouted for corrosion protection, but since the sheaths are primarily not in contact with the concrete, the stays are unbonded and the external tendons are discretely bonded only at the deviators.

1.2 Post-tensioned Tendons.

1.2.1 Description. As shown in Figure 1.1 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" (12.7 mm) diameter or 0.6" (15.2 mm) diameter seven-wire strands are the preferred types of prestressing steel. The duct usually consists of galvanized steel or high density polyethylene.

1.2.2 Concerns.

1.2.2.1 FRICTION REDUCTION. During stressing of multi-strand tendons friction forces are encountered between the tendon and the duct as shown in Figure 1.2a. 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 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.

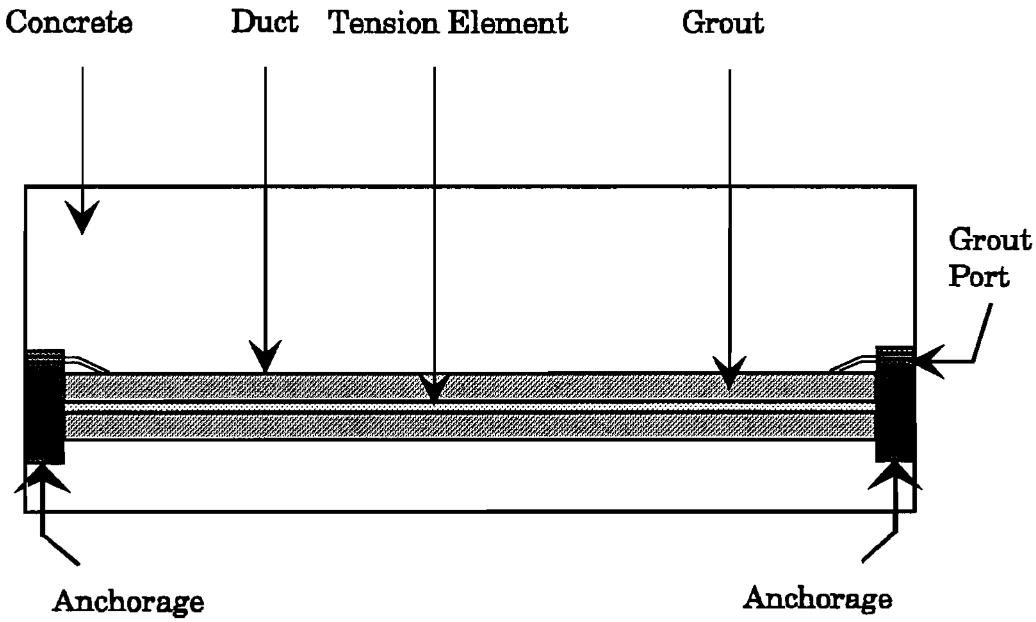


Figure 1.1 Bonded post-tensioned tendon.

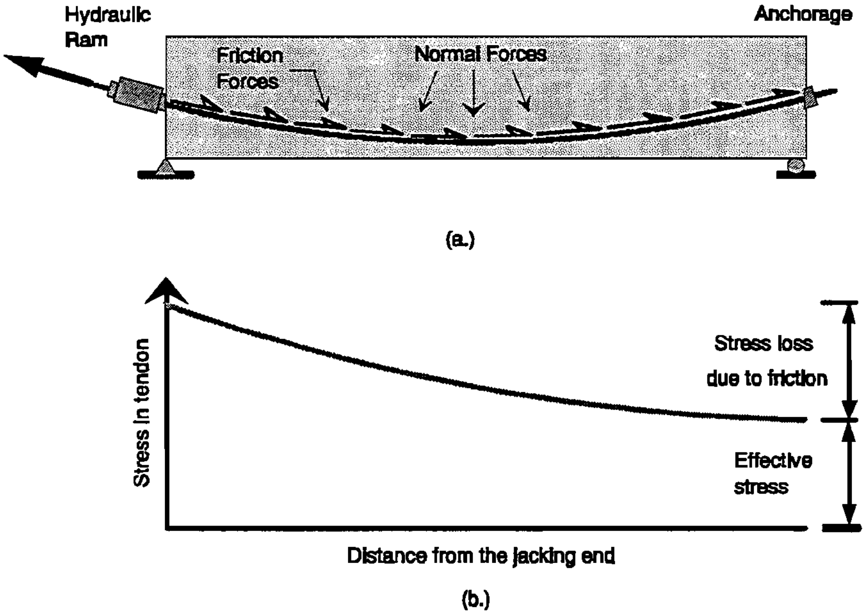


Figure 1.2 Friction during stressing of post-tensioned tendon.

Substantial research has been completed on friction during stressing of post-tensioned tendons [3,4] 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 1.2b 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 may 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.

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 sometimes been offset by lubrication of the tendon. Historically, the lubricant of choice has been some type of emulsifiable oil. The manufacturers of these oils have not developed them or marketed them for use in the post-tensioning industry. This type of lubricant has been claimed by contractors and post-tensioning suppliers 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. In addition, it is assumed that any effect of such lubricants to reduce the bond between the tendons and the grout is eliminated by flushing. This has not been verified.

1.2.2.2 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 are recommended for short-term usage and tend to be preferred over emulsifiable oils for short-term protection of the tendon after installation in the duct [5]. However, both vapor phase inhibitors and emulsifiable oils are used by strand manufacturers for protection of strand during long storage periods [6,7]. Again, there are numerous emulsifiable oils currently available but there is no test data comparing the corrosion protection offered by different oils.

1.3 Cable-Stays.

1.3.1 Description. Cable-stays are another form of a post-tensioned tendon. A cable-stay consists of a tension element anchored at both ends passing through a duct which is in open air, but usually grouted inside the duct for corrosion protection. The grout serves no direct structural purpose other than some minor increase in stiffness and damping to reduce local vibrations 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.

1.3.2 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.

1.4 Objectives.

Emulsifiable oils, soaps and powdered graphite have been used for friction reduction in post-tensioned tendons and emulsifiable oils have been used for 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 agents, an in-depth evaluation was performed. The objectives of this evaluation were to:

1. Identify emulsifiable oils, and other common agents, such as soaps and powered graphite, that could be effectively used for lubrication and/or temporary corrosion protection of seven-wire strand.

2. Evaluate the performance of these agents in small-scale corrosion, bond and friction 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 agents in post-tensioning or cable-stay applications.

1.5 Scope.

In the following chapters an evaluation of thirteen candidate agents is presented. Of these thirteen agents, ten are emulsifiable oils, one is a sodium silicate solution used only for corrosion protection, one is a soap and one is powered graphite. The latter two are used only as lubricants. The candidates 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 along with results of small-scale friction tests. 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, and recommendations for further research are given.

CHAPTER 2
STATE-OF-THE-ART AND FRICTION TESTS

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 and temporary corrosion protection of multi-strand 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 [8].

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 top four candidates were selected and used in large-scale friction tests by Tran [9]. Subsequently, two additional lubricants were added to the program by Davis [10]. Since they were not advised for corrosion protection, they were subjected to only the small-scale friction and pullout tests. They are included in this report and were used in the large-scale friction tests with the segmentally cast girder.

2.2 Background on Emulsifiable Oils.

Historically, emulsifiable oils have been the most common products used for friction reduction of post-tensioned tendons. They 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 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.

2.3 Findings from Literature Review.

2.3.1 Evaluation of Temporary Corrosion Inhibitors. Previous NCHRP research on 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 but cannot provide any lubrication during stressing.

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 (Neither of these products are currently manufactured [13]. Shell VPI No. 250 (Dichan 100) was the vapor phase inhibitor. This inhibitor is in the form of fine crystals. These crystals slowly sublime to create a vapor that prevents corrosion.

In the accelerated corrosion tests involving dipping in a 3.5% NaCl solution every 48 hours, the organic corrosion inhibitors performed best. On the average they prevented corrosion about 250% as long as the Dromus B and about 700% as long as the sodium silicate - sodium nitrite solution. The vapor phase inhibitor showed success but in a completely different, non-comparable test.

Table 2.1 Additives Commonly Used in Emulsifiable Oils (from Reference [11]).

Type Additive	Type of Compounds Used	Reasons for Use	Mechanism of Action
Anti-Oxidants or Oxidation Inhibitors	Organic compounds containing sulfur, phosphorus or nitrogen such as organic amines, sulfides, hydroxy sulfides	To prevent varnish and sludge formation on metal parts. To prevent corrosion	Decompose peroxides, inhibit free radical formation.
Oiliness, Film Strength, Extreme Pressure (E.P.) and Anti-Wear Agents	Organic compounds containing chlorine, phosphorus and sulfur such as chlorinated waxes, organic phosphates and phosphites such as tricresol phosphate and zinc dithiophosphate.	To reduce friction, prevent galling, scoring and seizure. to reduce wear.	By chemical reaction film is formed on metal contacting surfaces which has lower shear strength than base metal thereby reducing friction and preventing welding and seizure of contacting surfaces when oil film is ruptured.
Solid Fillers	Graphite, talc, clay, calcium carbonate, sodium silicate.	To prevent metal pick-up or welding.	Provide a physical spacer to prevent metal to metal contact.
Rust Preventives	Sulfonates, amines, fatty oils and certain fatty acids, oxidized wax acids, phosphates, halogenated derivatives of certain fatty acids.	To prevent rust of metal parts during shutdown periods, storage of new or shipment of new or overhauled equipment.	Preferential adsorption of polar type surface active materials on metal surface. This film repels attack of water. Neutralizing corrosive acids.
Metal Deactivators	Complex organic nitrogen and sulfur containing compounds such as certain complex amines and sulfides.	Passivate, prevent or counteract catalytic effect of metals on oxidation.	Form inactive protective film by physical or chemical adsorption or absorption. Form catalytically inactive complex with soluble or insoluble metal ions.
Stringiness and Tackiness Agents	Certain high molecular weight polymers and aluminum soaps of unsaturated fatty acids.	Increases adhesiveness of lubricant on metal surfaces, form protective coating.	Increases viscosity of lubricant and imparts adhesive and tackiness characteristics.
Emulsifiers	Certain soaps of fats and fatty acids, sulfonic acids or naphthenic acids.	Used to emulsify mineral oils with water to give coolant lubricant type fluid	Surface active chemical agents reduce interfacial tensions so oil can be dispersed in water.
Odor Control Agents	Certain oil soluble synthetic perfumes	Used to provide distinctive or pleasant odor or mask undesirable odors.	Small amounts of highly odoriferous substances impart fragrant or pleasant odor when mixed with lubricants.
Antiseptics (Bactericide or Disinfectant)	Certain alcohols, amines, aldehydes, phenols, mercuric compounds and chlorine containing compounds.	Used to control odor, metal staining, emulsion breaking in emulsion type lubricants.	Used in soluble oils to reduce or prevent growth of bacteria causing deleterious effects in emulsion lubricants.
Pour Point Depressants	Wax alkylated naphthalene or phenol and their polymers. Methacrylate polymers.	To lower pour point of lubricating oils.	Wax crystals in oils coated to prevent growth and oil absorption at reduced temperatures.
Foam Inhibitors	Silicone polymers.	To prevent formation of stable foam.	Reduces interfacial tension so small air bubbles can combine to form larger bubbles that separate faster.

The small-scale bond tests completed in that study used single 0.25" (6.4 mm) diameter prestressing wire specimens and single 0.5" (12.7 mm) diameter seven-wire strand specimens surrounded by a sand-cement mortar. 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 stressed to 7000 lbs. (31.1 kN) and held at that load while a sand-cement mortar was placed around the center section of the strand.

After curing, the strand was unloaded incrementally while the strain in the mortar block and the load in the strand were recorded. By comparing the strain in the mortar block with the load in the strand, the bond-slippage load could be determined.

For the strands coated with the sodium silicate-sodium nitrite solution the average slip load was 10% less than the bare strand. The organic coatings and the emulsifiable oil caused major reductions in bond. The 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.

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 pre-dried 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 [7]. This study used the test setup shown in Figure 2.1 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 1/4 in. wire (6.4 mm), 1/2 in. (12.7 mm) drawn strand, 0.6 in. (15.2 mm) round wire strand, and 0.7 in. (17.8 mm) drawn strand. The surface conditions were clean, rusty, and oiled. 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.

There was essentially no difference between the friction coefficients for the clean strands and the friction coefficients for the oiled strands. Results 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.

In a related study, five post-tensioned beams containing clean and lubricated post-tensioning bars were tested [7]. These quarter-point load flexural tests showed no major difference in the cracking and deflection behavior of bonded beams containing a "clean" bar and beams containing a lubricated bar that was flushed before grouting. All developed significantly more moment than an unbonded bar beam.

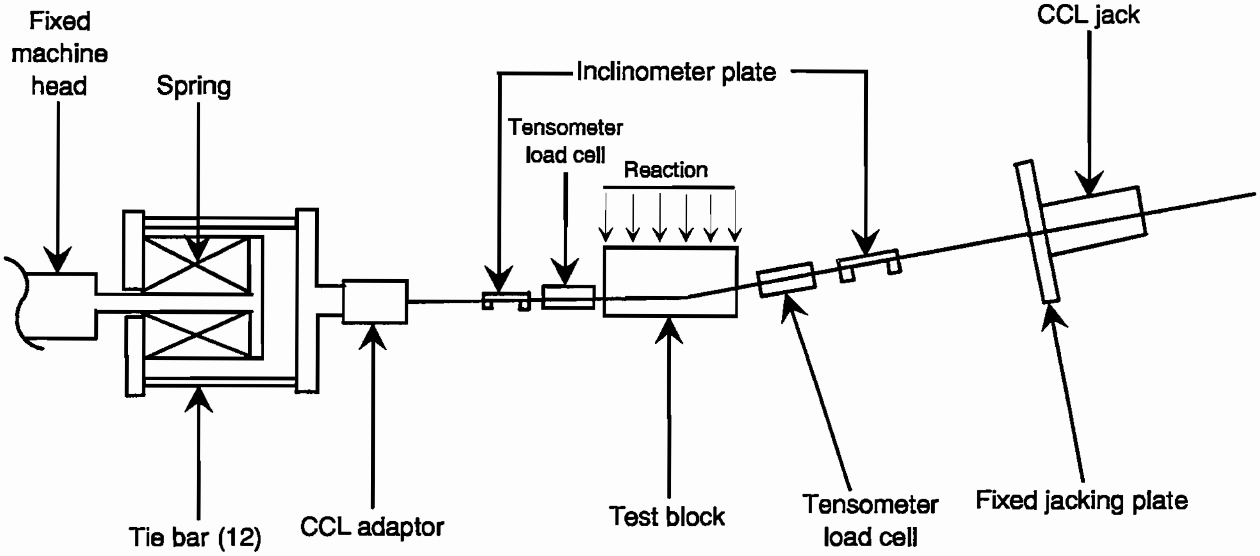


Figure 2.1 Test setup for friction tests performed by Owens and Moore (from Ref. [7]).

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.

Crack patterns and crack widths were similar for all four of the bonded beams. 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 post-tensioned parallel wire tendons by approximately 15%. However, when the same type flexible duct was used with a single large wire strand pre-formed from the wires, no reduction in friction was noted when the oil was applied [18]. In these tests four tendons, described in Table 2.2, 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.

Table 2.2 Lubricated Tendons Tested in Reference [18].

Tendon Type	Duct Type
40 - 0.25" (6.4 mm) BBRV, galvanized wires	Bright, thin wall tubing
40 - 0.25" (6.4 mm) BBRV, bright wires	Bright flexhose
1 - 11/16" (17.5 mm) diameter performed wire strand	Galvanized flexhose
1 - 11/16" (17.5 mm) diameter performed wire strand	Bright flexhose

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 preformed 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" (12.7 mm) diameter strands having an ultimate strength of 270 ksi (1860 MPa). The sheathing was a semi-rigid corrugated galvanized 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 (190 ℓ) 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 [7], 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 [7].

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 report, should 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 five methods:

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.

2.6 Candidate Lubricants Selected for Evaluation.

Table 2.3 shows the fourteen conditions that were selected as possible candidates for temporary corrosion protection and/or lubrication of prestressing steel. These include nine emulsifiable oils, one emulsifiable oil-free fluid, one soap, one sodium silicate solution, powdered graphite and bare strand as a control for comparison. These products were selected after reviewing the literature and completing the informal phone survey. The soap and the powdered graphite were not reputed to be corrosion protection agents so they were not included in the corrosion testing. The graphite was used only in full-scale friction tests to be reported in CTR Report 1264-2. The sodium silicate solution is not designed for use as a lubricant, but was also investigated 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.

Six of the thirteen agents described in Table 2.3 have been used for temporary corrosion protection and/or friction reduction of post-tensioned tendons. Two of these lubricants have 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 the corrosion protection series of this research had been completed. Aqualube MX has been used for friction reduction and thus was included in friction and bond tests. The other three lubricants have been used for temporary corrosion protection of prestressing steel during storage [6, 7, 19]. None of the latter three lubricants were used in this study.

2.7 Small-Scale Friction Tests.

As part of the overall lubricant evaluation, small-scale friction tests were performed to compare the relative lubrication properties of twelve of the products (graphite was used only in the full-scale tests). 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.

2.7.1 Procedures. The test setup used for the small-scale friction tests is shown in Figure 2.2. A single 1/2" (12.7 mm) diameter seven-wire strand was positioned between two concrete blocks. Each concrete block contained a 1.25" (32 mm) x 12" (305 mm) strip of galvanized steel

Table 2.3 Products or Conditions Selected for Evaluation

Lubricant	Description of Lubricant and Reasons for Selection
L1 - Visconorust 8415E Formerly manufactured by Viscosity Oil Co.	Emulsifiable oil marketed for temporary corrosion protection of post-tensioned tendons before grouting. Documented use as a corrosion inhibitor for cable-stays in cable-stay bridge. Recognized by several of the contacts in phone survey as a product that has been used for temporary corrosion protection of post-tensioned tendons or cable-stays in several projects in the United States. This oil is no longer manufactured.
L2 - Dromus B Manufactured by Shell Oil Co.	Emulsifiable oil designed for use as coolant-lubricant and rust preventative in metalworking operations. Has been used for temporary corrosion protection and friction reduction in post-tensioning projects in the United States and Europe. According to former manufacturer of Lubricant L1, this lubricant is very similar to L1. Used in previous research concerning temporary corrosion protection and friction reduction of post-tensioned tendons. Also used in research to study behavior of a post-tensioned beam containing a single lubricated tendon.
L3 - Unocal 10 Manufactured by Union 76	Emulsifiable oil designed for use a coolant-lubricant and rust preventative in metalworking operations. Also used for corrosion protection in hydraulic systems when water is used as the coolant. Has been used as a lubricant to reduce friction in post-tensioned tendon in concrete segmental bridge.
L4 - Unocal MS Manufactured by Union 76	Emulsifiable oil designed for use as coolant-lubricant and rust preventative in metalworking operations. Also used for corrosion protection in hydraulic systems when water is used as the coolant. Same manufacturer as Lubricant L3. Recommended by manufacturer because it supposedly offers slightly better corrosion protection than L3.
L5 - Texaco Soluble D Manufactured by Texaco Oil Co.	Emulsifiable oil designed for light machining where very lean emulsions are required. Provides good lubricity and corrosion protection. Selected from literature provided by manufacturer.
L6 - Rust-veto FB-20 Manufactured by E.F. Houghton and Co.	Emulsifiable oil designed for temporary corrosion protection of metals. Can provide corrosion protection on plain carbon or low alloy steel for six months to one year indoors. Length of protection depends on storage conditions and emulsion concentration. Recommended by manufacturer because of its corrosion protection properties.
L7 - Hocut 737 Manufactured by E.F. Houghton and Co.	Emulsifiable oil designed for use as coolant-lubricant in metalworking operations. Can be used on variety of machines and a variety of metals. Provides corrosion protection during metalworking operations. Recommended by manufacturer because of its lubrication properties. Same manufacturer as Lubricant L6.
L8 - Hocut 4284 Manufactured by E.F. Houghton and Co.	Heavy-duty, oil-free synthetic coolant designed for machining and grinding of aluminum alloys, as well as heavy duty ferrous applications. Provides corrosion protection during metalworking operations. Recommended by manufacturer because of its lubrication properties and because it contains no oil. Same manufacturer as Lubricants L6 and L7.
L9 - Nalco 6667 Manufactured by Nalco Chemical Co.	Emulsifiable oil designed for heavy drawing of ferrous metals. Recommended by manufacturer because of its corrosion protection and lubrications properties.
L10- Sodium silicate "N" Manufactured by the PQ Corporation	Sodium silicate solution designed for use in several types of industries. These industries include ceramics, building products, detergents, and water treatment. In these industries Lubricant L10 can function as a binder, adhesive, buffer, or corrosion inhibitor. Used in previous research concerning temporary corrosion protection of prestressing steel.
L11- Wright 502 Manufactured by Wright Oil Co.	Emulsifiable oil designed for metal working operations. Has been used as a lubricant to reduce friction in tendons of concrete segmental bridge.
L12- Bare Strand	Bare strand with no lubricant was used as a control for comparison.
L13- Aqualube MX Manufactured by Dura-chem Inc.	Water soluble coolant designed for cutting and grinding use on a variety of metals. This biodegradable soap is formulated to provide maximum lubrication performance, be safe to personnel and to provide corrosion resistance in its undiluted form.
L14- Graphite Flakes #2	Dry lubricant used as an additive in other lubricants to reduce friction between mechanical parts.

