

**ACCEPTANCE TESTS FOR
SURFACE CHARACTERISTICS OF
STEEL STRANDS IN PRE-STRESSED CONCRETE**

APPENDIX A: REVIEW OF STRAND BOND LITERATURE

Prepared for
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NCHRP Project 10-62

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TABLE OF CONTENTS

Literature Review	A-1
Description of Prestressing Strand	A-1
Manufacture and Surface Condition of Prestressing Strand - Pre-treatment and Lubrication	A-2
Manufacture and Surface Condition of Prestressing Strand - Residual Film.....	A-4
The Nature of Bond between Prestressing Steel and Concrete	A-5
ACI Code and AASHTO Specifications	A-9
Historical Strand Bond Qualification Tests	A-11
Weigh Strip Method	A-11
Friction Bond Pull Out Test.....	A-11
Electron Optics Test	A-11
PTI Test	A-12
Moustafa Test	A-12
NASPA Test	A-13
Comparison of Large Concrete Block and NASPA Test Methods.....	A-13
Other Pull Out Tests of Tensioned and Untensioned Strand in the Literature.....	A-13
References	A-17
Figures.....	A-21

LITERATURE REVIEW

As part of NCHRP Project 10-62, the relevant practice, performance data, research findings, research in progress and other information related to strand surface factors that affect the bond of prestressing strand have been reviewed. In particular, literature pertaining to high strength steel wire and strand manufacture, wiredrawing lubricants and the residues remaining on the strand surface after manufacture was reviewed in detail.

To better understand the processes and products involved with wire manufacture and to gain ready access to a significant literature base in this area, the project team became a member of *The Wire Association International*. This membership includes a copy of the annual directory and reference guide, and access to abstracts of all articles published in the *Wire Journal International*. The project team also visited a strand production facility and interviewed personnel in the strand production and wire lubricant industries.

An extensive bibliography of relevant literature on strand bond performance has been collected and is provided in Appendix E: Bibliography of Strand Bond.

Description of Prestressing Strand

Prestressing steel as used in precast concrete in the United States is predominately seven-wire strand. Of the seven wires, six outer wires are wound helically around a center, straight wire called the “king wire” (see Figure A-1). The king wire is typically 3 to 5% larger in diameter than the surrounding six wires. This configuration assures that when the strand is tensioned, the outer wires will grip the king wire. Virtually all seven wire strand used in the United States is intended to conform to ASTM A416 Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete. According to ASTM A416-06, strand is available in two grades: 250 and 270. These grade values, 250 and 270, refer to the guaranteed minimum ultimate tensile strength (GUTS) of the strand in ksi. Strand is further designated as normal-relaxation or low-relaxation. The vast majority of strand sold in the United States is 270 ksi, low-relaxation. Strands are available in several diameters. Diameters of 270 ksi strand listed in ASTM A416 are 0.375 (3/8), 0.438 (7/16), 0.500 (1/2), 0.520 (1/2-special), 0.563(9/16), 0.600 and 0.700 in. Diameters are measured across the outermost surface of the wires.

The majority of prestressing strand used in the United States for bridge products has a diameter of 0.500 in. or 0.600 in., designated by ASTM A416 (ASTM 2002) as No. 13 and 15, respectively.

ASTM A779-05 Standard Specification for Steel Strand, Seven-Wire, Uncoated, Compacted, Stress-Relieved for Prestressed Concrete specifies compacted strand (commonly called “Dyform” - where the outer wires are trapezoidal in cross-section) with diameters of 0.5, 0.6, and 0.7 in. This strand is not often used in the U.S.

Beyond the strand types cited by current ASTM standards, at least one strand producer is offering 300 ksi strand in several sizes.

This project is aimed at developing standardized test methods for 0.5-in. and 0.6-in. strand sizes conforming to ASTM A416 or AASHTO M203. It is expected that the findings can be extrapolated to other sizes. A typical process for the manufacture of pre-stressing strand consists of the following steps: 1) steel rod stock is pretreated to facilitate lubrication during drawing, 2) rod stock is cold drawn through progressively smaller dies (typically 6 to 8) until the desired diameter is achieved, 3) the wires are stranded, i.e., six wires are wound around a center wire, 4) the strand is heated under tension to relieve

stresses and stabilize the steel, and 5) the strand is cooled then packaged. An example of such a process is given in the Project Report.

Manufacture and Surface Condition of Prestressing Strand - Pretreatment and Lubrication

The character and quantity of the residual film on the prestressing strand is governed by the pretreatment of the rod, lubricants used during manufacture, and post drawing processes, including stress relieving. The purpose of the pretreatment, which is typically conducted on the spooled rod stock, is to provide a foundation for the drawing lubricants. The drawing lubricants are applied to minimize friction, which dictates the amount of energy required for drawing, and to prolong the life of the dies.

The cleaning and pretreatment performed on the rod stock are critical and influence all remaining steps in the production process. This is because the surface quality of the resultant steel that must be subsequently drawn through the dies governs the lubricant selection and effectiveness.

For strand production, the most common coating applied to rod stock during the pretreatment process is zinc phosphate, which serves as a carrier for the lubricants applied during the wiredrawing process. The phosphating process often consists of some of the following steps: 1) mechanical cleaning, 2) pickling - cleaning in acid, 3) rinsing - using neutralizing lime solution or water to remove all chloride if HCl is used for pickling and 4) activating pre-rinse - a dip in a solution or suspension of titanium phosphate to produce a thinner zinc phosphate layer, and 5) zinc phosphating in a solution that may also contain orthophosphoric acids and sodium nitrate (Wire Industry 1992, Liberati 1994).

The cleaning, i.e. descaling, of the wire may be done mechanically or chemically. Mechanical methods of descaling include reverse bending, belt sanding, or shot blasting. Chemical descaling usually involves a soak in an acid solution and is typically more effective than mechanical methods. As a result, acid baths are common in strand plants, since high carbon steel is difficult to clean using other methods.

Zinc phosphating deposits a thin layer of zinc phosphate crystals on clean wire to act as substrate for dry lubricating soaps and provides a barrier to metal-to-metal contact. The best results are achieved with a dense layer of fine crystals. The phosphating process is influenced by temperature and acidity of the phosphate bath since these factors influence the phosphate solubilities. A longer immersion time will produce a heavier coating (Liberati 1994). It has been observed that zinc phosphate/lubricant coated wires have better corrosion performance suggesting that a residual film may be left on the wire produced with such a pretreatment (Rutledge 1974). Phosphate coatings are themselves difficult to remove (Wire Industry 1992).

Borax and lime may also be used for pretreatment either alone or in combination with zinc phosphate. A fundamental difference between phosphate coatings and other coatings such as borax is that the phosphate reacts with the steel surface to provide the foundation for lubricant while the borax does not. Borax is more likely to be removed during processing than phosphate coatings but is less effective at aiding lubrication (Hajare 1998). Therefore, while a non-phosphate-based process is used in at least one manufacturer's plant for pollution control reasons, that approach is rare. The most common combination of pretreatments is to follow the zinc phosphate treatment with a bath in hot borax solution prior to drying. The alkalinity of borax serves to neutralize acid from the pickling process not removed by washing. However, borax has some disadvantages including its highly hygroscopic nature (absorbs water) (Wire Industry 1992). It should also be noted that both zinc and borax can act as retarders in concrete.

Following the pretreatment processes, lubricant is applied to the wire at each die during the drawing process. Dry lubricants are used exclusively by strand manufacturers in the U.S in the wire drawing process for prestressing strand. The lubricity agent in such lubricants is typically a chemical compound of a metallic element (calcium, sodium, aluminum, potassium, barium and combinations of these) plus a fatty acid (such as stearic acid). The dry lubricants may also contain borates. It is commonly felt that calcium-based dry lubricants provide the lubricating properties needed for wire drawing more cheaply and effectively than any other material.

Powdered wire drawing lubricants are usually classified by their solubility in water. Insoluble lubricants are usually calcium-based, e.g., calcium stearates; partially soluble lubricants are usually mixtures of sodium stearates and calcium stearates; and soluble lubricants are typically sodium stearates. Within each classification, additives are used to modify the properties of the lubricant to a considerable extent. Thickeners or fillers are usually unreactive, fine powders blended into the lubricant base to increase its viscosity, or resistance to flow under pressure at a given temperature. While lime (probably limestone dust in quantities of 30% to 70%) is the most popular thickener additive in general wire drawing lubricants, the choice of thickener depends on the application and the end use of the wire; for example, coatings which must be easily cleaned should contain soda ash, borax or other soluble material. Calcium and sodium sulfate compounds are also potential fillers. Extreme pressure additives are used in dry lubricants to reduce friction and increase die life. Molybdenum disulfide is the most popular of such agents; however, it is relatively expensive and may leave a very slippery and difficult to clean surface on finished wire. Graphite, sulfur, chlorine, and phosphates are also possible additives (Gzesh and Colvin 1999).

One of the key properties that determines which lubricants are most suitable in a given operation is the softening point (melting point) since this governs how the lubricant is applied to the wire and how quickly it is removed during drawing. If the lubricant is too soft at operating temperatures, it may come off before the drawing is complete. If too hard, the lubricant film is not applied uniformly and scratching or feathering (flaking) will result (Gzesh and Colvin 1999). The temperatures generated at the strand surface are determined by the plant configuration including the drawing speed, die geometry and area reduction in each die. As a result, the desirable lubricant properties vary from plant to plant and even die to die. The softening point is determined by the alkali and the fatty acids (such as stearic acid or tallow acids) on which the lubricant is based. The viscosity of the lubricant, which affects the thickness of the coating applied to the steel, is determined by the fat content and filler materials. To minimize the amount of residual film, the ideal lubricant system would be one that, at the plant die operating temperatures, provides a coating of just sufficient thickness to facilitate drawing but which would be nearly all removed from the wire by the dies.

As previously stated, the two most common lubricants are sodium and calcium stearate-based materials. These lubricants are compounds made from sodium hydroxide or calcium hydroxide and a fatty acid (stearic acid) in combination with additives to impart special properties to the lubricant. These materials are soaps (*Ivory* soap, for instance, is 99% sodium stearate) and are supplied in dry form. Calcium stearate typically has a lower softening point than sodium stearate (Gzesh and Colvin 1999).

Calcium stearate at one time may have been more appealing to strand manufacturers because its lower softening point permits calcium stearate to produce a more effective coating on the wire early in the drawing sequence where the rate of draw is slower, and the wire is at lower temperatures. In addition, it is typically cheaper than sodium stearate. As a result, it is not uncommon for calcium stearate to be used for the first one to three drafts (dies) and then sodium stearate to be used for the remainder (Wire Industry 1991). The drawback in the use of calcium stearate-based lubricants is that they are more difficult to remove from the drawn wire since they are water insoluble. In fact, calcium stearate lubricants may be chosen in certain applications (such as nails or coat-hangers) because they leave a residue film which

makes certain subsequent wire processing procedures easier (Platt 1991). On the other hand, sodium soaps or lubricants are “generally used when subsequent operations demand wire that may be readily cleaned” (Wire Association 1980).

The strategy of using calcium stearate in only the first die(s) does not necessarily limit the residual film of the final product. This is because 80% of the lubricant needed is applied in the ripper box (the first die. Subsequent applications of lubricant retards loss but typically does not significantly add to the residual lubricant (Gzesh and Colvin 1999, Wire Association 1980).

The effectiveness of lubricants is also influenced by the pretreatment selected for use during cleaning. For example, insoluble lubricants (calcium and aluminum) are most compatible with both borax and zinc phosphate coatings. Soluble lubricants (sodium and potassium) react with borax pretreatments to such a degree that the film is weaker and adequate lubrication may not be provided (Dove et al. 1990).

When the strand bond problems first began to surface in the U.S. in the early 1990s, one of the causes was thought to be the use of calcium stearates. As a result, North American strand producers reportedly stopped using calcium stearates, at least in the second and subsequent dies. However, it has been reported that European strand producers still use them.

Manufacture and Surface Condition of Prestressing Strand - Residual Film

Residual films are always present after wire drawing (Wire Association 1980). Prior to about 20 years ago, residual films and possibly other organic residues on prestressing strand that may have been detrimental to bond with the concrete were burned off during the stress-relieving operation (Preston 1963). However, as noted in a 1982 article (Quick 1982) the replacement of open flame furnaces with far more efficient induction furnaces that greatly improved line speed, but residues were no longer being burned off during stress-relieving operations. While the newer induction coils were effective in heating the strand and altering the physical characteristics of the steel, the short duration heating does not burn-off surface contaminate like convection heating. "Contaminants, such as the efficient wire drawing lubricant calcium stearate, which do not sublime at stress-relieving temperatures in an induction furnace and are insoluble in water, are of particular concern ... Induction heating only promoted surface flow of this contaminant, resulting in a glazed surface appearance which tended to seal other surface contaminants (i.e., zinc phosphate)". In addition, convection heating, unlike induction heating, is a combustion-based process and that “may have aided in oxidizing impurities on strand surfaces” (Rose and Russell 1997).

The link between residual films and poor bond was verified when scanning electron microscopy with energy dispersive spectroscopy (SEM/EDS) analyses conducted on strand tested in structural bond tests confirmed the presence of "copious amounts of surface process chemical ... on the outer wires of uncleaned strand which failed bond development tests” (Quick 1982).

Additional evidence of an increase in residual film on prestressing strand was found in the early 1980s, when bright prestressing strand exhibited approximately six times the chloride ion corrosion threshold of black reinforcing bar in a FHWA sponsored study (Pfeifer 1986). It is believed that the unexpected corrosion protection was due to the presence of residual rod treatments and wiredrawing lubricants, namely zinc phosphate and calcium stearate, on the strand as manufactured. The corrosion performance of strand that had been subsequently “ultrasonically cleaned” by the manufacturer was indistinguishable from that of the “as manufactured” strand, suggesting that the drawing lubricants were not removed by the cleaning. Similar corrosion behavior was noted in 1984 by another researcher, who reportedly cleaned the strand with xylene prior to testing (Stark 1984).

Quantifying the amount of residual film present on prestressing strand is typically performed through gravimetric methods that consist of weighing a segment of strand before and after stripping with sodium hydroxide (Wire Association 1980) or some solvent. In several investigations of suspected strand bond problems, the research team has employed a method involving a solvent (acid/chloroform) extraction of residue from the 1/2-in. diameter strand surface and the cement paste in contact with the strand, and Fourier-transform infrared (FTIR) spectroscopy analyses for stearates. Stearate levels ranging from 0.3 to 2.8 mg/inch of strand length (note: for 1/2-in. strand, 1 mg/in. = 69 mg/ft²) have been measured in these investigations, and levels in excess of approximately 1 mg/inch have been associated with strand bond problems in this work.

The removal of residual films on drawn wire is a non-trivial process. The cleaning mechanisms applicable to wire reviewed in a recent article included: detergency (displacement of soil by active agents with greater affinity for the substrate surface), chemical reaction (conversion of soil from an insoluble form to a soluble form), mechanical removal (external physical action), and dissolution (residue dissolved with solvent cleaner) (Colvin and Carlone 1998). For strand production, a post-drawing cleaning operation employing the first two mechanisms listed above is not typically performed because of the high line speeds involved. However, individual wires may be dipped in water before stranding or the stand may be rinsed with water to cool and clean the strand if soluble lubricants have been used.

When insoluble lubricants are present, cleaning is more difficult. In tests of cleaning solutions, a sodium hydroxide solution was able to remove all but 10 of 300-400 mg/ft² of an insoluble stearate lubricant residue originally on the tested wire. However, cleaning effectiveness is enhanced by increased solution temperature and higher rinse volumes and temperatures, all of which require additional effort to produce (Colvin and Carlone 1998). Multi-pass immersions in sodium hydroxide solutions have been used in the production of other wire products where surface cleanliness is critical, such as aluminum clad steel wire, but these methods are not ideal because of the hazardous nature of the caustic solutions and the large volume of waste solution that is generated (Chow 2001). As alternatives, in-line methods incorporating neutral salt water electrolysis and high frequency focused ultrasound have been proposed (Quick 1982, and Chow 2001). However, because of cost, these methods have not found widespread acceptance in strand production.

The Nature of Bond between Prestressing Steel and Concrete

In prestressed concrete production, prestressing steel is initially tensioned, concrete is cast around it, the concrete hardens, and the strand is released. After release, the strand attempts to return to its original length, but this tendency is resisted by the surrounding concrete through bond. As described in many references, (for example see Rose and Russell 1997, Hyett et al. 1994, and Stark 1984), bond of prestressing strand in concrete is a complex subject. Bond occurs on a microscopic scale. There is no way to directly observe it or measure it. Thus, bond properties of prestressing steel in concrete have to be interpreted from tests. Another barrier to our understanding of bond is that some of the variables that appear to influence bond are interdependent. For instance, some researchers cite concrete strength as an important variable. But two concrete mixes, one with high strength and one with low strength, are also likely to have different shrinkage properties, which will also certainly affect the results of bond tests. Recent studies by Peterman (2007) have indicated a correlation of bond with top concrete cover and plastic concrete fluidity. These studies will be discussed more fully later in this document.

Although the references more or less agree on the various components of bond (adhesion, mechanical interlock, and friction), they do not agree about the relative importance of each component. Of the three factors that affect bond (adhesion, mechanical interlock, and friction) perhaps the most important for structural performance is friction. Friction is the shearing resistance to interfacial movement. Friction is

related to transverse or radial pressure. The higher the radial pressure, the higher will be the resistance to linear movement due to friction.

For strand pretensioned, cast into concrete, then released, the radial pressure arises out of the Hoyer effect and shrinkage of the surrounding concrete. When strand is tensioned, its diameter decreases in proportion to the tension based on Poisson's ratio. When it is released, the strand tries to return to its original diameter. Since the expanding strand is constrained by the surrounding concrete, a pressure is created. The effect is named the Hoyer effect (Hoyer and Friedrich 1939).

The magnitude of the radial pressure is related to the original strand tension, the concrete shrinkage strain, and the concrete modulus of elasticity. Eventually, this radial pressure lessens because of concrete creep, but strand tension losses over time tend to increase the Hoyer effect.

The transverse strain generated by releasing the strand is equal to its initial tensile strain minus its tensile strain after release multiplied by Poisson's ratio. The difference between prestress and strand tension after release is generally going to be less than 10,000 psi. So the maximum immediate lateral strain arising from the Hoyer effect is about $(10,000/28,500,000 \times 0.3 = 300 \text{ microstrain})$. Over time, this strain will increase as the strand further relaxes.

Shrinkage and thermal contraction of the concrete also add to the radial strain and pressure. The thermal contraction of the concrete occurs early as the concrete cools after curing. On the other hand, the shrinkage effect initially is small. But after a few months, the shrinkage strain will be comparable in magnitude to the Hoyer effect strain.

Concretes containing relatively soft limestone coarse aggregates tend to crack less because they have less shrinkage strain, lower modulus of elasticity, and greater creep. That may explain why pull out test forces in concretes containing soft limestones are lower than similar concretes with harder aggregate.

The early research in the U.S. concerning strand bond was performed by Janney (1954), Hanson and Kaar (1959) and Kaar et al. (1963). These researchers developed equations for transfer and development length that are still in use today. Transfer length is defined as the distance over which the effective prestressing force is transferred to the concrete element. In other words, this is the distance from the end of the strand where no stress is applied to the concrete to the point where all the tension in the strand has been transferred into the concrete. [Equilibrium should exist everywhere, even within the transfer length.] The development length is the sum of the transfer length and the additional distance over which the stress in the strand is developed from the effective prestress to the stress in the strand at the ultimate flexural strength of the member.

Transfer and development length is directly influenced by the effectiveness of the bond between the strand and the concrete, which is determined by the following three mechanisms:

- Adhesion - the chemical bond between the strand and concrete
- Hoyer's Effect - the frictional force generated by the outward radial force as the prestressed wire attempts to expand upon release
- Mechanical Interlocking - the resistance to movement produced by the deformations cast into the concrete resulting from the twisted nature of the strand.

The original research in strand bond was based on 250 ksi stress-relieved strand, and subsequently verified for the 270 ksi low-relaxation strand commonly used currently. This early work developed transfer and development length equations based on the average of measured data, instead of the 5 percent fractile as typically is done today. Nevertheless, the empirical relations for development and transfer length currently provided in the American Concrete Institute (ACI) Building Code (ACI Committee 318

2005) and the American Association of State Highway Transportation Officials (AASHTO) Standard Specification for Highway Bridges (AASHTO 2003) are based on this work. The transfer length assumed in these codes is given as 50 times the diameter of the strand. A re-evaluation of the early research by Martin and Scott (1976) and Zia and Mostafa (1977) resulted in recommendations for up to a 60 percent increase in transfer and development lengths, and for the inclusion of a concrete strength parameter in the equations. However, no changes were made to the codes.

