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Bond and Corrosion Studies of Emulsifiable Oils Used for Corrosion Protection in Post-Tensioned Tendons

By Edwin Salcedo-Rueda[1], Andrea J. Schokker[2], John E. Breen[3], and Michael E Kreger[4]

ABSTRACT: Ideally during post-tensioned construction the grouting occurs soon after stressing of the strands. Occasionally, tendons may not be grouted within weeks or even months after prestressing. In these cases, the strand may need temporary corrosion protection. Emulsifiable oils have been used to provide a protective film for the strand. These oils also reduce friction losses during post-tensioning. While the corrosion protection may increase, the bond between the strand and grout is likely to decrease. Flushing the tendons with water is ineffective in removing the oils and may entrap water in the tendon. The behavior of the grouted tendon with oiled strand likely lies between the fully unbonded and fully bonded case. In cooperation, the Pennsylvania State University and the University of Texas at Austin developed a study to locate products that provide adequate corrosion protection while minimizing the bond loss. This document presents results from the study at Penn State University that included corrosion exposure tests and a small-scale pullout test for bond. Promising oils from this study will undergo large-scale testing at the University of Texas.

KEYWORDS: Bond, Emulsifiable Oils, Corrosion, Pullout, Post-tensioning, Grout

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1. INTRODUCTION

The post-tensioning industry has a need for temporary corrosion protection of PT (post-tensioned) tendons, and in many projects emulsifiable oils or spray-on corrosion inhibitors may be used. The dilemma that the owner faces is the lack of test data on the effects of these corrosion protection oils. In post-tensioned structures, cementitious grout is injected inside the tendons to provide an ideal surrounding with an alkaline environment. This environment provides protection against corrosive agents. In some cases, tendons may not be grouted for weeks or even months after prestressing. Grouting delays are usually a result of harsh environments with extreme temperatures, long construction periods, and/or staged construction. The steel is vulnerable to atmospheric moisture and infiltrating water (including saltwater in coastal areas): elements that can hinder the integrity of the system by creating a corrosive environment. When extended grouting delays are part of the construction planning, additional anticorrosive measures are put into action. Emulsifiable oils are one of many possibilities to provide corrosion protection to the post-tensioning steel in the tendons during unprotected periods. Emulsifiable oils are commonly used in the field, and they are usually directly applied to the steel before it is placed in the duct creating a protective film.

This investigation was intended to fill a need for information on the use of these products. The main objective of this study was to find good quality emulsifiable oils that produce the least detrimental effects on bond between the post-tensioning steel and grout, in addition to good corrosion inhibiting properties. Phase I of the research program conducted at Penn State is described in this paper. It included corrosion exposure tests and an adapted PTI/ASTM grouted single-strand pullout test. Oils showing promise in Phase I were moved to Phase II at the University of Texas at Austin: large scale post-tensioned beams to examine bond and ultimate flexural capacity of structural members.

Promising products were recommended from Phase I testing to proceed to Phase II testing. These recommendations were based on performance from the pullout and corrosion exposure tests. This paper presents the Phase I research program in detail.

2. SCOPE OF RESEARCH

There were two primary tests performed: the first was the exposure of oiled strands to three environments, and the second was a small-scale bond test utilizing a modified version of a pullout PTI/ASTM standard test. The process was generalized in three subcategories: a) Oil selection process, b) Corrosion exposure test, and c) Pullout test. Each are described in detail in this section.

2.1. Oil Selection Process

A report by Kittleman et al.[1] is the primary study in the United States about temporary corrosion protection agents used for post-tensioning applications. This report provided a starting point for the current study. Additionally, a nationwide web-based survey was developed to determine current products, field practices, and standards on the subject from manufacturers, contractors, and governmental institutions. Oil manufacturers were also contacted individually to determine if any oils they had in production might be suitable for the PT industry. A final list of eighteen oils available in the U.S. was selected as well as a product from Europe that had shown promise in a Swiss study[2]. These oils are shown in Table 1.

Oil 1 (O 1) : Anticorit AQ 31	Oil 11 (O 11) : Nox-Rust 707
Oil 2 (O 2) : Citcool Concentrate 33	Oil 12 (O 12) : Rheocrete 222+
Oil 3 (O 3) : Cutting Oil NC 205	*Oil 13 (O 13) : RustBan 310
Oil 4 (O 4) : Dromus ABD	Oil 14 (O 14) : Rustphree 4746 A
Oil 5 (O 5) : Emulsifiable Cutting Oil	Oil 15 (O 15) : Rust-Veto 342
Oil 6 (O 6) : 5-Star Protective Coating	Oil 16 (O 16) : Rust-Veto FB 20
Oil 7 (O 7) : Hocut 4284-B	Oil 17 (O 17) : Tectyl 810
Oil 8 (O 8) : Hocut 795	Oil 18 (O 18) : VpCI 377
Oil 9 (O 9) : Lubrol 215 B	**Oil 19 (O 19) : VpCI 389
Oil 10 (O 10) : Nox-Rust 703D	