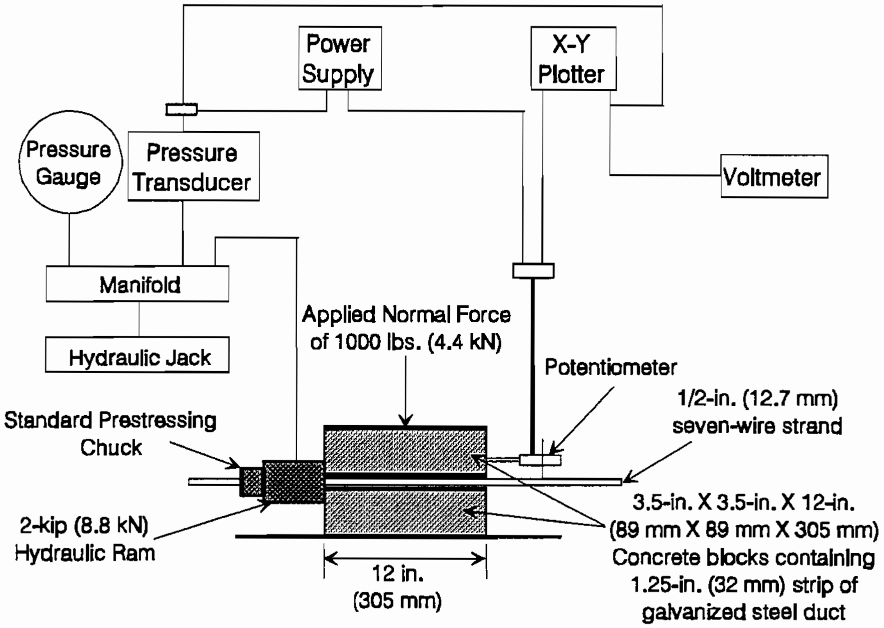


Figure 2.2 Setup for small-scale friction tests

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. (4.4 kN) was applied to the top block by a 60 kip (267 kN) 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 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" (32 mm) x 12" (305 mm) 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 Figure 2.3. 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.

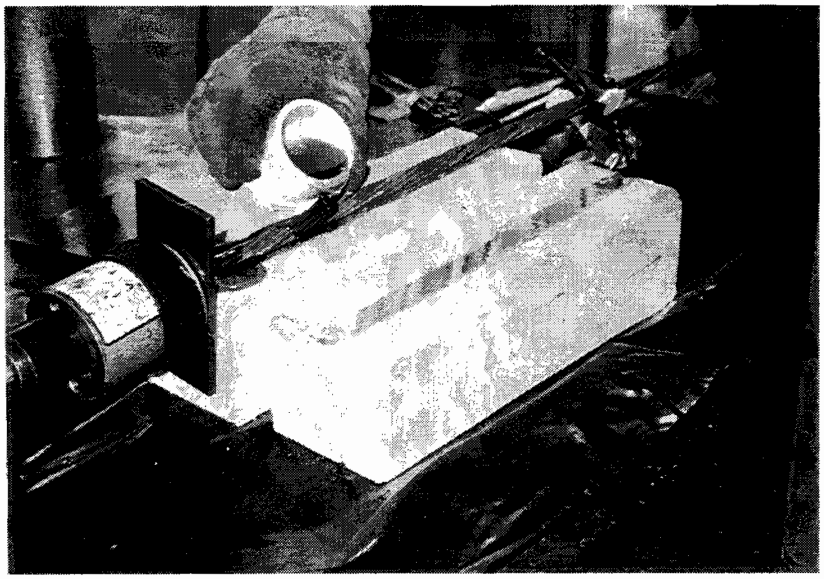
2.7.2 Results. Figure 2.4 shows typical results for one pair of blocks. The top two curves represent the data for two pulls of the same bare strand. The bottom two curves represent the data for two pulls of the same bare strand, after the strand had been lubricated with Lubricant L8. The average load at 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 2.4 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.

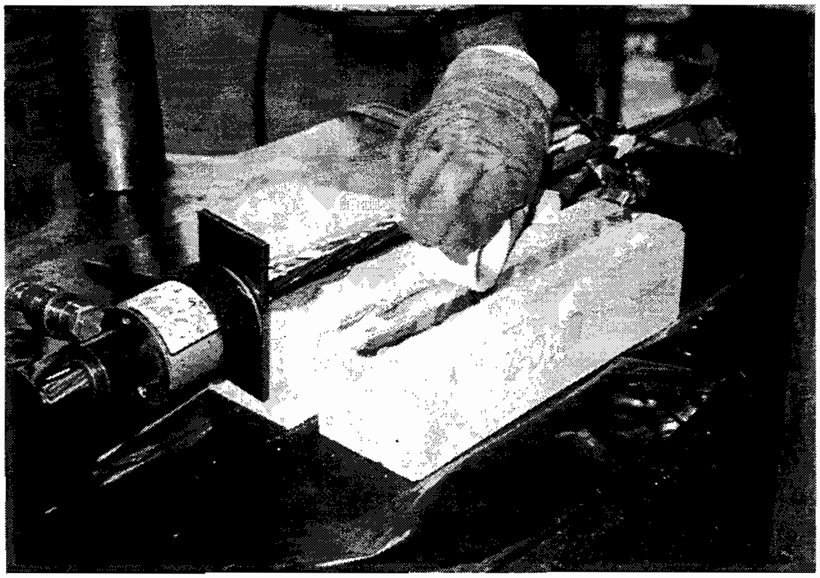
The "dynamic" load for each pull was obtained by using the loads at the first three "peaks" after the strand began to pull through the blocks. Typical "peaks" are marked with circles in Figure 2.4. An average "dynamic" load for each pull was determined by calculating the average of the three "peak" loads. 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 2.4 and 2.5 show the average static and dynamic friction factors for the bare and lubricated strands for each lubricant and each pair of blocks. The agents are in descending order according to their average friction reduction.

As indicated by Tables 2.4 and 2.5 the amount of friction reduction varied depending on the lubricant. For static friction the "ideal" reduction with Teflon was 61 percent. Reductions with candidate lubricants varied from 27% to -31%. For dynamic friction the reductions varied from



(a) Lower block



(b) Upper block

Figure 2.3 Lubrication of Strand for Small-Scale friction Tests.

14% to -26%. 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 used as a corrosion protection agent 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 was possibly due to duct grooving with the lubricants acting somewhat as cutting agents.

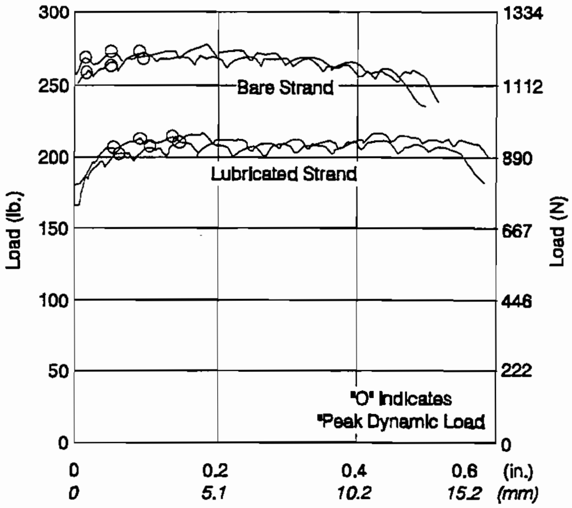


Figure 2.4 Typical results from small-scale friction tests.

The results of the current small-scale friction tests 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 current tests did agree somewhat with preliminary findings from large-scale friction tests performed by Tran at the University of Texas at Austin [9]. Tran's preliminary results showed average friction reductions of 10%, 16%, 18%, and 23% for L2, L8, L5, and L11 respectively. The 80' (24.4 m) lubricated tendons used in Tran's tests consisted of seven, 1/2" (12.7 mm) diameter seven-wire strands in a 2" (5.1 mm) diameter corrugated galvanized steel duct. Final results will be given in CTR Report 1264-2.

The average static and dynamic friction reductions shown in Tables 2.4 and 2.5 for each of the lubricants were used in the overall lubricant evaluation reported in Chapter 7.

Coefficients of friction, both static and dynamic, for unlubricated strand on galvanized duct are 0.25 or larger. This is somewhat higher than what is actually seen in the field in draped ducts, and corresponds to the upper limit of the curvature coefficient of friction recommended by AASHTO. In all cases, visual inspection showed that the strand cut into the duct surfaces and essentially screwed itself out of the specimen under the ram load. Coefficients of friction for each block could be consistently obtained with little scatter for about five test repetitions. Coefficients of friction for additional tests were larger. This behavior can be attributed to removal of the galvanization, and continued deeper grooving of the duct surfaces.

Lubricants tested either decreased the coefficients of friction or increased them. The greatest decrease in dynamic coefficient of friction was 0.035. This related to a 14% decrease in ram load needed to keep the strand moving steadily through the specimen. Static coefficients of friction were smaller than the dynamic coefficients of friction when lubricants were used. The overall reduction in static friction of 27% for L5 approached friction reduction seen by Dywidag [19] in field tests in draped ducts with lubricants L13 (35%) and L2 (28%). Several lubricants acted like cutting

Table 2.4 Static Coefficient of Friction from Small-Scale Specimens.

Lubricant		Static Friction Factor[1]		Percent Reduction in Friction	Average %
		Bare	Lubricated		
Teflon	(1)	0.31	0.12	61	61
L5	(1)	0.26	0.19	27	27
L5	(2)	0.25	0.18	28	
L11	(1)	0.26	0.20	23	21
L11	(2)	0.27	0.22	18	
L13	(1)	0.23	0.21	11	19
L13	(2)	0.30	0.22	26	
L8	(1)	0.25	0.18	28	18
L8	(2)	0.24	0.22	8	
L1	(1)	0.26	0.22	15	17
L1	(2)	0.26	0.21	15	
L2	(1)	0.26	0.22	15	17
L2	(2)	0.27	0.22	18	
L4	(1)	0.26	0.23	11	14
L4	(2)	0.23	0.19	17	
L3	(1)	0.27	0.23	15	14
L3	(2)	0.24	0.21	12	
L9	(1)	0.27	0.23	15	12
L9	(2)	0.24	0.22	8	
L6	(1)	0.25	0.25	0	0
L6	(2)	0.25	0.25	0	
L7	(1)	0.26	0.26	0	-9
L7	(2)	0.22	0.26	-18[2]	
L10	(1)	0.27	0.36	-33	-31
L10	(2)	0.28	0.36	-29	

[1] Force, required to extract strand from specimen by normal force. "Static" indicates friction values for initial slip of strand.

[2] Indicates an increase in friction with strand lubricated with oil.

Table 2.5 Dynamic Coefficients of Friction from Small-Scale Specimens.

Lubricant		Dynamic Friction Factor[1]		Percent Reduction in Friction	Average %
		Bare	Lubricated		
Teflon	(1)	0.31	0.13	58	58
L5	(1)	0.25	0.21	16	14
L5	(2)	0.24	0.21	13	
L11	(1)	0.25	0.21	16	14
L11	(2)	0.26	0.23	11	
L13	(1)	0.26	0.25	6.0	13
L13	(2)	0.32	0.26	20	
L8	(1)	0.25	0.23	8.0	10
L8	(2)	0.25	0.22	12	
L1	(1)	0.24	0.23	4.2	6.1
L1	(2)	0.25	0.23	8	
L2	(1)	0.25	0.24	4.0	5.9
L2	(2)	0.26	0.24	7.7	
L4	(1)	0.26	0.25	3.8	6.0
L4	(2)	0.24	0.22	8.3	
L3	(1)	0.25	0.24	4.0	6.0
L3	(2)	0.25	0.23	8.0	
L9	(1)	0.26	0.25	3.8	1.9
L9	(2)	0.25	0.25	0	
L6	(1)	0.26	0.27	-3.8[2]	-6.1
L6	(2)	0.24	0.26	-8.3	
L7	(1)	0.24	0.26	-4.2	-6.3
L7	(2)	0.24	0.26	-4.2	
L10	(1)	0.26	0.31	-19	-26
L10	(2)	0.25	0.33	-32	

[1] Force, required to extract strand from specimen by normal force. "Dynamic" indicates friction values for steady movement of the strand.

[2] Indicates an increase in friction with strand lubricated with oil.

agents and actually increased friction by increasing duct grooving. Duct grooves on the small-scale friction specimen are shown in Figure 2.5.

Many of the water soluble lubricants were difficult to remove from the strand and duct surface. Emulsification of the oil by rinsing alone proved ineffective. Some of the lubricants were retested in the small-scale friction test specimen after they had apparently been flushed from the duct surfaces with a prolonged stream of water. The friction reduction seen after flushing was similar to that of the fully lubricated test. The results of the flushed test are shown in Figure 2.6. This behavior can be attributed to residual traces of lubricant remaining on the duct surface, and the removal of dirt and grit of flushing. Overall the effectiveness of lubricants tested was marginal to poor.

Figure 2.5 Small-scale friction test duct grooving.

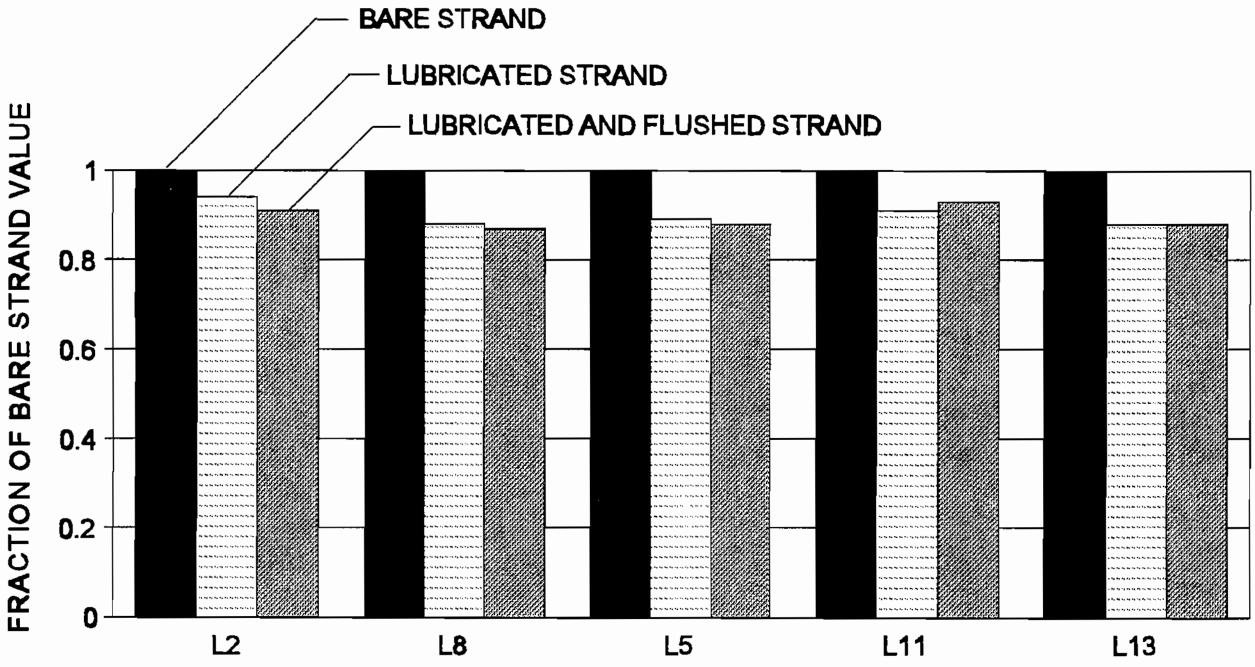


Figure 2.6 Small-scale friction test results - flushed.

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 eleven of the lubricants in two accelerated corrosive environments. In these tests small prestressing wire specimens were coated with each of 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 at least three days of immersion.

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 [20]. In this process iron from the steel is oxidized to ferrous ions:

$$Fe \longrightarrow Fe^{2+} \quad 2e \quad \textit{(oxidation of iron)}$$

While oxygen is reduced to hydroxyl ions:

$$O_2 + 2H_2O + 4e- \longrightarrow 4OH- \qquad \textit{(Reduction of oxygen)}$$

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

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

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

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

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, $Fe \rightarrow Fe^{2+} + 2e-$ has a potential of -0.44 V with respect to the standard hydrogen electrode, while $O_2 + 2H_2O + 4e- \rightarrow 4OH-$ 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 $Fe \rightarrow Fe^{2+} + 2e-$.

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.

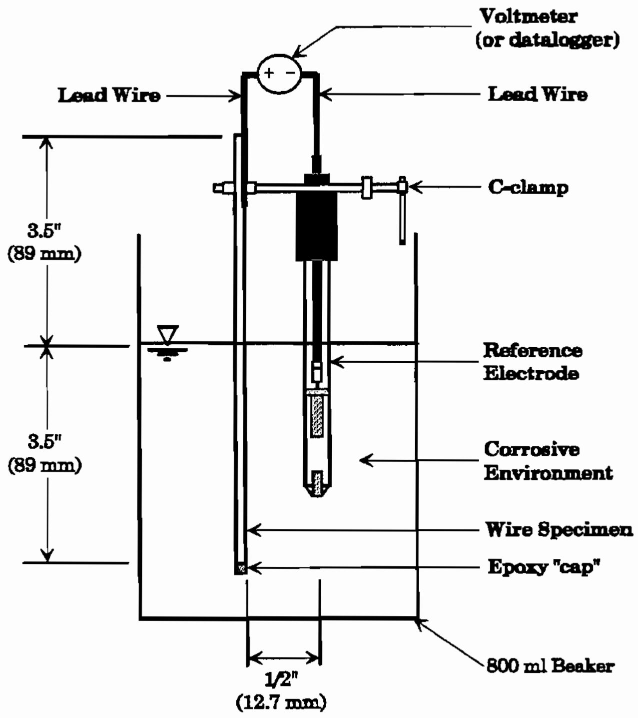


Figure 3.1 Mixed potential test setup for accelerated wire corrosion tests.

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

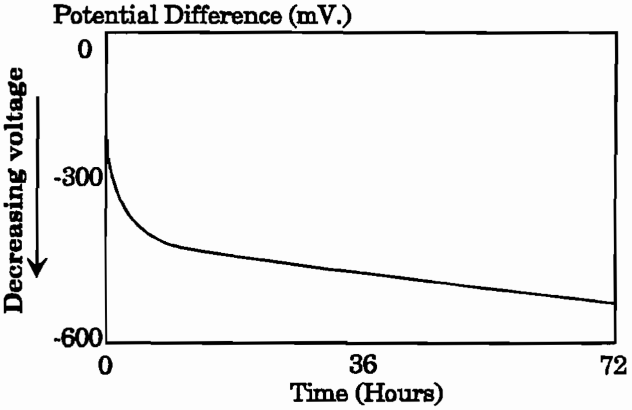


Figure 3.2 Potential difference data for bare wire immersed in deionized water.

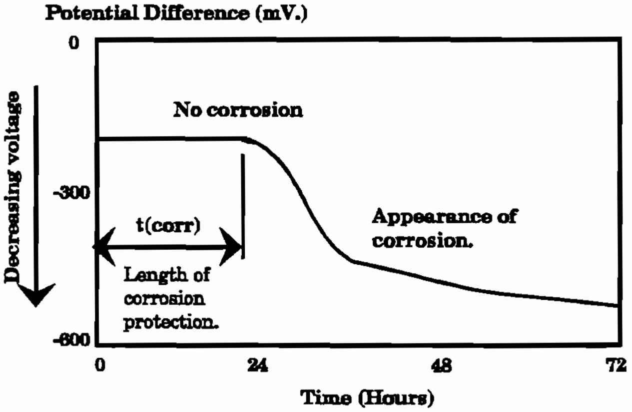


Figure 3.3 Idealized results for lubricated wire immersed in deionized water.

