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FINAL REPORT

CORROSION CHARACTERISTICS OF POST-TENSIONING STRANDS IN UNGROUTED DUCTS

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Final Report to Florida Department of Transportation

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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16. Abstract

Present FDOT construction specifications require post-tensioned ducts to be grouted within seven days of strand placement, to prevent corrosion. This specification may be too conservative under some mild service environments. This project had as objectives determining the relevant issues to establish fact-based guidelines for the duration of the ungrouted period for post-tensioning strand in FDOT construction and propose for consideration updated guidelines if appropriate. A literature review indicated that a 7-day limit is often specified by transportation agencies but that also allowable periods of up to 40 days are proposed for environmental conditions that are deemed to be not aggressive. Field tests with unstressed ungrouted strand, showed conspicuous corrosion only if free water had been contained in closed ducts. Even in those cases the corrosion was mostly in the form of shallow pits after as much as 8 weeks of exposure, with no clear loss of strength revealed by subsequent tensile tests. There was no discernable effect from having one end of the duct continuously open to the external environment even in a seashore facility. Inhibitor presence had no well-defined effect on mitigating corrosion. Possible approaches for consideration in updating FDOT exposure duration guidelines were formulated, including extending the current limit to 2 weeks and 4 weeks depending on environmental classification, if assurance can be made that in-duct or on-strand free water is absent.

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EXECUTIVE SUMMARY

Present FDOT construction specifications require post-tensioned ducts to be grouted within seven days of strand placement, to prevent the development of corrosion. This specification may be too conservative under some mild service environments. In such cases the requirement could unnecessarily have an adverse impact on erection schedule, or even require changes in design solely to allow for immediate grouting of tendons as opposed to grouting after fit-up of matching structural components. Conversely, even a one-week period may be too long under particularly severe exposure conditions, and either a shorter duration or alternative corrosion protection steps may be needed.

This project included the following objectives:

- Determine the relevant issues to establish fact-based guidelines for the duration of the ungrouted period for post-tensioning strand in FDOT construction, based on environmental service classification;

- Propose for consideration updating guidelines for allowable duration of the ungrouted period and feasible contingency measures;

- Identify appropriate contingent alternative corrosion protection steps that may be feasible if the specified ungrouted period were to be exceeded.

To achieve those objectives the project included a literature and experience review, a field investigation, and evaluation of results.

For the literature / experience review, current guidelines for allowable exposure duration stated by U.S. State DOTs and Federal agencies, as well as in relevant foreign specifications and technical literature on the subject were reviewed and discussed with FDOT stakeholders. In addition, visits were conducted in Florida to a strand manufacturer and a post-tensioning construction site, to assess actual present practice. The information was used to adjust the scope of the remaining tasks as needed and to aid in establishing final recommendations.

For the field investigation, tests in near-full-scale polymer ducts containing ungrouted strand with various levels of moisture exposure and with and without a corrosion inhibitor were conducted over periods of 1 to 8 weeks. Polymer ducts were chosen as those are used by FDOT for internal tendons, which are in the majority. The ducts were placed at two locations, one inland and the other at a marine shore. The after-exposure condition of the strand was determined and correlated with the test variables.

The literature review indicated that a 7-day limit for the ungrouted strand condition, similar to that currently adopted by FDOT, is often specified by transportation agencies. However, allowable periods of up to 40 days are proposed for environmental conditions that are deemed to be not aggressive. Corrosion inhibitor injection and oil coatings are the approaches most often listed as the means of addressing cases when the limit is to be exceeded, but there are negative factors, including loss of bond, associated with their use.

Field tests with unstressed ungrouted strand showed conspicuous corrosion only if free water had been contained in closed ducts. Even in those cases the corrosion was mostly in the form of shallow pits after as much as 8 weeks of exposure, with no clear loss of strength revealed by subsequent tensile tests. There was no discernable effect from having one end of the duct continuously open to the external environment even in a seashore facility. Inhibitor presence had no well-defined effect on mitigating corrosion.

The field test results and experience from extended exposure of ungrouted strand elsewhere indicated that the strand has significant tolerance, from the standpoint of mechanical performance as evaluated by the tensile test, to the presence of in-duct corrosion that may be otherwise visually striking.