* Product from European Study
**Diluted oil O 19D in Fig. 6 is same oil as O19 (dilution 5:1 water to oil ratio)

***Table 1** - List of Oils Tested

Many factors influence the performance of the oils in this study. Discussions with users in the PT industry showed a wide variance in the proportion of water mixed with the oil (if any). Due to the uncertainties of water influence (i.e. hardness), the oils investigated were not mixed with water to limit variability and they were applied onto the post-tensioning steel directly. For this study, the absence of water in the emulsion prevented additional variability and it also provided the worst case for bond losses.

2.2. Corrosion Exposure Test

Three distinct environments were chosen to represent possible field conditions for long-term corrosion testing of the oil's protection properties. Another factor that may affect the oils is microbiologically influenced corrosion; therefore, providing an environment where microorganisms can flourish was an additional parameter taken into account.

The three environments chosen for the study were:

1) Environment 1: Outdoor exposure including a Pennsylvanian winter that later proved to be the worse winter in the last four years,

2) Environment 2: Control temperature 73°F (23°C) at 95% relative humidity (RH), and

3) Environment 3: Semi-control temperature, variable relative humidity and in direct contact with a 5% NaCl diluted water solution.

Environment 1, the Pennsylvanian outdoor exposure provided a harsh environment that can be comparable to the northern states of the country. Some oils may break down in very cold conditions. Environment 2, warm temperature and high humidity levels was comparable to atmospheric characteristics of some southern states, and in addition the environment was conducive to microorganism development. Finally, Environment 3 was representative of the possibility that during construction harmful intrusive agents (i.e. saltwater) migrate inside ungrouted tendons. For each oil, the established testing program had three specimens in each environment for repeatability (a total of 177 specimens). The time of exposure was six months for all specimens.

2.3. Single Strand Small-Scale Pullout Test

The testing program incorporated a PTI/ASTM (ASTM A 981-97) grouted single-strand standard pullout test. Several pullout test studies have been performed for bond in pretensioning applications; however, little research has been done on pullout and bond tests in relation to PT applications. The research team decided to utilize a standard test for the foundation of the study. Development of a new test or bond model that could replicate the actual behavior of post-tensioned structural elements proved to be difficult without the use of large-scale tests. The PTI/ASTM grouted single-strand standard test was first developed to assess the bond of 0.6 in. (15.24 mm) diameter strand when used for ground anchors, and later to evaluate strand surface condition.[3,4]

For the present study, changes were made to the original procedures of the pullout test. The first change established was to consider complete bond rupture at 0.1 in. (2.54 mm) of strand displacement, rather than at 0.01 in. (0.254 mm) as suggested by ASTM standards. This value was recommended by Russell et al.[3,4] in a report for the North American Strand Producers Association (NASP). The other major change to the standard test was the use of a mechanical restraint designed at Penn State University to decrease the tendency of the strand to rotate while it was being pulled. This mechanism allowed longitudinal displacement of the strand but it prevented the strand from rotating while it pulled out. The pullout test presented in the Kittleman et al.[1] report, allowed significant twisting of the strands as they were being pulled that would be uncharacteristic of an actual PT strand where significant twisting is inhibited by the anchored wedge. The mechanical restraint developed did not provide full restraint against rotation of the strand, but it provided adequate restraint at early stages of the test when the load had not reached extreme values. Both mechanical interlock and the chemical bond between the grout and strand are significant in the overall bond capacity of a pull-out specimen; however, the mechanical interlock is expected to take a more critical role as the chemical bond decreases due to the application of oils.

After considering the different aspects of the pullout test, a testing program was developed as follows:

1) Preliminary testing of each oil of two specimens to be tested with the mechanical restraint,
2) A minimum of six non-oiled strand specimens were tested with the mechanical restraint and six without it,
3) Additional testing was performed for tests with larger variability and for oils showing the most promise for moving to Phase II (large-scale testing).

3. RESEARCH OBJECTIVES

The primary objectives of the proposed research program to be completed at Penn State were:

1) To identify commercially available emulsifiable oils that can provide good or excellent temporary corrosion protection for strands in post-tensioned tendons,
2) Determine the extent of bond reduction caused by these oils in pull-out testing, and
3) Select candidate products to be used for large-scale testing.