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 20.

This study recognizes that mixed-potential data has not previously been used in this manner, but seems very useful in the current test setup since 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" (3.96 mm) were used in the accelerated wire corrosion tests. These wires were outside wires obtained by untwisting 7" (178 mm) strand samples cut from two reels of 1/2" (12.7 mm) diameter, Grade 270 (1860) 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. All of the wires tested in the accelerated wire corrosion tests were from R1 except for the two 7" (178 mm) 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 [6]. It should also be mentioned that the strand from R1 was approximately two years old,

Table 3.1 Wire Specimens Tested in Accelerated Wire Corrosion Tests.

Lubricant	Number of Wires Tested in Deionized Water.	Number of Wires Tested in 3.5% NaCl Solution.
L1	2	2
L2	2	2
L3	2	2
L4	2	2
L5	2	2
L6	2	2
L7	2	2
L8	2	2
L9	2	2
L10	2	2
L11	2	2
Bare	2	2
Totals	24	24

Table 3.2 Additional Wires Tested in Accelerated Wire Corrosion Tests.

Lubricant	Description of specimen and test
L4	One 3 1/2" (89 mm) wire specimen totally submersed in deionized water for three days.
L4	One 3 1/2" (89 mm) wire specimen totally submersed in deionized water for three days. During this time air was bubbled into the water.
Bare	Two 7" (178 mm) wire specimens from second reel of strand immersed in 3.5% NaCl solution for three days.
Totals	4

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 testing.

Table 3.3 Strand Properties Reported by Manufacturer.

	R1 (Reel 1)	R2 (Reel 2) Stearate Soap Present on this Strand.
Ultimate Breaking Strength	43,000 lb. (191 kN)	43,505 lb. (194 kN)
Load at 1% Extension	40,500 lb. (180 kN)	40,447 lb. (180 kN)
Ultimate Elongation	4.95%	5.09%
Area	0.153 in^2. (99 mm^2)	0.153 in^2. (99 mm^2)
Modulus of Elasticity	28,200,000 psi. (194 GPa)	28,600,000 psi. (197 GPa)

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. After lubrication the wires were left undisturbed for twenty-four hours on a "drying rack" to "cure" before immersion into the corrosive environment.

3.6 Test Setup.

The overall test setup is shown in Figure 3.4. 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 which 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 half of the 7" (178 mm) length of the wire specimens were immersed into the corrosive environment. The wires were positioned approximately 1/2" (12.7 mm) away from the tip of the reference electrode.

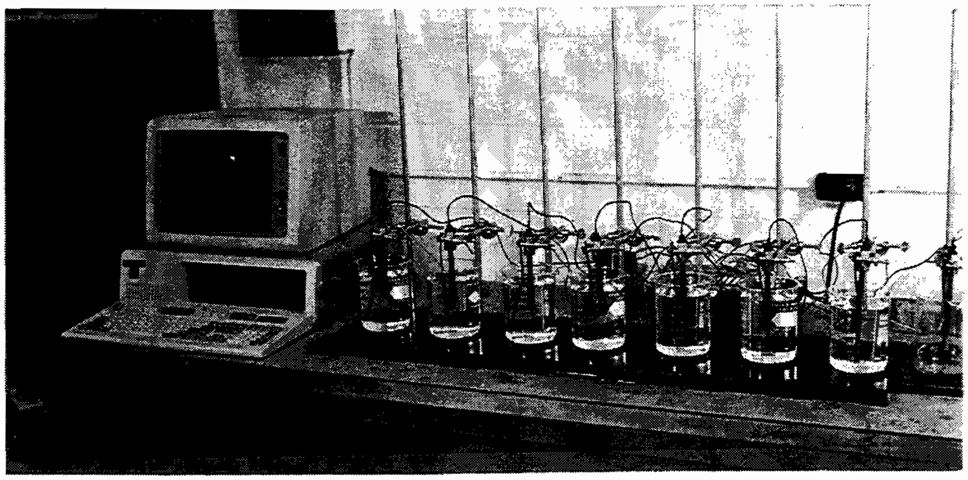


Figure 3.4 Test setup used for accelerated wire corrosion tests.

3.7 Instrumentation.

3.7.1 Reference Electrodes. A saturated calomel reference electrode was used to measure E_{corr}. This electrode, which has a 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. E_{corr} measurements were recorded by a datalogger and then downloaded to a personal computer for analysis.

3.8 Test Procedure.

The test procedure consisted of immersing the bare and lubricated 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. The data that was generally plotted consisted of the readings taken at 0, 1, 3, 5, and 60 minutes followed by readings at 120 minute intervals.

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. Supplementary painted wires were used as visual references to compare the amount of corrosion present on the wire specimens.

3.9 Results.

Figure 3.5 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, 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. For example, 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

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

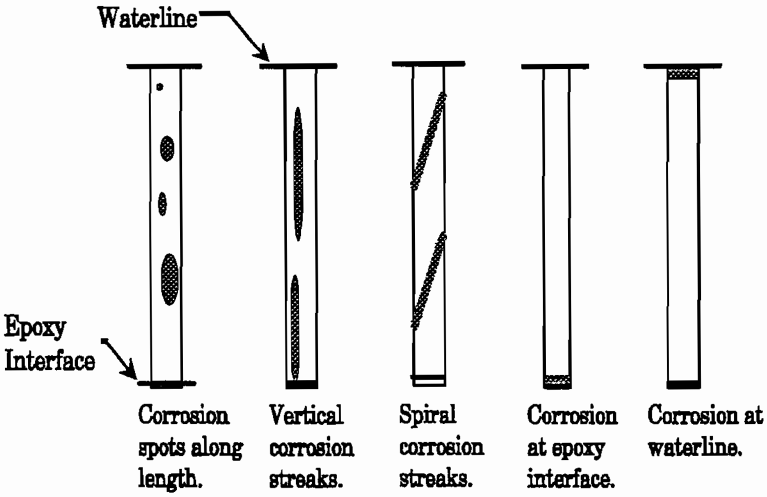


Figure 3.5 Five patterns of corrosion observed during accelerated wire corrosion tests.

(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.

Table 3.4 Typical Visual Observations for Wire Specimens in Accelerated Wire Corrosion Tests.

Specimen	24 Hours	48 Hours	72 Hours
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.

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 reported in Tables A.1 through A.4 in Appendix A of Ref. 21.

Figure 3.6 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

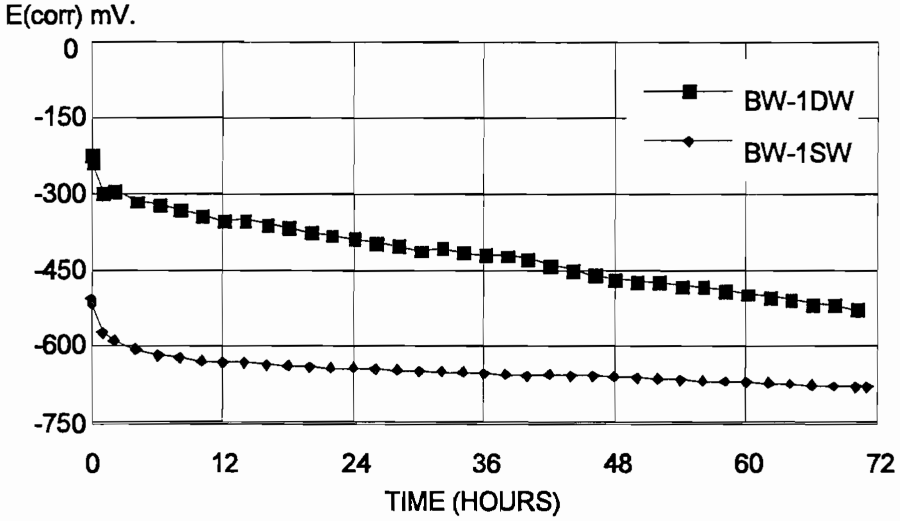


Figure 3.6 Typical E_{corr} data for bare wire specimens.

their 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 3.7 shows the 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 3.8 through 3.11. 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.

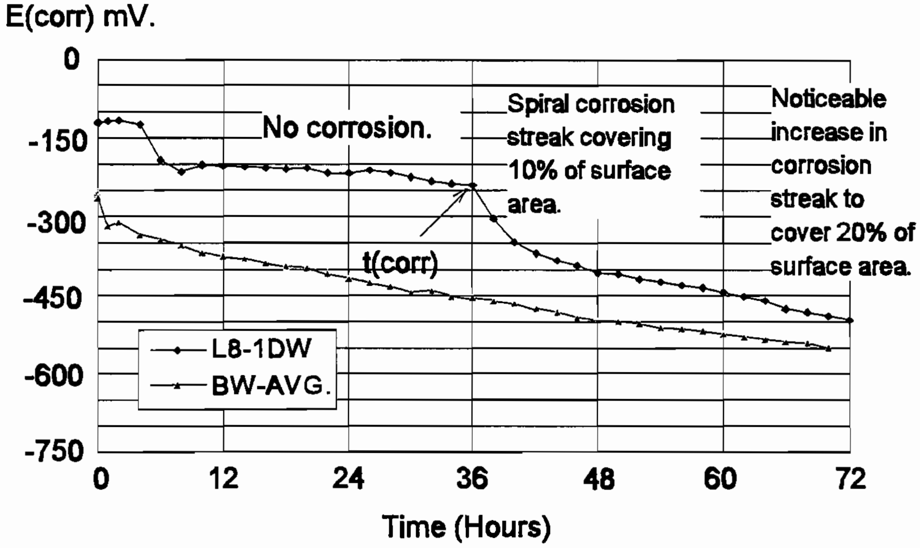


Figure 3.7 Edata and visual observations for L8-1DW.

Figure 3.8 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 of Ref. 21.

Figure 3.9 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. No explanation can be offered for the several sharp dips in Figures 3.8 and 3.9.

E_{corr} results were noticeably different when the 3.5% NaCl solution was used for the corrosive environment. Figures 3.10 and 3.11 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

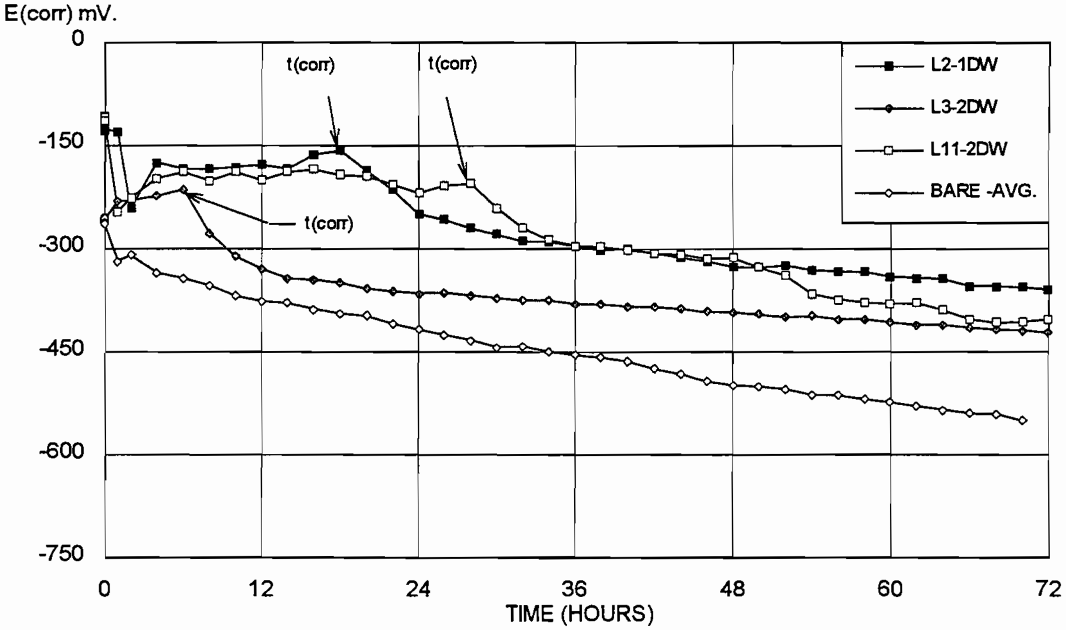


Figure 3.8 Typical E_{corr} data in deionized water where t_{corr} values could be determined.

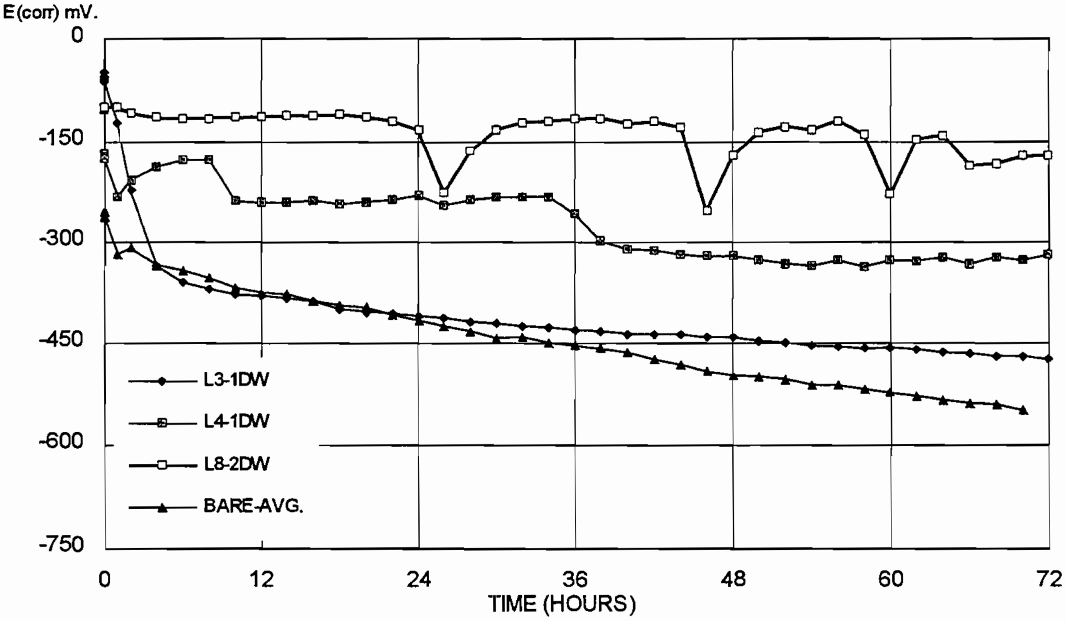


Figure 3.9 Typical E_{corr} data in deionized water where t_{corr} values could not be determined.

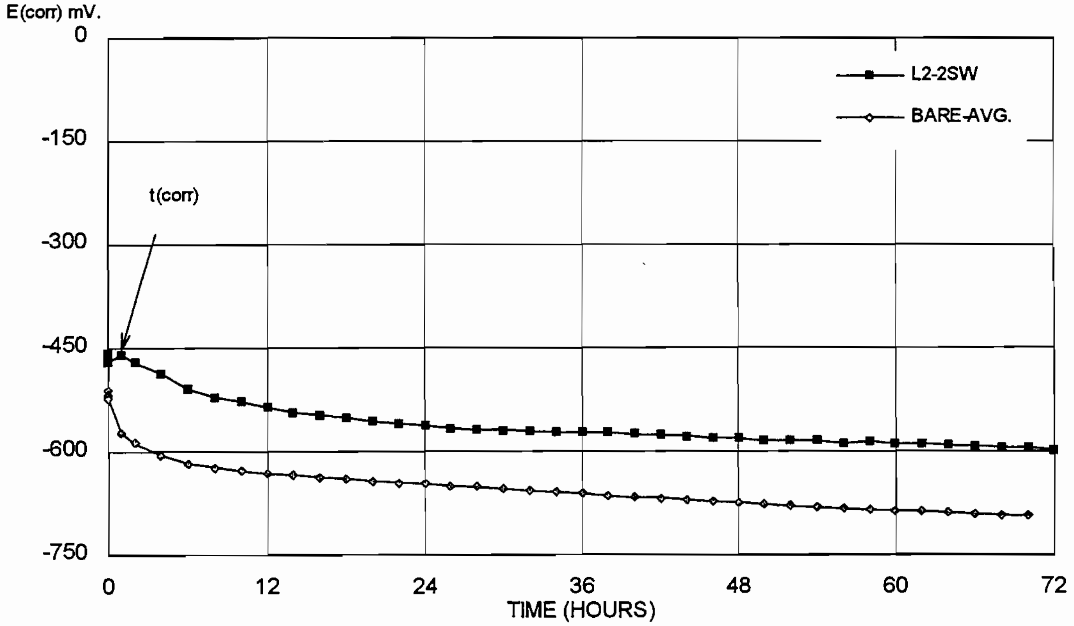


Figure 3.10 Typical E_{corr} data in 3.5% NaCl solution where t_{corr} values could be determined.

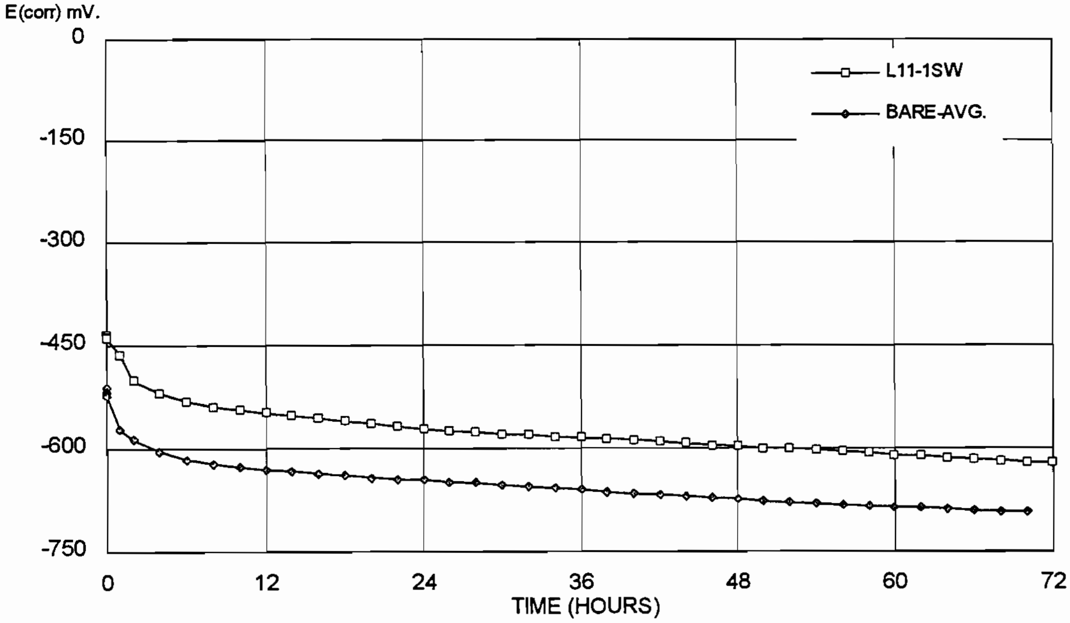


Figure 3.11 Typical E_{corr} data in 3.5% NaCl solution where t_{corr} values could not be determined.

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 3.12 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 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.

Table 3.5 Percent Corrosion on Wire Specimens after Three Days in Deionized Water.

Specimen	t(corr) (Hours)*	% Corrosion after 3 days.**	Average Corrosion (%)
L5 - 1DW	42	0	0
L5 - 2DW	68	0	
L9 - 1DW	-----	0	0
L9 - 2DW	-----	0	
L6 - 1DW	6	1	0.5
L6 - 2DW	-----	0	
L4 - 1DW	34	1	0.5
L4 - 2DW	-----	0	
L11 - 1DW	34	0	1
L11 - 2DW	28	2	
L7 - 1DW	14	1	2
L7 - 2DW	32	3	
L2 - 1DW	18	0	3.5
L2 - 2DW	-----	7	
L3 - 1DW	-----	15	10
L3 - 2DW	6	5	
L8 - 1DW	36	20	10
L8 - 2DW	-----	0	
L10 - 1DW	-----	20	15
L10 - 2DW	-----	10	
L1 - 1DW	-----	35	30
L1 - 2DW	-----	25	
BW - 1DW	-----	50	55
BW - 2DW	-----	60	

* "-----" indicates t(corr) could not be determined.