The early tests had some interesting findings regarding approximate bond stress at early slip (approximately 0.1 in.). It was typically reported that bond stresses in the transfer length ranged between 200 to 600 psi. This is similar to the range measured in pull out tests. Usually, in pull out tests in concrete, transfer lengths that exceed ACI equation are generally associated with bond stress less than 400 psi at 0.1 in. of slip. (0.1-in. slip approximately corresponds to $300 \times 0.1 = 30$ in. transfer length. Bond area of strand = $30 \text{ in.} \times 2.083 \text{ in}^2/\text{in} = 62.5 \text{ in}^2$. Prestress after loss = approx. $160,000 \text{ psi} \times 0.153 \text{ in}^2 = 24,500 \text{ lbs}$. Bond stress = $24,500 \text{ lbs} / 30 / 2.083 = 392 \text{ psi}$.)

The transfer length of strand is typically determined by measuring the strain of a prestressed concrete beam after the prestress on the strand is released shortly after casting. A strain gradient is present over the transfer length of strand, while in the center of the strand where the prestress has been transferred and stress is constant, the strain is constant. When strand transfer length is to be determined, it has been believed that the most appropriate specimen configuration is a single-strand specimen of sufficiently small cross-section that the stress produced by the strand causes an easily-measurable deformation. Whittemore or Demac gauges are typically used to determine strain on the concrete surface.

This measurement approach is less effective for multi-strand specimens. This is because, with the Whittemore-Demac gauge based measurements, transfer length data are only a reflection of the average transfer length of all the strands, and no information is gained about the individual bond variability among these multi-strands. The most accurate method to measure bond variability in multi-strand specimens is to individually measure the strand end slip at release on each separate strand. The correlation between strand end slip and transfer length has been shown to be strong (Anderson and Anderson 1976, Rose and Russell 1997). The traditional method of measuring transfer length using the typical 4.5 in. x 4.5 in. x 8 ft long prisms is now in doubt as a result of recent research by Peterman (2007). In Peterman's tests, pretensioned strands were placed at various distances from the top of precast members. The overall depth of the members was also varied. Peterman found that the closer a strand is to the top as-cast surface of the concrete member; the longer and more variable the transfer length. This finding does not bode well for the traditional transfer length prism, which has a concrete top cover of only about 2-in. This research helps explain why transfer lengths measured from rectangular prisms is so variable. These prisms should no longer be used to measure transfer length. Beam specimens, at least 12 in. deep, should be used instead.

In 1985, the North Carolina Department of Transportation (DOT) and Federal Highway Administration (FHWA) funded a study at North Carolina State University (NCSSU) entitled *Bond of Epoxy Coated Prestressing Strand* to evaluate such strand's suitability for use in prestressed concrete bridge members (Cousins et al. 1986). This study examined 3/8-, 1/2-, and 0.6-in. diameter epoxy-coated strand, with bright strand serving as the control. While the measured transfer and development lengths of the epoxy-coated strand were shorter than those predicted by code (AASHTO and ACI), the lengths for bright strand were much longer than predicted by the code equations.

In addition, the data for the bright strands were characterized by wide variability. For example, the reported transfer lengths of 1/2-in. diameter bright strand ranged from 32 to 74 in. (64 to $148 d_b$). End slips reported for the 1/2- and 0.6-in. diameter bright strands in both the transfer length and the development length tests were also deemed excessive. Further, all six development length tests of the 1/2-in. diameter

bright strand failed in bond rather than flexure, as did three of the four development length tests of 0.6-in. diameter bright strand. No chemical tests for possible surface contaminants were made on the strand at NCSU.

Based on the NCSU study, FHWA issued a memorandum imposing restrictions on the use of seven-wire strand in bridge applications on October 26, 1988 (USDOT 1988). Among other things, the memorandum banned the use of 0.6-in. diameter strand in pretensioned applications and required a 1.6 multiplier on the AASHTO development length equation for fully bonded strands.

The FHWA restrictive-use memorandum precipitated a number of research projects on transfer and development lengths of prestressing strand. These included projects by Florida DOT (Shahawy et al. 1992), multiple test programs on ½- and 0.6-in. diameter bright strand at the University of Texas-Austin funded jointly by FHWA and Texas DOT (Unay et al. 1991, Russell and Burns 1993), and a major study of 3/8-, 1/2-, 1/2-in. special and 0.6-in. diameter epoxy-coated and bright strand by FHWA at its research facility in Virginia (Lane 1990). The transfer lengths resulting from the initial phases of these various projects were similar to those reported by NCSU, and again no chemical tests of possible surface contaminants were made. The data were again highly variable, and excessive end slips were again noted. Significantly, all these research projects utilized exclusively Grade 270 low-relaxation strand from the same manufacturer that provided strand for the NCSU research and for the corrosion study for FHWA discussed below, where evidence of unexpected surface conditions was noted.

In spite of the 1988 FHWA memorandum, no changes were made to the ACI Code equations for transfer and development length. As a result, there was relatively little interest in this potential problem at the Prestressed Concrete Institute (PCI). However, in 1991, a strand lifting loop pulled out of a precast member during handling. As a result, in 1992, a series of pull out tests to investigate this failure were conducted by Moustafa in accordance with the test procedure that he had developed in 1974 (Logan 1997). His results were startling for the industry because four of seven manufacturer's strands had pull out capacities substantially lower and more variable than those measured in 1974 (see Figure A-2).

Meanwhile, studies of transfer and development lengths were performed by various universities and laboratories continued to produce contradictory conclusions. In 1993, tests at McGill University in Canada using ½-in. low relaxation 270 ksi strand produced by Stelco Corp. found that concrete strengths at release from 3000 to 7300 psi produced transfer length from 28 to 13 in., all less than 56 diameters (Mitchell et al. 1993). This demonstrated that strand from at least one supplier could produce transfer and development lengths that matched values predicted according to the historical ACI-AASHTO equations.

In an attempt to clarify these issues and assess their significance, in 1995, Dr. C. Dale Buckner was hired by FHWA to review these and other studies (Buckner 1995). He concluded that the erratic behavior of the strand in transfer and development length tests created concerns over the potential for bond and /shear failure concerns. Buckner also determined that the use of 270 ksi versus 250 ksi strand could not explain this erratic behavior. He did point out that none of the previous studies had tested the strand for residual drawing lubricants but did not recommend investigating this potential cause. As a result, while it was concluded that strand bond failures could pose a significant problem, little direction was provided on means for identifying the source of the problem.

Research was conducted at Stresscon Coporation in Colorado, led by Mr. Donald Logan, on six samples of ½-in. diameter strand provided by precasters in widely separated regions of North America (Logan 1997). Four of the six samples were found to possess shorter transfer and development lengths than predicted by the ACI/AASHTO equations, while the remaining two exhibited poor bond quality. It was concluded that, "There is a significant difference in the transfer/development performance in pretensioned concrete beams among strands produced by different strand manufacturers." It also was noted that the

end slip immediately on release of prestress was a good indicator of bond performance and that the end slip of the strands with poor bond characteristics increased over time. Additional noteworthy observations from this research included that the amount of residue that could be wiped off the strand was not a reliable indication of bond performance and that minor differences in the lay or pitch of the outside wires had no effect on bond.

The observation that strand end slip continues with time in poor bonding strand is worrisome. This observation also was made in a NCHRP-funded corrosion study (Perenchio et al. 1989). Significant end slips were noted in 12-ft. long beams pretensioned with ½-in. diameter bright strands and subjected to a 30 °F temperature variation each 3½ days for 11 months. An increase in maximum end slip of 0.137 in. was measured in an uncracked beam. This indicates a transfer length increase of about 35 to 40 in. in an 11-month period with essentially no live load effect. Further, the research team is aware of at least two situations involving pretensioned double-tee beams in parking structures where this mechanism is the suspected cause of end shear problems that developed over time. Some beams in one of these structures actually collapsed as a result of shear failures occurring more than six years after construction.

Since its initial research, Stresscon has continued to conduct pull out tests for the precast industry using the Moustafa test. This testing has generated a significant database of strand bond performance. Poor bonding strand is characterized by a broad variation in pull out strength (coefficients of variation of up to 50 percent) and significant time-dependent end slip. Strand with good bond performance, on the other hand, is characterized by consistent pull out strengths (coefficients of variation approximately 10 percent or less) and a modest (10 percent) increase in transfer length with time.

In Logan's Moustafa test, poor bonding 1/2-in. diameter strands generally have pull out capacities of 10 to 25 kips. Good bonding 1/2-in. diameter strand has pull out capacities in excess of 36 kips. The bond represented by intermediate values between 25 and 36 kips is considered uncertain. Recently, Logan has come to realize the ultimate pull out force may not be the only, or even best, criterion on which to judge strand bond. Instead, current research by Stresscon has focused on the force corresponding to first observable slip. Logan believes that this force should exceed 16 kips for 1/2-in. diameter strand.

It was not the goal of this study to completely understand the controversial issue of what constitutes bond. Rather, this study was intended to develop tests that will assure that prestressing strand that passes certain tests has the potential to bond to the concrete in prestressed members at least as well as assumed by the ACI Code and the AASHTO Standards.

ACI Code and AASHTO Specifications

The expectation for bond of prestressing steel in precast/pre-tensioned concrete is indicated by ACI Code (ACI Committee 318 2005) Section 12.9, wherein the required development length of strand is specified. The development length is the bonded length of the strand measured from the end of the member, sufficient to develop a prestress of f_{ps} , the stress in the strand corresponding to the nominal flexural strength of the member. The Commentary to Section 12.9 explains that the development length equation is the sum of two terms as follows:

$$(1) \quad + \quad (2) \quad = \text{ACI Eqn. 12.9}$$

$$L_d = \frac{f_{se}}{3} \times d_b + (f_{ps} - f_{se}) \times d_b = (f_{ps} - \frac{2}{3} \times f_{se}) \times d_b$$

where:

f_{se} = effective stress (ksi) in prestressing steel after allowance for all losses

f_{ps} = effective stress (ksi) in prestressing steel at nominal strength of the member

The first term in the above equation is the transfer length, which is the length from the end of the member needed to develop the prestress, f_{se} . Typically, this term will range from 50 to 60 d_b . The second term is the additional length needed to develop the stress in the strand that coincides with the ultimate flexural strength of the member, (i.e. $f_{ps}-f_{se}$). Typically, the second term is about 50% greater than the first term.

The AASHTO LRFD Specifications (AASHTO LRFD 2003) specifies development length requirements in equations 5.11.4.2-1 and 5.11.4.2.2-2 (note: equation 5.11.4.2-1 is the same as Standard Specifications (AASHTO 2003) equation 9-42) as follows:

$$L_d = 1.6 \times (f_{ps} - \frac{2}{3} \times f_{pe}) \times d_b \quad (2003 \text{ LRFD Eq. 5.11.4.2-1})$$

$$L_d = (\frac{4 \times f_{pbt} \times d_b}{f'_c} - 5) + (\frac{6.4 \times (f_{ps} - f_{pe}) \times d_b}{f'_c} + 15) \quad \begin{array}{l} (2003 \text{ LRFD Eq. 5.11.4.2-2}) \\ \text{modified to look like the original formula} \\ \text{proposed by Lane} \end{array}$$

Where: f_{pe} = effective prestress in the steel after all losses

f_{pbt} = stress in prestressing steel immediately prior to transfer

The first equation above is similar to the ACI equation except for the factor 1.6. Since 1988, as a result of a memorandum issued by the FHWA (USDOT 1988), the factor K has been set equal to 1.6. The FHWA memorandum was issued as a result of research performed at NCSU (Cousins et al. 1986).

The second equation is based on research performed by Lane at the FHWA (Lane 1998). Like the ACI equation, the first term refers to the transfer length, and the second term is the remainder of the development length. There is controversy regarding the applicability of the second equation because it was developed using strand that was later shown to have poor or variable bond properties, primarily, it is believed, as a result of excessive residual wire drawing lubricants. Interestingly, the second AASHTO equation becomes less conservative than the first equation at concrete strengths exceeding 10,000 psi (see Figure A-3). This suggests that with sufficient concrete strength, the deleterious effects of wire drawing lubricants on bond may be reduced. This phenomenon was further illustrated by Barnes and Burns (2000).

Figure A-4, taken from Barnes and Burns (2000) shows that for $\frac{f_{pt}}{\sqrt{f'_c}} \leq 180\sqrt{MPa}$ where f_{pt} = prestress

transfer at release, the scatter of data is much less pronounced, even for strand with proven poor bond characteristics and that all measured development lengths in this range were less than the current ACI provision. This limit corresponds to a concrete compressive strength of about 8,000 psi. In other words, the data show that for concrete strengths greater than about 8,000 psi, the effect of surface residues on strand may be less pronounced than for lower strength concretes.

The current AASHTO LRFD Design Specifications (AASHTO LRFD 2007) specify the following calculation for transfer and development length, based on research sponsored by the Florida DOT (Shahawy 2001).

$$L_d = 1.6 \times \left(f_{ps} - \frac{2}{3} \times f_{pe} \right) \times d_b$$

Development length
(2007 LRFD Eq. 5.11.4.2-1)

$$L_d = 60 \cdot d_b + 1.6 \times \left(f_{ps} - \frac{2}{3} \times f_{pe} - 38 \right) \times d_b$$

Development length broken into
components of transfer length and
flexural bond length

Historical Strand Bond Qualification Tests

The best qualification test for a strand is to establish its development length by conducting flexural beam tests using the materials that will comprise the structure. However, flexural beam tests are complicated and expensive to conduct. As a result, several other test methods have been developed as proof tests to indicate the relative bond capacity of strand. Tests have also been attempted by several researchers using substitute materials and procedures, but these have been largely unsuccessful. Two of the most promising tests methods developed to date are the Moustafa test and the North American Strand Producers Association (NASPA) test. Both are pull out tests of untensioned strand. These two tests are briefly described later.

In their Round One and Round Two reports, Russell and Paulsgrove (1999a, 1999b) investigated several methods to evaluate the bond performance of strand. Briefly stated, the methods were as follows:

Weigh Strip Method

This method involves measuring the material removed from the surface of the six outer wires of a strand after cleaning. Cleaning was accomplished by boiling the strand in water for five minutes, drying, then wiping with acetone. Weights of the wires before and after cleaning were used to determine the amount of residual lubricants on the wires. This test did not correlate well with the pull out tests discussed later and, therefore, its use was not recommended.

Friction Bond Pull Out Test

The ends of two strands were butted together inside a steel tube. The steel tube was crimped in a hydraulic press. The strand assembly was tested in tension and the maximum pull out force recorded. This test did not correlate well with the pull out tests discussed later and, therefore, its use was not recommended.

Electron Optics Test

SEM/EDS (Scanning Electron Microscopy/Energy Dispersive Spectroscopy) techniques were used to semi-quantitatively measure the amount of certain elements on the strand wires. Zinc and Phosphorous were considered to be elements associated with the initial coating of the rod stock. Calcium and sodium were considered to be components of wire drawing lubricants. Other elements were considered to be part

of the base metal. This test did not correlate well with the pull out tests discussed later. However, other researchers (Quick 1982) have found this test to be effective.

PTI Test

This is a pull out test defined by ASTM A 981-97 (2002) Standard Test Method for Evaluating Bond Strength for 15.2 mm (0.6-in.) Diameter Prestressing Steel Strand, Grade 270, Uncoated, Used in Prestressed Ground Anchors wherein 0.6-in. diameter strand is embedded in a 5-in. diameter by 18-in. long steel cylinder filled with cement/water grout. The top 2 in. of the strand is debonded. The test was developed by the Post-Tensioning Institute (PTI) (Hyett et al. 1994 and Post-Tensioning Institute 1996) as a way to test strand intended for use as a rock anchor. The test result is the load corresponding to a dead end strand slip of 0.01 in. Although the ASTM method lists no target test value, the PTI Specification *Recommendations for Prestressed Rock and Soil Anchors* (PTI 1996) states that the force corresponding to a slip of 0.01 in. shall not be less than 8,000 lb. Russell and Paulsgrove (1999a, 1999b) modified the test to use 1/2-in. diameter strand and to record the pull out force corresponding to 0.1-in. slip and the maximum pull-out force. This test correlated better with the Moustafa and NASPA pull out test methods described below than the other test methods described above. However, the range of pull out values, from 4 kips to about 14 kips, was not as great as the other methods, and the correlation with other test methods ($R^2 = 0.7$) was not as good, especially when the tests were performed at multiple sites.

Moustafa Test

Dr. Saad Moustafa developed a simple pull out test in 1974 for the purpose of determining the capacity of prestressing strands used as lifting loops (Moustafa 1974). The test procedure, described in detail by Logan (Logan 1997) consists of embedding six 1/2-in. diameter strands 18 in. into a block of concrete. The strands are then individually pulled out of the concrete at a rate of 20 kips/minute. The maximum pull out force is recorded for each strand length, and the average of the six pull out tests is used to qualify the strand. The 1/2-in. diameter strand is considered to have adequate bond if the average maximum pull out force is greater than 36 kips. The test was intended to be a rigorous one, providing for pull out capacities near the ultimate strength of the strand to maximize the range and readily differentiate between good and poor bonding strands.

The use of this test has been observed by Logan at numerous facilities, and test results similar to Stresscon were reproduced as long as the aggregates used were relatively hard aggregates with Moh's hardness exceeding 6.0 similar to aggregates used originally by Moustafa in the Pacific Northwest. Concrete with relatively soft limestone aggregates consistently produced lower pull out capacities than concrete with the harder aggregates.

The Moustafa test has been adapted and modified by Logan and Dr. Robert Peterman of Kansas State University (KSU). The modified test is now called the Large Block Pullout Test. Logan modified the test by setting certain standards for the concrete mix (no admixtures), the aggregates (Moh's hardness must be greater than 6.0), and the age of concrete (essentially controlling the concrete strength) at test (one day -- heat cure). He also modified the test to include measurement of first observed slip at the stressing end (must occur at a load greater than 16 kips to qualify a 1/2-in. diameter strand), which was found to correlate well with flexural beam results and serves as a check of the pull out strength. Peterman built on Logan's work by developing a test using spirally reinforced cylinders of concrete. In addition, Peterman measures the forces and slips using electronic instrumentation. Figure A-5 is a photograph of KSU specimen arrangement prior to concrete placement. The criteria currently proposed for this test to qualify 1/2-in. diameter, Grade 270 strand calls for a free end slip of less than 0.05 in. at a pull out force of at least 16 kips.

NASPA Test

Dr. Bruce Russell at the University of Oklahoma (now at Oklahoma State University) developed a test under contract with the North American Strand Producers Association (NASPA). His work was conducted in four phases. In the first, Russell studied the Moustafa test and a modified PTI test (Russell and Paulsgrove 1999a).

Russell subsequently modified the PTI test further by using mortar instead of grout for the embedment material, thereby creating an early version of the NASPA test (Russell and Paulsgrove 1999b). The NASPA test was later modified in NCHRP 12-60 (Ramirez 2002) and NASPA Rounds III and IV (Russell 2001, Russell 2006). The NASPA test in its current form has the following components:

There are 6 specimens. For each specimen, a strand sample is placed in the middle of a 5-in. diameter by 18-in. long steel cylinder with a wall thickness of less than 0.135 in.

The cylinder is filled with a sand/cement mortar then vibrated to consolidate. The ingredients ratio is not specified. Sand cement ratio of 2:1 and a W/C ratios of 0.45 has been suggested in the past. The mortar mix is supposed to have a flow per ASTM C1437 of between 100 and 125.

The mortar filled cylinder is cured at 73°F for 24+/- 2 hours, then a pull out test is performed

The mortar strength at time of test must be between 4,500 psi and 5,000 psi.

The strand is pulled at a rate of 0.1 inch per minute.

The load rate during the test must not exceed 7,500 lb per minute. The test frame must not allow torsional rotation.

The proposed (in 2006) acceptance criteria for 1/2-in. strand, are: the average of six pull out forces, corresponding to a free end slip of 0.1 in., must exceed 10,500 lbs, and no single pull out force may be less than 9,000 lbs. For 0.6 in. diameter strand, acceptance criteria are: the average of six pull out forces, corresponding to a free end slip of 0.1 in., must exceed 12,600 lbs, and no single pull out force may be less than 10,800 lbs. Figure A-6 presents a NASPA test specimen installed in the test frame (Russell 2006).