After the combined research program is finished, the collective effort between the two universities will ultimately establish to what extent bond strength reduction is caused by the selected oils, how they affect the flexural capacity and behavior of a structural post-tensioned concrete element, and the development of recommendations for new design specifications or code provisions to account for reduction on friction losses and flexural capacities of post-tensioned structures when the use of emulsifiable oils is to be expected. This investigation provides the first steps toward a better understanding of the actual behavior of post-tensioned structures when constructed with the latest technology with respect to emulsifiable oils for corrosion protection.

4. RESEARCH PROGRAM

4.1. Corrosion Exposure Tests

The corrosion tests exposed post-tensioning steel strands to three different environments to simulate conditions where the strands might be exposed to harmful elements in tendons during ungrouted periods.

The program consisted of nine specimens per oil tested in addition to non-oiled control samples. The specimens were monitored once a month (30 days) for a total exposure period of 6 months (180 days). Corrosion progress reports were maintained during the exposure period. After the exposure period ended, corrosion products were removed and the extent of corrosion was determined for each specimen.

4.1.1. Testing Program

Oils were blown onto the strand utilizing a cup sprayer. The oiled strands were left untouched for one week (7 days) without being exposed to their corresponding environment. During this week the specimens are indoors, and uncovered exposed to semi-controlled temperature and relative humidity.

Fig. 1 displays the two different specimen types used for the three investigative environments. Steel strand was placed inside PVC tubes with holes and the edges sealed with slip end caps. The holes allowed oxygen ingress simulating a tendon in the field that has not been fully capped and sealed after stressing. Plastic star shaped spacers were fitted inside the tubes to center the strand within the PVC tube.

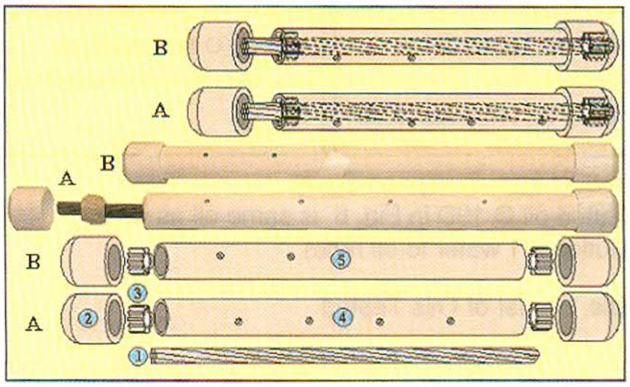

Fig. 1 - Long-Term Corrosion Specimens

For Environment 3 the evaporated salt water solution was refilled every 2 weeks (14 days) to simulate worst case conditions where salt water is rechargeable. The specimens for the other two environments were left untouched until inspection of the strand was required. Corrosion and surface changes were checked every month for six months and detailed information about the corrosion observed was recorded as per the rating system shown in Table 2. Specimens were coded and a *"blind"* inspection procedure strictly followed the rating system to determine levels of corrosion. After six months of exposure the specimens were taken out of their environment for final corrosion evaluation.

Rating	Description
1	As received from manufacturer and completely clean from any corrosion products
2	No signs of corrosion at any level, or there might be small spots of rust material present
3	Small blisters, superficial but widely spread corrosion, pitting is unusual
4	Small blisters, uniform corrosion or initial signs of wide pitting in centralized areas
5	Large blisters, trail of blisters does not exceed 2-in. (51-mm.), deep and wide pitting is visible, corrosion products and pitting does not affect more than 50% of steel area
6	Large blisters, trail of blisters along the strand exceeds 2-in. (51-mm.), deep and wide pitting cover most of the strand surface, corrosion products and pitting affect over 50% of the steel surface, and several forms of corrosion are present simultaneously
7	High levels of corrosion with visible large areas of steel lost

Note: Rating system is precise to ± 0.5 (i.e. borderline specimens may receive ratings of 2.5, 3.5, 4.5, etc.)

Table 2 - Rating System for Corrosion Tests

4.2. Pullout Test

Characterization of the effects on bond between the grout and oiled steel strand was the main objective of the study. Bond losses due to the use of EOs may impact how structures are designed in the future. Due to logistics and economics, large-scale tests could only be performed on a few promising products. Therefore, a qualitative approach using the small-scale pullout test was developed. Although the pullout test did not fully mimic actual behavior in a continuous post-tensioned member, it was a valuable tool for qualifying oil performance for the large-scale testing phase.

The adopted pullout test was first outlined by PTI in their guide specification *"Recommendations for Prestressed Rock and Soil Anchors,"*[5] and later adopted by ASTM standards as ASTM A 981 - 97. The adopted procedures were modified to prevent twisting of the strands and facilitate constructability of the testing frame. This test provided sufficient data for a comparative study between specimens tested. The recorded data provided the forces at corresponding strand displacements.