Possible approaches for consideration in updating FDOT exposure duration guidelines include extending the current limit to 2 weeks and 4 weeks depending on environmental classification, if assurance can be made that in-duct or on-strand free water is absent.

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1 INTRODUCTION

1.1 Project Scope

Several major FDOT bridges (Corven 2001, Powers 2002, Sagüés 2006, Wang 2005a, 2005b) experienced in the last decade severe corrosion distress of post-tensioning (PT) strands, mainly in the anchorage area. The corrosion was associated with bleed water formation during grouting, which led to the formation of grout voids. In those voids the strands were not in efficient contact with the highly alkaline, protective environment of hardened grout, which would have otherwise promoted passivation of the strand steel surface. Extensive research conducted on this problem (Shokker 1999) (Podolny 2001) (FDOT 2002-2004) (Salas 2003, 2008) (Bricker 2005) led to strong improvement in design and construction guidelines by FDOT (2008a, 2008b) (Pielstick 2002) with multiple levels of corrosion protection, which are expected to substantially reduce the chance of similar corrosion events in newly constructed bridges.

The FDOT PT guidelines in the Standard Specification for Road and Bridge Construction include also avoidance of corrosion during construction after strand placement but before grouting takes place, by limiting that period to a duration of 7 days. During that period the high strength strand steel is directly exposed to air and to any moisture that penetrates the anchor and ducting areas, without the benefit of contact with protective grout. The moisture may be in the form of water vapor which precipitates liquid water on the metal surface, or rainwater that enters by direct intrusion. The latter form may contain some chloride and sulfate ion from seawater spray in marine or estuary bridge locations. Some of those species may also be present in small amounts on the strand surface due to environmental exposure of the strand spools, or when the strand is being transferred from the spools into the ducts, so contamination may be present also even when the liquid water comes from vapor only. Without any protective coating, the steel surface may then be in contact with thin films of (or even immersed in) neutral or slightly acidic water with some salt content. If the water partially evaporates, the salts may concentrate up to the solubility limit. Through their natural deliquescence those salts may help retain a film of liquid water on the steel surface, even if the relative humidity were to become quite low as it could during daytime warming. Oxygen will likely remain plentiful most everywhere in the ducts and anchorage, providing for a strong oxidizing environment. Due to the neutral-acidic water and the presence of salts that promote passivity breakdown, conditions may be favorable for the rapid progression of corrosion on the steel surface. In that process, oxygen reduction is expected to be the main cathodic reaction and iron oxidation to ferrous and ferric ions the anodic reaction. If regions of oxygen depletion were to develop at localized spots, the possibility of microbiologically influenced corrosion (MIC) there could not be completely ruled out (Staehle 2002).

Factors, such as the amount and chemical composition of water, the type of anchorage and duct (e.g., galvanized steel vs polymer) and whether corrosion inhibitors have been injected, would determine the specific forms of corrosion that may appear. Those can range from relatively uniform wastage to strongly localized attack in the form of pits, or of environmentally assisted cracking (EAC, including possible hydrogen embrittlement) when under tension. Various forms of corrosion and extents of severity could be present simultaneously along different segments of the tendon, as moisture accumulation and materials in contact with the strand would vary depending on elevation, tendon profile and whether the tendon is internal or external.

The reality of corrosion on strand in ungrouted ducts during construction has been demonstrated in recent experience by the California Department of Transportation (Caltrans) during construction of the San Francisco-Oakland Bay Bridge (SFOBB) Skyway Seismic Replacement Project. Because of bridge erection constraints, which at times prevented grouting until matching elements were in place, numerous internal tendon ducts with tensioned PT strands were ungrouted for periods that were in some cases as long as 15 months. After discovery of rust-colored water at vent ports and anchorage heads at some locations, Caltrans conducted an extensive and thorough investigation of the extent of corrosion and evaluation of possible loss of strength of affected strands (Reis 2007). The investigation involved borescope examination of the strands` at over 4,300 grout vent tubes at ungrouted locations, direct examination of strand at locations exposed by direct excavation, removal of entire lengths of corroded strand from various tendons, direct characterization of corrosion condition, mechanical determination of strand residual strength, analyses of retained water and electrochemical measurements, and microstructural examination and determination of hydrogen pickup for selected strands.