Comparison of Large Concrete Block and NASPA Test Methods

Numerous comparisons between the NASPA test and Moustafa test have been performed by Russell (1999b, Russell 2001, and Ferzli 2000). These comparisons show some correlation. However, that correlation is far from perfect. Ferzli (2000) also compared the Moustafa test to transfer length tests and determined that the Moustafa test was not a good index test. Russell also concluded that the NASPA test was more repeatable between sites and correlated better with transfer length tests. However, none of the comparisons performed examined the first observed slip as opposed to the ultimate pullout force. An unpublished comparison of NASPA tests performed at University of Oklahoma (Russell 1999b) and first slip data for large block pullout tests performed at Stresscon indicate good correlation, as shown in Figure A-7.

Other Pull Out Tests of Tensioned and Untensioned Strand in the Literature

Numerous articles were found that reported the results of research of tensioned and untensioned strand of various diameters, prestressing wire, and smooth reinforcing bars. In these projects, bond lengths ranged from 0.5 to 40 in. In some cases, the pull out testing was performed on tensioned strand. Test media included cement grout, cement/sand mortar, or concrete. No research was found that used an alternate homogeneous material as an embedment material.

There were also numerous reports where strand transfer and development lengths were determined based on full scale beam specimens. Unfortunately, for the vast majority of these projects, the strands, bars, or wires tested were obtained from a single supplier. Typically, measurements of the surface condition of the reinforcement were not given except to describe it as smooth or rusty. Therefore, it is difficult to use these studies to examine and compare the effects of different kinds and quantities of residual surface lubricants.

Perhaps the most exhaustive study of strand bond found was one by Stocker and Sozen (1971). That project involved several strand diameters (1/4-in. to 1/2-in. diameter), several embedment depths (0.5 to 20 in.), and several concrete compressive strengths (ranging from 2200 psi to 8300 psi). Concrete mix designs were varied in terms of slump (0.3 to 7.1 in.) and water/cement ratio (0.4 to 0.9). The study examined issues pertaining to the lay, or pitch, of the strand, the surface profile of the strand wires, the perturbations in the strand diameter along its length, curing conditions, depth of concrete below strand, effects of time, and comparisons with strand bond behavior to that of plain wire and twisted, smooth reinforcing bars.

The most frequently tested specimen was 7/16-in. diameter strand with a 1-in. long bonded length in order to achieve a uniform bond stress. Most of their tests only pulled strand to a dead end slip of 0.15 in. This is comparable to the slip displacements used in the NASPA test, but significantly less than the slips measured in the Moustafa test. Their parametric studies proved that the short bond length was representative of bond stresses measured at the longer lengths. It was the approach of the research to try to test specimens subjected to almost uniform bond, similar to the studies done by Rehm (1961).

The Stocker and Sozen study had several interesting findings, some of which would appear to contradict prevailing theory then and now. To determine the effect of mechanical interlock, they studied the difference between normal, twisted strand and a specially made strand consisting of only straight wires. They found that the presence or absence of twist of the steel made little difference in the pull out force. To study the effect of rotational restraint, they constructed specimens that were free to rotate and compared them to specimens that were not free to rotate. The differences were found to be very small. They inadvertently discovered differences between two spools of as-received strand, when two spools of strand from the same supplier were compared. The strand from the different spools had different initial force/slip behavior, but the pull out forces corresponding to 0.15-in. slip were relatively close. Their primary finding was that surface smoothness and the perturbations in the strand diameter act as deformations on the strand that influence its bond characteristic after initial slip. They measured variations in strand diameter of ± 0.01 in. within a 1 in. length of strand.

Contrary to the work of Kaar et al. (1963), Stocker and Sozen (1971) found that there was a relationship between concrete strength and pull out force. They measured, on average, a 7% change in bond strength for each 1,000 psi change in compressive strength over the range of 2,400 psi to 7,500 psi. In other words, the maximum bond stress at 0.1 in. slip for 7,500 psi concrete was about 35% greater than the bond stress in 2,400 psi concrete. The effect of concrete compressive strength has been noted by other researchers as well (Collins and Mitchell 1991, Cousins et al. 1986, Lane 1998, and Shahawy 2001). Interestingly, the work of Barnes and Burns (2000) shows both the effect of compressive strength and different strand sources on development length. In their report, there is a pronounced reduction in scatter of the data for concrete compressive strengths greater than about 8,000 psi. This is implied by the development length formula developed by Lane (1998) and currently offered as an alternate design equation by AASHTO (2003) wherein, for strengths greater than about 10,000 psi, the Lane equation gives the same development length as the ACI equation.

Anis (1977) discovered that the maximum pull out force measured in mortar specimens corresponded to the pitch of the strand divided by 6. Strands tested by Anis resulted in shearing of the ridges between wires.

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FIGURES

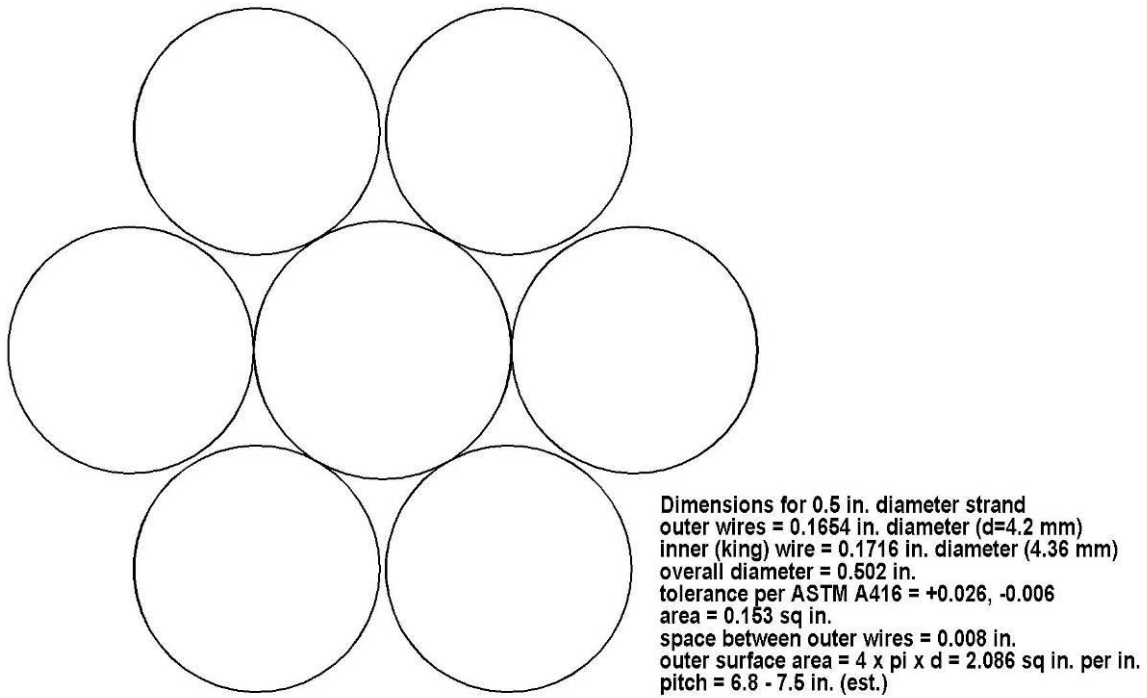


Figure A-1 - Details of 0.5 in. diameter strand.

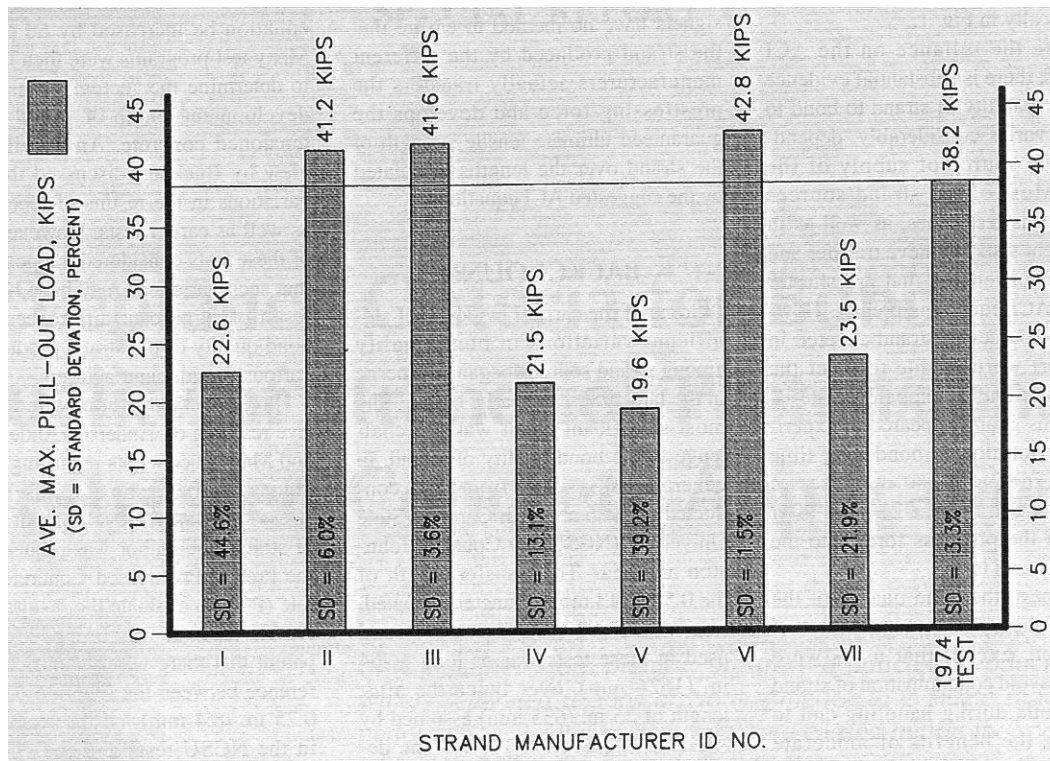


Figure A-2 - Concrete block pull out test results measured by Moustafa in 1992.

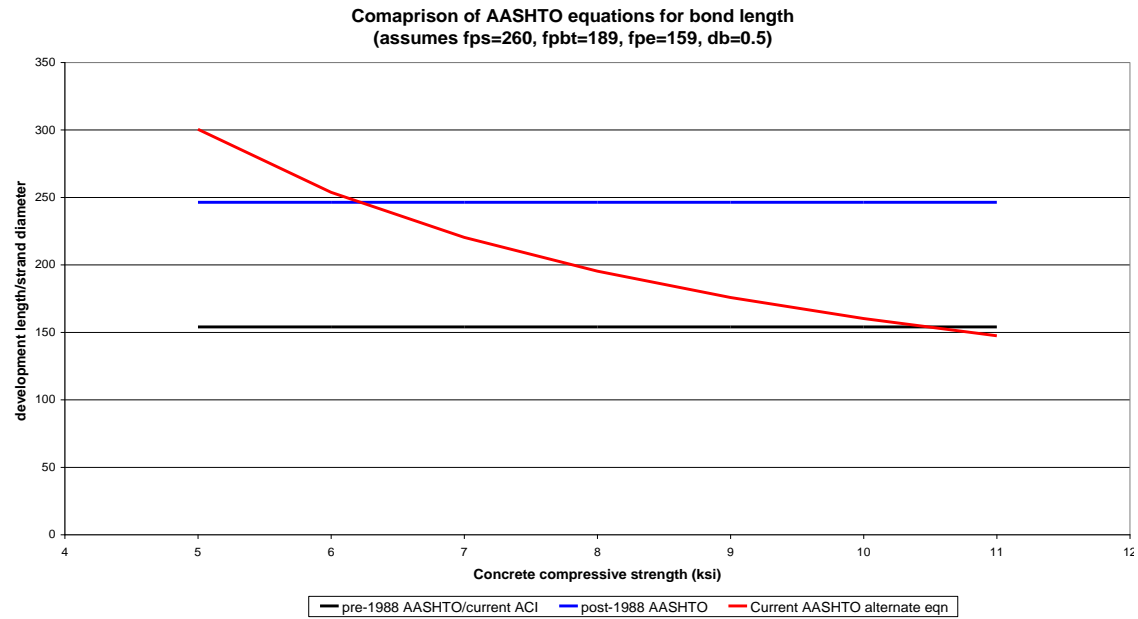


Figure A-3 - Comparison of development length equations, ACI and AASHTO.

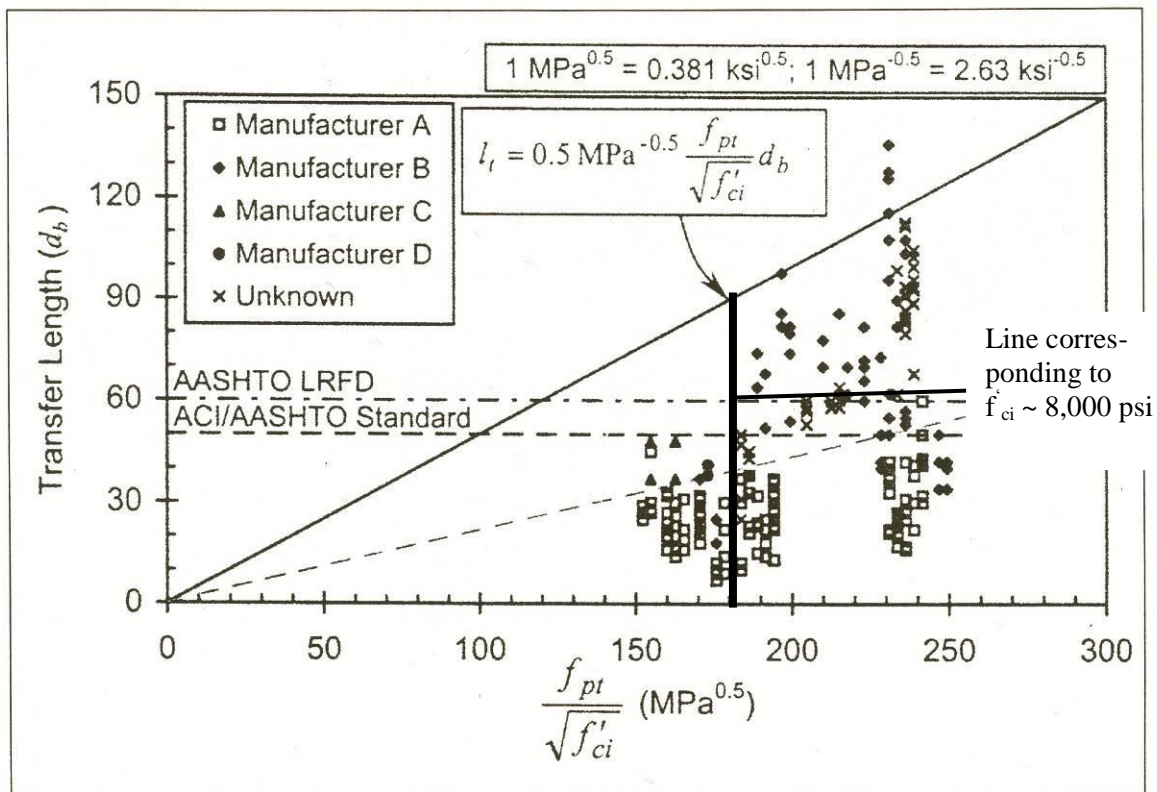
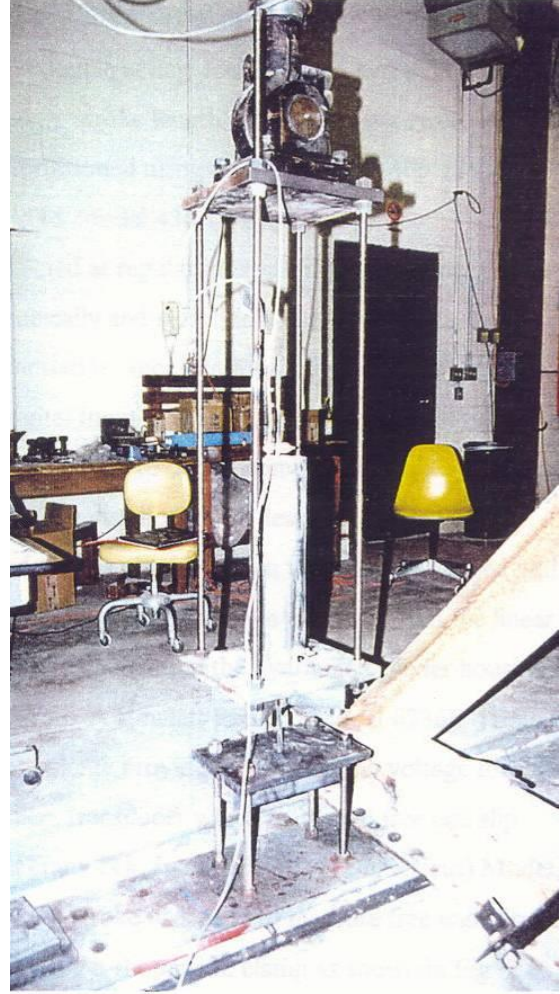


Figure A-4 - Transfer length versus term including compressive strength (from Barnes and Burns 2000).



*Figure A-5 - KSU cylindrical specimen
prior to concrete pour.*



*Figure A-6 - NASPA test specimen being
installed in the test frame.*

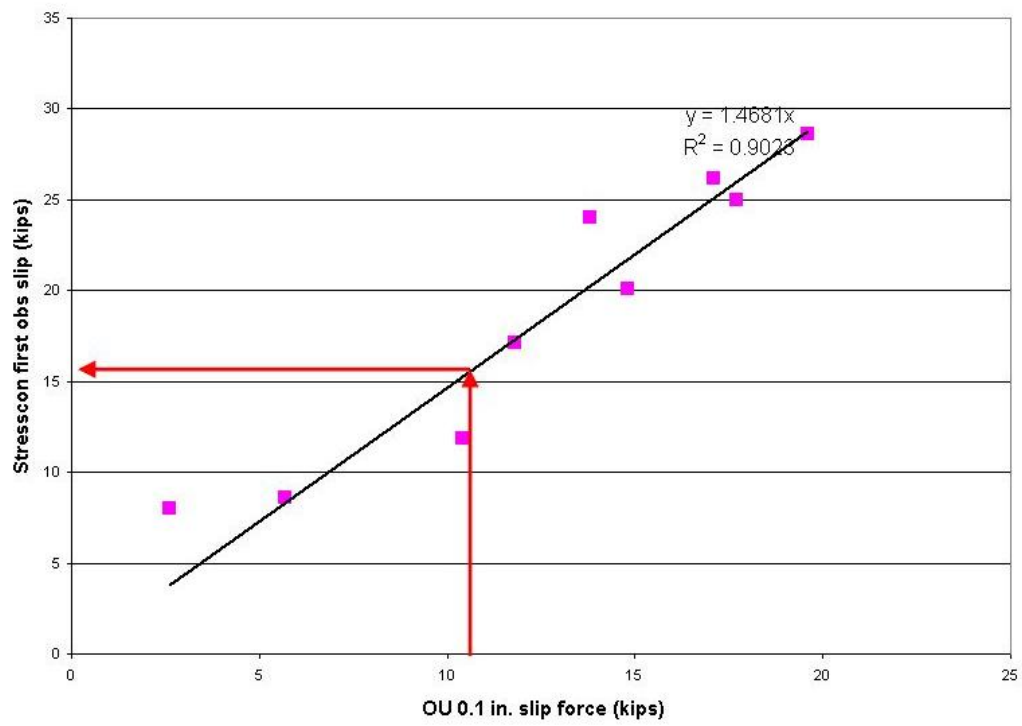


Figure A-7 - Comparison of pull out capacities in mortar vs. concrete.