4.2.1. Testing Program

The program consisted of two specimens per oil, and the results were compared with six specimens without any oil on the strands. Prior to casting the specimens, the post-tensioning steel was checked for any considerable corrosion. The post-tensioning steel used was 0.5 in. (12.7 mm) diameter; Grade 270 low-relaxation strand and complied with ASTM A416 Specifications. All the specimens tested were cut from the same spool to avoid variations with the steel pitch and other properties that may have caused variability for bond.

The EOs were sprayed onto the strands twenty four (24) hours prior to casting of the specimens; but, without exceeding the thirty six (36) hour window. The 24 hour minimum allowed the oils to adhere to the steel prior to grouting. Studies in Switzerland showed that grouting prior to drying can have a significant effect on bond2 For research purposes, it was determined that undiluted oils would produce the maximum impact on bond reduction between the grout and steel due to the major content of oil particles in the solution.

Each cylinder specimen consisted of a 46 in. (1169 mm) long strand embedded in cement grout and centered inside a steel pipe, with a base plate welded on one end. A typical cylinder specimen is provided in Fig. 2. A 2 in. (50 mm) long debonded segment of the strand is created from the base plate edge towards the grouted section in the steel cylinder. The specimens were cast and cured in a vertical position to accomplish full contact between the grout and the strand along its entire length. A grout mixture of Type I portland cement with a 0.45 water to cement ratio was used for casting. Additionally, a minimum of three cubes 2 x 2 x 2 in. (50 x 50 x 50 mm) were made according to specification ASTM C 1019 for strength testing.

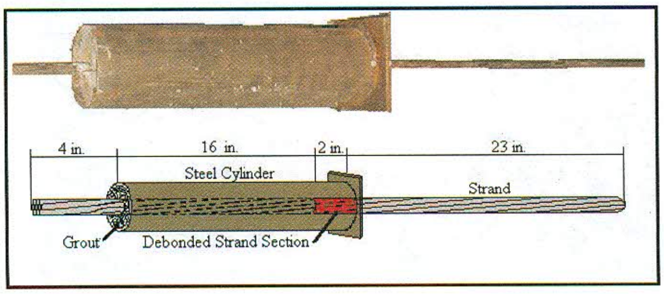

Fig. 2 - Pullout Specimens

The specimens were moist cured in accordance to specification ASTM C 511 at a 74 ± 3°F (23 ± 1.7°C) temperatures with a minimum 95% relative humidity until the specified grout compressive strength of 4000 psi (28 MPa) was reached. When the strength was reached, the pullout test was performed on those specimens. Preliminary strength tests proved that the grout reached or exceeded the minimum strength at fourteen days curing.

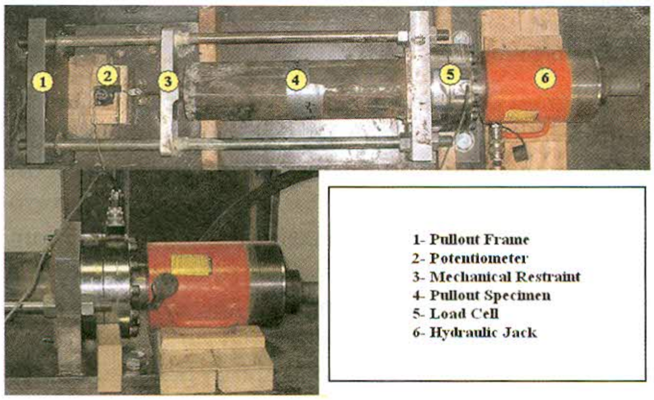

Fig. 3 - Pullout Testing Frame Setup

The cylindrical specimens were mounted on the testing frame as shown in Fig. 3. With the specimen base plate fully attached to the frame, the free strand protruding from the base plate was gripped by an adapted PT chuck attached to a 60 ton hydraulic jack with a 3 in. (75 mm) stroke that provided the mechanical pulling force on the strand. A load cell monitored the loading applied to the specimen. The additional free strand projecting from the grouted end was restricted by a chuck and a mechanical device on the testing frame. Figs. 4 and 5 illustrate close-ups of the testing setup. The mechanical device allowed longitudinal movement of the strand with minimum resistance; while partially restricting the twisting effects produced by the mechanical interlocking of the wires when a strand was being pulled out. A potentiometer with a maximum extension of 2 in. (50 mm) measured the translational displacement of the *"semi-free end"* on the cylindrical specimen.