An independent assessment of the effectiveness of the Caltrans SFOBB test approach and of the causes of the corrosion was prepared by Sagüés (2007). In that assessment it was indicated that the Caltrans investigation visual examinations showed that most of the strands showed minor or no corrosion, and that only about 2% of the tendons examined had enough corrosion to merit a "moderate" classification (characterized in the report as being "significant enough to result in pits detectable by unaided eye observation") (Reis 2007). Mechanical tests of strands extracted from some of those locations showed compliance with strength specifications for new material in most cases, and only small deficiency (better that 94% of specified strength) in the rest. A special case involved one tendon that had suffered actual failures of some strands during the period of concern. However, those failures appeared to have occurred because of unusual distress of mechanical origin due to the combined presence of a hardpoint (irregular kink in the duct embedded in concrete) and midframe jacking operations. Some indications of environmentally assisted cracking were nevertheless seen in metallographic examination of the failed strands of that tendon and others, indicating that this possible deterioration mechanism (Mietz 1999, 2002, 2008) (Sanchez 2007) (Hartt 2008) be considered in future investigations. The assessment concluded based on the available evidence that, for this particular bridge and exposure conditions, delayed grouting appeared to have had little impact on strand integrity other than for the special case indicated above. It was emphasized however that the apparently limited corrosion effects seen in this case should in no way be viewed as dismissing the adverse consequences of delayed grouting in future construction projects. In that context it is noted that analyses of the water accumulated in ungrouted ducts revealed only slight contamination with saltwater (possibly due to the high elevation over the bay water of the superstructure spans concerned), and a relatively elevated pH due to some contact with recently placed concrete. Furthermore contact between galvanized ducts and the strand was a plausible source of corrosion protection of the latter at least in submerged portions of the strand bundle, and the bridge is located in a moderate temperature region. Those circumstances may have combined to significantly mitigate corrosion that might have been otherwise very severe. The outcome could have been quite different if the ungrouted tendons were part of a segmental bridge approach being built at low elevation over very saline water with strong wave action, with parts of the tendon placed in plastic ducts and with sustained high temperatures and high humidity (as it may be the case for example in the Florida Keys). It is conceivable that under those circumstances local strand corrosion rates could have been one or two orders of magnitude greater than those experienced at SFOBB, with comparable or worse local corrosion distress possibly occurring in a matter of days. Caution regarding these issues has been pointed out by other collaborators in the SFOBB investigation (Lee 2007).

Present FDOT construction specifications require PT ducts to be grouted within seven days of strand placement, to prevent the development of corrosion similar to that described above. This specification may be too conservative under some mild service environments. In such cases the requirement could unnecessarily have an adverse impact on erection schedule, or even require changes in design solely to allow for immediate grouting of tendons as opposed to grouting after fit-up of matching structural components. Conversely, even a one-week period may be too long under particularly severe exposure conditions, and either a shorter duration or alternative corrosion protection steps may be needed.

1.2 Project Objectives and Research Tasks

The above discussion established the need for the present investigation, which has the following main objectives:

- Determine the relevant issues to establish fact-based guidelines for the duration of the ungrouted period for post-tensioning strand in FDOT construction, based on environmental service classification and type of tendon;

- Based on findings prepare specific recommendations to FDOT for consideration on updating guidelines for allowable duration of the ungrouted period and feasible contingency measures;

- Identify appropriate contingent alternative corrosion protection steps that may be feasible if the specified ungrouted period were to be exceeded.

To achieve those objectives the investigation included a literature and experience review, a field investigation, and evaluation of results.

For the literature / experience review, current guidelines for allowable exposure duration stated by U.S. State DOTs and Federal agencies, as well as in relevant foreign specifications and technical literature on the subject were reviewed and discussed with FDOT stakeholders. In addition, visits were conducted in Florida to a strand manufacturer and a posttensioning construction site, to assess actual present practice. The information was used to adjust the scope of the remaining tasks as needed and to aid in establishing final recommendations.

For the field investigation, tests in near-full-scale ducts containing ungrouted strand with various levels of moisture exposure and with and without a corrosion inhibitor were conducted over periods of 1 to 8 weeks. The ducts were placed at two locations, one inland and the other at a marine shore. The after-exposure condition of the strand was determined and correlated with the test variables.