Project No. 10-62

**ACCEPTANCE TESTS FOR
SURFACE CHARACTERISTICS OF
STEEL STRANDS IN PRE-STRESSED CONCRETE**

APPENDIX D: SUPPLEMENTAL INVESTIGATIONS OF STRAND BOND

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
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**TRANSPORTATION RESEARCH BOARD
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NCHRP Project 10-62

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SURFACE CHARACTERISTICS OF
STEEL STRANDS IN PRE-STRESSED CONCRETE

APPENDIX D: SUPPLEMENTAL INVESTIGATIONS OF STRAND BOND

14 April 2008

TABLE OF CONTENTS

Introduction to the Supplemental Investigations	D-1
Metallographic Investigation of Surface Roughness	D-1
Introduction	D-1
Method.....	D-1
Results and Discussion.....	D-1
Conclusions	D-2
Scanning Electron Microscopy of Strand	D-2
Introduction	D-2
Method.....	D-3
Results and Discussion.....	D-3
Conclusions	D-4
Investigation of Link Between Electrochemical Impedance Spectroscopy and Bond	D-4
Introduction	D-4
Method.....	D-4
Results and Discussion.....	D-5
Conclusions	D-6
Cement Hydration Study	D-7
Introduction	D-7
Method.....	D-7
Results and Discussion.....	D-8
Mortar Composition.....	D-8
Comparison of Interfacial and Bulk Properties.....	D-8
Conclusions	D-9
Effect of Residue in Transfer Zone	D-10
Introduction	D-10
Sample	D-10
Petrographic Examination of Specimen with Long Transfer Length	D-10
Method of Petrographic Examination	D-10
Results and Discussion of Petrographic Examination	D-10
Spectroscopical Studies.....	D-11
Method of Spectroscopical Studies	D-11
Conclusions	D-12
Measurement of Variations in Wire and Strand Diameter	D-12
Introduction	D-12
Method.....	D-12
Results and Discussion.....	D-13
Conclusions	D-13
Conclusions of Supplemental Investigations	D-13
References.....	D-14
Tables	D-15
Figures.....	D-19

INTRODUCTION TO THE SUPPLEMENTAL INVESTIGATIONS

In addition to testing performed to evaluate the proposed QA/QC testing methods, supplemental investigations were conducted to provide insight into the causes of poor bond. These investigations aided in developing and interpreting the results and applicability of the QA/QC tests. The supplemental investigations included studies of surface roughness and distribution of lubricant residue along the strand, studies of the concrete/strand interface, and measurement of the variations of diameter in the strand. The studies of surface roughness included metallographic studies of strand from poor and good bonding sources, scanning electron microscopical studies of strand, and study of surface roughness by electrochemical impedance spectroscopy. Investigation of the concrete/strand interface included: a study of the cement hydration at the strand interface, and a petrographic and chemical investigation of the strand/concrete interface in the transfer length prisms in which poor bond was observed.

METALLOGRAPHIC INVESTIGATION OF SURFACE ROUGHNESS

Introduction

The effect of surface roughness of strand was investigated to determine if a correlation between surface roughness and bond strength could be found. Surface roughness is known to have an influence on bond strength for a wide variety of systems. Greater surface roughness can lead to increased bond strength because of greater surface area for bonding, and increased mechanical interlocking. However, in the case of strand, increased surface roughness may lead to increased retention of lubricant residue, leading to decreased overall bond. To study this phenomenon, the surface roughness of four strand samples was characterized metallographically and related to bond strength.

Method

Four strand samples representing strands that exhibited low and high first slip pullout stress were provided for metallographic examination of the wire surface characteristics. The strand samples were identified as Sources 101, 102, 103, and 151. Sources 101 and 102 both exhibited low bond strengths. Source 103 exhibited high bond strength. Source 151 exhibited intermediate bond strength.

Metallographic cross-sections obtained from Sources 101, 102, 103, and 151 were prepared in both the transverse and longitudinal orientation. The specimens represented a randomly selected wire in the sample strand and consisted of approximately a ¾-in. length in the longitudinal direction. The transverse oriented specimen was obtained from the same wire at an adjacent location. Specimens were initially cleaned in an ultrasonic bath containing acetone to remove surface films (i.e., lubricants, paints) that could interfere with surface adherence of the bakelite mounting material and subsequent edge retention of the prepared cross-section. Mounted samples were polished to prepare a surface suitable for microscopic examination.

Results and Discussion

Microscopic examination of the edges of prepared specimens showed similar surface texture over the entire surface of the specimen. Consequently, a randomly selected area of the edge was chosen for photographic mapping of the edge profile. Composite micrographs are shown in Figure D-1 and Figure D-2 for the two specimens oriented in the transverse and longitudinal directions, respectively.

The surface edges of the composite micrographs of longitudinally-oriented specimens were electronically traced and digitized to produce a simulated profile of the surface texture (see Figure D-3). The profiles could then be analyzed statistically to quantitatively measure the relative roughness of the wire surface. Standard statistical parameters such as standard deviation and coefficient of determination (R^2) for regression fits were computed for the sample data sets as possible measures of the relative surface roughness. Table D-1 provides a summary of the computed parameters.

Visual examination of the wire edge profiles shown in Figure D-1 and Figure D-2 indicated that the surface roughness of the four samples was very small, measuring only several microns in depth variation. A large difference in the surface roughness between wire samples was not observed. Based on a visual inspection of the micrographs, Source 103 exhibited the least surface roughness in both transverse and longitudinal directions, while Sources 101 and 151 exhibited the greatest surface roughness in both directions. The images of Source 102 show a similar surface roughness as Source 103 in the longitudinal direction, but a roughness intermediate between Source 103 and Sources 101, 151 in the transverse direction. As discussed in the section entitled “Scanning Electron Microscopy of Strand” below, the surface roughness has a directional component that may impact results of a cross-sectional study.

Statistical analysis of the images provided some correlation to the visually interpreted surface roughness. With the exception of Source 151, the standard deviation appeared to follow a similar trend as the visual observations of the wire edge profile. Larger standard deviations, suggesting greater surface roughness, are measured in Sources 101 and 102 in comparison to 103. Source 151, however, indicated the lowest standard deviation; this is inconsistent with the interpretation.

Conclusions

The bond strengths of Sources 101 and 102 were low, while that of Source 103 was high. The surface roughness data does not show a large difference in roughness between the samples, indicating that if roughness is a factor contributing to bond, small variations may be important. However, Source 103 has the lowest surface roughness and highest bond strength, suggesting that lower surface roughness may be related to increased bond strength. Little extraction residue was obtained from Source 103, suggesting that lower surface roughness may be correlated with lower amounts of lubricant residue on the strand, which may lead to increased bond strength. However, with the limited data set, a definite relationship between bond strength and surface roughness cannot be asserted.

SCANNING ELECTRON MICROSCOPY OF STRAND

Introduction

Electron microscopy and elemental analysis of strand with the associated lubricant residue was performed to gain a better understanding of the combined system. Surface microscopy (as opposed to the cross-sectional metallography discussed previously) can be used to understand the morphology of the surface roughness across a wire, although roughness profiles cannot be obtained with this method. The combination of morphological investigation and elemental analysis possible with a scanning electron microscope equipped with energy dispersive x-ray spectroscopy (SEM/EDS) can show the relationship of lubricant residue to the roughness and depressions in a wire.

Method

Three sections of as-received strand were chosen for analysis by scanning electron microscopy (SEM): Sources 102, 103 and 151. These samples were chosen to represent a range of pull out performance and different surface pre-treatments. The presumed pretreatments and lubricants used on the sources that were examined, based on testing reported in Appendix A, are given in Table D-2.

Two-inch sections of strand were cut for analysis. The top surface of one wire within the strand was analyzed. Areas for analysis were randomly selected after the wire was briefly examined. Samples were imaged with both backscattered electron (BSE) imaging and secondary electron (SE) imaging. BSE imaging gives information related to elemental composition. Differences in composition of the phases present are represented by different brightness levels. Phases consisting of heavy elements are lighter in brightness than phases consisting of lighter elements. SE imaging gives topographical information regardless of phase composition, and is useful for imaging surface roughness. In addition to these two types of images, energy dispersive x-ray spectroscopy (EDS) was used to determine the composition of a given area within a SEM image. EDS analysis can be used to give an average composition over an area or the elemental composition of a point. The EDS cannot process data from elements lighter than carbon. Therefore, the boron from the borax pre-treatment cannot be detected. In a BSE image, boron would appear very dark, but would be indistinguishable from carbon.

Micrographs illustrating the findings of the SEM investigation are presented below. Most contain two images along with an EDS spectrum. The image on the left is lower magnification, and shows the outline of a box. The image on the right is a higher magnification image from the area of the box. A very small box outlines an area in the image on the right. This very small box designates the point that the EDS spectrum, shown below both images, represents.

Results and Discussion

The surface roughness of the wire is directional, with features occurring primarily parallel to the length of the wire. The roughness of Source 103 can be seen in Figure D-4 below accentuated by the dark area representing the lubricant and pre-treatment. BSE imaging and EDS spectra confirm the presence of both steel and lubricant.

Figure D-5 and Figure D-6 show BSE images of Source 102, with different areas selected for EDS analysis. The spectrum in Figure D-5 describes relatively clean steel area without corrosion products (oxides), pre-treatment residue or lubricant residue, while the spectrum in Figure D-6 describes an area where a calcium compound, possibly calcium stearate, is present. Figure D-7 shows an x-ray dot map showing the distribution of elements along a similar area of Source 151.

In the BSE images of Sources 102 and 151, dark color indicates the presence of lubricant (and possibly borax pre-treatment as well). The dark area can be seen running parallel to the length of the wire and appears to coincide with surface roughness seen in the wire. The lubricant does not generally appear as “lumps” on the surface, but occurs in long streaks coincident with the surface roughness of the wire.

As seen in Figure D-8, the lubricant can be found in narrow features in the wire. The black areas shown with corresponding EDS spectrum can occupy a space less than a micron across, but extend the length of the image. A corresponding SE image in Figure D-9 shows the topography of the wire. The correlation of the lubricant and the surface roughness can be clearly seen, indicating that the lubricant phase can be found in depressions in the wire surface.

The zinc phosphate pre-treatment can be seen in the images and EDS spectra of Source 103 (Figure D-10 and Figure D-11). The zinc to phosphorus ratio (as seen in the relative intensities of the EDS peaks) is not identical throughout the sample. Figure D-12 is a SE image of the same area as shown in Figure D-11. This image shows the topography of the wire surface. It can be seen that the zinc phosphate pre-treatment and the sodium-based lubricant phase shown in Figure D-11 is not associated only with the striations as the other pretreatments were.

Conclusions

The SEM/EDS analysis shows that the surface roughness occurs mainly in the form of striations oriented longitudinally on the wire. These striations are likely a result of the drawing process. These features may explain some of the variations found in surface roughness in the metallographic study. If a longitudinal cross-section is cut parallel to the striations, a different surface roughness will be observed, compared to a specimen that is cut at a slight angle to the striations.

Residue of the surface pre-treatment and lubricant is non-continuous and well-distributed on the wire surface. If the surface pre-treatment is applied prior to the drawing process, it is expected that it will become discontinuous as the wire is elongated. The lubricant residue is generally found coincident with the striations found along the length of the strand. The lubricant is likely to become pressed into the minute depressions on the wire surface during the drawing processes.

INVESTIGATION OF LINK BETWEEN ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY AND BOND

Introduction

The surface roughness of the wires of prestressing strand may have considerable impact on bond strength of those strands to concrete. While a profilometer or metallographic examination is capable of measuring surface roughness, the unique shape of strands makes this measurement difficult. Microscopic techniques examine a limited area and do not provide information about the entire strand. Electrochemical Impedance Spectroscopy (EIS), a standard electrochemical technique used in corrosion science, is a possible candidate for surface roughness measurement.

When immersed in solution, a metal surface can be viewed as a resistor in parallel with a capacitor. The capacitance of the capacitor is largely proportional to the total area of the actual surface in contact with the solution. Because a rougher surface will have larger area in contact with solution, a larger capacitance is expected. Since the capacitance can be effectively estimated by electrochemical impedance spectroscopy, this technique can be used to indirectly assess metal surface roughness. Unlike a profilometer or analysis of metallographic sections, which estimate the surface roughness of a confined linear region, EIS estimates the overall surface roughness of the entire sample immersed in solution.

Method

To exclude any possible complicating factors, individual wires instead of strands were tested. Each wire segment was approximately 6-in. long, and one of the two cut-ends was ground with 180-grit sandpaper to produce a reproducible condition. At least two wires were tested per strand source. The following procedure was used during the testing:

1. Wipe a wire segment with acetone-soaked paper towel
2. Ultrasonically clean the wire in a methanol bath for 10 minutes
3. Rinse the wire with de-ionized water and set dry with paper towel
4. Place the wire into a beaker with 450 ml 0.5 M NaOH solution, resulting in an immersion length of approximately 4 in.
5. Introduce a titanium mesh and a saturated Calomel electrode into the solution to form a standard three-electrode corrosion cell
6. Allow the corrosion cell to rest for 30 minutes
7. Perform EIS test with a test frequency range from 100 kHz to 0.01 Hz.

A simple equivalent circuit was used to analyze the collected data. The circuit, as shown in Figure D-13, consists of a solution resistor R_s , an interfacial resistor R_p and a pseudo-capacitor (known as constant phase element [CPE]) which has two characteristic components (Y_o and n). The capacitance (C) of the capacitor can be calculated as the following

$$C = Y_o \times (\omega)^{n-1} \quad (1)$$

where $\omega = 2\pi f$ (f is frequency, Hz) and n has a value between 0 and 1. When $n=1$, this CPE element is identical to a pure capacitor and $Y_o = C$. For simplicity, Y_o was viewed as the nominal capacitance of the capacitor.

Results and Discussion

Table D-3 summarizes the EIS test results. To aid direct comparison, values of the average capacitance per nominal unit area (C_o) for each wire source were calculated. C_o was defined as the following

$$C_o = \frac{Y_o}{S} \quad (2)$$

Where S is the nominal surface area of the wire (surface area of a cylinder of the same diameter and length) immersed in the testing solution. This nominal surface area is not to be confused with the actual surface area, which takes into account the roughness of the surface. Higher C_o values suggest rougher surfaces. Accordingly, the surface roughness of the wires from different sources can be ranked as follows:

Source 151 > Source 960 > Source 697 > Source 548 > Source 717

Attempts were made to correlate C_o with various parameters, including bond stress, change in corrosion potential, corrosion rate, and surface roughness measurements made with a profilometer, but no strong correlation could be made. C_o has no apparent correlation with corrosion rates or R_a (surface roughness measured with a profilometer). Excluding Source 717, C_o appears to have a fair correlation with bond stress and corrosion potential change, respectively; a wire with rougher surface (higher C_o value) tends to have a lower bond stress value and a larger corrosion potential change. Because a rougher surface without lubricant residue is expected to have more contact area with concrete and consequently higher bond stress, this observation suggests that other factors, such as residual lubricant concentration, also play a role in the bond of the strands.

It was noted that the Source 717 wires had the highest weight loss on ignition (LOI) and extracted organic residue concentration. As both parameters are indicators of the amount of residual lubricant on a strand, it is judged that residual lubricant is an important contributing factor that should be assessed together with

surface roughness. A regression analysis considering extracted organic residue and C_o as dependent variables versus bond stress (expressed in terms of mortar pull out stress at 0.1-in. slip) was performed according to the following expression:

$$\text{Bond Stress} = \beta_0 + \beta_1 \times C_o + \beta_2 \times \text{Extracted Organic Residue} \quad (3)$$

where β_0 , β_1 , and β_2 , are constants. The R^2 adjusted (per discussion in Appendix A, R^2 adjusted is used for multiple predictor regression analyses) of the above equation obtained from the analysis was 0.88, suggesting that this model equation describes the system moderately well. When LOI was used in Equation 3, as shown in Table 4, R^2 adjusted was 0.74.

Because actual lubricant coverage is affected by surface roughness, a new parameter LC was defined to represent lubricant coverage

$$LC = \frac{\text{Extracted Organic Residue}}{C_o} = \frac{\frac{\text{Lubricant Mass}}{S}}{\frac{Y_o}{S}} = \frac{\text{Lubricant Mass}}{Y_o} \quad (4)$$

The relation between dependent variables (LC and C_o) and the bond stress was then described with a similar regression model

$$\text{Bond Stress} = \beta_0 + \beta_1 \times C_o + \beta_2 \times LC \quad (5)$$

A standard regression analysis yielded the following estimates: $\beta_0 = 1.445$; $\beta_1 = -4753.6$; $\beta_2 = -0.00063$; and R^2 adjusted = 0.95. As shown in Figure D-14, a strong correlation between $\beta_0 + \beta_1 \times C_o + \beta_2 \times LC$ and bond stress is evident. When LOI was used instead of extracted organic residue in Equations 4-5, as shown in Table D-4, a R^2 adjusted of 0.92 was obtained.

Equation 5 suggests that bond stress is controlled by both surface roughness and amount of residual lubricant; given a surface roughness (C_o), more lubricant residue (higher Extracted Organic Residue or LOI) will lead to lower bond stress.

Conclusions

Electrochemical impedance spectroscopy (EIS) was found to be capable of quantifying overall surface roughness of individual wires. Higher values of average capacitance per unit area (C_o) suggest a rougher surface. Poor correlation between C_o and R_a (calculated based on measurements made with a profilometer) was observed. Because profilometric methods only measure surface roughness along a line (and roughness was found to be directional), EIS methods, which provide information about the entire immersed specimen, are expected to provide a better overall assessment of surface roughness.

Regression models considering the combined effect of C_o and extracted organic residue/ C_o (or LOI/ C_o) yielded the best correlation with the observed bond stress, suggesting bond stress is controlled by both surface roughness and amount of residual lubricant.

CEMENT HYDRATION STUDY

Introduction

Concern about the bond of prestressing strand to concrete is not just limited to the lubricating effect of the drawing compound (lubricant) residue. The residue may affect hydration of the cement, therefore affecting bond. To determine if strand residues can affect hydration of the cement paste adjacent to the strand, a simple cement hydration study was conducted. The objective of this study was to determine if the microstructure of the cementitious paste and the hydration characteristics of the cement are different in the interfacial region than in the bulk concrete away from the strand. The cement hydration was compared using petrographic methods of analysis.

Method

Four strands from the Sources (102, 103, 151, and 151 after a cleaning procedure) were selected for this study. Strand Sources 102, 103 and 151 had been previously studied microscopically, chemically, and mechanically, and the cleaned sample (151C) was presumed to have minimal residue on the surface. Source 103 had good bond characteristics, and is presumed to have been manufactured with a zinc phosphate pre-treatment and sodium stearate lubricants. Source 102 demonstrated poor bond characteristics, and is presumed to have been manufactured with a borax pre-treatment and sodium/calcium stearate lubricants. Source 151 had poor to intermediate bond characteristics, and is presumed to have been manufactured with a borax pre-treatment and calcium stearate lubricants.

As a control sample (strand with no lubricant residue), a sample of Source 151 was cleaned by immersing it in 25% sodium hydroxide solution for 15 minutes, a process reported to remove essentially all of the lubricant residue (Maehata 2006). The appearance of the strand was affected by the sodium hydroxide cleaning, indicating that the surface had been cleaned. Figure D-15 is a photograph of a section of strand that was partially cleaned.

Strand samples were embedded in mortar with at 1:3 cement-sand ratio and 0.48 water-cement ratio. The sand was a graded standard sand conforming to ASTM C778, and the cement was a Type I portland cement. The samples were cured at approximately 73°F and 50% relative humidity of four hours, then placed in plastic Ziploc bags to retain moisture and cured at 60°C (140°F) for 12 hours. These conditions were chosen to simulate the casting of prestressed concrete up to the point at which the strand would be released. After cooling for 5 - 7 hours, the specimens were cut in half lengthwise to remove the strand from the mortar and immediately rinsed in acetone and dried for approximately 3 minutes at 110°C to stop the cement hydration.

Small sections of the mortar were cut and rinsed in acetone and dried at 48°C for 4 hours to stop any further hydration of the cement from the cutting process. These specimens were embedded in epoxy and then prepared in thin section for microscopic examination. Thin sections were prepared from the mortar portion of the specimens only, and the sections were oriented perpendicular to the long axis of the strands. The samples were prepared and examined in general accordance with the procedures outlined in ASTM C 856, *Standard Practice for Petrographic Examination of Hardened Concrete*.

Results and Discussion

Mortar Composition

The portland cement grains are uniformly distributed. The extent of cement hydration is low. The thickness of the hydration rims on partly hydrated cement grains is less than 5 μm . Calcium hydroxide (CH) is abundant, well crystallized, and uniformly distributed. The sand particles are frequently partially surrounded by a thin coating of calcium hydroxide. These rims are usually less than 5 μm thick. The estimated air content is 3 to 5 percent. The air voids are mostly oval to irregular in shape, and are fairly small (less than 1 mm in diameter). No deposits are observed in the air voids. No significant microcracks are observed in the body of the mortar. No paste carbonation is detected.

Comparison of Interfacial and Bulk Properties

The extent of hydration was quantified in terms of the quantity of unhydrated portland cement grains (UPC's) and of calcium hydroxide. Calcium hydroxide is a product of the cement hydration reaction that is visible early in the hydration process; more CH is indicative of more advanced hydration. Paste characteristics are summarized in Table D-5 and are illustrated in Figure D-16 through . A description of the features that are common in all samples (in the body of the mortar) is followed by a description of the individual features of each sample.

Observations of the Body of the Mortar Common to All Samples

The paste in the body of the mortar contains an estimated 30 to 40 percent unhydrated and partly hydrated cement grains, and 8 to 12 percent calcium hydroxide crystals. Calcium hydroxide crystals are tabular and range in size from 5 to 25 μm across. Hydration rims are typically 2 to 4 μm thick. Overall, the extent of cement hydration is not far advanced. Traces of carbonate crystals are observed in the body of the mortar.