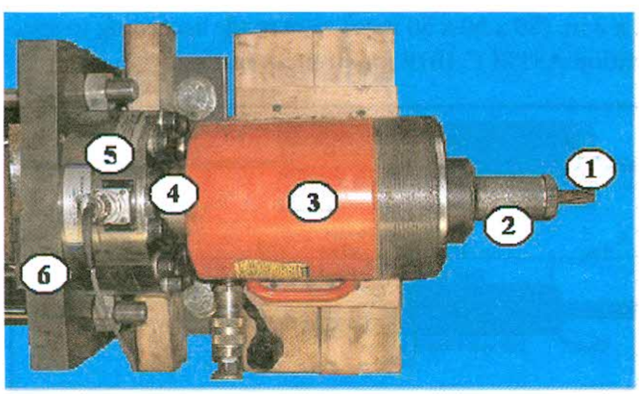

Fig. 4 - Front Frame Setup Close Up

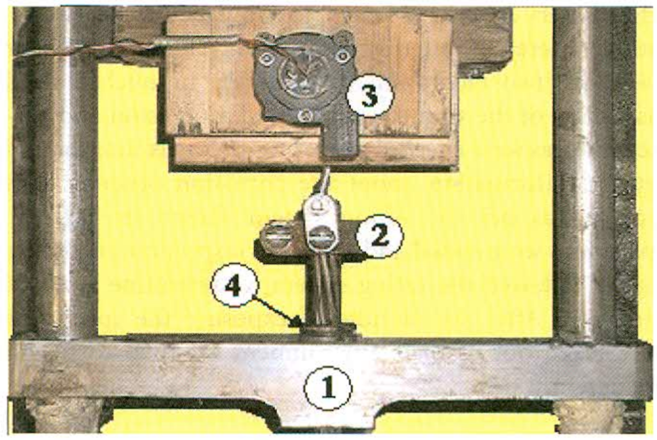

Fig. 5 - Back Frame Setup Close Up

Prior to starting the testing, a minimum force was applied to let anchorage seating occur. The loading was then increased until the displacement of the strand on the unloaded side reached 0.1 in. (0.25 mm). A load-displacement curve was recorded for each specimen and archived in a personal computer. The data collected was later analyzed and DasyLab™ software was used to filter the noise in the data.

5. RESULTS

5.1. Corrosion Exposure Test Results

The corrosion testing, by nature, may not be directly interpolated to service life. The corrosion study was a subjective study, and the research team understood the limitations of the procedures from the start. Therefore, the rating system shown in Table 2 has clearly defined categories to limit the subjectivity during the monitoring periods. The rating was random so the examiner did not develop a bias toward any particular specimen set.

Table 3 and Fig. 6 report the final corrosion ratings for the specimens in all three environments. The data shown in this table and figure correspond to the average rating values of the specimens from each environment.

Environment	NO	O 1	O 2	O 3	O 4	O 5	O 6	O 7	O 8	O 9
1	3.00	3.67	3.67	3.00	2.33	2.17	4.00	3.33	2.83	2.83
2	3.67	3.67	3.67	3.00	2.33	3.33	4.00	3.33	3.00	3.00
3	5.33	4.33	7.00	3.83	3.00	3.67	4.33	4.67	5.67	4.33
Environment	O 10	O 11	O 12	O 13	O 14	O 15	O 16	O 17	O 18	O 19
1	2.00	3.67	4.00	2.00	3.17	3.17	2.83	2.67	2.33	3.33
2	2.67	4.33	4.50	2.33	4.50	3.00	3.00	3.33	4.33	4.00
3	3.67	5.67	5.17	2.33	3.00	4.67	4.00	4.00	4.67	4.00

Table 3 - Final Corrosion Rating Stage

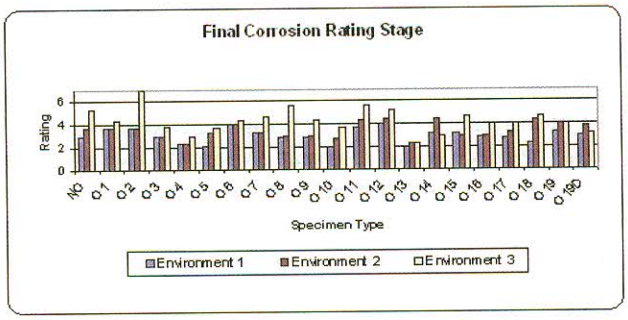

Fig. 6 - Corrosion Rating Results for Final Stage

In Fig. 6, the oiled specimens O 19D and O 19 are the same oil; however, O 19D was in a diluted form. The dilution of this oil was mixed because this product was very difficult to spray onto the strands since it has a thick consistency, and the use of its diluted form was recommended by a state Department of Transportation with experience using the product. The oil to water dilution ratio was 5:1; this ratio was based on a recommended range of ratios provided by the manufacturer of the product.