**Corrosion < 10% was estimated to nearest 1% while corrosion >, = 10% was estimated to nearest 5%.

Table 3.6 Percent Corrosion on Wire Specimens after Three Days in 3.5% NaCl Solution.

Specimen	t(corr) (Hours)*	% Corrosion after 3 days.**	Average Corrosion (%)
L9 - 1SW	-----	0	0
L9 - 2SW	-----	0	
L3 - 1SW	-----	1	1
L3 - 2SW	6	1	
L6 - 1SW	-----	4	2.5
L6 - 2SW	14	1	
L7 - 1SW	1	5	3
L7 - 2SW	-----	1	
L4 - 1SW	4	10	6
L4 - 2SW	-----	2	
L5 - 1SW	1	7	6
L5 - 2SW	1	5	
L2 - 1SW	-----	5	7.5
L2 - 2SW	-----	10	
L11 - 1SW	4	15	12.5
L11 - 2SW	14	10	
L8 - 1SW	-----	20	15
L8 - 2SW	-----	10	
L10 - 1SW	-----	25	32.5
L10 - 2SW	-----	40	
L1 - 1SW	-----	25	32.5
L1 - 2SW	-----	40	
BW - 1SW	-----	50	60
BW - 2SW	-----	70	

* "-----" indicates t(corr) could not be determined.

**Corrosion < 10% was estimated to nearest 1% while corrosion >, = 10% was estimated to nearest 5%.

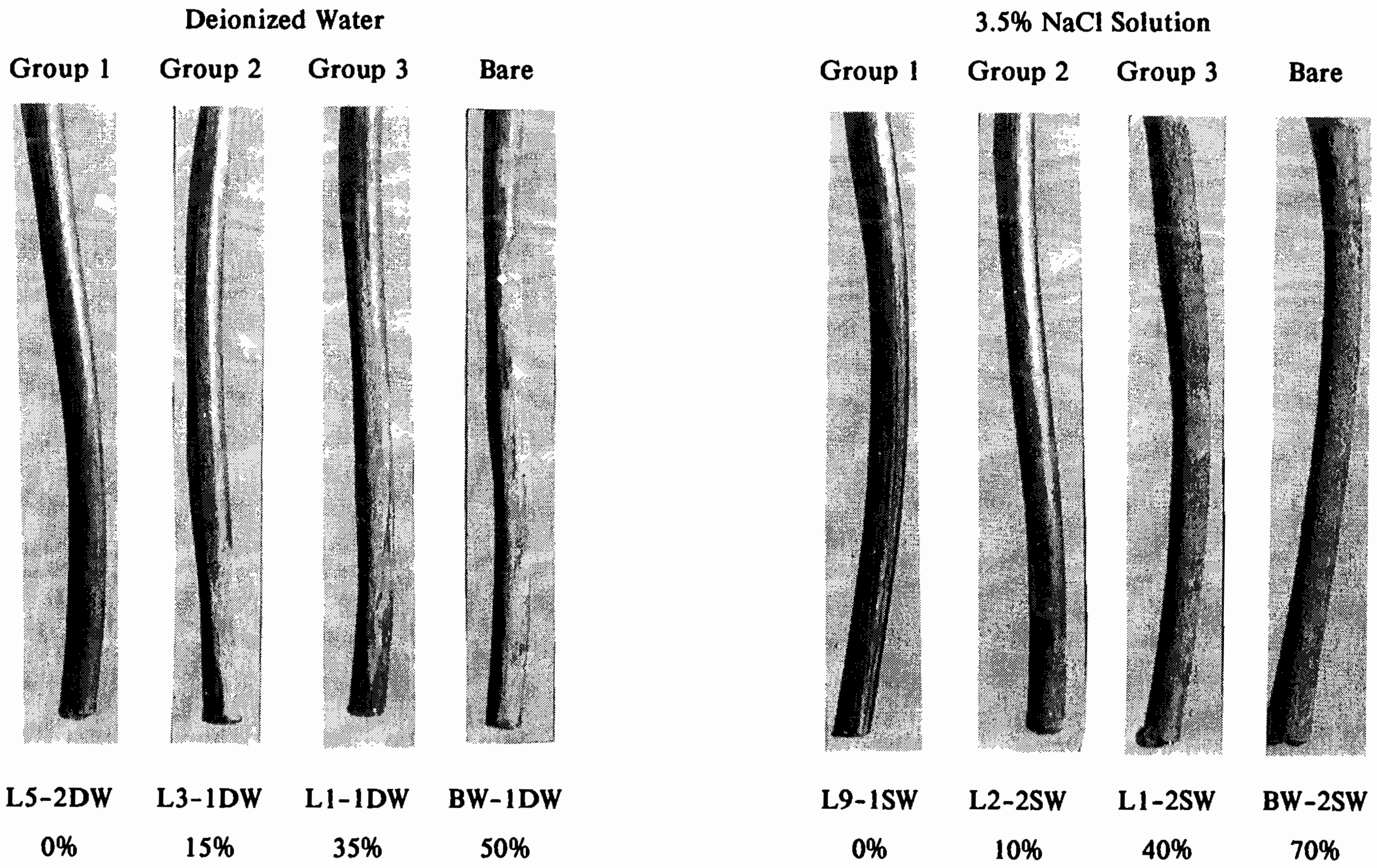


Figure 3.12 Sample wires at conclusion of accelerated wire corrosion tests.

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].

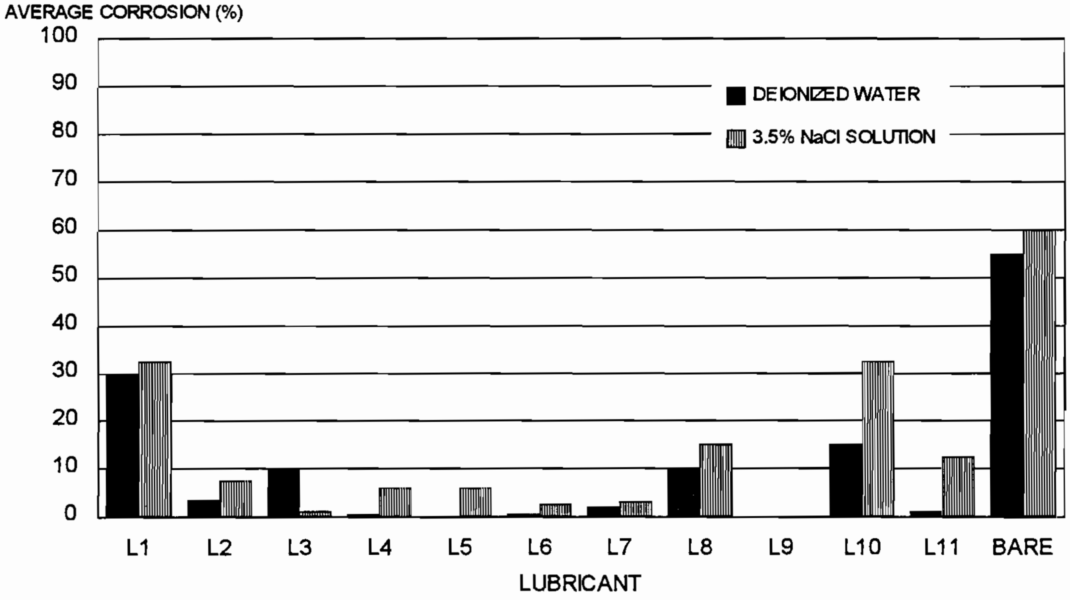


Figure 3.13 Lubricant performances in deionized water and 3.5% NaCl solution.

Figure 3.13 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 3.13 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.

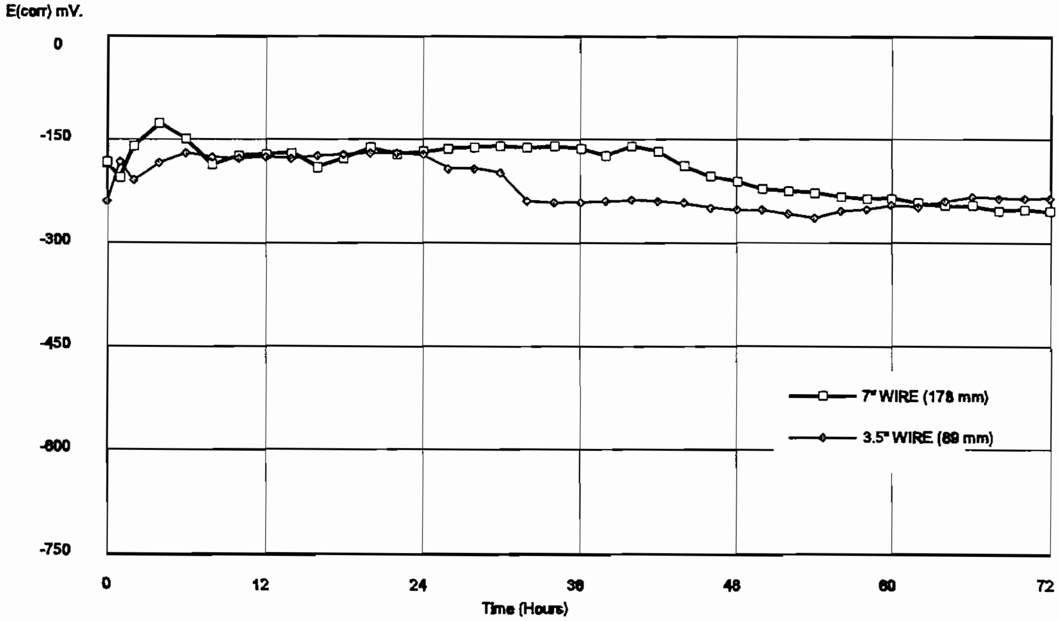


Figure 3.14 E_{corr} data for 3.5-in. (89 mm) and 7-in. (178 mm) wire specimens.

3.10 Comparison of Wires from Different Reels.

For the two additional tests that used bare wire specimens from R2 (Reel 2), seven-inch (178 mm) 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 effect 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 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. Theoretically, 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 prevent introduction of differential rates of corrosion. To determine if this change in setup would affect the E_{corr} readings an additional test using a 3.5" (89 mm) 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" (89 mm) length was equivalent to the length of wire that was immersed for the 7" (178 mm) long specimens. As shown in Figure 3.14 the E_{corr} data for the 3.5" (89 mm) specimen was similar to the E_{corr} data for the 7" (178 mm) 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 effect of the lubricants on the corrosivity of the deionized water environment another 3.5" (89 mm) 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 probably not affected by the presence of lubricant in the water.

Figure 3.15 shows the E_{corr} data for this test along with the data from the 3.5" (89 mm) lubricated wire, which did not have air bubbled into its environment. 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.

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

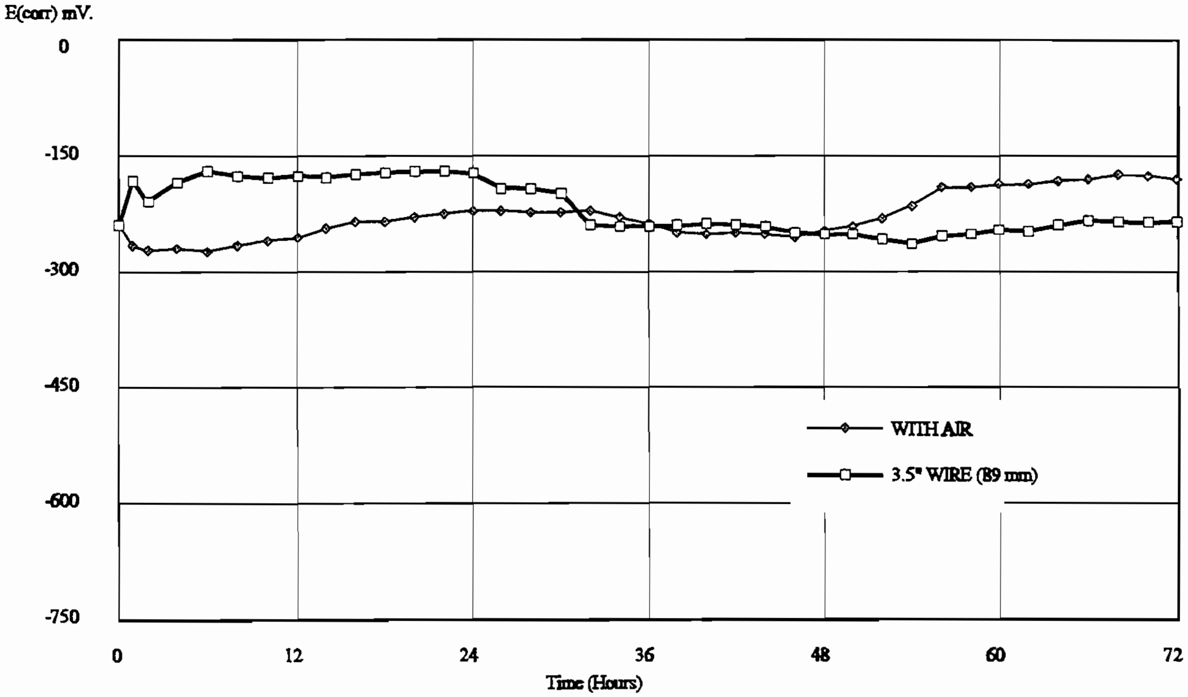


Figure 3.15 E_{corr} data for lubricated wires with and without air.

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 3.7. 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.

The test setup as used worked well. From a more theoretical basis, it might be possible to improve the test setup used for the accelerated wire corrosion tests by totally submersing the wire specimens 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 should 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. Lack of these provisions did not cause significant problem in the current tests, but their usage should improve repeatability if large numbers of tests are run.

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" (89 mm) 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" (89 mm) 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" (89 mm) 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. 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. 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 considered to be more thorough than flushing procedures in the field where a stream of water is pumped through the duct. The procedure in this study 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.

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 (21 C) to 102 F (39 C) with 85 F (29 C) being the average daily temperature. During the sixty-eight days of the separate exposure test, five inches (127 mm) of rain were recorded. The temperature during this period varied from 47 F (8 C) to 98 F (37 C) with 77 F (25 C) being the average daily temperature[23].

4.6.2 Wetting Cycle. A garden hose 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 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.

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" (1.6 mm) 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" (89 mm) long compared to the 15" (381 mm) 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" (1.6 mm) 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. 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.

Labelling System for Unflushed and Flushed Specimens

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)

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 given in Tables B.1 through B.4 in Appendix B of Ref. 21.

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

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

Specimen	Observations
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.

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 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 4.1. 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 4.1 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 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 4.1) was probably due to the nature of this lubricant. L10 is a sodium silicate solution that dries to form a clear, glassy

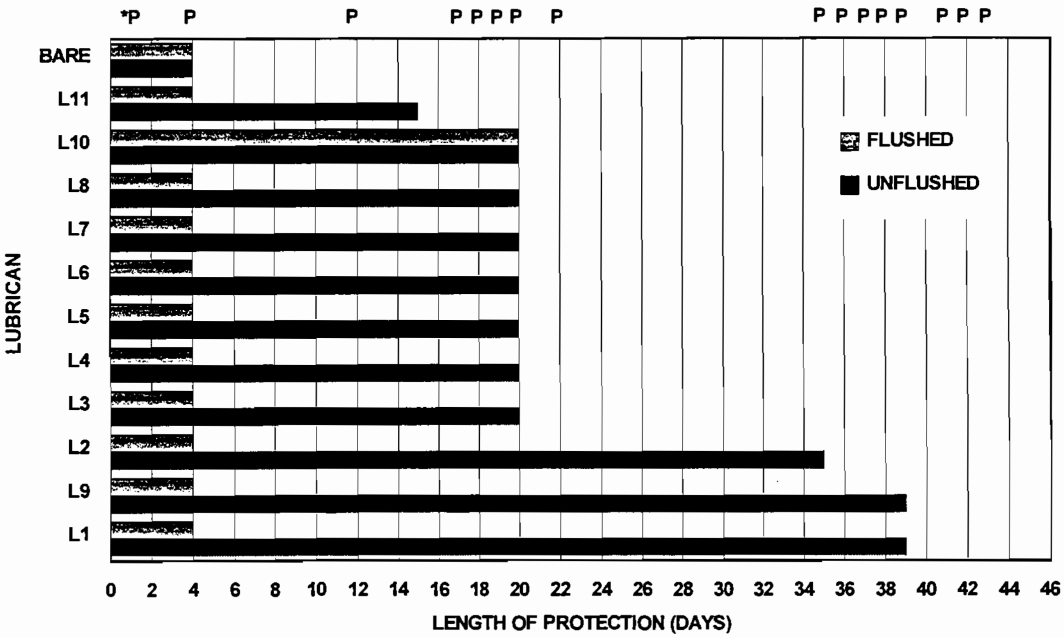


Figure 4.1 Length of corrosion protection offered by unflushed and flushed lubricants.

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

Figure 4.2 L10-F at conclusion of exposure tests.

interstices of both the unflushed and flushed strands as shown in Figure 4.2, 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.

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.

Table 4.2 Corrosion Rate Data for Bare and Unflushed Strands.

Specimen	% Corrosion at 46 Days.	Time of initial corrosion. (Days)	Corrosion Rate. (% / Day)
L1-UF	15	39	2.14
L9-UF	15	39	2.14
L6-UF	35	20 (35)	3.18
L11-UF	40	--------	1.14
L2-UF	50	35	4.54
L4-UF	50	20 (28)	2.78
L5-UF	50	20 (28)	2.78
L3-UF	60	20 (28)	3.33
L10-UF	95	20	3.65
L7-UF	100 (at 35 days)	20	6.67
L8-UF	100 (at 43 days)	20	4.35
Bare Strand	100 (at 26 days)	4	4.54

Table 4.3 Corrosion Rate Data for Bare and Flushed Strands.

Specimen	Time of initial corrosion. (Days)	Day of 100% corrosion.	Corrosion Rate. (% / Day)
L10-F	20	46 (90% Corrosion)	3.46
L1-F	4	26	4.54
L2-F	4	26	4.54
L3-F	4	26	4.54
L4-F	4	26	4.54
L5-F	4	26	4.54
L6-F	4	26	4.54
L7-F	4	26	4.54
L8-F	4	26	4.54
L9-F	4	26	4.54
L11-F	4	-------	1.78
Bare Strand	4	26	4.54

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.

Corrosion protection of the inner strand was evaluated by cutting a 3" (76 mm) length of strand from each unflushed, flushed, and bare strand specimen. The 3" (76 mm) 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% 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 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.

Table 4.4 Inner Strand Corrosion for Bare and Unflushed Strands.

Specimen	% Corrosion after 46 days.
L2-UF	0
L3-UF	0
L4-UF	0
L6-UF	0
L9-UF	0
L5-UF	10
L11-UF	15
L8-UF	45
L7-UF	85
Bare	85
L1-UF	90
L10-UF	95

Table 4.5 Inner Strand Corrosion for Bare and Flushed Strands.

Specimen	% Corrosion after 46 days.
L9-F	0
L10-F	70
L3-F	80
Bare	85
L4-F	90
L6-F	90
L1-F	95
L2-F	95
L5-F	95
L7-F	100
L8-F	100
L11-F	100

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 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 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

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

Lubricant	Length of corrosion protection in exposure tests. (days)	Average % corrosion after 3 days in deionized water.	Average % corrosion after 3 days in 3.5% NaCl solution.
L9	39	0	0
L1	18	30	32.5
L4	18	0.5	6
L6	18	0.5	2.5
L2	14	3.5	7.5
L3	14	10	1
L5	14	0	6
L7	14	2	3
L8	14	10	15
L10	11	15	32.5
Bare	11	55	60
L11	7	1	12.5

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 4.1 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 4.3 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 4.4 through 4.8 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 4.5 and the unflushed Group 3 specimen shown in Figure 4.8. For L9-UF (Figure 4.6) 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.