Source 151

Figure D-16 and show the interfacial region around Source 151. The paste in the region adjacent to the steel (interfacial region) is optically cloudy. A fine-grained layer approximately 10 μm thick is observed at the interface between mortar and steel. This layer contains very small calcium hydroxide crystals (less than 3 μm). Under the fine-grained layer is a layer of densely packed unhydrated portland cement grains (UPC's) and partly hydrated cement grains approximately 50 to 70 μm thick. The hydration rims on the partly hydrated cement grains in this layer are typically less than 2 μm thick. The extent of portland cement hydration in the cloudy layer is interpreted to be somewhat lower than in the body of the mortar. The paste in the interfacial region contains an estimated 40 to 50 percent unhydrated and partly hydrated portland cement grains, and very little calcium hydroxide. A few calcium carbonate crystals are observed in the cloudy region, and are also occasionally observed in the body of the mortar. These scattered small carbonate rhombs appear to be a minor contaminant of the cement.

Source 151C

through show the interfacial region around Source 151C. A fine-grained layer, approximately 4 μm thick, containing very small calcium hydroxide crystals is observed at the interface between the mortar and the steel. The thin section also includes a substantial amount of debris (angular fragments consisting of the same fine-grained material) in the strand impression, entrapped in the epoxy used during sample preparation. No differences are detected in the abundance of portland cement and calcium hydroxide between the body of the mortar and the interfacial region. No differences in portland cement hydration characteristics are detected between the body of the mortar and the interfacial region.

Source 102

and show the interfacial region around Source 102. A thin, birefringent layer approximately 2 μm thick is observed at the interface between the mortar and the steel (and). In plane-polarized light, this layer is somewhat pinkish brown and possibly contains an organic compound. The layer appears to act as a substrate for the crystallization of coarse CH crystals. The CH crystals may be responsible for the apparent birefringence of the thin film. A layer of cloudy paste 20 to 25 μm thick is observed under the surface film. Only small amounts of CH are observed within the cloudy layer. A few short tears (typically 0.2 mm long or less) are observed at the base of the cloudy layer, and are parallel to the interface. The extent of portland cement hydration in the cloudy layer is interpreted to be somewhat lower than in the body of the mortar. The paste in the interfacial region contains an estimated 40 to 50 percent unhydrated and partly hydrated portland cement grains, and very little calcium hydroxide.

Source 103

through show the interfacial region around Source 103. A patchy layer that resembles laitance is observed at the interface between the mortar and the steel. The layer contains small calcium hydroxide crystals, small cement grains, and occasionally, small sand grains. The optical characteristics do not suggest the presence of an organic compound. The thickness of this layer ranges from 5 to 50 μm . A layer of cloudy paste 20 to 30 μm thick is observed under the surface film. The extent of portland cement hydration in the cloudy layer is interpreted to be somewhat lower than in the body of the mortar. The paste in the interfacial region contains an estimated 40 to 50 percent unhydrated and partly hydrated portland cement grains, and very little calcium hydroxide.

Conclusions

Only Source 102 (poor bond) had a discrete film at the contact between the mortar and strand. The film is approximately 2 μm thick. It is optically somewhat pinkish brown in plane-polarized light, and possibly contains an organic compound. The film also displays unusual anisotropy in cross-polarized light. The film appears to be a substrate for the crystallization of fairly large tabular calcium hydroxide crystals. The physical characteristics of these crystals may be contributing to the poor bonding performance of this strand source.

Sources 151 and 151C (intermediate bond) exhibited a thin, fine-grained layer at the contact between the mortar and strand. The layer is 10 μm thick on Source 151 and 4 μm thick on Source 151C. The crystals comprising this layer were too small for identification with the petrographic microscope.

Source 103 (good bond) exhibited an intermittent coating at the contact between the mortar and strand. The coating somewhat resembles laitance (a partially carbonated mixture of water-rich “paste” and fine particles of cement and sand). It is unlikely that this material was deposited by bleed water migrating to a void adjacent to the strand. It is possible that this material is debris deposited into a crevice between the mortar and the epoxy created during sample preparation.

Except for Source 151C (cleaned to remove the lubricant residue), all the samples exhibited a region of optically cloudy paste at the interface with the strand. The thickness of the cloudy layer in the interfacial region was greatest (50 to 70 μm) in Source 151 and was approximately the same thickness (20 to 30 μm) in Sources 102 and 103. The cloudy region has a slightly higher percentage of unhydrated portland cement grains (UPC's) and contains only traces of calcium hydroxide (CH). This suggests that portland cement hydration might be impeded in the region adjacent to the steel. The optically cloudy paste may also be attributed to residue of an organic substance in the interstitial spaces between the cement particles. These changes in the interfacial region may affect bond strength.

EFFECT OF RESIDUE IN TRANSFER ZONE

Introduction

The effect of lubricant residue on bond strength can be further studied by examining the concrete in the transfer zone. Any lubricant residue in this area may have an impact on the concrete, leaving specific features that can be detected petrographically and chemically. As discussed previously, the presence of lubricant residue on the strand surface appears to affect the hydration of the cement at the interface, and produces an optically cloudy layer at the interface. The presence of residual lubricant on the cement surface can be studied with chemical extraction and analysis procedures. Both methods were used to study the transfer zone of a sample with poor bond.

Sample

Sections of concrete taken from a prism specimen used in a transfer length test of strand were studied petrographically and chemically to investigate strand slippage. Both ends of this test prism, which contained strand from Source 102, demonstrated transfer lengths of at least 48 in. (average bond stress less than 293 psi). Such a long transfer length is characteristic of poor bond, and this investigation was initiated to determine if the mechanism by which this excessive strand slip occurred could be identified.

Petrographic Examination of Specimen with Long Transfer Length

Method of Petrographic Examination

The concrete and strand in this prism were examined in two orientations. In the first, a broken face parallel to the strand containing an impression of the strand was obtained by splitting the prism along the longitudinal axis of the strand with a compressive load applied through line contacts along the top and bottom of the prism. The 6-in. long section of concrete parallel to the strand came from the north end of the south prism (11 to 17 in. from the end of the prism) cast around the sample of strand from Source 102. In the second orientation, cross-sections cut perpendicular to the strand from either end of the same prism were examined. The cross-sections contained the strand with the concrete. The cross-sections were taken approximately 18 in. from either end of the beam. The study was performed in general accordance with ASTM C 856, *Standard Practice for Petrographic Examination of Hardened Concrete*.

Results and Discussion of Petrographic Examination

The face of the prism containing the strand impressions is shown in Figure D-28. The sample studied is shown in Figure D-29. A significant portion of the strand impression exhibits dark-colored, shiny paste that was in contact with the steel. One of the cross-sections is shown in Figure D-30 to Figure D-32. The dark paste is visible in these images as wedge-shaped regions between the wires and as thin rims that extend partially around the individual wires that make up the strand.

In the cross-section of the prism, the cementitious paste in contact with the strand is darker than the surrounding paste and of inconsistent color. This is shown in Figure D-30, and is particularly noticeable in the crevices formed between the wires (Figure D-31) and in the interstitial space within the strand (Figure D-32). On the outer surface of the wires, the dark layer is intermittent and reaches a maximum thickness of approximately 0.05 millimeters. The microcracks observed in the strand impression (discussed below) were not obvious in these samples.

The cementitious paste that was in contact with the strand on the broken face is smooth and light gray to dark brownish-gray. The dark, brownish-gray paste is hard and shiny (Figure D-33). The dark paste is more prevalent in ‘ridges’ where the paste penetrated the interstitial spaces between the helically arranged wires. The light gray paste is soft and easily scratched (Figure D-34). The dark paste appears speckled when viewed using stereomicroscope magnification (Figure D-35). The shiny appearance of the dark paste suggests the presence of an organic residue; however, in its current condition the paste is not appreciably hydrophobic. Longitudinal and, rarely, transverse microcracks are observed in the impressions. The longitudinal microcracks are occasionally accentuated by rust-colored staining (Figure D-36), presumably related to the steel strand. A few entrapped air voids are also observed in the contact region (Figure D-37). The largest of these entrapped voids is 4 mm across.

The hard, shiny, dark, brownish-gray paste in the impressions at the interface of the strand and concrete consists of a very thin layer of low water-cement ratio paste (Figure D-38). The estimated thickness of this layer is 30 to 50 micrometers. The speckled appearance of the dark paste is caused by the abundance of unhydrated portland cement grains. The paste is not carbonated. A small amount of finely crystalline calcium hydroxide is present. The paste is nearly isotropic (glassy); however, the optical characteristics are inconclusive with regard to the presence of organic residue. The paste underlying the thin dark layer is similar to the paste in the body of the concrete.

The soft, light gray paste in the impressions at the interface of the strand and concrete is also a very thin layer that is underlain by paste that is visually similar to the paste in the body of the concrete. The soft paste is carbonated and has a higher water-cement ratio, based on the scarcity of residual portland cement grains (Figure D-39). The optical characteristics of the paste appear normal. The presence of organic residue is not indicated.

Spectroscopical Studies

Method of Spectroscopical Studies

Two samples of the prism were selected for chemical analysis. Sample 1 was a 12-in. segment of concrete prism with corresponding strand that measured 6 to 18 in. inward from prism end. Sample 2 was an 11-in. segment of concrete prism with corresponding strand that measured 1/2 to 11-1/2 in. inward from another prism end.

The purpose of these studies was as follows: (1) isolate, by acid digestion and solvent extraction, residual stearate-based lubricant from strand surfaces and corresponding socket surfaces that were exposed by the split procedure; (2) determine the amount of strand lubricant transfer to concrete surfaces by comparison of residue weights; and (3) identify the residues by spectroscopical analysis.

Each concrete socket surface was ground to pulverize a thin layer of the cement paste and fine aggregate that had been in contact with the strand. This concrete interface powder from each sample was subjected to an acid-digestion, solvent-extraction procedure to isolate the acidified forms of stearate-based lubricants, similar fatty acids, and other solvent-soluble organic components that may be present. The dried residues were weighed. The powders from the concrete sockets of Samples 1 and 2 yielded 1.1 and 0.8 milligrams of dried residue, respectively. Both residues appeared to be resinous solids at both 23°C and 105°C.

The Fourier transform infrared (FTIR) spectra of the residues from concrete socket surfaces were not similar to each other; although, both spectra indicated minor amounts of fatty acid. The residue from Sample 2 contained relatively more fatty acid than that of Sample 1. Based on the physical appearances

of these trace residues and their FTIR spectra, polymeric components are indicated in both concrete residues. The Sample 2 concrete residue had a significant amount of epoxy, while the Sample 1 concrete residue had a very minor amount. The Sample 1 concrete residue had a significant amount of alkyd resin.

Each strand surface was subjected to an extraction method similar to that used in the testing reported in Appendix A. The method involved two wash procedures: the first wash used an acid solution, and the second wash used solvent suitable for isolating acidified forms of stearate-based lubricants, similar fatty acids, and other solvent-soluble organic components that may be present. The dried residues of the extraction method were weighed. The strands of Samples 1 and 2 yielded 4.4 and 4.3 milligrams of dried residue, respectively. The residues from the strands of Samples 1 and 2 appeared very similar to each other. Both residues were wax-like solids at 23°C and oil-like fluids at 105°C.

The FTIR spectra of the residues from strands were similar to each other and to reference spectra of stearic acid and palmitic acid.

Conclusions

The petrographic examination demonstrated that the cement paste in the transfer zone is different from the underlying paste. The dark-colored, shiny paste on portions of the strand impressions is the result of a thin, hard, paste layer having a low water-cement ratio. The hardness and gloss of the paste surface may indicate less friction in this area. Other portions of the impressions have a softer, light gray paste layer that is now carbonated. Carbonation may have occurred since the beam was split. Some organic substances can interfere with normal cement hydration. The presence of an organic residue at the interface between the strand and the paste could not be ruled out, based on paste characteristics observed with the polarized-light microscope.

The spectroscopical analysis of the strands yielded very similar amounts of wax-like residues that were identified as either stearic acid or palmitic acid. The extractions and analyses of the two concrete interface samples yielded very little fatty acid residue, but polymeric components were detected. The source of these polymeric components was not determined. Thus, it appeared that very little strand lubricant transferred to the concrete surface.

MEASUREMENT OF VARIATIONS IN WIRE AND STRAND DIAMETER

Introduction

Some researchers have suggested that there is a possible influence of variations in strand or wire cross-section on bond (Stoker 1971). To investigate this possibility, strands and wire diameters were measured to determine the variations within provided samples.

Method

Measurements of strand and wire diameter were conducted using calipers with 0.0005-in. resolution. The diameter of the recently-manufactured strand sources were measured on three Sources, 102, 103 and 151. Two pieces of strand were measured from each source every inch over a foot. The king wire from one piece of strand from each source was measured every inch over a foot, and the other six wires from the strand were measured at one location.

Results and Discussion

The strand was measured across each of three maximum diameters formed by the seven wires, and the average diameter is plotted versus location on the strand in Figure D-40. The diameter of the king wire versus location on the wire is plotted in Figure D-41. The diameter of the strand varied approximately 0.005 in. over the length observed for each piece. The king wire diameter varied 0.001 in. over the same length. The diameter of the non-king wires was consistent for each source.

Conclusions

Despite some small variations in strand and wire diameter, no clear link to bond performance was observed between variation measured on this scale and bond.

CONCLUSIONS OF SUPPLEMENTAL INVESTIGATIONS

The supplemental investigations provided information about the strand and strand/concrete interface, resulting in a greater understanding of some factors that may influence bond. Studies of surface roughness and the relationship between surface roughness and lubricant residue were carried out by metallographic, SEM/EDS, and EIS studies. The effect of lubricant residue was evaluated with petrographic and chemical investigation of the concrete.

The effects of surface roughness, together with the amount of residual lubricant on the strand were compared with known bond strengths. The relationship between surface roughness and bond strength is complicated by the presence of residual lubricant. Residual lubricant appears to be associated with surface roughness, with the lubricant occurring predominately within microdepressions on the wire surface, as demonstrated by SEM/EDS analysis. A strong correlation between surface roughness and bond strength was not apparent based on metallographic studies, but only a very limited amount of data was collected. EIS studies found a correlation between bond strength and the combination of a roughness parameter (based on the capacitance per nominal unit area) and the lubricant concentration.

Petrographic studies have shown that there is a difference in cement hydration at the interface of strand that appears to be a direct result of the presence of residual lubricant. Cement hydration studies comparing the interfacial features of as-received strand with strand that had been cleaned and stripped of its residual lubricant demonstrate that the cement particles at the strand interface of the as-received strand appears to be less hydrated than the surrounding cement, while the interface of the cleaned strand is similar to the bulk cement. This reduction in cement hydration at the interface was also seen in studies of the transfer zone of a strand/concrete sample with poor bond. The organic residue on the strand appears to be affecting cement hydration adjacent to the strand.

These supplemental investigations, while not directly involved in formulating the QA/QC tests, provided a greater understanding of the entire concrete, lubricant and strand system. The presence of residual lubricant on the surface of the strand is a result of the amount of lubricant used, washing procedures, and the surface roughness. The residual lubricant appears to have an impact on cement hydration, possibly also reducing the strength of the bond.

REFERENCES

Maehata, Toshio and Ioka, Hiroichi (2006). "Bond strength of PC wire in concrete" Wire Journal International, Vol. 39 No. 4 pg 94.

Stocker, M.F., and Sozen, M.A. (1971). "Investigation of Prestressed Reinforced Concrete for Highway Bridges, Part V: Bond Characteristics of Prestressing Strand, "Engineering Experiment Station 503, The University of Illinois.

TABLES

Table D-1. Summary of statistical parameters calculated for wire surface profile

Strand Source	Std. Dev. (μm)	Coeff. of Deter. (R^2)
101	4.153	0.9604
102	2.481	0.9484
103	1.830	0.9744
151	1.650	0.8267

Table D-2. Presumed compounds used in manufacture of each source

Strand Source	Prominent Elements	Presumed Pretreatment	Presumed Lubricants	Concrete Pull out Bond Stress at First or 0.1-in. Slip (psi)
102	Na, Ca, B	borax	Na/Ca stearate	441
103	Zn, Na	zinc phosphate	sodium salt of fatty acid	944
151	Na, B	borax	calcium stearate	541

Table D-3. EIS test results and relative surface roughness

Wire source	S (nominal wire area in solution) (cm^2)	n	Nominal capacitance Y_o (F)	C_o , average Y_o/S^1 (F/ cm^2)
151	14.4	0.92	0.00404	0.00023
151	14.8	0.92	0.00266	
548	13.5	0.93	0.00188	0.00013
548	13.9	0.93	0.00176	
548	13.9	0.94	0.00181	
548	14.3	0.93	0.00191	
697	13.9	0.88	0.00228	
697	13.9	0.87	0.00247	0.00016
697	13.9	0.87	0.00189	
717	14.3	0.92	0.00111	
717	13.9	0.92	0.00105	0.00009
717	13.9	0.92	0.00133	
717	13.9	0.92	0.00128	
717	13.9	0.91	0.00168	
960	13.9	0.89	0.00252	0.00018
960	13.9	0.91	0.00259	

1. The average nominal capacitance per nominal surface area.

Table D-4. Regression models

Regression model	R ² adjusted	
	LOI	EOR ¹
$Bond \cdot Stress = \beta_0 + \beta_1 \times C_o + \beta_2 \times LOI(orEOR)$	0.74	0.88
$Bond \cdot Stress = \beta_0 + \beta_1 \times C_o + \beta_2 \times \frac{LOI(orEOR)}{C_o}$	0.92	0.95

¹ EOR: extracted organic residue

Table D-5. Microscopical characteristics of test specimens

Source	Interface / Contact Between Mortar and Steel	Interfacial Region Beyond Contact	Body of Mortar
151 "Intermediate" Bond	Fine-grained layer 10 µm-thick; possibly composed of intermixed CH and CSH	50 to 70 µm-thick cloudy layer with 40 to 50% UPC's and <4% small CH crystals; UPC's have thin hydration rims	30 to 40% UPC's with thin hydration rims and 8 to 12% medium-sized CH crystals; sand grains are partly coated with CH
151C (cleaned) "Intermediate" Bond	Fine-grained layer 4 µm-thick; possibly composed of intermixed CH and CSH	No difference between interfacial region and body of mortar. 30 to 40% UPC's with thin hydration rims, and 6 to 10% small CH crystals	30 to 40% UPC's with thin hydration rims and 6 to 10% small CH crystals; sand grains are partly coated with CH
102 "Poor" Bond	2 µm-thick film, possibly organic, CH crystallized below film	20 to 25 µm-thick cloudy layer with 40 to 50% UPC's and <4% small CH crystals; UPC's have thin hydration rims; short tears parallel to interface	30 to 40% UPC's with thin hydration rims and 8 to 12% medium-sized CH crystals; sand grains are partly coated with CH
103 "Good" Bond	Intermittent layer 5 to 50 µm thick containing cement grains, CH, small sand particles (resembles laitance or possibly sectioning debris)	20 to 30 µm-thick cloudy layer with 40 to 50% UPC's and <4% small CH crystals; UPC's have thin hydration rims	30 to 40% UPC's with thin hydration rims and 8 to 12% medium-sized CH crystals; sand grains are partly coated with CH

UPC's - unhydrated portland cement grains

CH - calcium hydroxide

FIGURES

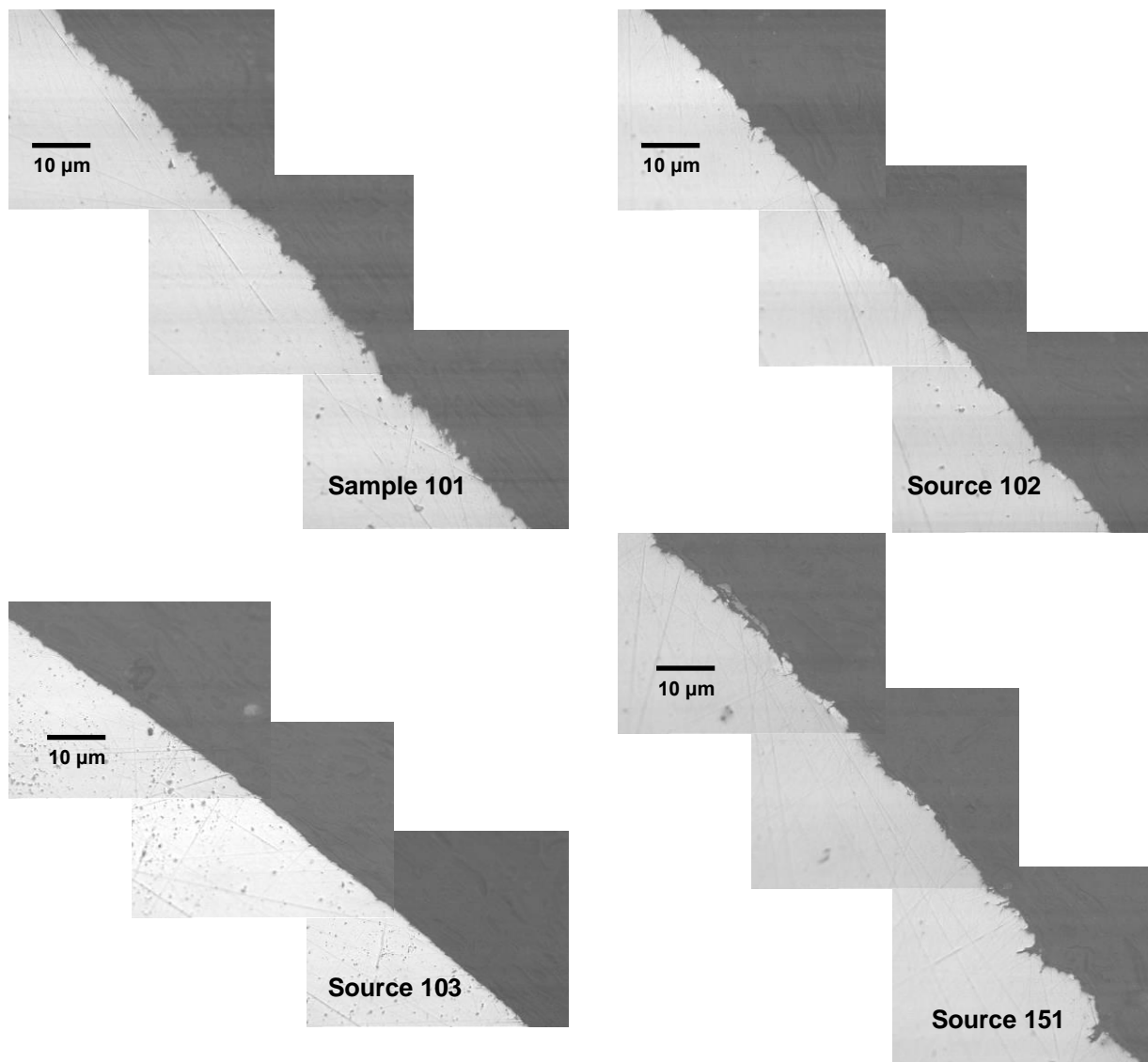


Figure D-1 - Transverse cross-sections of wire edge profiles.