Specimens for oils O 3, O 4, O 5, O 9, O 10, O 13, O 16, and O 17 received lower rating values for all three environments in comparison to those assigned to the control specimens (NO). This group of oils had the best performance out of all the specimens. The other oiled specimens had at least one rating value worse than those given to the control specimens. From the collected data it was established that the majority of the oils behaved well up to three months of exposure, but after three months a break down occurred in many of the oils' level of protection and the rating values worsened.

The growth of mold on one of three specimens exposed to Environment 2 for oil O 12 was observed. The growth of mold can result in the development of microbiologically induced corrosion, but this investigation did not cover this topic, therefore future studies should consider this possibility in the testing program. This type of corrosion would be pronounced in stressed strand specimens.

For the recommendations to the research team at the University of Texas, a base line parameter was established to provide the best set of products tested in this investigation. After several considerations the higher bound parameter of 4.0 for corrosion rating was established. This means that for any oil to be recommended for the second phase of the study, the oil's corrosion ratings shall not exceed the established bound value. The bound value was set based on the description in Table 2 and the observed corrosion levels from the specimens. It was decided that higher levels of corrosion would not be acceptable in the construction industry for use in PT tendons.

5.2. Pullout Test Results

Twelve control specimens were tested: six of these specimens were pulled out utilizing the mechanical restraint (NO-R) and the other six were pulled out without it (NO). The pullout force at 0.1 in. (2.54 mm) of strand slip was presented as the criteria for evaluation as recommended by the North American Strand Producers Association (NASP).[3,4] In the event that the ultimate load was recorded prior to 0.1 in. (2.54 mm) strand slip displacement, that higher load value was used.

It was observed that after an ultimate value was reached during pullout procedures, the strand forces dropped drastically and it did not develop a similar ultimate force later on. The pullout graphs for oiled specimens show that the load at 0.1 in. (2.54 mm) strand slip was considerably lower than those obtained from the control specimens. In some cases the ultimate value reached by oiled specimens was close to the control set values with much higher displacements of the strand. Other oils performed very poorly with very low load values, below the precision ranges of the load cell (less than 1 kip).

The grout strengths recorded had a range from a minimum value of 4813 psi (33.2 N/mm^2) to a maximum value of 6270 psi (43.2 N/mm^2). The maximum value of the pullout test results was 19.1 kips for a specimen in the control set NO, and the minimum value was less than 1.0 kip that occurred in two occasions, the first for oil set O 15 and the second for oil set O 19. The control specimen sets NO-R and NO had coefficients of variance of 19.6% and 16.4% respectively. The lowest coefficient of variance was obtained by specimen set O 6 (7.6%), followed very closely by specimen set O 13 (9.2%). The largest coefficient of variance was achieved by specimen set O 2 (76.1%) followed by specimen set O19 (75.6%).

The research team developed a variability and precision study to find the validity of repeatability for all the specimen sets. This study was based on standard practice ASTM C 670 - 96, *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials.* The standard provided guidance in preparing precision statements for ASTM test methods to certain construction materials. This investigation adopted one to develop a variability study on the pullout test results. More specifically statements 3.3.1 - "*Acceptable difference between two results*," and 3.3.2 - "*Acceptable range of more than two results*," were the basis for this variability study. The main purpose of the study was to decide if the results obtained were within acceptable difference.

Fig. 7 shows the data from the pullout test for the oils that showed potential in the corrosion testing. The figure also shows load values (kips) for each column and in parenthesis are the corrosion ratings for Environment 3. This figure illustrates the final results for the pullout-testing program from the selected oils after the statistical study was performed on the data. Fig. 8 shows the results from Fig. 7 expressed as percentage of the control set NO-R indicating variable bond reduction from 31% to 65%. From these tables, the best candidates were recommended for Phase II large-scale testing to be performed in Texas.