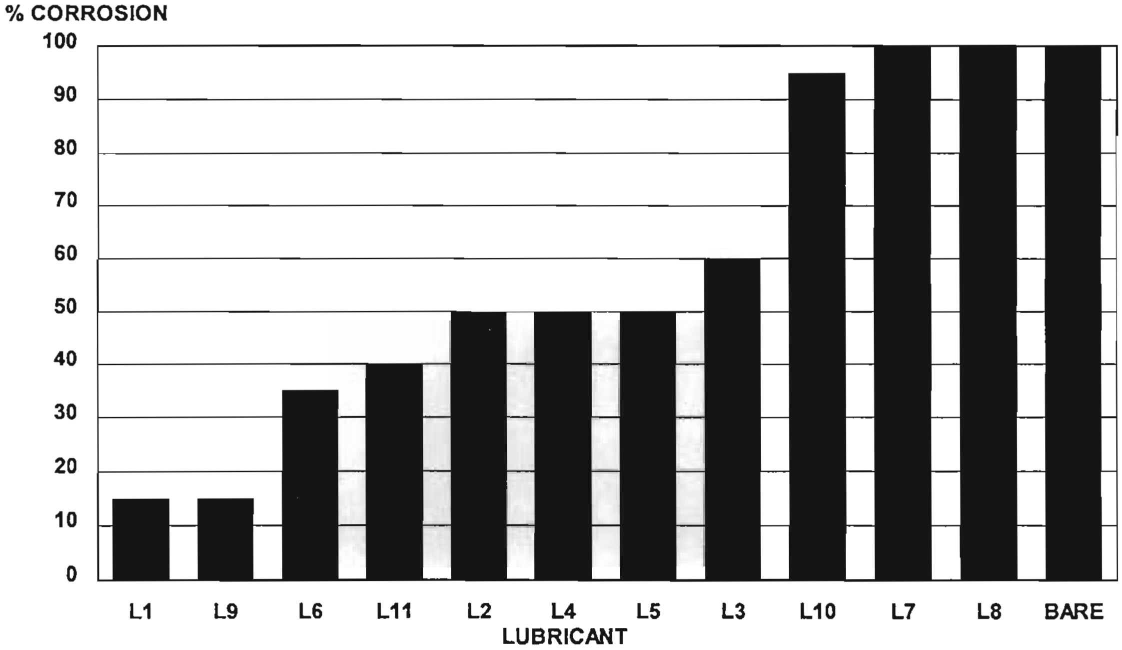


Figure 4.3 Percent corrosion on unflushed strands at conclusion of exposure tests.

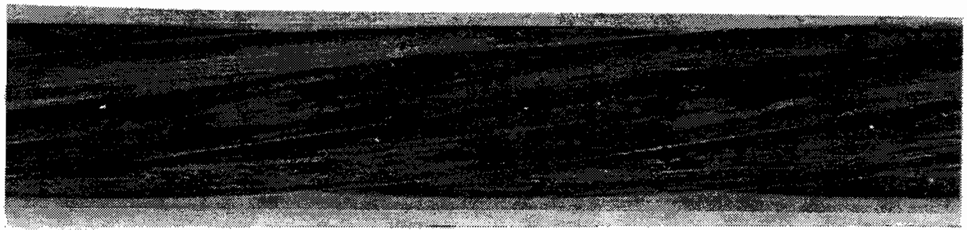


Figure 4.4 Bare strand before exposure tests.

Figure 4.5 Bare strand after exposure tests.

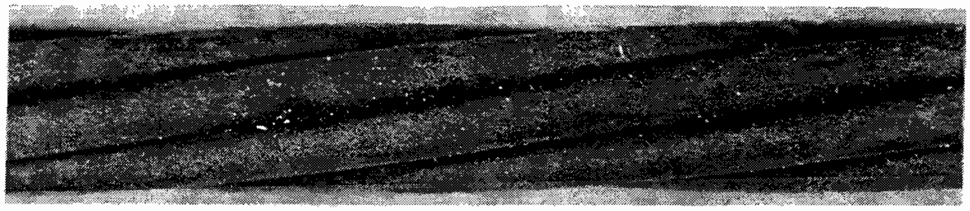


Figure 4.6 Unflushed strand from Group 1 (L9-UF).

Figure 4.7 Unflushed strand from Group 2 (L2-UF).

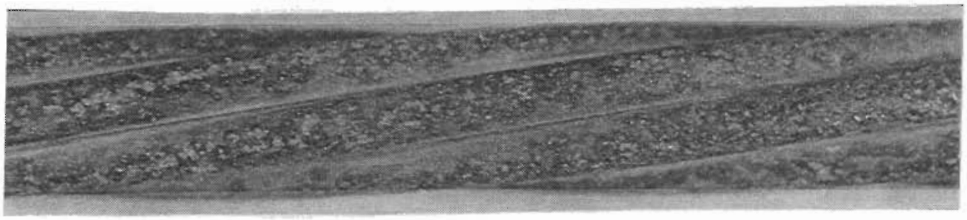


Figure 4.8 Unflushed strand from Group 3 (L7-UF).

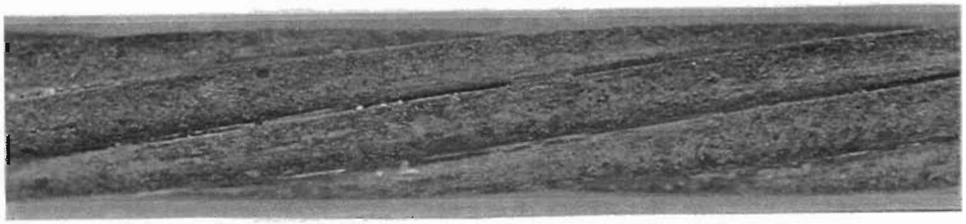


Figure 4.9. L10-F at conclusion of exposure tests.

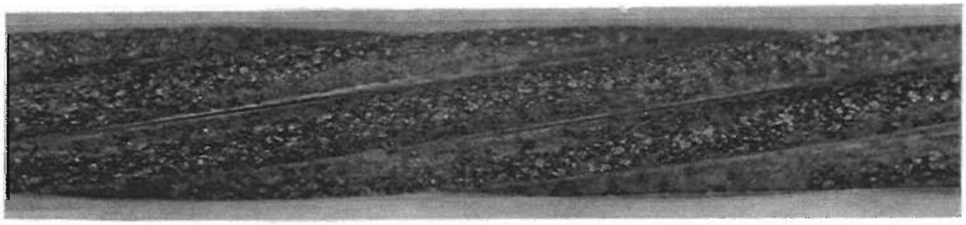


Figure 4.10 L2-F at conclusion of exposure tests.

As indicated in Figure 4.1 only one of the lubricants provided any corrosion protection after flushing. This lubricant was L10, which is a sodium silicate solution. Figures 4.9 and 4.10 show L10-F and L2-F after forty-six days of exposure. L10-F 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 4.1 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.

CHAPTER 5
PULL-OUT TESTS

5.1 Introduction.

In order to compare the relative effect of the 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" (200 mm) x 8" (200 mm) x 12" (300 mm) 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, three groups of specimens were constructed. The first two groups evaluated lubricants L1 - L11. The first group consisted of bare strand and unflushed specimens, while the second group consisted of bare strand and flushed specimens. The third group were all conditions for lubricants L13 and L14. All 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 dimensions of the surrounding concrete were 8" (200 mm) x 8" (200 mm) x 12" (300 mm). The actual adhesion length between the strand and the grout was 10.5" (267 mm) due to the use of grout plugs at the ends of the duct during specimen construction.

Sixty-two specimens were tested, two unflushed specimens for each of the thirteen lubricants, two flushed specimens for each of the thirteen lubricants, eight bare strand specimens, and two additional unflushed specimens. The eight bare strand specimens consisted of three

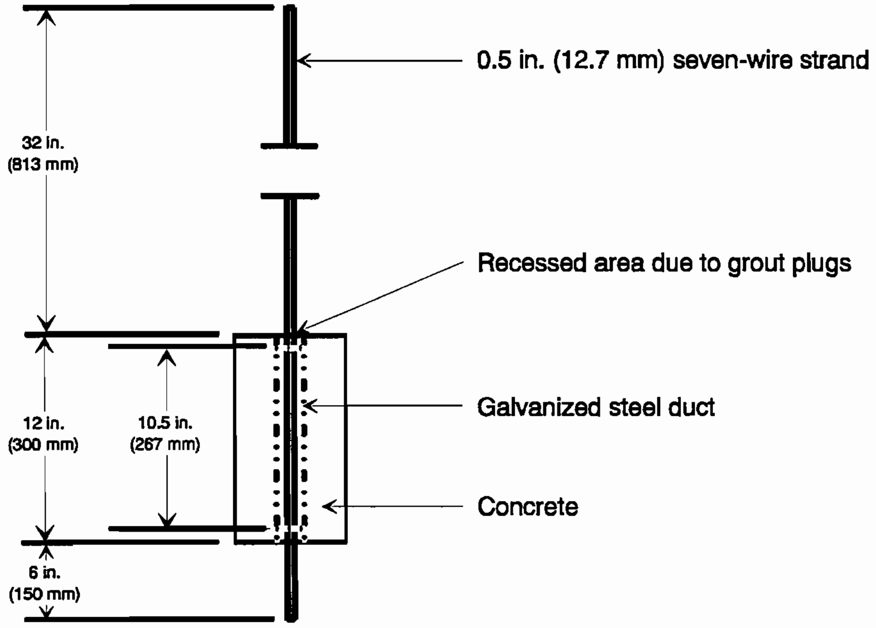


Figure 5.1 Pull-out specimen for small-scale pull-out tests.

Table 5.1 Mix Quantities for Grout.

	Group 1	Group 2
Water	35.0 lbs. (15.9 kg)	37.0 lbs. (16.8 kg)
Cement	79.2 lbs. (35.9 kg)	84.2 lbs. (38.2 kg)
w/c	0.44	0.44

Table 5.2 Seven-day and 28-day Cube Strengths for Grout.

	7-day compressive strength		28-day compressive strength	
	psi	Mpa	psi	Mpa
Group 1	5660	39	7270	50
Group 2	7750	53	9080	63

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 [6]. The additional unflushed specimens were used to correlate data between the groups of specimens.

A 60-kip (267 kN) 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" (19 mm) 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 averaged 7500 psi (52 MPa).

5.4.2 Cement Grout. Cement grout having a water-cement ratio of 0.44 was used for all 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 (12.7 mm) diameter, Grade 270 (1860) 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" (51 mm) was used in the pull-out specimens. This duct is typical of duct used in post-tensioned concrete construction.

5.4.5 Grout Hose. Three quarter inch (19 mm) 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 was used for specimen construction. Twelve-inch (300 mm) steel ducts were placed in the forms before placing concrete.

5.5.2 Batching. Concrete was batched using a 6 ft^3. (0.17 m^3) mixer. 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.

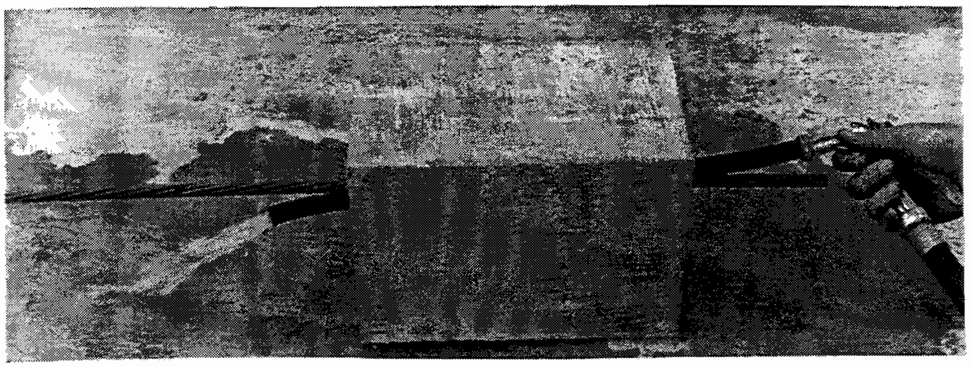


Figure 5.2 Flushing of pull-out specimen.

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 5.2. 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} (11.3 ℓ) /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.

5.8 Grouting.

A hand grout pump 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 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 5.3. In this setup a 60 kip (267 kN) 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.

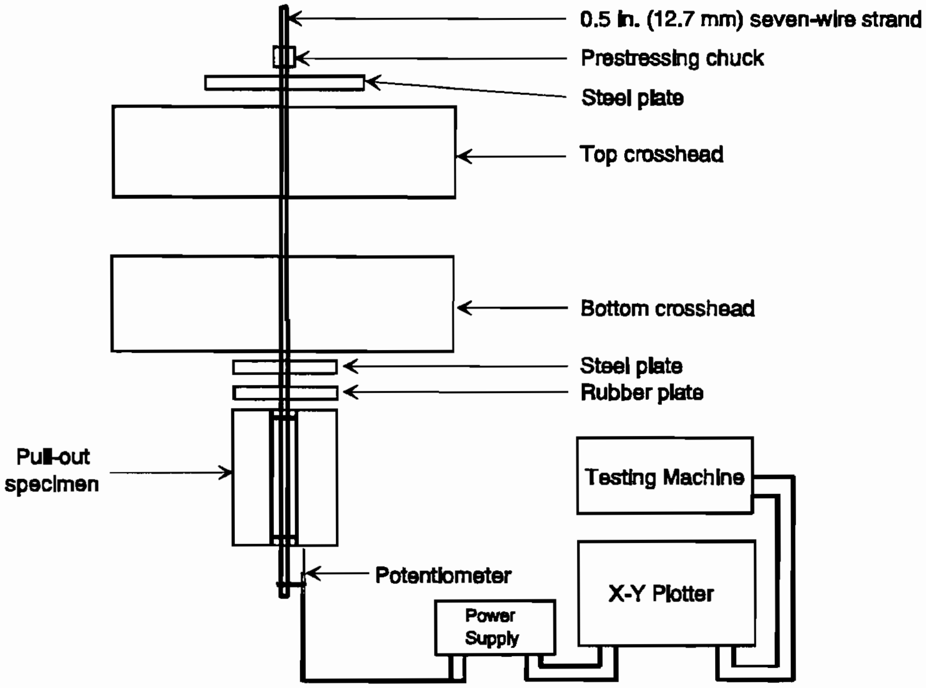


Figure 5.3 Test setup for pull-out tests.

5.10 Instrumentation.

Instrumentation for the pull-out tests consisted of a potentiometer, power source for the potentiometer, and an X-Y plotter. The 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. (6.67 kN/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. (6.67 kN/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. (22 N).

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. 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.

Labelling System for Pull-out Specimens:

L# = Lubricant Number

UF = Unflushed Specimen

F = Flushed Specimen

R1 = Bare Strand from Reel 1

R2 = Bare Strand from Reel 2

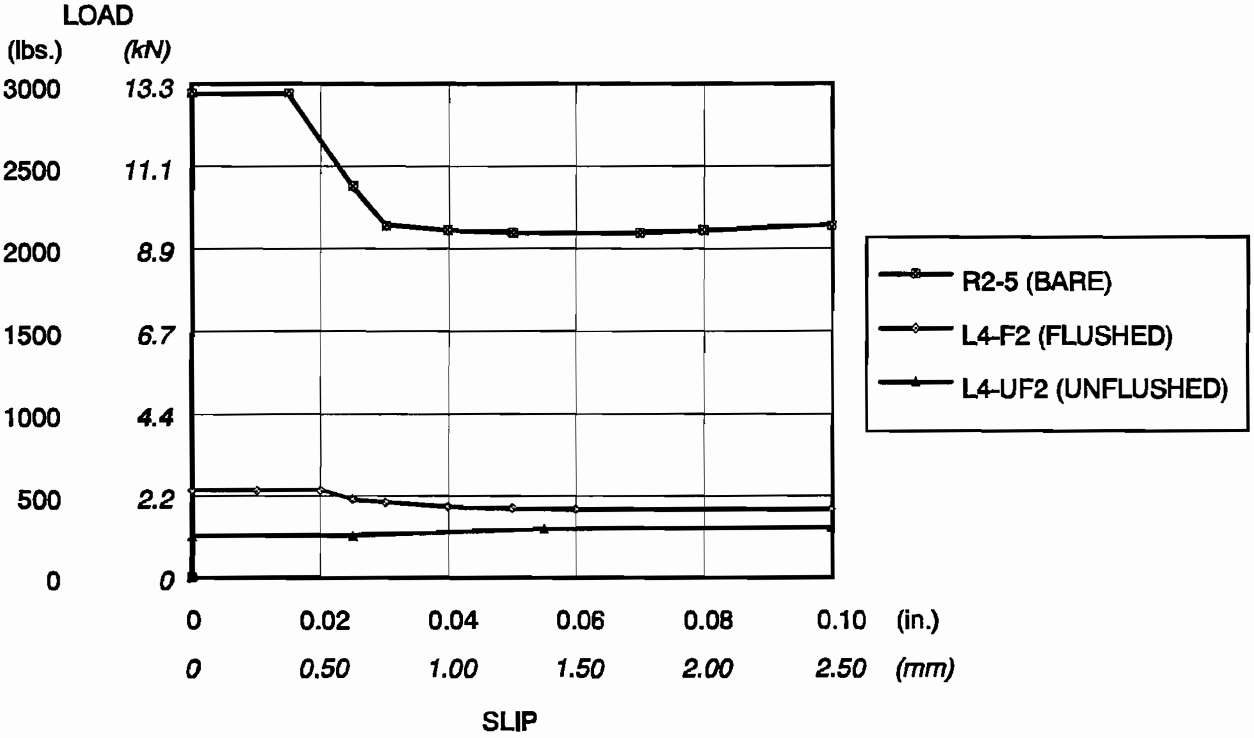


Figure 5.4 Typical results from small-scale pull-out tests.

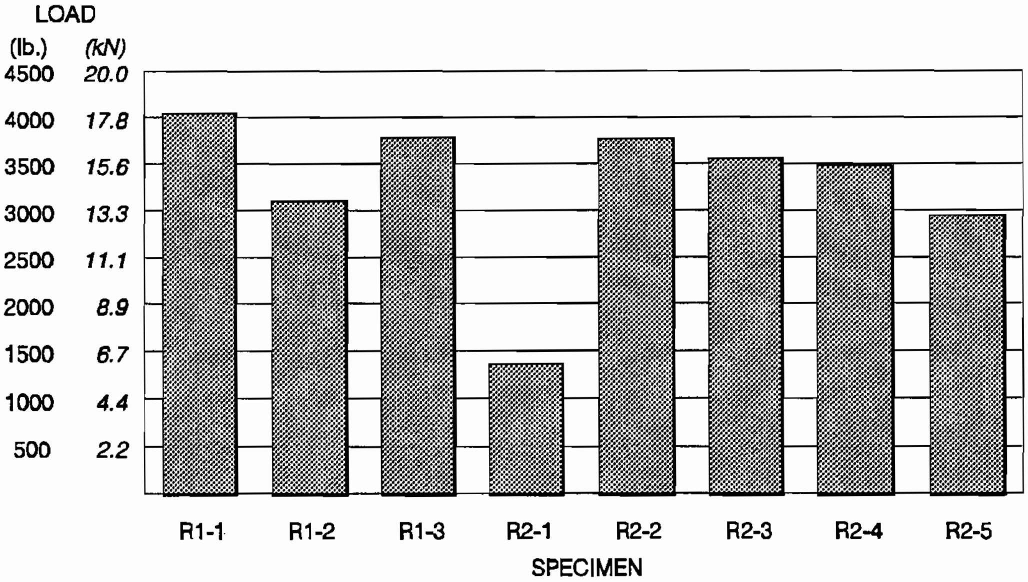


Figure 5.5 Slip loads for bare strand specimens.

Typical results for bare, flushed, and unflushed specimens are shown in Figure 5.4. For these specimens the strand began to pull through the specimen at 2950 (38.7), 540 (2.4), and 260 (1.2) lb. (kN), 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 5.5 shows the slip loads for the eight bare strand specimens. These loads varied from 1360 lb. (6.0 kN) for R2-1 to 4040 lb. (18.0 kN) for R1-1. The overall average was 3260 lb. (14.5 kN) and the standard deviation was 850 lb. (3.8 kN). The average slip load for the strands from R1 was 3640 lb. (16.2 kN). For strands from R2 the average slip load was 3020 lb. (13.4 kN) when all five specimens were included and 3330 lb. (14.8 kN) 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. (13.3 kN).

Average slip loads for the unflushed and flushed specimens are shown in Figures 5.6 and 5.7 as a percentage of the average 3260 lb. (14.5 kN) slip load for the bare strands.