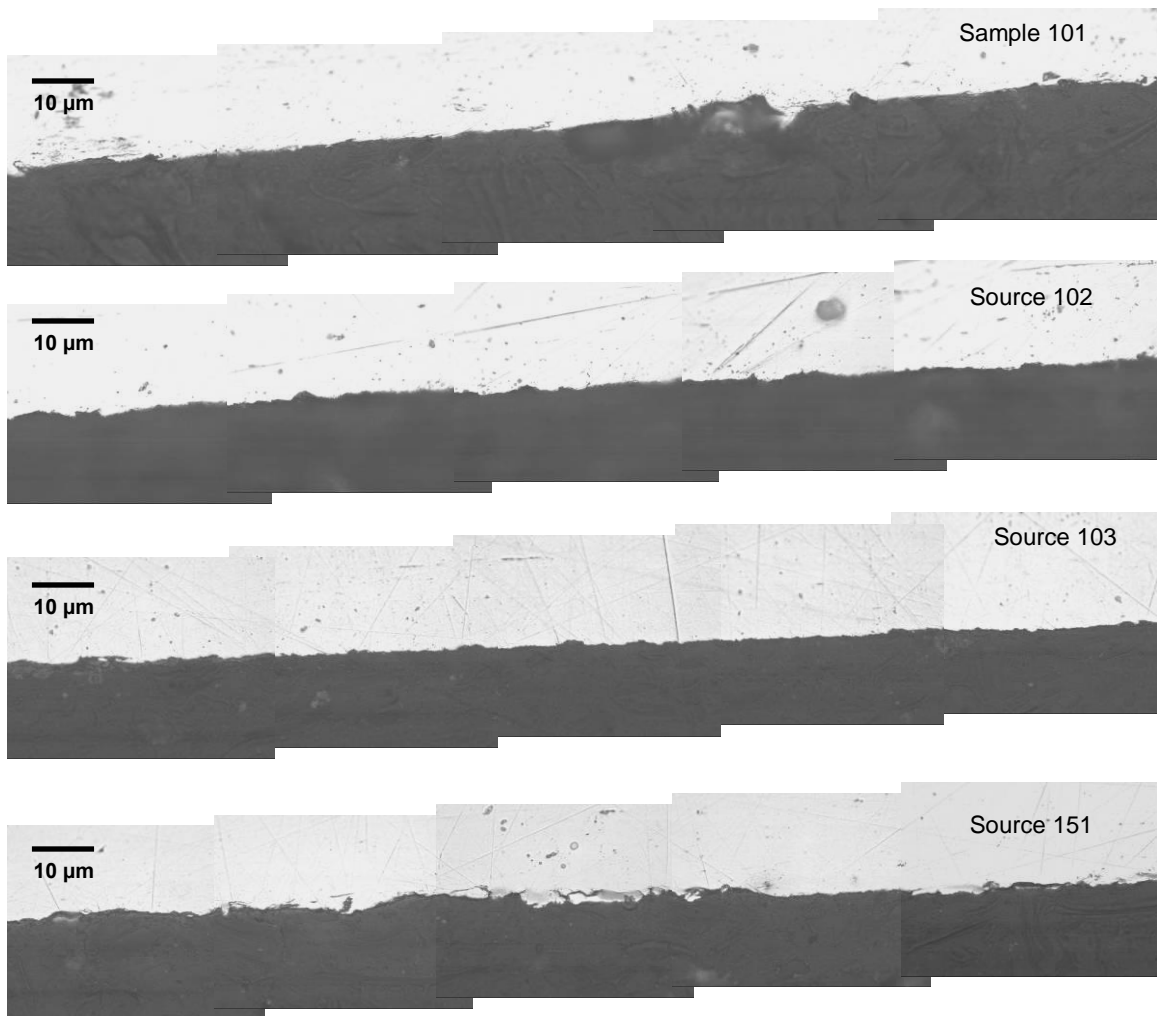


Figure D-2 - Longitudinal cross-sections of wire edge profiles.

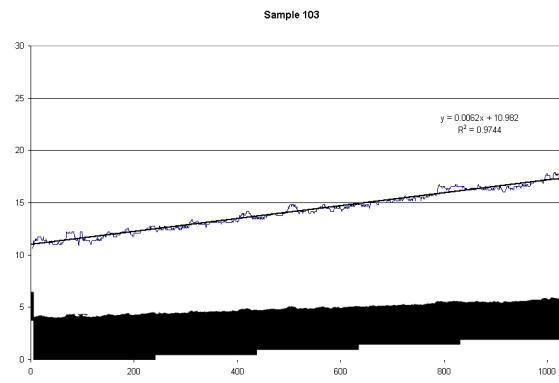
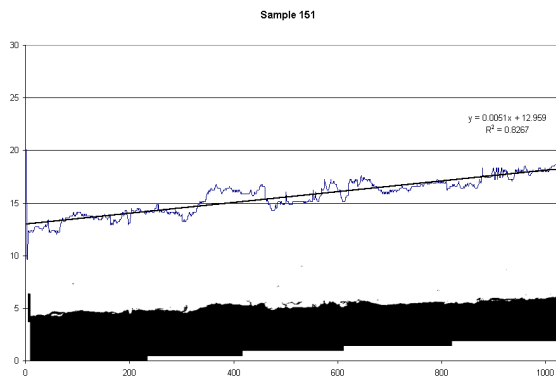
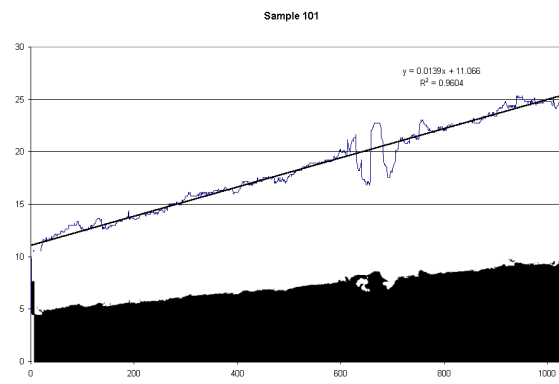
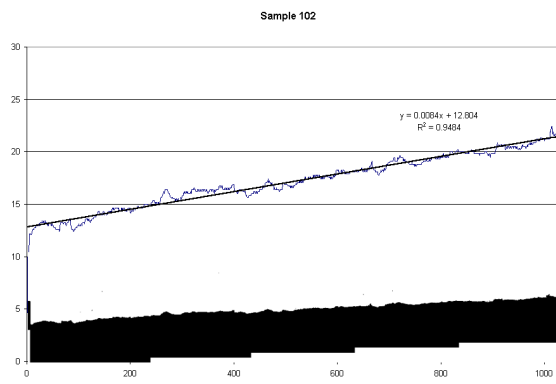


Figure D-3 - Measured roughness profile of transverse cross-sections.



Figure D-4 - Low magnification (17X) BSE image of Source 103.

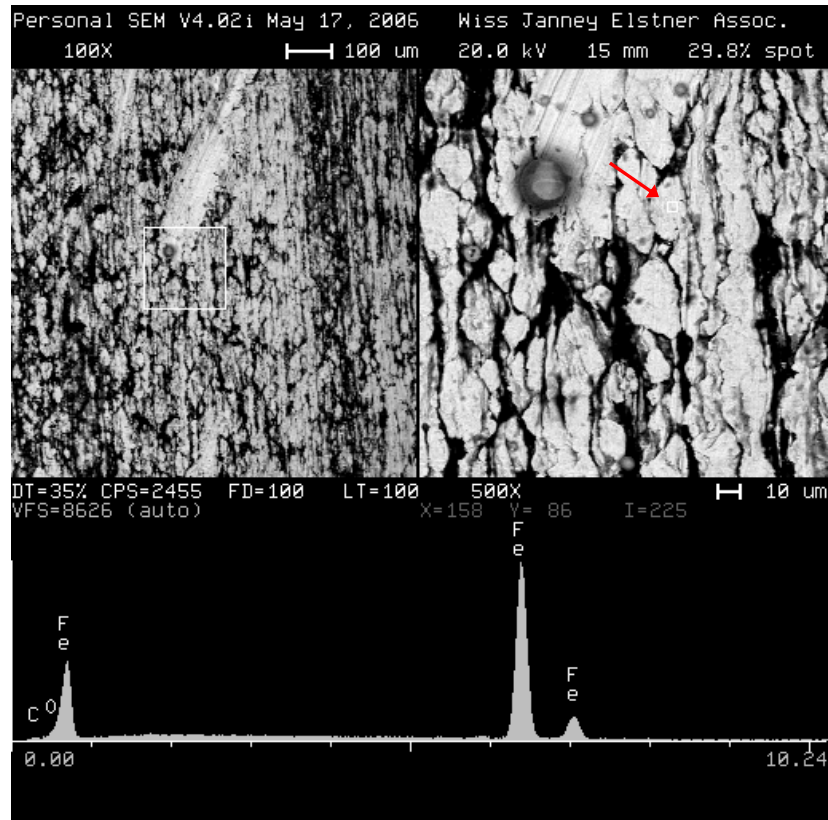


Figure D-5 - BSE images and EDS spectrum from Source 102. An arrow indicates the location where the EDS spectrum was taken. The EDS spectrum shows iron, indicating the presence of steel with no oxide, pre-treatment or lubricant.

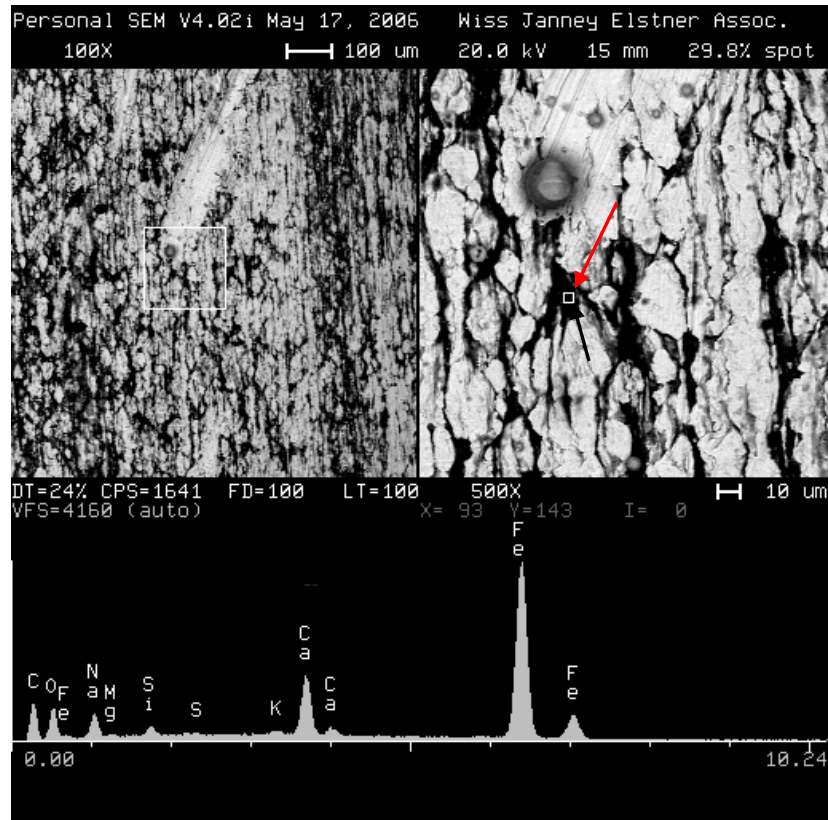


Figure D-6 - BSE images and EDS spectrum from Source 102. The EDS spectrum is from the point shown by the arrow and shows Ca, Na, O and C from the lubricant (and possibly from the pre-treatment, although the boron is not detected). The presence of small amounts of Mg, Si, S and K detected are impurities in the pre-treatment or lubricant.

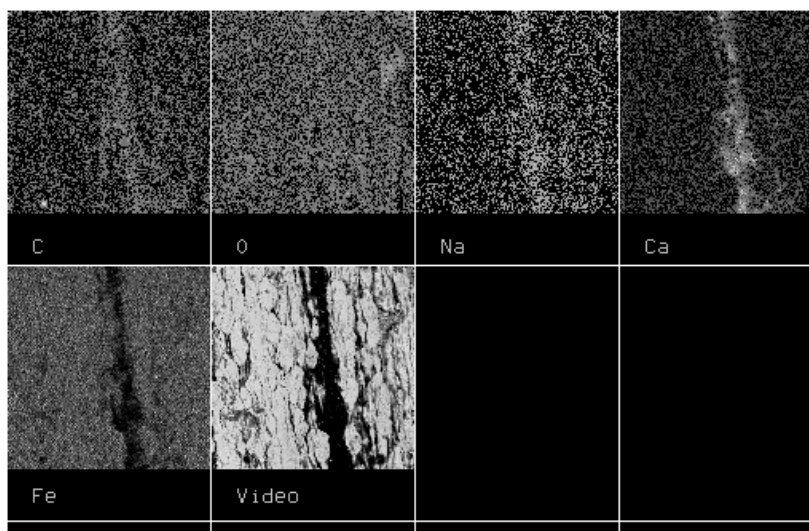


Figure D-7 - X-ray dot map of Source 151, with BSE image, indicating the distribution of various elements within the sample. C, Na, and Ca are more prevalent within the depression (dark area in the video image).

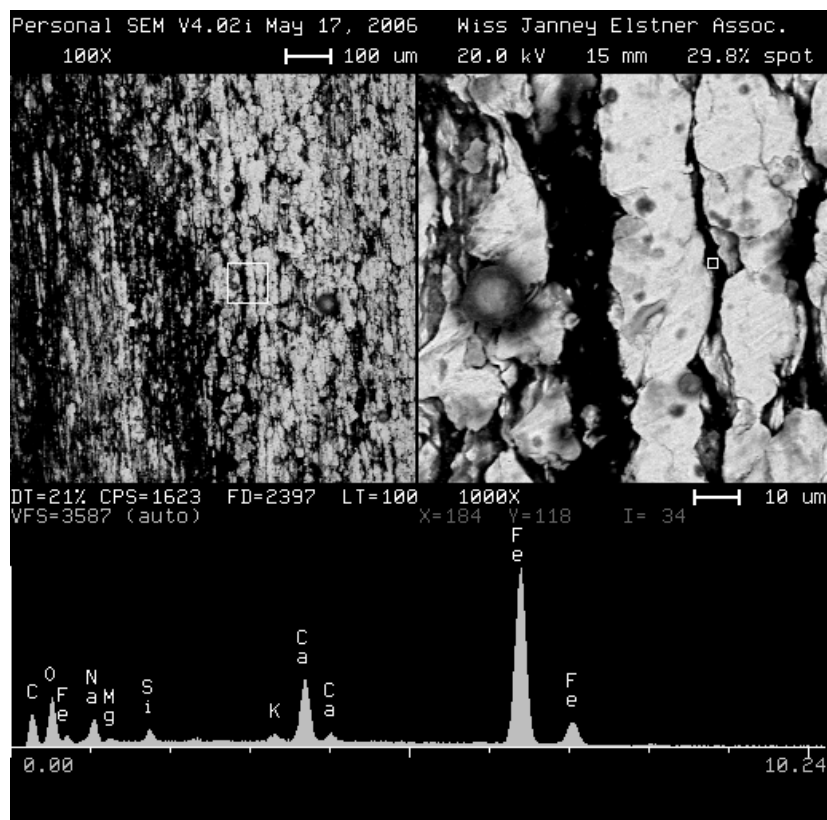


Figure D-8 - BSE images and EDS spectrum of Source 102, showing the presence of lubricant residue in the narrow surface features.

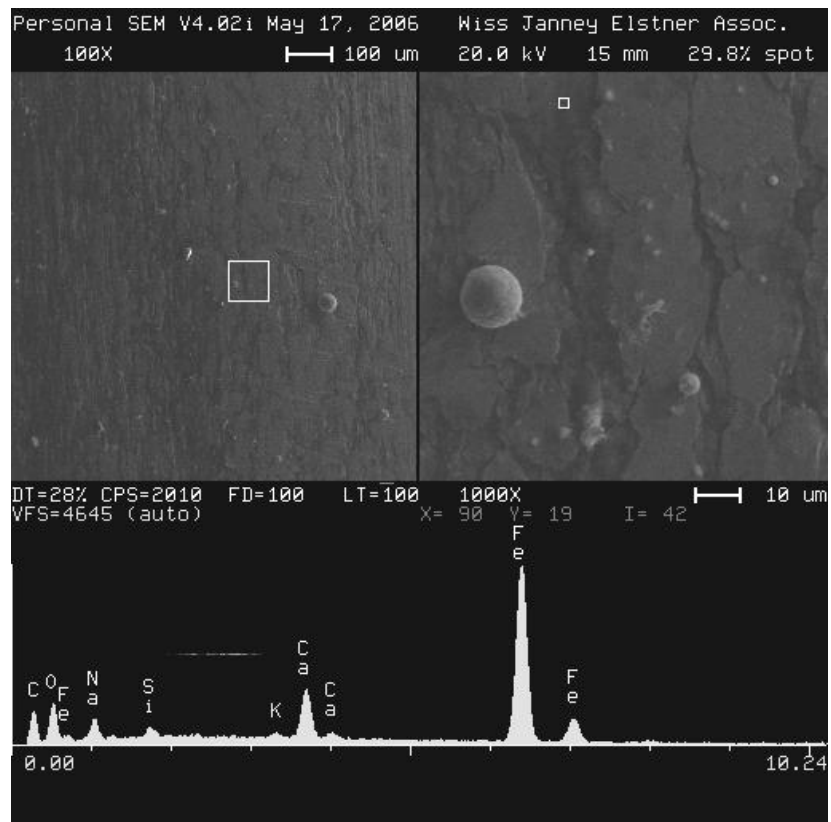


Figure D-9 - SE images and EDS spectrum of Source 102 of the same area pictured in Figure D-8.