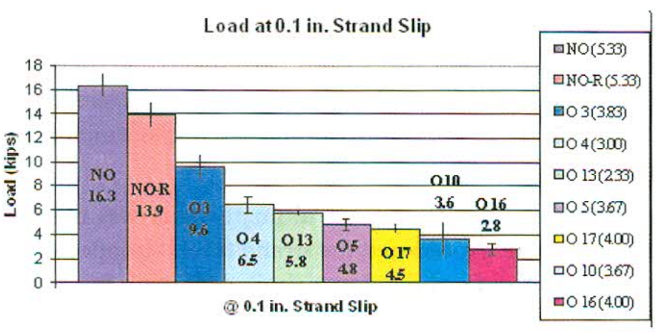

Fig. 7 - Pullout Bond Results of Selected Oils

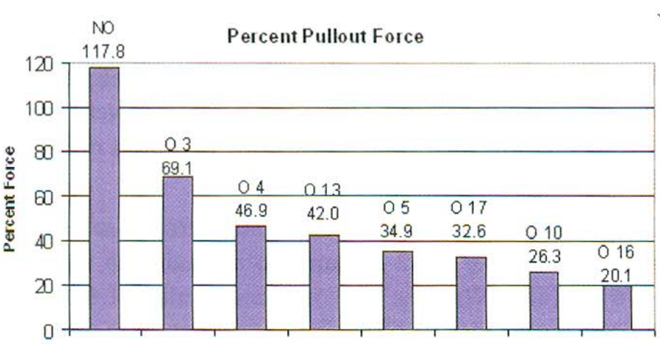

Fig. 8 - Pullout Bond Results Expressed as Percentage of Control Set

In the results, variability increased as the load development increased. Specimen sets that developed loads higher than 6.0 kips (26.7 kN) had wider spread test results compared to those specimen sets with lower load results. Possible explanations for this behavior include the following:

1) Oil residue deposited in the interstitial crevices of the strand may impede good mechanical interlocking development between strand and grout. When a particular oil leaves residue, the grout may not penetrate deep into the crevices of the strand, and therefore the mechanical interlocking was not developed properly. It was observed that oils with a considerable thick film on the strand had low bond capabilities.
2) The mechanical restraint may have different effects at different load levels. The mechanical restraint was devised to prevent twisting of the strand while being pulled out of the specimen, but the restraint may only work up to certain loads. The main factor of twist prevention was the friction developed between the wedge and the mechanical restraint. When the twisting force reached the maximum friction force from the mechanical restraint, the wedge tended to push out the restraint releasing the force and allowing the strand to slip more rapidly.
3) The oiled specimens with relatively better bond allowed for the force to build up until it suddenly released due to a failure. From the plots of load vs. displacement, the behavior between a set of a particular oil specimens may be the same. However, one of the specimens may have a sudden release of force slightly before or after the 0.1-in. (2.5-mm.) slippage point causing the appearance of large variability at higher loads. The sudden load release may cause the disparity even though the ultimate load failure has not been reached. In most cases the oils with good bond developed the same ultimate load as the non-oiled counterparts but at a much larger end displacement. This is probably not the case for the lower loads because those oils broke the bond between the grout and the steel immediately causing a constant slippage without sudden load releases.

The use of mechanical restraint lowered the ultimate load approximately 18%, but the variability for the two sets of data was roughly close from one to the other, where NO-R had a coefficient of variance of 19.6% and NO had a coefficient of variance of 16.7%. However, if one of the test data results was taken out (as an outlier that may have been accidentally overloaded during the preload stage) the arguments vary as follows: the use of the mechanical restraint lowered the ultimate load approximately 14%, but the variability of NO-R was nearly one half of that obtained for NO, where NO-R had a coefficient of variance of 7.4% and NO had a coefficient of variance of 13.6%. The researchers feel even though the use of the mechanical restraint appears to have lowered the ultimate load developed, its use provided more standardized and consistent results.

6. CONCLUSIONS

6.1. Conclusions from Corrosion Testing Program

1. Six out of the eighteen tested emulsifiable oils available in the U.S. market provided adequate temporary corrosion protection when applied onto prestressing strand. The oils considered as adequate for temporary protection were O 3, O 4, O 5, O 10, O 16, and O 17. The performance of such oils was based on a corrosion rating system developed by the investigating team. The corrosion program included three environments: central Pennsylvania outdoor exposure, control temperature 73°F (23°C) and relative humidity (>95%RH) exposure, and salt water (5%NaCl distilled water solution) exposure. The program called for monthly ratings for a period of six months of exposure.

2. The salt-water exposure environment proved to be the harsher environment for the majority of the oils tested. 53% and 58% of the oils tested were considered to provide adequate corrosion protection to the strand for the outdoor exposure and the control temperature and relative humidity exposure respectively. Only 42% of the oils provided adequate corrosion protection to the strand when exposed to salt water.

3. Oil sets O 2, O 8, O 12 and O 11 showed poor corrosion protection in the salt water environment when compared to the control set of bare strand. Oil sets O 6, O 11, O 12, O 14, O 18, and O 19 showed poor corrosion protection in the controlled temperature and relative humidity environment when compared to the control set of bare strand.

4. Oil set O 12 showed the growth of mold after two months of exposure in the control environment. The growth of mold may point to the possibility of microbiologically induced corrosion. This investigation did not include microbiologically induced corrosion testing, thus future studies should consider such testing with tensile tests of prestressing strand to observe any effects of the development of microorganisms around the strand caused by the use of emulsifiable oils. While only oil O 12 showed visible evidence of mold (on only one of three specimens), other strands may have been influenced by a similar phenomenon without visible evidence.