5.13 Discussion of Test Results and Conclusions.

All of the strands in the pull-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 5.5 indicates that the stearate soap present on the strands from R2 does not appear to have a significant effect on the adhesive properties of the strand. The difference in average slip loads for the two reels of strand

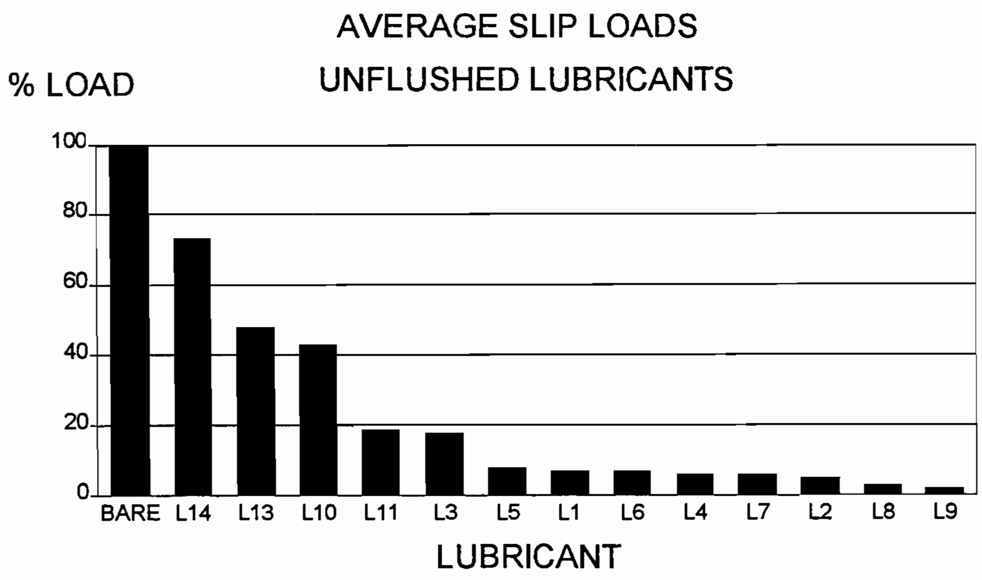


Figure 5.6 Average slip loads for unflushed lubricants.

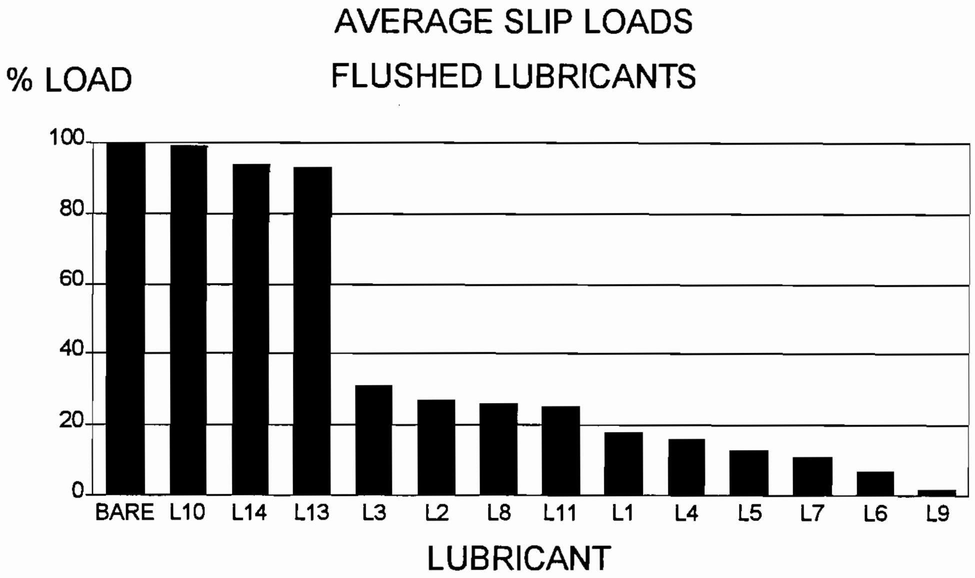


Figure 5.7 Average slip loads for flushed lubricants.

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.

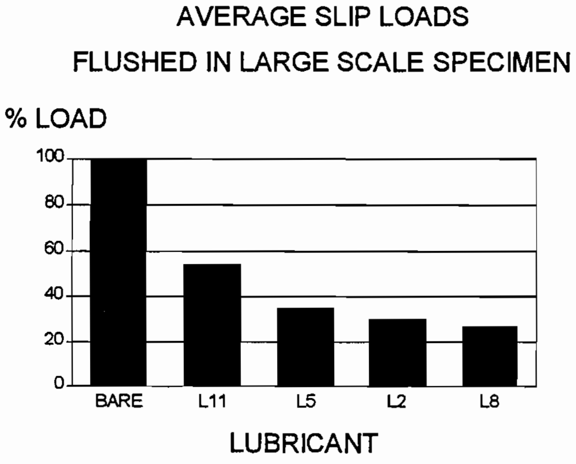


Figure 5.8 Average slip loads for lubricated strand flushed in large scale specimen.

Figure 5.6 clearly shows that nearly all the lubricants tested have the capability of substantially reducing strand to grout bond strength. Only L14, Graphite Flakes, had less than a 30% reduction. Figure 5.7 more importantly shows that most of the lubricants tested were unable to be flushed clean of the strand. Only three of the lubricants/corrosion inhibitors tested (L10, L14, and L13) had minimal impact on bond strength after thorough flushing. Use of the other lubricants should be avoided when development of the tendon subsequent to grouting is required by design. Strand flushed in the large scale specimen gave similar results in the pullout test to strand flushed in the small-scale pullout specimens [10]. Figure 5.8 shows that less than 50% of bare strand bond strength could be recovered in similar small-scale pullout tests of strand samples taken from tendons flushed in the full-scale girder friction tests.

The pull-out tests performed in this research showed that the presence of most lubricants on the strand before grouting significantly reduces the adhesion between strand and grout. These tests also indicated that the water soluble oil lubricants could not be removed using the flushing procedures utilized in this study which are similar to those that are used in the field. Figure 5.7 indicates that the soap (L13) and graphite (L14) lubricants could be effectively flushed and bonded.

The pull-out tests performed in this research provided good, relative results that were used to compare the lubricants. However, there were two concerns with these tests: (1) the strands twisted out of the specimens during testing; (2) 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-in. (200 mm) x 8-in. (200 mm) x 12-in. (300 mm) 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 lbs. (28.6 kN), 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.

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 water soluble lubricants even in the flushed specimens which had improved but still greatly reduced adhesion.

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 of the water soluble oils 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 contained six bare strands, two lubricated strands, and two lubricated and then flushed strands. Each strand was grouted inside a 2" (51 mm) diameter, 6' (1.83 m) 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.

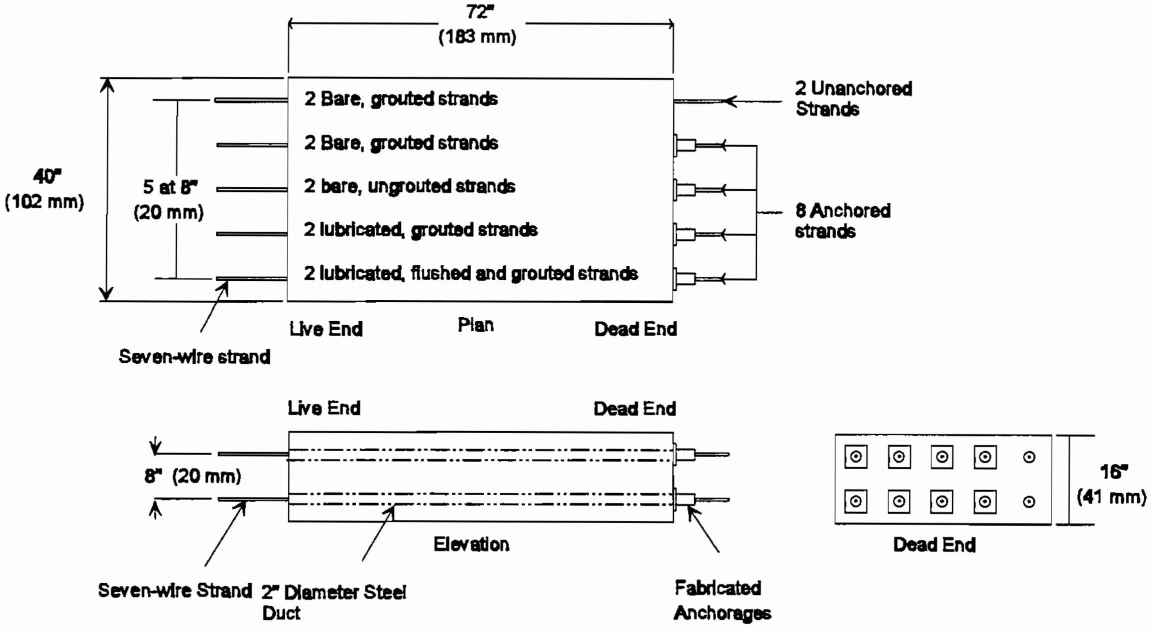


Figure 6.1 Anchored pull-out specimen used for anchored pull-out tests.

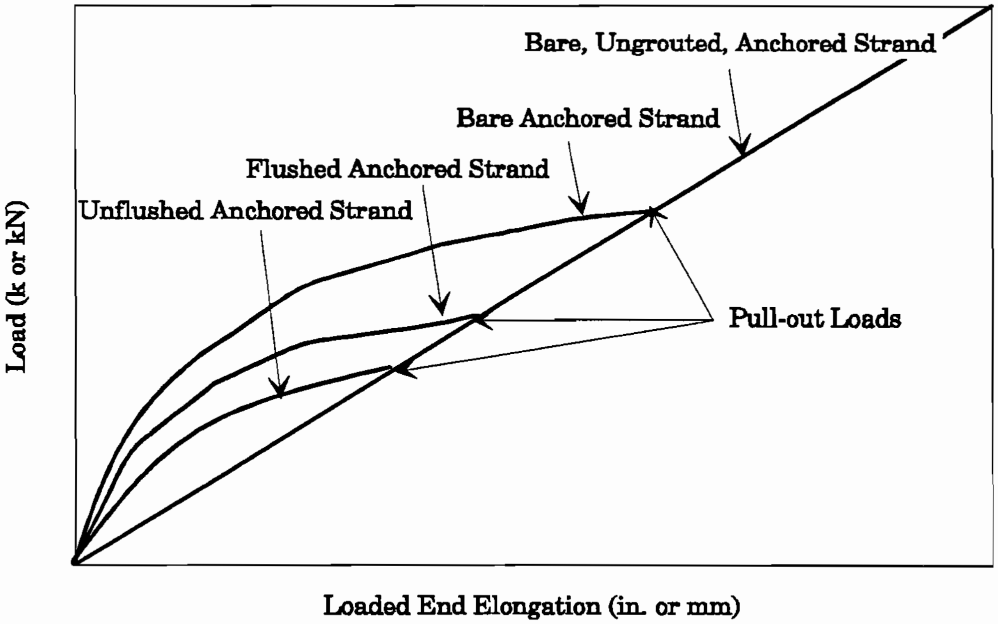


Figure 6.2 Hypothetical results from anchored pull-out tests.

For the bare, unanchored strands the slip of the strand at the dead end of the 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" (19 mm) limestone aggregate, sand, water, Type I Portland cement, and Rheobuild superplasticizer. The twenty-eight day compressive strength of the concrete was 7770 psi. (54 MPa).

6.3.2 Steel Reinforcement. Grade 60 (414), #3 (ϕ10) 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.

Table 6.1 Mix Quantities for Grout

Water	60 lbs. (27.2 kg)
Cement	136 lbs. (61.7 kg)
w/c	0.44

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

	Compressive Strength (psi.)	 (Mpa)
7 - day	5660	(39.0)
28 -day	6150	(42.4)

6.3.4 Prestressing Strand. One-half inch (12.7 mm) diameter, Grade 270 (1860) low-relaxation strand from R2 (Reel 2) was used for the strand specimens in the anchored pull-out tests. The properties for this strand are shown in Table 3.3.

6.3.5 Duct. Corrugated, galvanized steel duct with a 2" (51 mm) 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. Dead end anchorages as shown in Figure 6.3 were fabricated by welding standard prestressing chucks to 5/8" (16 mm) thick steel bearing plate. Strands were seated in the anchorages with a preload of 4 kips (18 kN) by using a 60 kip (267 kN) testing machine. It was felt that a seating load of 4 kips (18 kN), which is approximately 10% of the ultimate strand load, would be suitable to prevent twisting of the strands during testing.

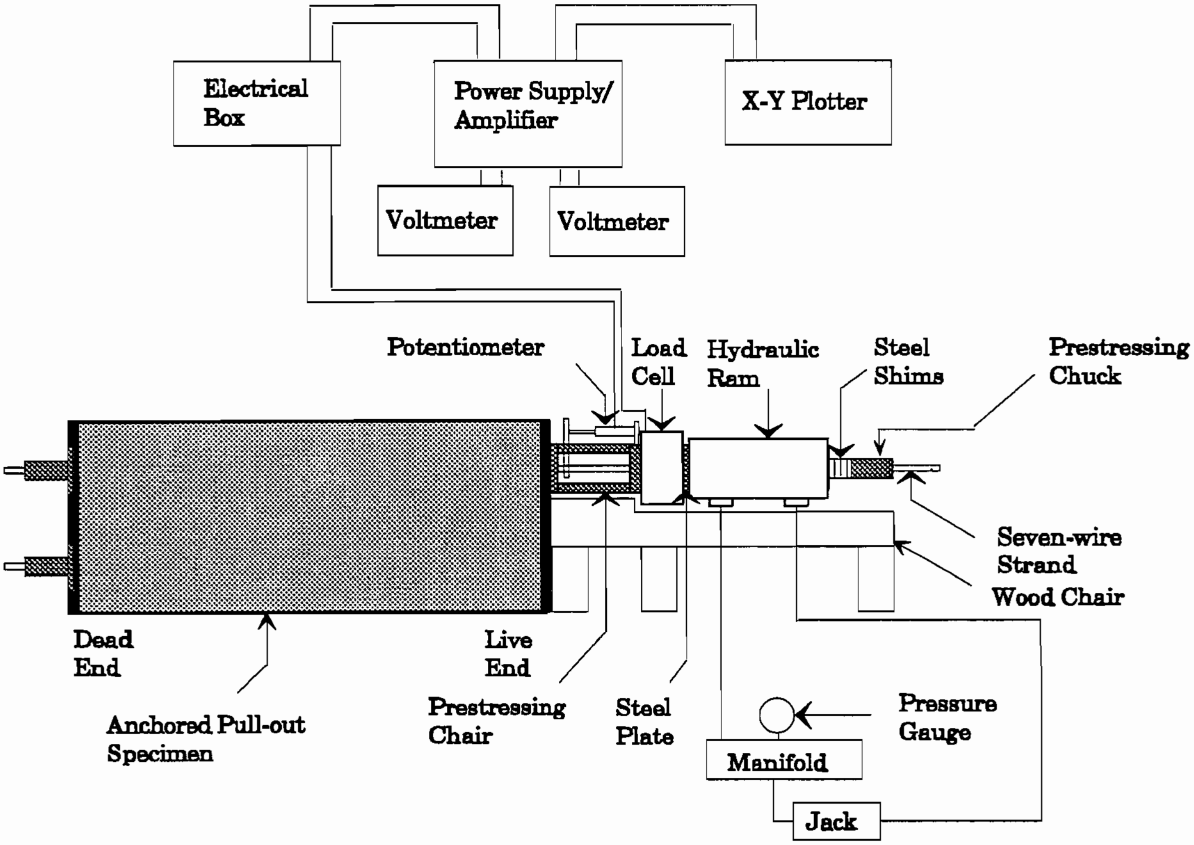


Figure 6.3 Test setup for anchored pull-out tests.

6.4 Construction.

6.4.1 Formwork. Woodens forms were used for the anchored pull-out specimen. A steel cage made from number three (ϕ10) 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" (12.7 mm) 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 hand-operated compressed air sprayer was used to spray lubricate the strands as they were inserted into the ducts. This lubrication method is similar to lubrication methods used in post-tensioned concrete construction. The bare strand specimens were never lubricated.

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 (50 mm) diameter wood grout plugs and 3/4" (19 mm) diameter grout hose were used to create water-tight ducts that could be flushed and grouted easily.

6.4.5 Flushing. Flushing was accomplished, by using a garden hose with a spray nozzle. During this process water was sprayed through the grout hose at the live end of the specimen at a rate of 0.5 $ft.^3$ (14 ℓ) /min. for two minutes.

The flushing procedure 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 of 480 lbs. (2.1 kN) was applied to each strand.

6.4.7 Grouting. A hand grout pump 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 consisted of four, Grade 60 (414), #7 (ϕ22) reinforcing bars and 1" (25 mm) thick steel plate. The reinforcing bars were 6" (150 mm) long and the dimensions of the steel plate were 4" x 6" (100 mm x 150 mm).

6.5.2 Load Cell. A 50-kip (222 kN) load cell was used to measure the jacking load 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 (356 kN) 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 (12.7 mm) thick, slotted, steel shims with a diameter of 1 1/2" (38 mm) 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" (50 mm) 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.

6.6 Instrumentation.

Instrumentation for the anchored pull-out tests consisted of 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 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 (9 kN) kips were used in the first and second tests. In the third tests 2 kip (9 kN) load increments were used initially, but were changed to 4 kips (18 kN) after a load of 10 kips (45 kN) had been reached.

For the unflushed and flushed strands the load increments were usually 1 kip (4.5 kN), but 0.25 (1.1 kN) and 0.5 (2.2 kN) 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.

6.8 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 6.4 and 6.5. Results for the first tests of the unbonded strands were not presented due to problems with the test setup during testing.

As shown in Figures 6.4 and 6.5, 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

Table 6.3 Labelling System Used for Strands in Anchored Pull-Out Tests.

Strand Surface Conditon	Anchorage Condition	Bond Condition	No. of Strands	No. of Tests per Strand
Bare	Anchored	Grouted	2	1
		Ungrouted	2	3
	Unanchored	Grouted	2	1
Unflushed	Anchored	Grouted	2	1
Flushed	Anchored	Grouted	2	1

B = Bare UF = Unflushed F = Flushed	A = Anchored UA = Unanchored	G = Grouted UG = Ungrouted	1 = Strand 1 2 = Strand 2	1 = Test 1 2 = Test 2 3 = Test 3

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 6.4 and 6.5. 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 prestressing chucks used in 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 chuck 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. (155 GPa) with a standard deviation of 1190 ksi. (8.2 GPa). 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" (0.025 mm) at a load of 30 kips (133 kN). 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

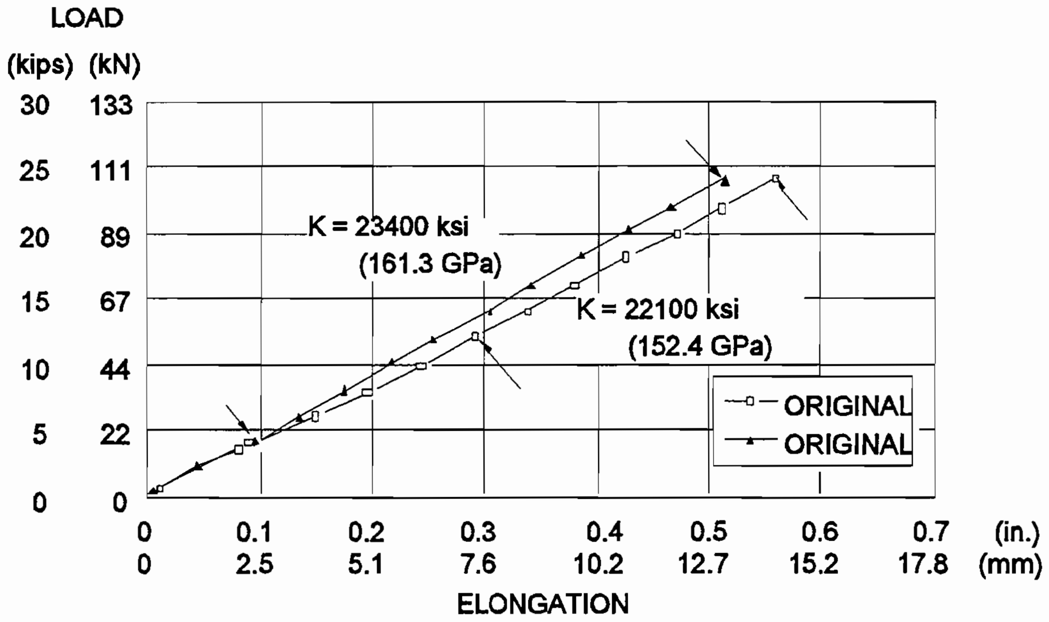


Figure 6.4 Results from second testing of unbonded strands.