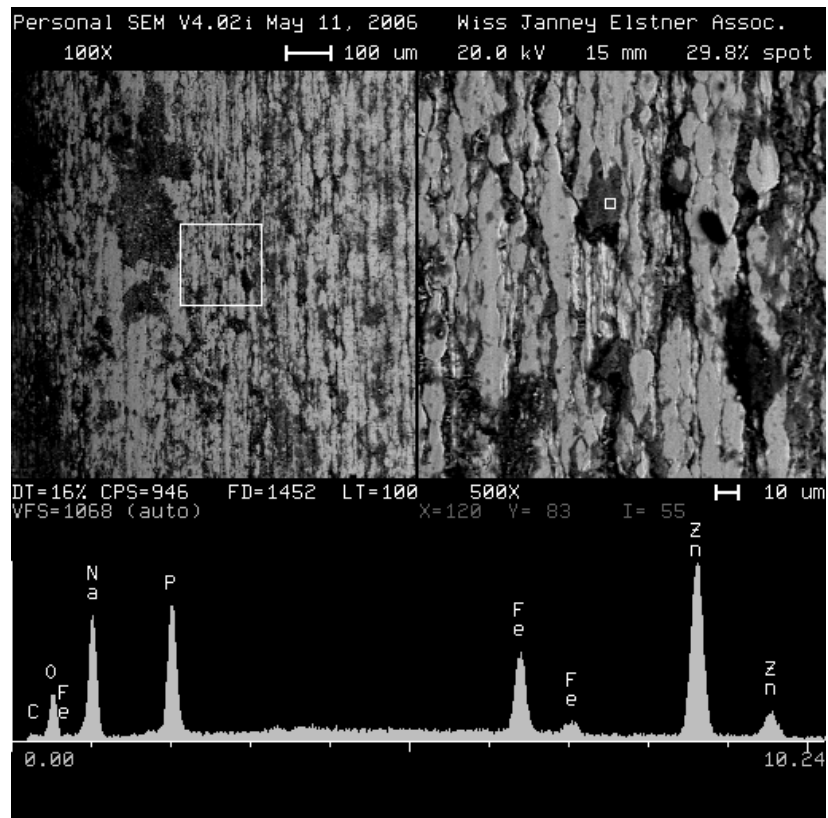


Figure D-10 - BSE images of Source 103, with EDS spectrum of the zinc phosphate phase.

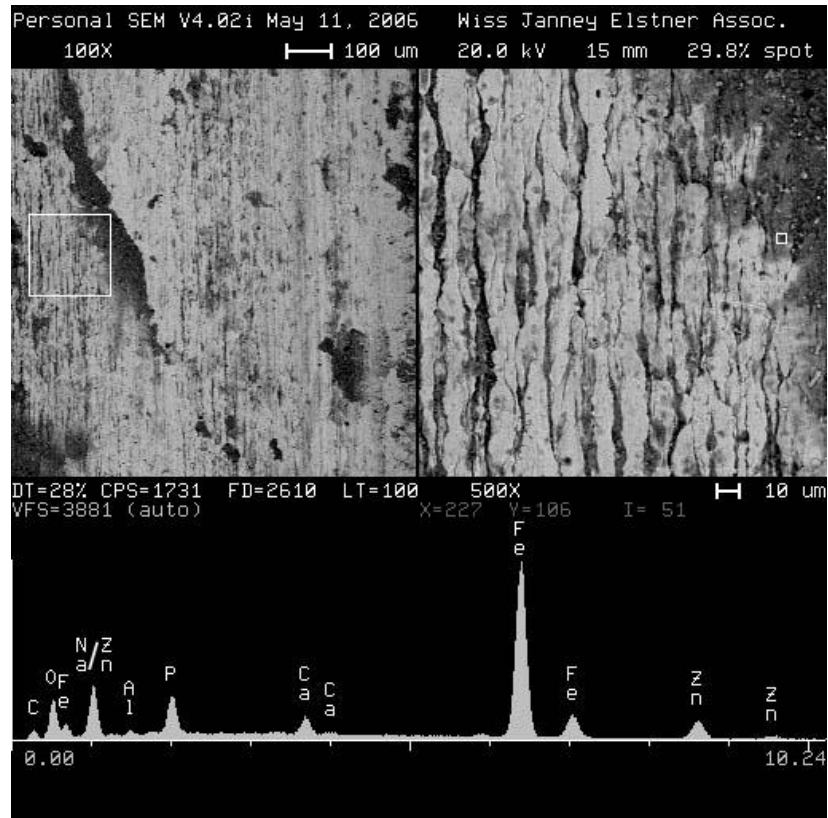


Figure D-11 - BSE images of Source 103, with EDS spectrum of zinc phosphate and lubricant-containing area.

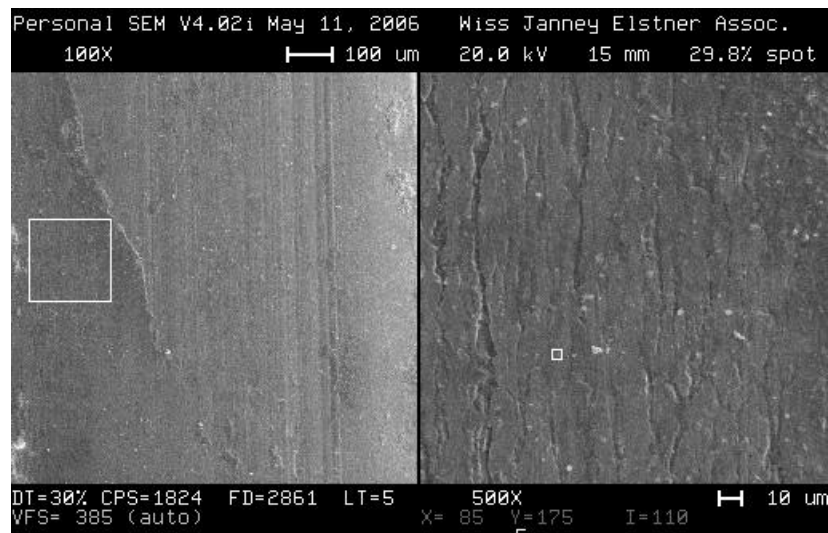


Figure D-12 - SE images of Source 103, showing the surface topography of the strand.

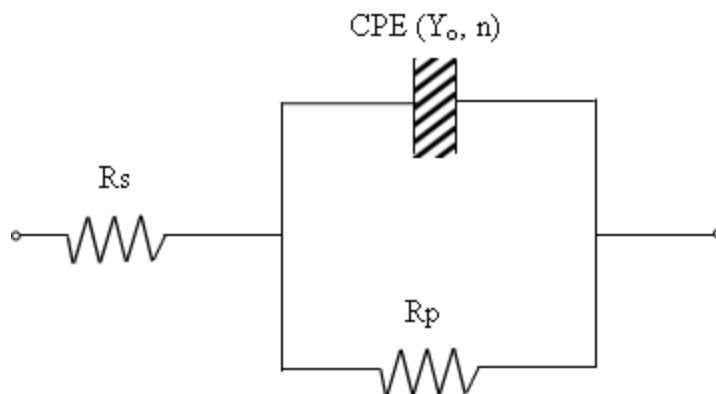


Figure D-13 - Equivalent circuit used to analyze EIS data.

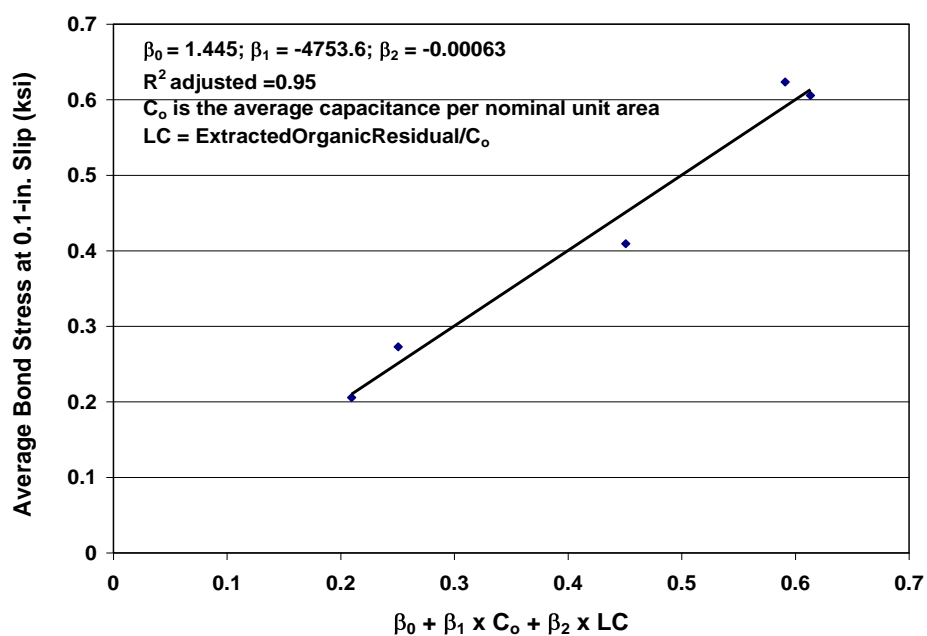


Figure D-14 - Good correlation (1:1) between bond stress and a customized parameter related to lubricant coverage.



Figure D-15 - Photograph showing Source 151 after the sodium hydroxide cleaning procedure. The strand to the right of the line was immersed in sodium hydroxide solution.

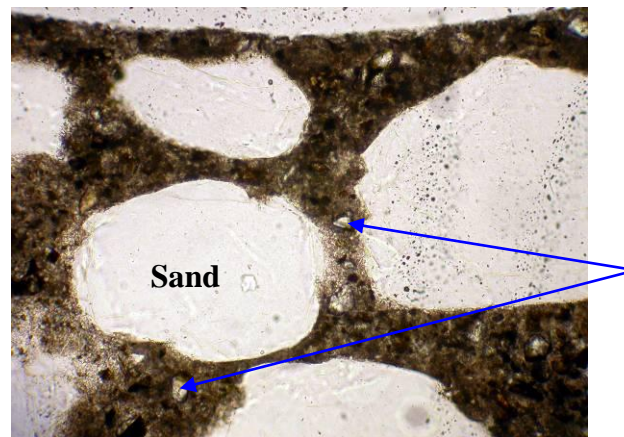


Figure D-16 - Source 151- Interface with strand is at top. Plane-polarized light. Blue arrows show examples of cement grains. Width of field is 1 mm.

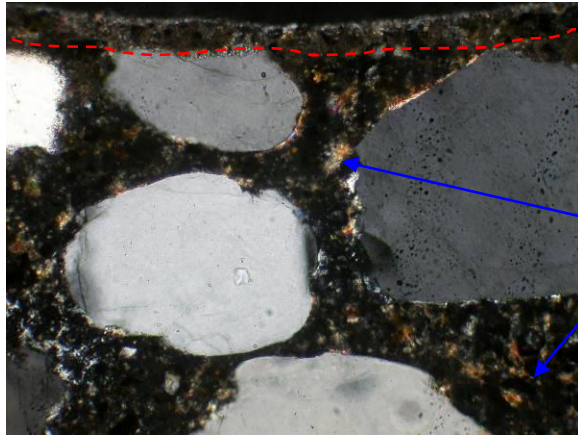


Figure D-17 - Source 151- Interface with strand is at top. Red dashed line shows depth of 'cloudy' paste layer. Yellow crystals are calcium hydroxide (blue arrows). Cross-polarized light. Width of field is 1 mm.

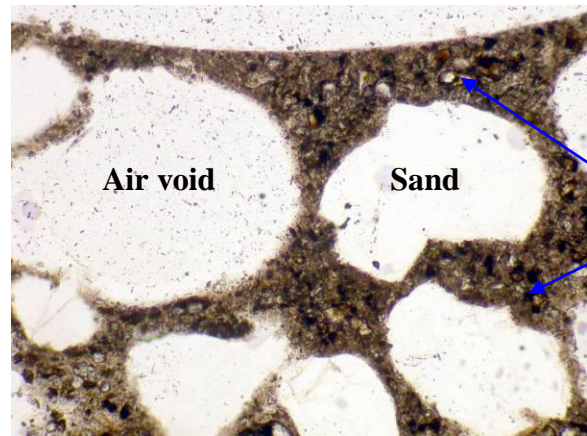


Figure D-18 - Source 151C - Interface with strand is at top. Plane-polarized light. Blue arrows show examples of cement grains. Width of field is 1 mm.

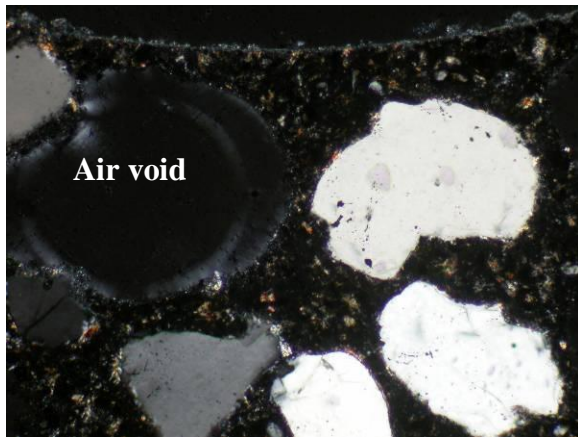


Figure D-19 - Source 151C- Interface with strand is at top. Small, brighter crystals in the paste are mostly calcium hydroxide crystals. Cross-polarized light. Width of field is 1 mm.

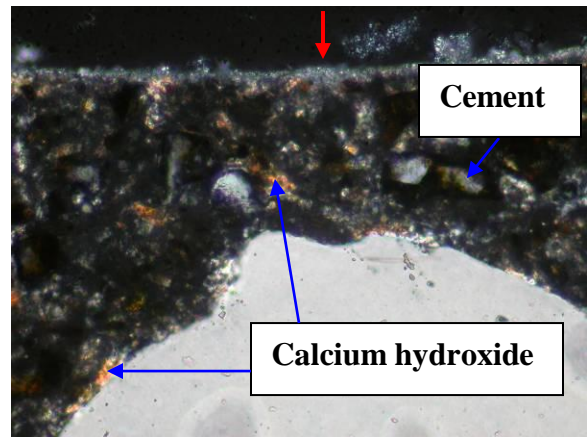


Figure D-20 - Higher magnification view of a portion of the field shown above. A thin, bright, fine-grained layer is present at the interface (red arrow). Yellow-orange calcium hydroxide crystals and cement grains are seen more easily. Cross-polarized light. Width of field is 0.6 mm.

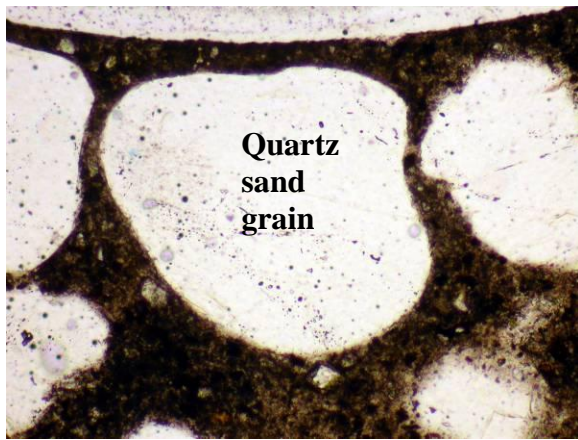


Figure D-22 - Source 102- Interface with strand is at top. A thin layer at the interface is somewhat darker than the body of the paste. Plane-polarized light. Width of field is 1 mm.

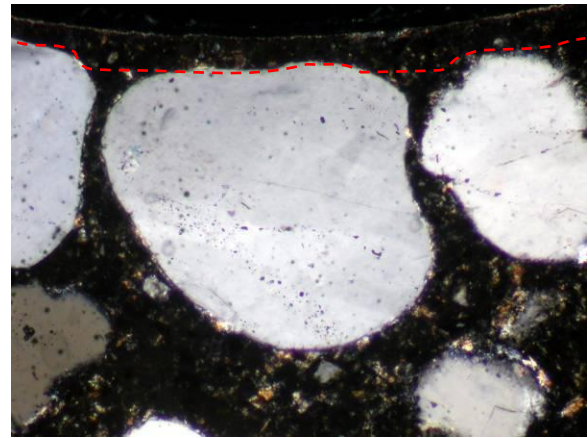


Figure D-21 - Source 102- Interface with strand is at top. Red dashed line shows depth of 'cloudy' paste layer. Calcium hydroxide crystals are scarce in the interfacial region. Cross-polarized light. Width of field is 1 mm.

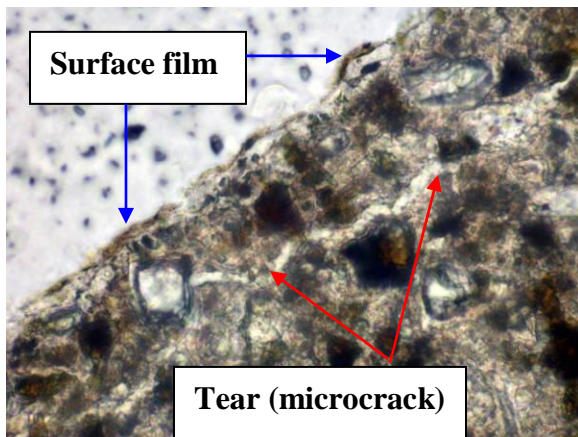


Figure D-23 - Source 102- Surface film on interface with strand and narrow tear parallel to interface. Plane-polarized light. Width of field is 0.6 mm.

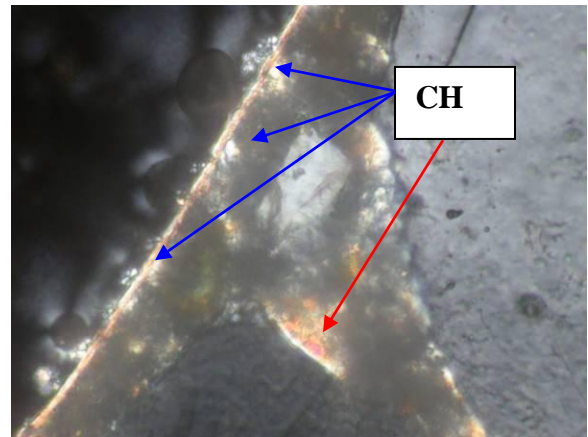


Figure D-24 - Source 102- Surface film on interface exhibits high birefringence, in part due to coarse crystallization of CH (blue arrows). For comparison, CH between cement grains (interstitial) is indicated by the red arrow. Cross-polarized light. Width of field is 0.2 mm.

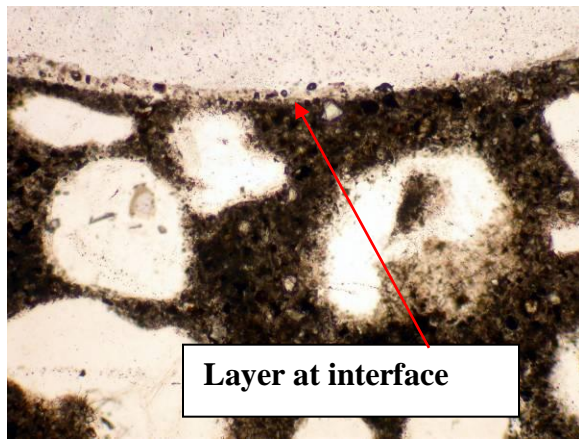


Figure D-26 - Source 103- Interface with strand is at top. A layer resembling laitance is observed at the interface. Plane-polarized light. Width of field is 1 mm.

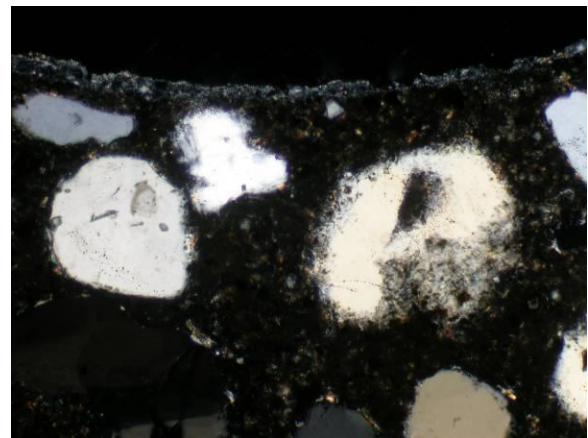


Figure D-25 - Source 103- Small bright specks in the interfacial layer are calcium hydroxide crystals. Cross-polarized light. Width of field is 1 mm.