6.2. Conclusions from Pullout and Bond Testing Program

1. For this particular testing program, the use of emulsifiable oils on post-tensioning steel caused a bond reduction varying from 31% to 97% compared to non-oiled results. The pullout and bond testing was a qualitative comparative program, meaning the test was not a genuine representation of how an actual post-tensioned element behaves at the steel level. However, the program provided sufficient information to assess the effects on bond when the post-tensioning steel was coated with emulsifiable oils. The test called for minimum grout strength of 4000 psi (27.6 N/mm^2) and it was found that the grout mix used for this program reached the desired strength at fourteen days moist curing. The program selected oils (O 3, O 4, and O 5) that provided adequate corrosion protection as the best prospects for testing to be done at the University of Texas. A statistical analysis was performed on the results (ASTM C 670- 96 sect. 3.3.1 and 3.3.2). Bond reduction from the selected oils varied from 31% to 65%.

2. Moderate variability between grout strength, steel contact length, and loading rate did not drastically influence the final results obtained. These parameters had some influence on bond but if the variability remained within the ranges obtained in this investigation, the effects of their influence were minimized. The major parameter influencing the bond was the surface condition of the strand.

3. The oil sets that developed a substantial thick protective film on the strand surface proved to destroy the bond between the grout and steel almost completely and the results showed this behavior. These oils included oil sets O 15 and O 19.

4. The use of the mechanical restraint was found to have two effects on the testing: It was found to lower the ultimate developed load and it was found to improve variability between sample sets.

5. The critical slip value for bond testing should be 0.1 in. (2.5 mm)

   Currently there is a dispute between what point is critical for the single strand pullout test. The test described by PTI and ASTM documents currently suggest the critical displacement value of 0.01 in. (0.25 mm) for recording the developed load.[5,6] The NASP reports suggest changing this value to 0.1 in. (2.5 mm).3,4 This report confirms that the better critical value for the single strand pullout test is 0.1 in. (2.5 mm). It was found that the variability at lower strand slip was significantly larger than the variability at 0.1 in. (2.5 mm). In addition, it was found that non-oiled specimens have a critical bond load failure around this value.

6. According to the NASP results, it was found that specimens that obtain higher average pullout strengths had larger standard deviations. Similar behavior was observed with the results obtained in this study.

7. FINAL RECOMMENDATIONS

The recommended products for Phase II testing including the European product are shown in Table 4 with ratings of 1, 2, 3 or 4 based on how they compared to one another for the different tests performed. The rating of the corrosion testing was based on the average of the final corrosion ratings received for the three environments of exposure. This table also includes the pullout force for each oil expressed as a percent of the pullout force from the control non-oiled specimens. Several products were recommended for Phase II since the pullout test performed in this study was not a true representation of the behavior of a post-tensioned element. The possibility that one oil may perform better than predicted by the findings of this investigation in the large-scale tests may still be present. The European product is of interest to this investigation because it was recommended by a study in Switzerland. Furthermore, the North American post-tensioning industry was considering the importation of such product at a possible higher cost than those available in the U.S. market. This study established that there are adequate products available in North America, which can be used for temporary corrosion protection in post-tensioned tendons with similar characteristics as those available in Europe. The study also provided a significant contribution to the understanding and applicability of emulsifiable oils for this industry.

Oil Name (Manufacturer)	Corrosion Performance (averaged ratings)	Bond Performance (Pullout Force (kips))	Bond Reduction (%)
O 3: Cutting Oil NC 205*(Citgo)	4(3.67)	1(9.6)	30.9%
O 4: Dromus ABD* (Shell/Texaco)	2(2.56)	2(6.5)	53.1%
O 5: Emul. Cutting Oil*(Shore Chemical)	3(3.06)	4(4.8)	65.1%
O 13: RustBan 310**(Esso)	1(2.33)	3(5.8)	58.0%

* Recommended products for phase II

** European product not available in U.S. market.

Table 4 - Final List of Recommended Products

Differences in environment, oil dilution with water, strand manufacturer, etc. may all influence the behavior of the strand in lab testing in the corrosive environment or in the bond testing. This study was intended as a starting point to develop information about the properties of emulsifiable oils. Owners should be aware that a fully sealed, dry tendon may be the best method of protection for many circumstances, particularly in light of the results that indicate the possibility of increased corrosion in particular environment/oil/strand combinations. The tendon, including anchorage and strand tails should be well-protected from the environment between stressing and grouting if delay is expected.

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