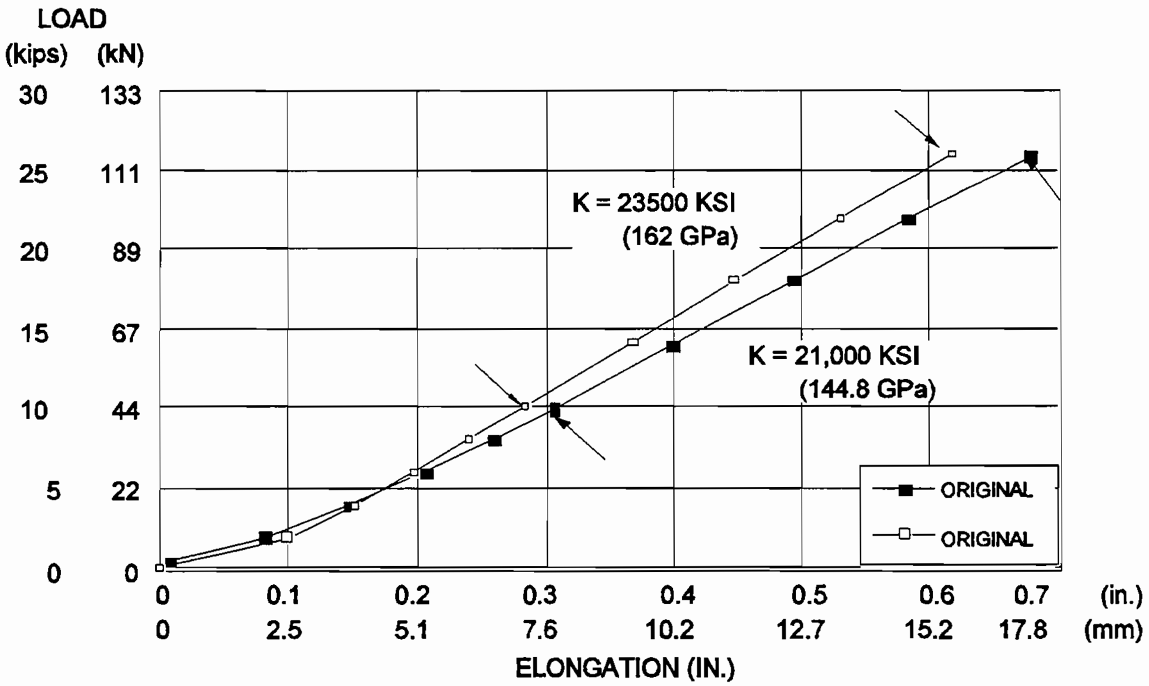


Figure 6.5 Results from third testing of unbonded strands.

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" (3.2 mm). This pull-in was measured using a steel tape with divisions of 1/32" (0.8 mm). Pull-in was not examined during the first and second tests of the unbonded strands.

In order to address the possible anchorage teacup, the elongation results for the unbonded strands were recalculated assuming a gradual anchorage teacup of 0.1" (2.5 mm) during the test. The amount of anchorage teacup varies depending on the type of prestressing chuck used. According to Lin and Burns a reasonable estimate is 0.1" (2.5 mm)[24].

The adjusted results for the unbonded strands are shown in Figures 6.6 through 6.9. 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. (190 GPa) with a standard deviation of 1800 ksi. (12.4 GPa). 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 teacup did occur during testing of the unbonded strands the original average stiffness value of 22,500 ksi. (155 GPa) 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 6.10 through 6.12 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 divisions of 1/32" (0.8 mm). 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 6.10, was 20.3 kips (90.3 kN). At this load the strand had just pulled through the anchorage at the dead end of the specimen approximately 1/16" (1.6 mm). 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

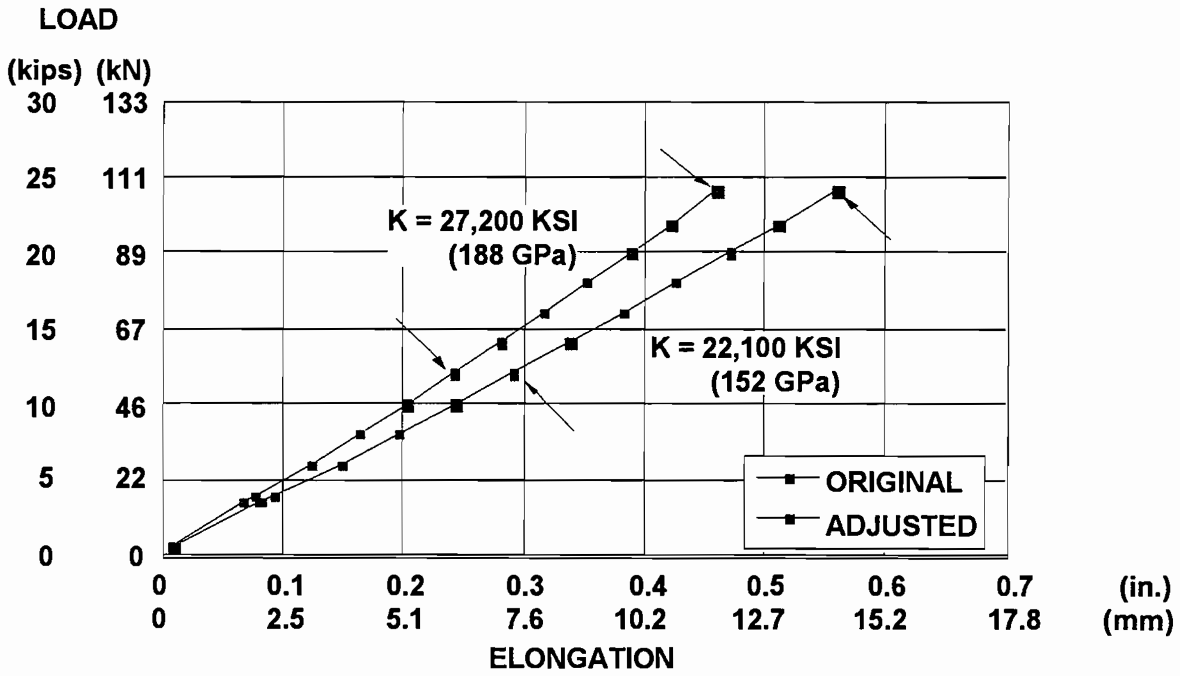


Figure 6.6 Original and adjusted data for BAUG12.

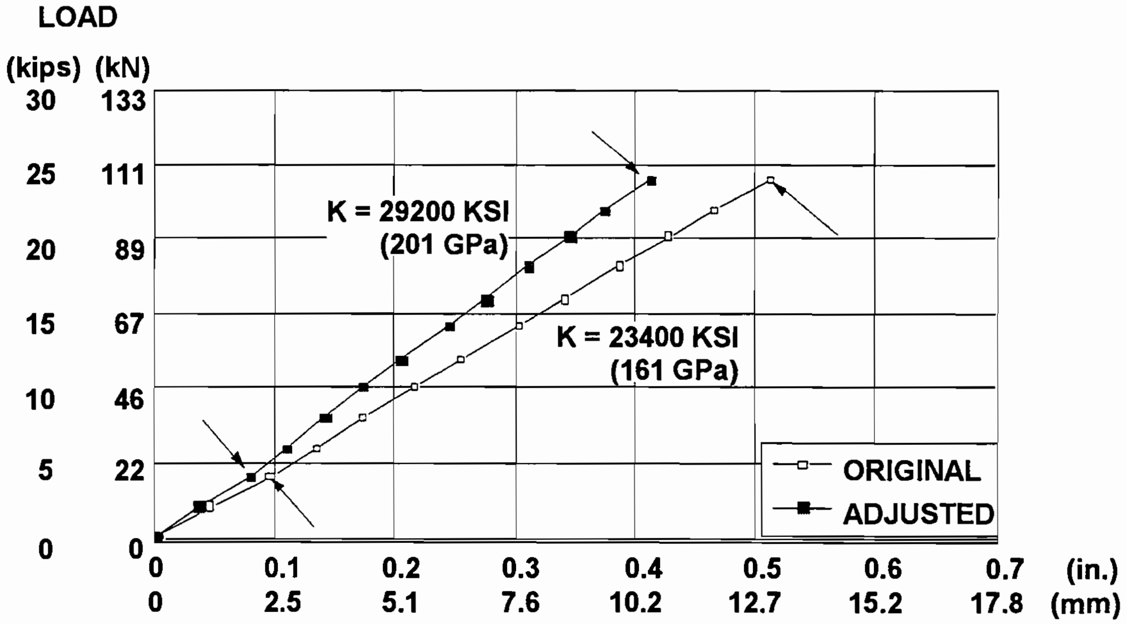


Figure 6.7 Original and adjusted data for BAUG 22.

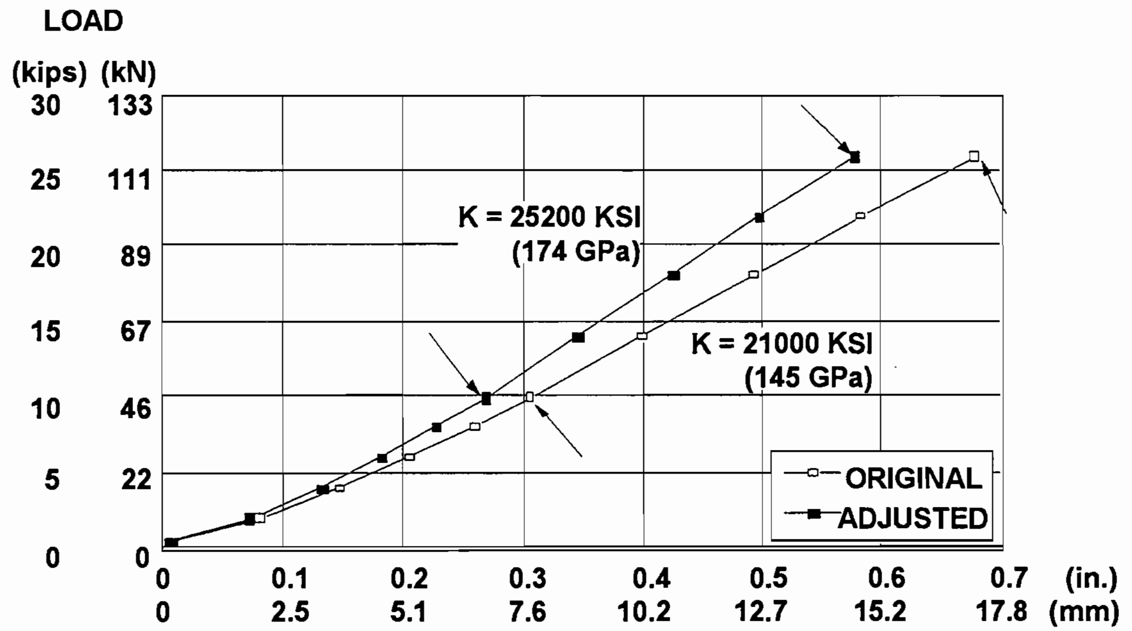


Figure 6.8 Original and adjusted data for BAUG13.

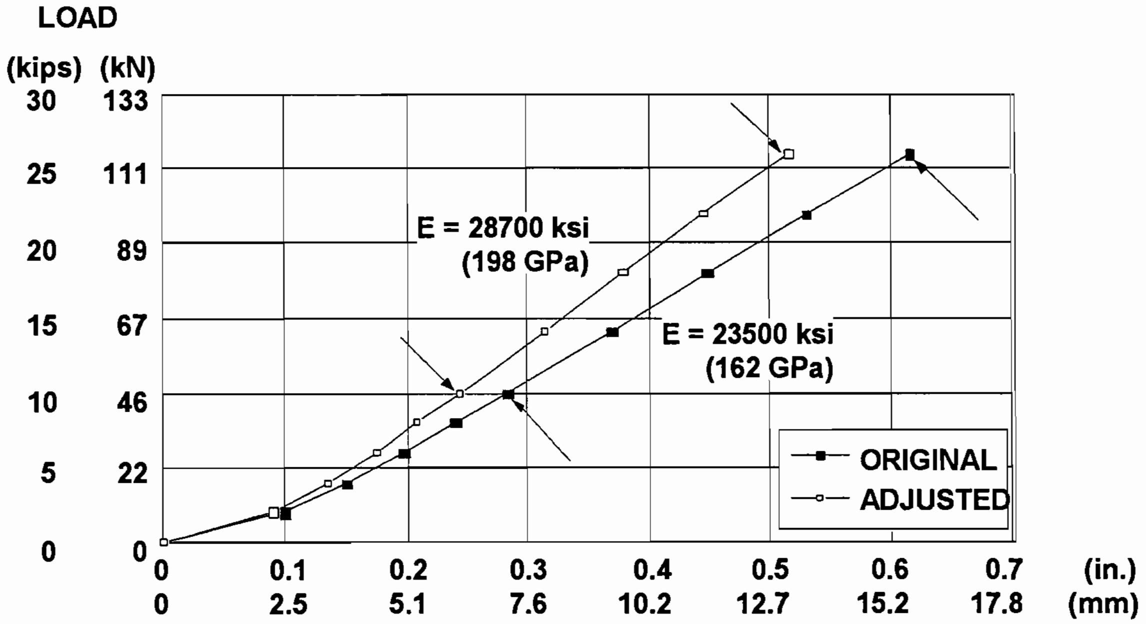


Figure 6.9 Original and adjusted data for BAUG23.

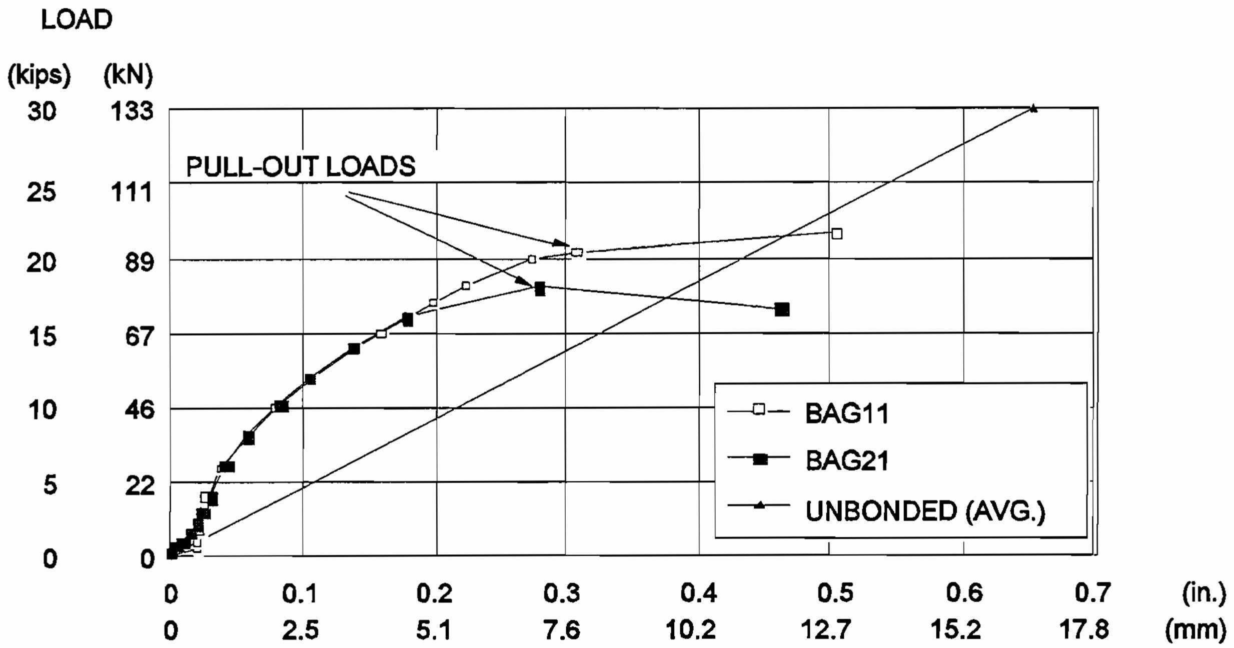


Figure 6.10 Results for bare, anchored strands.

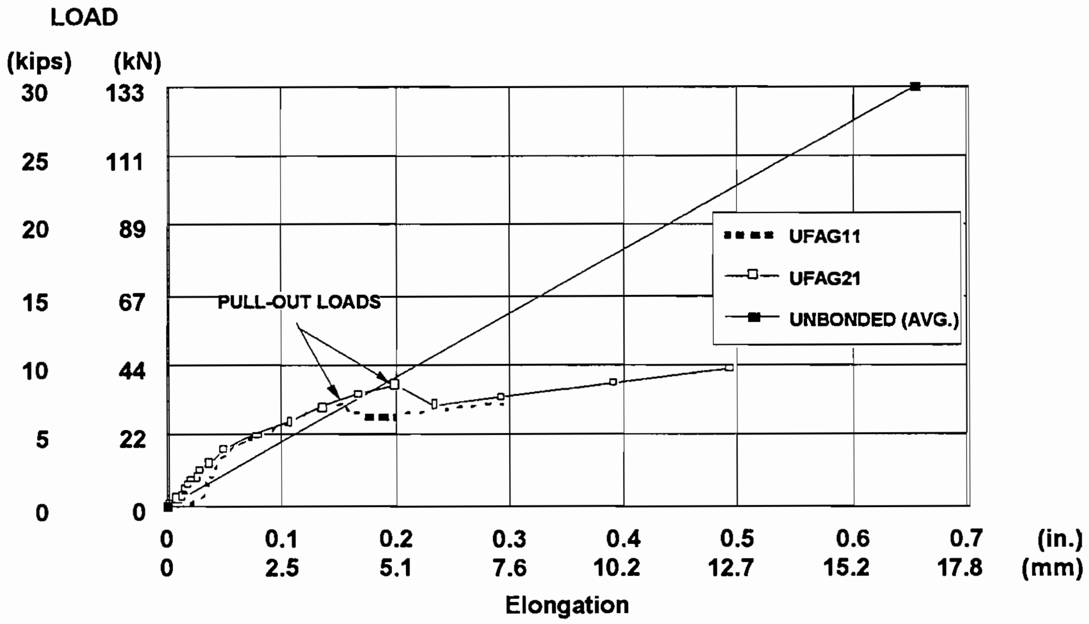


Figure 6.11 Results for unflushed, anchored strands.

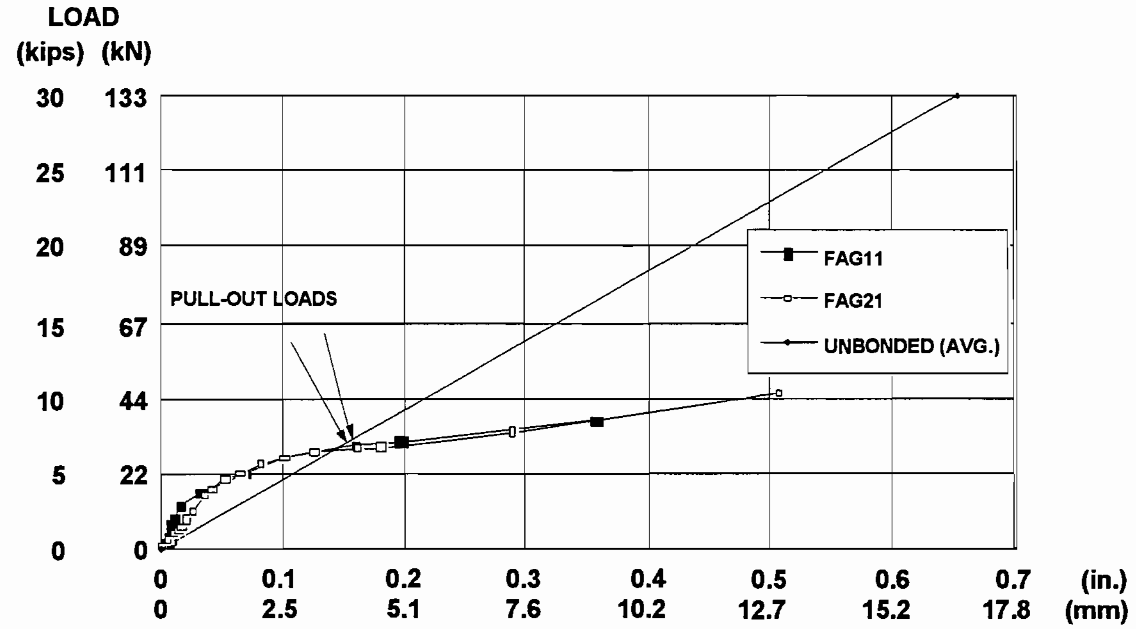


Figure 6.12 Results for flushed, anchored strands.