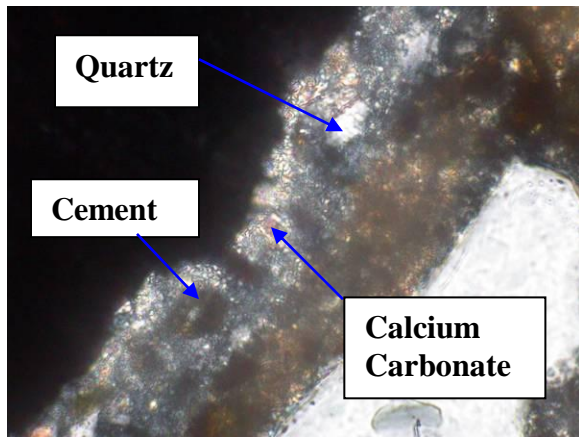


Figure D-27 - Source 103- Closer view of the interfacial layer shows that it contains cement grains, aggregate particles, calcium carbonate and calcium hydroxide. Plane-polarized light. Width of field is 0.6 mm.



Figure D-28 - Split prism samples. The location of the sample studied is shown by the red box.



Figure D-29 - Section of prism submitted for study. Strand impressions extend across the middle of the split section (arrows). Note the difference in paste color in the impressions.

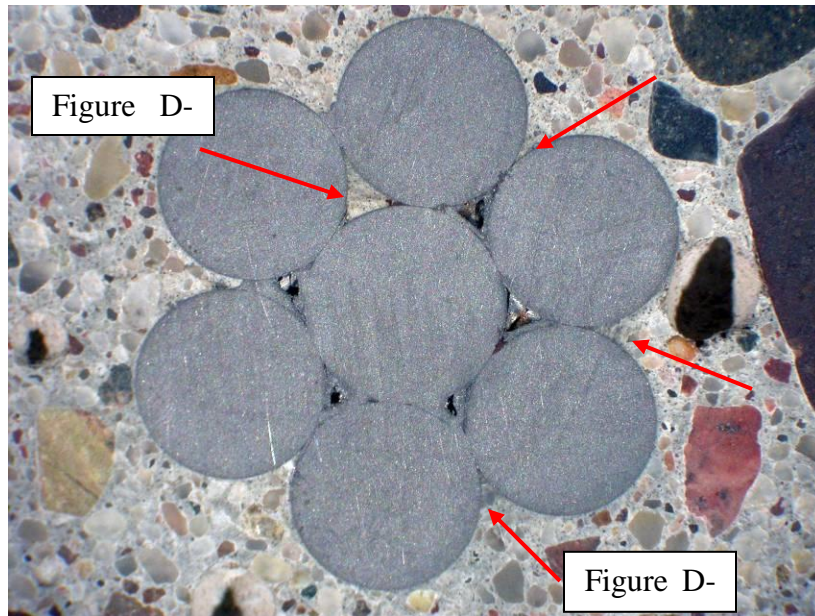


Figure D-30 - Cross section of the strand showing dark paste in the wedge-shaped interstitial regions (red arrows).

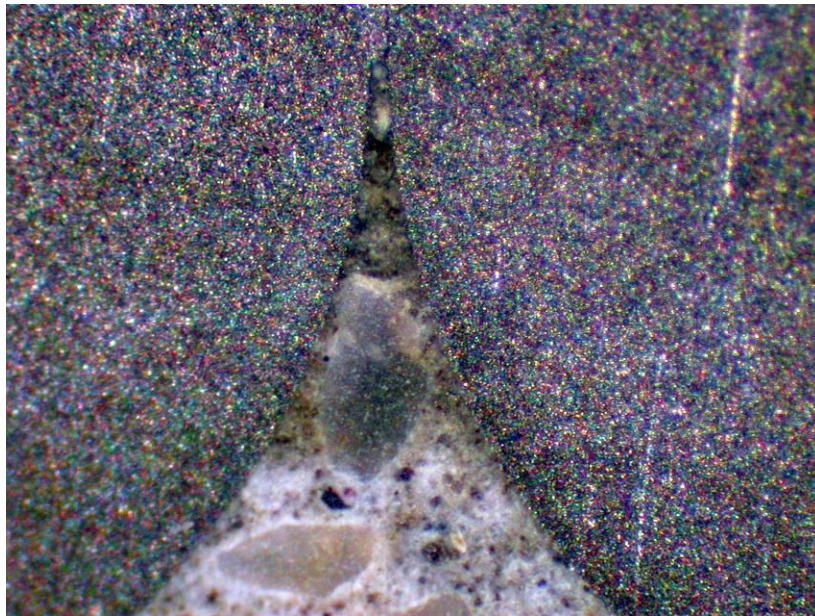


Figure D-31 - Close view showing the dark paste between the wires that comprise the strand.



Figure D-32 - Close view showing the dark paste between the wires that comprise the strand.

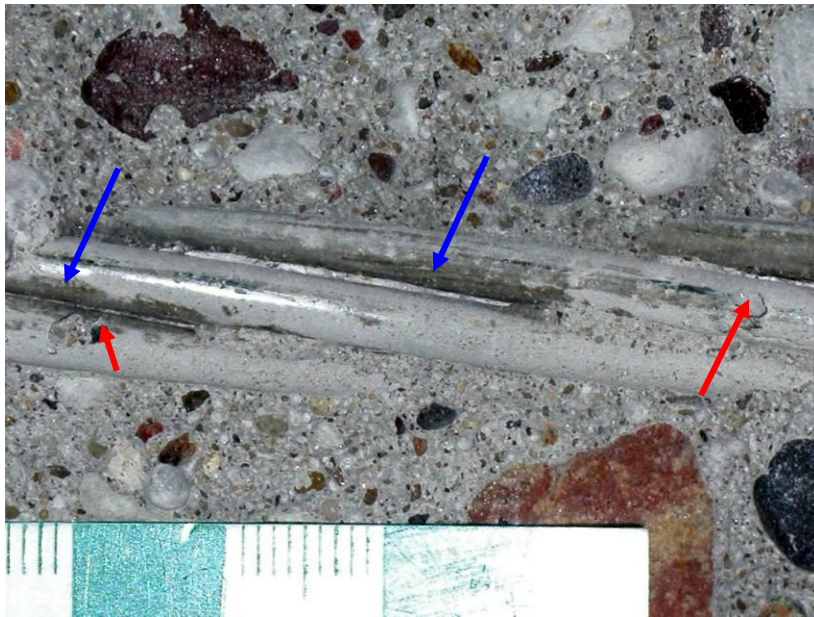


Figure D-33 - Patches of shiny, dark brownish gray paste (blue arrows) occur on some portions of the impressions. White streaks in photo are reflections. Red arrows show typical entrapped air voids. The scale is marked in millimeter increments.



Figure D-34 - Light gray paste is soft (scratches at bottom). Dark brownish gray paste is hard (scratch at top).

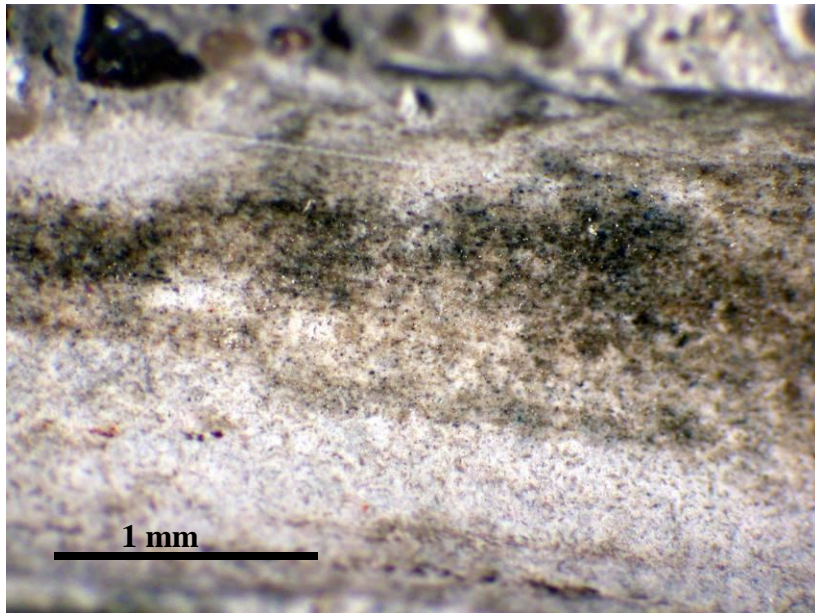


Figure D-35 - Close view showing the speckled appearance of the dark, brownish-gray, shiny paste.

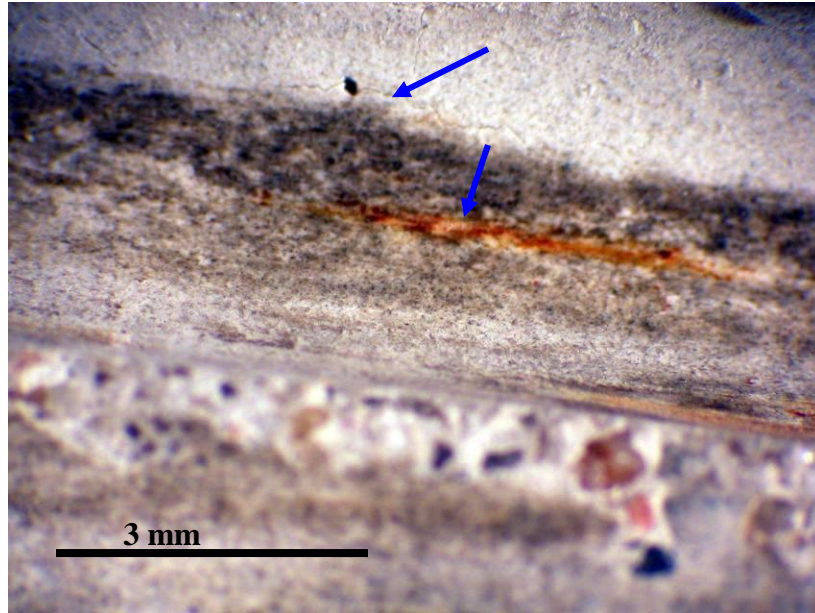


Figure D-36 - Longitudinal microcracks. One of the microcracks is accentuated by rust-colored staining.

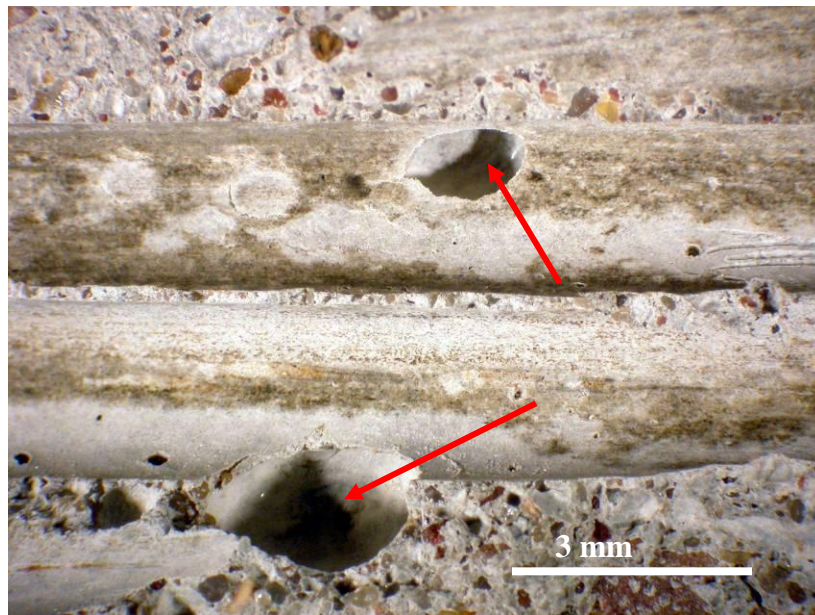


Figure D-37 - Air voids trapped against the tendons. Spherical features in upper left are voids covered by a thin layer of soft paste.

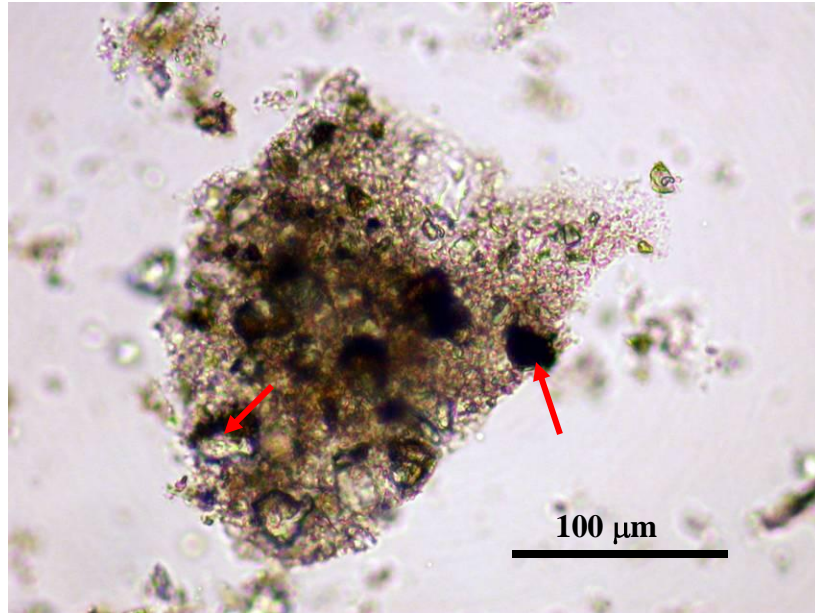


Figure D-38 - Abundant unhydrated and partly hydrated portland cement grains in the dark, brownish-gray paste. The presence of organic residue could not be excluded, based on optical properties..

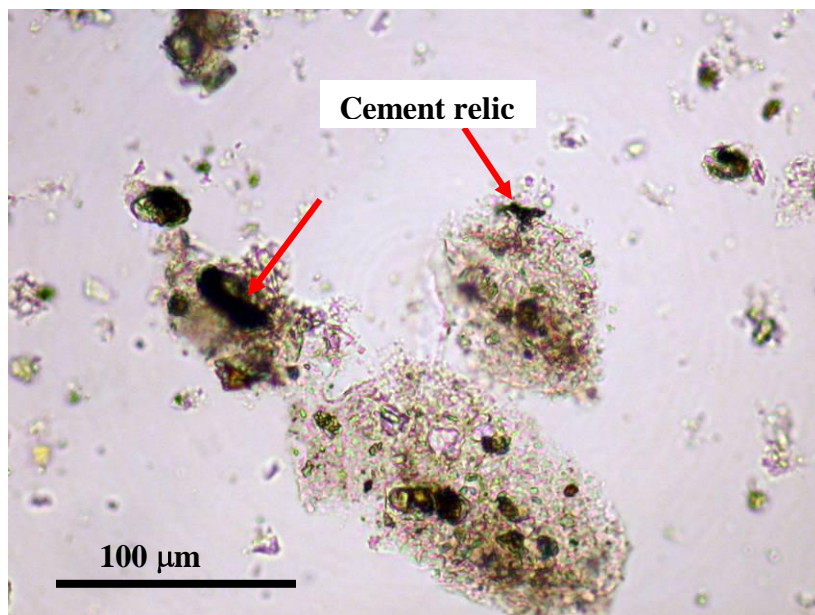


Figure D-39 - Residual portland cement grains are less abundant in the light gray paste. The paste is carbonated and does not appear to contain organic residue, based on optical properties.

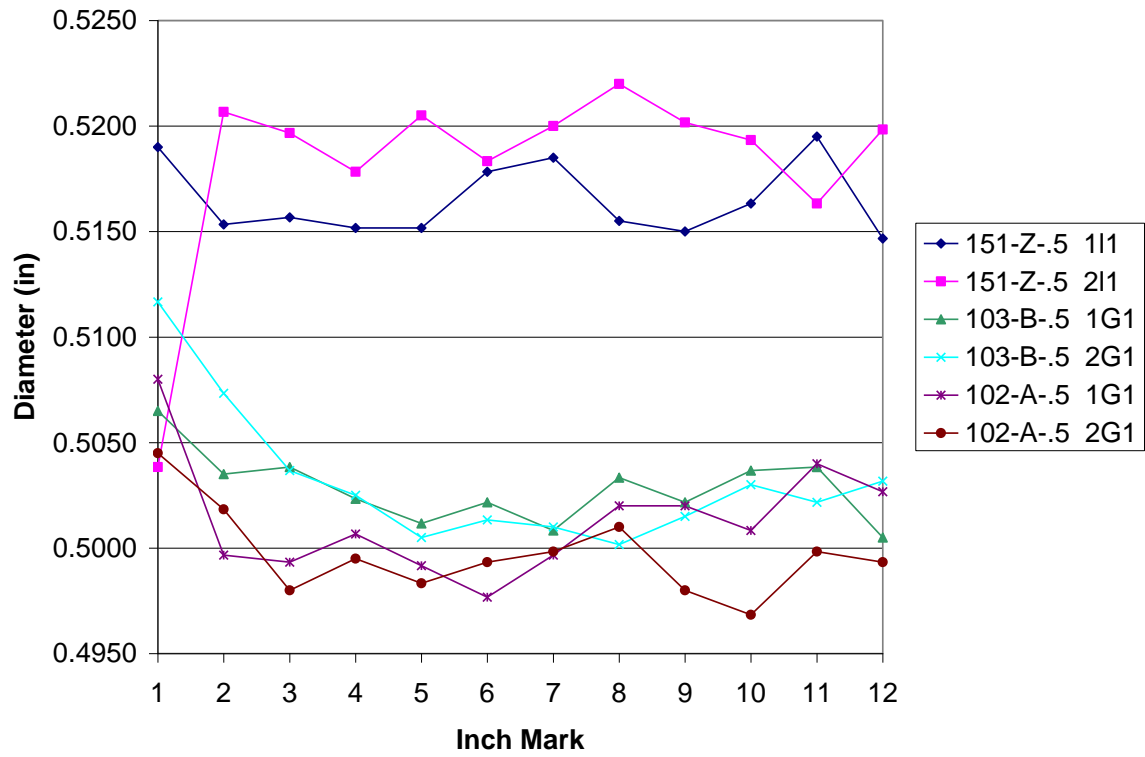


Figure D-40 - Average strand diameter measured every inch over 1 foot of strand.

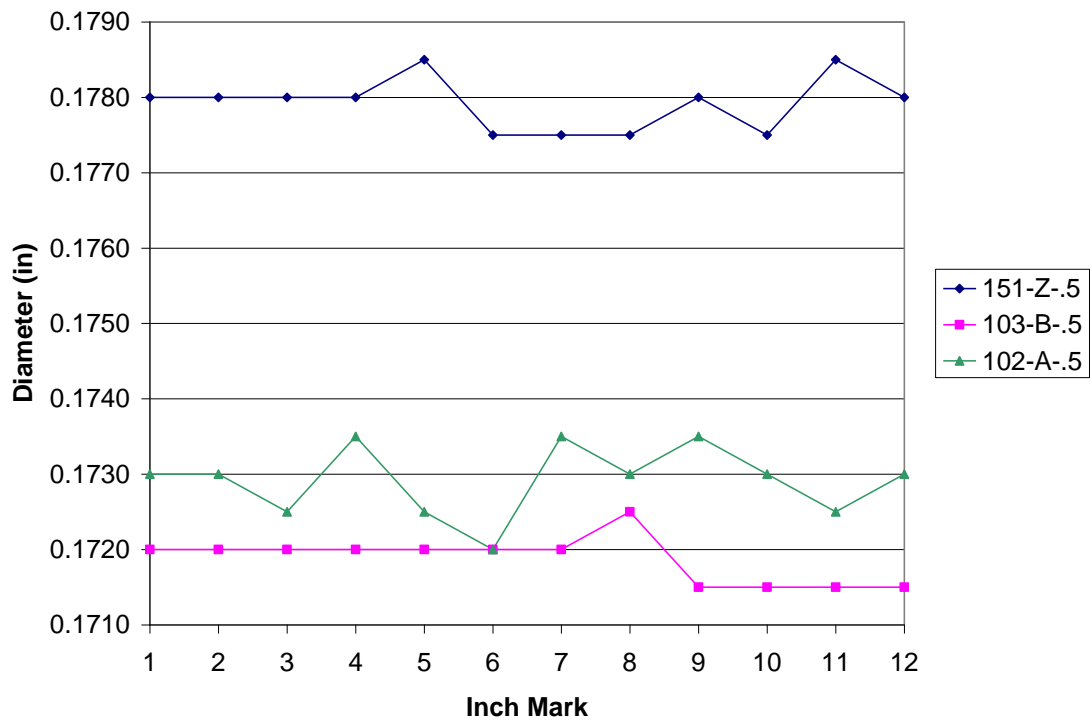


Figure D-41 - King wire diameter measured every inch over 1 foot of strand.

Project No. 10-62

**ACCEPTANCE TESTS FOR
SURFACE CHARACTERISTICS OF
STEEL STRANDS IN PRE-STRESSED CONCRETE**

APPENDIX E: BIBLIOGRAPHY OF STRAND BOND

Prepared for
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NCHRP Project 10-62

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14 April 2008

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