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 (80 kN). Therefore, this load was defined as the pull-out load for this specimen.

For the unflushed strands the pull-out loads were 7.25 (32.2) and 8.57 (38.1) kips (kN) for UFAG11 and UFAG21, respectively. Pull-out loads for the flushed strands were 6.89 kips (30.6 kN) and 6.60 kips (29.4 kN) 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 (17.8 kN) is applied to the strand, then the jaws will move a certain distance in the anchorage. However, if a force greater than 4 kips (17.8 kN) 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.

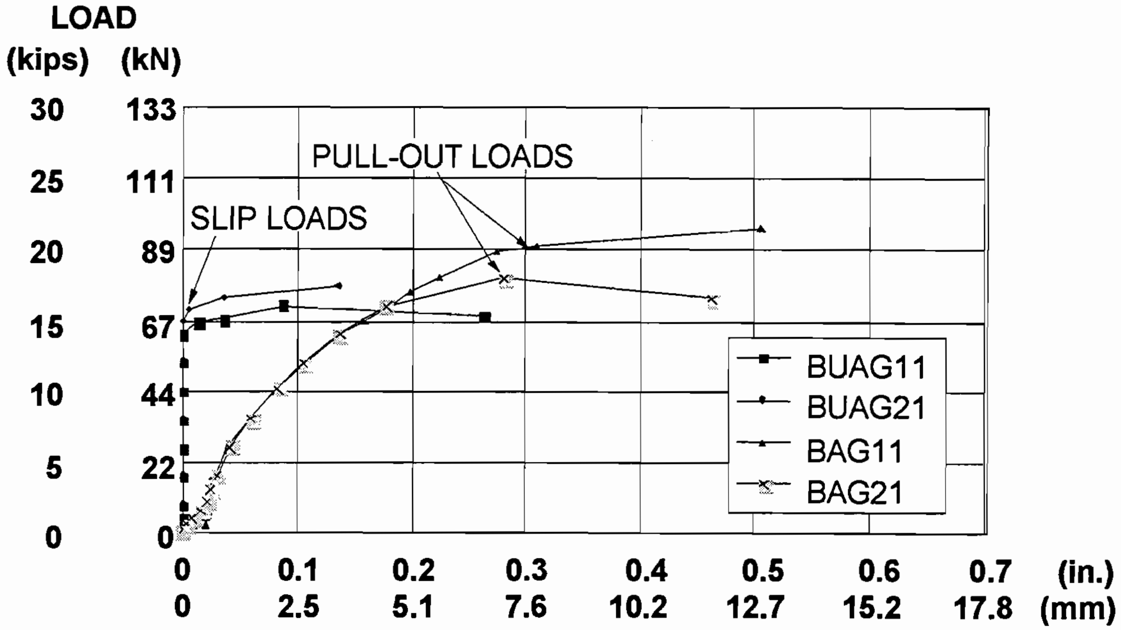


Figure 6.13 Results for bare, anchored and bare, unanchored strands.

Figure 6.13 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 (66 kN) and 15.8 kips (70.3 kN) for BUAG11 and BUAG21, respectively. The pull-out loads for the bare, anchored strands were 20.3 kips (90.3 kN) and 18.0 kips (80 kN) 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 hoped for 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 6.11 and 6.12), the pull-out loads for these 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

Table 6.4 Results of Anchored Pull-Out Tests.

Specimen	Pull-out Load (kips)	(kN)	Average Pull-out Load (kips)	(kN)	% Reduction in Pull-out Load
BAG11 (Bare)	20.3	90.3	19.2	85.4	-----
BAG21 (Bare)	18.0	80.1			
UFAG11 (Unflushed)	7.25	32.2	7.91	35.2	59
UFAG21 (Unflushed)	8.57	38.1			
FAG11 (Flushed)	6.89	30.6	6.74	30.0	65
FAG21 (Flushed)	6.60	29.4			

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.

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

Table 6.5 Comparison of Bare Anchored and Bare Unanchored Strands

Specimen	Pull-Out Load (kips)	(kN)	Average Pull-Out Load or Slip Load (kips)	(kN)	Average Pull-Out Load per foot (k/ft.)	(kN/m)
BAG11 (Bare anchored)	20.3	90.3	19.2	85.4	3.20	47
BAG21 (Bare anchored)	18.0	80.1				
BUAG11 (Bare unanchored)	14.8	65.8	15.3	68.0	2.55	37
BUAG21 (Bare unanchored)	15.8	70.3				

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. (50 kN/m) 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 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 water soluble oil lubricant on a seven-wire strand that is restricted from twist might still reduce the adhesion strength between strand and grout substantially.

CHAPTER 7
LUBRICANT EVALUATION

7.1 Introduction.

The purpose of this chapter is to evaluate the overall performance of the thirteen lubricants [21]; a secondary goal is to recommend the best four water soluble oils for use in large-scale friction tests. Lubricants L13 and L14 were added subsequently by Davis [10]. A Matrix Priority Rating System was selected for this evaluation because it can use several criteria of different importance to evaluate several alternatives. In this study the alternatives were the ten emulsifiable oils, a sodium silicate solution, a soap, graphite powder 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 fourteen alternatives were shown previously in Table 2.3.

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 7.1. These criteria were selected based on the demands of lubricants and the concerns associated

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* This criteria was not applicable to the soap or the graphite powder which were considered only as lubricants

Table 7.1 Criteria for Lubricant Evaluation.

Friction Reduction	Effect on Adhesion	Temporary Corrosion Protection	Safety Hazards	Lubricant Cost	Difficulty of Use

with their use. Friction reduction, effect on adhesion, temporary corrosion protection, and safety hazards were broken down further as shown in Table 7.2 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.

Table 7.2 Matrix Criteria.

FRICTION REDUCTION		EFFECT ON ADHESION		TEMPORARY CORROSION PROTECTION									SAFETY HAZARDS					
				UNFLUSHED STRAND			FLUSHED STRANDS			UNFLUSHED WIRES								
STATIC	DYN	UNFLUSH	FLUSHED	STRAND PROTECTION		CORR. RATE	STRAND PROTECTION		CORR. RATE	AMB.	DEION WATER	3.5%NaCl SOL'N	HEALTH	FLAMM.	REACT.	LUB. COST	DIFF.OF USE	TOTAL SCORE
				OUTER	INNER		OUTER	INNER										

Table 7.3 Importance Factors for Criteria.

	FRICTION REDUCTION		EFFECT ON ADHESION		TEMPORARY CORROSION PROTECTION									SAFETY HAZARDS					
					UNFLUSHED STRAND			FLUSHED STRANDS			UNFLUSHED WIRES								
	STATIC	DYN	UNFLUSH	FLUSHED	STRAND PROTECTION		CORR. RATE	STRAND PROTECTION		CORR. RATE	AMB.	DEION WATER	3.5%NaCl SOL'N	HEALTH	FLAMM.	REACT.	LUB. COST	DIFF.OF USE	TOTAL SCORE
					OUTER	INNER		OUTER	INNER										
IMPORTANCE																			

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 (208 l) 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 importance. This number of points could be any convenient number such as 50, 500 or 1000 since the importance are relative.

The distribution of points is shown in Table 7.3 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 criteria 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 criteria. These criteria 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 report 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 7.4 shows the rating systems that were used for the different criteria. All details on the background for each rating are given in Ref. 21. 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.

7.2.6 Evaluation Process. The matrix setup, which is shown in Table 7.5, 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

Table 7.4 Rating Systems for Criteria.

Criteria		Rating of Criteria		
Friction Reduction	Static	10 If....Reduction in static friction factor ≥ 33%.	5 If....Reduction in static friction factor = 11%.	0 If....Increase in static friction factor ≥ 10%.
	Dynamic	10 If....Reduction in dynamic friction factor ≥ 33%.	5 If....Reduction in static friction factor = 11%.	0 If....Increase in dynamic friction factor ≥ 10%.
Effect on Adhesion	Unflushed	10 If....Slip load ≥ 3200 lb. (14.2 kN)	5 If....Slip load = 1650 lb. (7.3 kN)	0 If....Slip load ≤ 100 lb. (0.4 kN)
	Flushed	10 If....Slip load ≥ 3200 lb.(14.2 kN)	5 If.... Slip load = 1650 lb. (7.3 kN)	0 If....Slip load ≤ 100 lb. (0.4 kN)
Temporary Corrosion Protection Unflushed Strands	Outer Strand Protection	10 If....No corrosion after 40 days.	5 If....Corrosion after 20 days.	0 If....Corrosion after 0 days.
	Inner Strand Protection	10 If....0% corrosion of inner strand after 46 days.	5 If....50% corrosion of inner strand after 46 days.	0 If....100% corrosion of inner strand after 46 days.
	Corrosion Rate	10 If....Corrosion rate of 0% / Day.	5 If....Corrosion rate of 5 % / Day.	0 If....Corrosion rate ≥ 10% / Day.
Temporary Corrosion Protection Flushed Strands	Outer Strand Protection	10 If.... No corrosion after 40 days.	5 If.... Corrosion after 20 days.	0 If.... Corrosion after 0 days.
	Inner Strand Protection	10 If.... 0% corrosion of inner strand after 46 days.	5 If.... 50% corrosion of inner strand after 46 days.	0 If.... 100% corrosion of inner strand after 46 days.
	Corrosion Rate	10 If.... Corrosion rate of 0% / day.	5 If.... Corrosion rate of 5% / day.	0 If.... Corrosion rate ≥ 10% / day.
Temporary Corrosion Protection Unflushed Wires	Ambient	10 If.... No corrosion after 40 days.	5 If.... Corrosion after 20 days.	0 If.... Corrosion after 0 days.
	Deionized Water	10 If.... 0% corrosion after 3 days.	5 If.... 50% corrosion after 3 days.	0 If.... 100% corrosion after 3 days.
	3.5% NaCl Solution	10 If.... 0% corrosion after 3 days.	5 If.... 50% corrosion after 3 days.	0 If.... 100% corrosion after 3 days.
Safety Hazards	Health Hazard	10 If.... Insignificant.	5 If.... Moderate.	0 If.... Extreme.
	Flammability	10 If.... Insignificant.	5 If.... Moderate.	0 If.... Extreme.
	Reactivity	10 If.... Insignificant.	5 If.... Moderate.	0 If.... Extreme.
Lubricant Cost		10 If.... Cost ≤ $2/gal. ($0.53/*l*)	5 If.... Cost = $11/gal. ($2.90/*l*)	0 If.... Cost ≥ $20/gal. ($5.30/*l*)
Difficulty of Use		10 If.... Usage is simple. Application takes no time and no cleanup is required.	5 If.... Usage is moderately difficult. Application and cleanup can be performed in reasonable time frames using normal procedures.	0 If.... Usage is very difficult. Application and cleanup require excessive time and special procedures.

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 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.

Table 7.5 Matrix Setup

	FRICTION REDUCTION		EFFECT ON ADHESION		TEMPORARY CORROSION PROTECTION									SAFETY HAZARDS			LUB. COST	DIFF. OF USE	TOTAL SCORE
	STATIC	DYN.	UNFLUSH	FLUSHED	UNFLUSHED STRANDS		CORR. RATE	STRAND PROTECTION		CORR. RATE	AMB.	DEION WATER	3.5% NaCl SOL'N	HEALTH	FLAMM.	REACT.			
					OUTER	INNER		OUTER	INNER										
IMPORTANCE	20	20	12.5	12.5	6	2	2	3	1	1	2.5	1.5	1.5	2	2	2	5	4	100
L1	6.28	3.75	0.48	1.44	9.75	1.00	7.86	1.00	0.50	5.46	4.50	7.0	6.75	7.50	7.50	10.0	8.89	5.0	
	126	75	6.00	18.0	58.5	2.0	15.7	3.00	0.50	5.46	9.00	10.5	10.1	15.0	20.0	44.5	20.0		
L2																			
L3																			
L4																			
L5																			
L6																			
L7																			
L8																			
L9																			
L10																			
L11																			
L12																			
L13																			
L14																			

Table 7.6 Decision Matrix for Lubricant Selection

Alternative	Friction Reduction		Effect on Adhesion		Temporary Corrosion Protection									Safety Hazards			Lub. Cost	Diff. of Use	Total Score
	Static	Dyn.	Unflush.	Flushed	Unflushed Strands			Flushed Strand			Unflushed Wires			Health	Flamm.	React.			
					Strand Protection		Corr. Rate	Strand Protection		Corr. Rate	Amb.	Deion. Water	3.50% NaCl Sol'n.						
					Outer	Inner		Outer	Inner										
Importance	20	20	12.5	12.5	6	2	2	3	1	1	2	1.5	1.5	2	2	2	5	4	100
L14	5.41	5.41	7.54	9.70	0	0	0	0	0	0	0	0	0	10.0	10.0	10.0	6.70	10	565
	108	108	94.3	121	0	0	0	0	0	0	0	0	0	20.0	20.0	20.0	33.5	40.0	
L13	6.81	5.45	4.95	9.60	0	0	0	0	0	0	0	0	0	10.0	10.0	10.0	5.50	9	550
	136	109	61.9	120	0	0	0	0	0	0	0	0	0	20.0	20.0	20.0	27.5	36.0	
L5	8.61	5.58	0.52	0.94	5.00	9.00	7.22	1.00	0.50	5.46	3.50	10.0	9.40	10.0	7.50	10.0	8.81	5.00	529
	172	112	6.50	11.8	30.0	18.0	14.4	3.00	0.50	5.46	7.00	15.0	14.1	20.0	15.0	20.0	44.1	20.0	
L11	7.21	5.58	1.60	2.02	3.75	8.50	8.86	1.00	0.00	8.23	1.75	9.90	8.75	7.50	7.50	10.0	9.24	5.00	517
	144	112	20.0	25.3	22.5	17.0	17.7	3.00	0.00	8.23	3.50	14.9	13.1	15.0	15.0	20.0	46.2	20.0	
Bare Strand	2.33	2.33	7.94	10.00	1.00	1.50	5.46	1.00	1.50	5.46	2.75	4.50	4.00	10.0	10.0	10.0	10.0	10.0	516
	46.6	46.6	99.3	125	6.00	3.00	10.9	3.00	1.50	5.46	5.50	6.8	6.00	20.0	20.0	20.0	50.0	40.0	
L2	6.28	3.70	0.14	2.26	8.75	10.0	5.46	1.00	0.50	5.46	3.50	9.65	9.25	10.0	7.50	10.0	8.58	5.00	475
	126	74.0	1.75	28.3	52.5	20.0	10.9	3.00	0.50	5.46	7.00	14.5	13.9	20.0	15.0	20.0	42.9	20.0	
L3	5.58	3.72	1.44	2.70	5.00	10.0	6.67	1.00	2.00	5.46	3.50	9.00	9.90	10.0	7.50	10.0	8.63	5.00	465
	112	74.4	18.0	33.8	30.0	20.0	13.3	3.00	2.00	5.46	7.00	13.5	14.9	20.0	15.0	20.0	43.2	20.0	
L1	6.28	3.75	0.48	1.44	9.75	1.00	7.86	1.00	0.50	5.46	4.50	7.00	6.75	7.5	7.50	10.0	8.89	5.00	454
	126	75.0	6.00	18.0	58.5	2.00	15.7	3.00	0.50	5.46	9.00	10.5	10.1	15.0	15.0	20.0	44.5	20.0	
L8	6.51	4.65	0.00	2.12	5.00	5.50	5.65	1.00	0.00	5.46	3.50	9.00	8.50	10.0	10.0	10.0	5.41	5.00	451
	130	93.0	0.00	26.5	30.0	11.0	11.3	3.00	0.00	5.46	7.00	13.5	12.8	20.0	20.0	20.0	27.1	20.0	
L4	5.58	3.72	0.29	1.16	5.00	10.0	7.22	1.00	1.00	5.46	4.50	9.95	9.40	10.0	7.50	10.0	8.53	5.00	434
	112	74.4	3.63	14.5	30.0	20.0	14.4	3.00	1.00	5.46	9.00	14.9	14.1	20.0	15.0	20.0	42.7	20.0	
L9	5.12	2.77	0.00	0.00	9.75	10.0	7.86	1.00	10.0	5.46	9.75	10.0	10.0	7.50	7.50	10.0	3.12	2.00	394
	102	55.4	0.00	0.00	58.5	20.0	15.7	3.00	10.0	5.46	19.5	15.0	15.0	15.0	15.0	20.0	15.6	8.00	
L10	0.00	0.00	3.82	9.39	5.00	0.50	6.35	5.00	3.00	6.54	2.75	8.50	6.75	10.00	10.00	5.00	9.36	0.00	359
	0.00	0.00	47.8	117	30.0	1.00	12.7	15.0	3.00	6.54	5.50	12.8	10.1	20.0	20.0	10.0	46.8	0.00	
L6	2.33	0.91	0.46	0.42	5.00	10.0	6.82	1.00	1.00	5.46	4.50	9.95	9.75	10.0	7.50	10.0	7.11	5.00	298
	46.6	18.2	5.75	5.25	30.0	20.0	13.6	3.00	1.00	5.46	9.00	14.9	14.6	20.0	15.0	20.0	35.6	20.0	
L7	0.23	0.86	0.25	0.68	5.00	1.50	3.33	1.00	0.00	5.46	3.50	9.80	9.70	7.50	7.50	10.0	6.33	5.00	219
	4.60	17.2	3.13	8.50	30.0	3.00	6.66	3.00	0.00	5.46	7.00	14.7	14.6	15.0	15.0	20.0	31.7	20.0	

7.2.7 Matrix Evaluation of Candidate Lubricants. The final matrix evaluation is shown in Table 7.6. The alternatives were placed in descending order according to their total scores. The two lubricants, L14 graphite and L13 soap, scored the highest (about 10 percent better than base strand) even though given arbitrary scores of 0 on the temporary corrosion protection values. Only water soluble oil (L5) score better than bare strand and even then only slightly better.

The performance of bare strand came out well 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 and normal friction. Clearly it is better than many of the alternatives proposed.

7.3 Recommendations.

Table 7.7 Top Four Lubricants.

Lubricants		Total Score
(1.)	L5	529
(2.)	L11	518
(3.)	L2	475
(4.)	L8	451

Table 7.7 shows the four water soluble oil lubricants that were recommended by Tran [9] for use in the large-scale friction tests that were a part of this overall project.** Excepting L13 and L14, 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 for the large-scale friction tests because L3 changed its formulation recently 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 [26] and would more than likely go unnoticed in post-tensioning operations. None of the other lubricant formulations have changed during this research.

** The L13 soap and L14 graphite flakes were added later by Davis [10]

It is interesting to note that the top four water soluble oil 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.

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. 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 initially 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. Subsequently two additional lubricants were identified (a soap and powdered graphite). These were added to adhesion and small-scale friction tests but not the corrosion protection series. 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. Inclusion of the two supplementary materials (L13 and L14) indicated superior performance.

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. Nine of the twelve lubricants reduced friction while three of the lubricants increased friction. The reductions in static friction varied up to 27% while the increases varied up to 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.

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 tested 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 unflushed lubricants except graphite essentially destroyed the adhesion between a single seven-wire strand and the hardened cement grout. For the water soluble oils, on average the reduction in adhesion was 90%. Results for pull-out tests using lubricated strands which had been generously flushed indicated the soap and graphite had minimal effect on slip load when flushed, but that for the water soluble oils even with flushed specimens the average reduction in adhesion was still approximately 75%. The sodium silicate solution 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 20 to 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. The presence of a flushed or unflushed lubricant thus might substantially reduce the development of a bonded tendon.

8.3 Recommendations.

Four water soluble oil lubricants were 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%. However, even when given zero rankings on corrosion protection, powdered graphite (L14) and a soap (L13) 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. They were also investigated in the full-scale tests to be reported subsequently.

If bonding of the tendons or stay is not important, 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 herein, 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 or in cable stays. However, it is felt that all five of these lubricants could easily provide excellent corrosion protection of ungrouted tendons or stays 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 report 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 identified was a biodegradable soap called Aqualube MX (L13). This product has shown to provide slightly more friction reduction than Lubricant L2, and to perform well after flushing in adhesion tests. Another possible lubricant was graphite powder (L14) which has been used in the field for friction reduction with multi-strand tendons. L14 performed very well in both friction and adhesion tests.

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, as report in Ref. 7, indicated that a flushed lubricant may 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.

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