The outcome of the previous tasks was integrated and analyzed to propose a set of guidelines for consideration by the Department in adapting as needed its specifications for length of the ungrouted period, and possible measures for corrosion control if extended exposures took place.

2 LITERATURE / EXPERIENCE REVIEW[1]

Agency specifications and literature sources have been reviewed. Relevant findings are noted, headed by the source noted as underlined text. Discussion of findings is addressed in Chapter 3 of this report.

2.1 FDOT specifications and practice

Subsection 2 of the current FDOT Specification 462-6 "Protection of Prestressing Steel" (FDOT 2008a) limits the time between the first installation of prestressing steel in the duct and grouting after stressing of the strands to a maximum of seven calendar days. Except when waived by the Engineer, failure to grout tendons within this period will result in stoppage of the affected work.

The current FDOT Specification Section 462-10.9 "Duct Pressure Field Test" (FDOT 2008a) requires that the duct be pressure tested after the stressing operation in order to demonstrate the integrity of the duct. All ducts are pressurized to 50 psi, the air supply is turned off and pressure drop noted after one minute. Short ducts, under 150 feet long, may lose 25 psi while longer ducts may lose only 15 psi after one minute. Ducts that have passed the pressure test are assumed to be relatively water tight and therefore able to protect the strand from rain and salt spray.

The following issues were discussed in meetings between the investigators, the project manager, and FDOT stakeholders for clarification and noting relevant issues of FDOT practice and its practical implementation at the time this project was started. In the following "specified" indicates a current provision under FDOT Section 462. "Not specified" simply indicates that 462 is silent on that item. The items considered focus on opportunities for water and corrosive substances to be present in the tendon.

Ducts

1. Specified: 462-7.6: Tendon duct systems (but not necessarily individual tendons) must be proof-tested for air tightness of design.

2. Specified: 462-7.2: Duct ends must be sealed from the moment of installation until strand placement.

3. Specified: 462-9: In "aggressive environment" locations, flush duct with lime treated water, and blow air to remove excess water from duct.

[1] Review of the material discussed in this chapter often includes paraphrasing and direct quotes, some of them redacted, from the publications examined. For readability, quotation marks have been inserted only in the more extensive excerpts.

Strand

4. Specified: 462-6.1: General shipping handling and storage requirements. Usual practice (but not explicitly specified): Strand comes coated with factory corrosion inhibitor in double wrapped ~>2,000 ft spools into construction site. Spools are kept in covered storage; usually with no walls.

5. Usual practice: Strand is either (a) removed by a device one at a time straight from package and placed directly in duct; or (b) cut out and placed in a bundle in a storage pipe prior to insertion in duct all together as a bundle.

6. Usual practice: Pre-bundling in (5b) would normally be inside bridge segments. If rain/weather would tend to get strand wet, work would normally stop until later.

7. Not specified: (a) limitation of duration of the period between removal of strand from spool to the moment of placement in duct; (b) requirement that strand does not get wet during placement, (c) drying of a bundle if it got wet.

8. Usual practice but apparently not specified: Strand is inspected immediately before it is placed in duct.

Period between placement and grouting

9. The specified 7-day allowable period for ungrouted conditions per 462-6.2 starts from the moment the strand is placed in the duct.

10. Not specified: covering the end of the anchorage, promptly inserting the wedges, or other provisions to minimize water ingress through the spaces between strand and anchor plate in the period between strand placement and tensioning.

11. Strand stressing normally tends to happen right after placement because it speeds up construction. Not specified: allowable duration of that interval.

12. Specified: 462-10.10: Strand ends to be cut out and grout caps put in place within 4 hours after stressing. Not specified: pressure testing immediately after grout cap placement.

13. Specified: 462-10.9: Pressure test directly before grouting, with compressed air. Not specified: maximum duration of interval between pressure testing and grouting.

Adherence to specifications, incidents, and other observations

14. Corrosion damage visible in strand packs is extremely rare (estimated to have been 2-3 times in a ~15 year period).

15. 7-day period is very rarely exceeded. Guesses of overall typical frequency ranged from a fraction of 1/1000 to 1/100 of all tendons installed. The instances may reflect extraneous circumstances like delay due to a workplace injury. For individual contractors frequency could be greater, a guess for an extreme of 1/50 was indicated.

16. Pre-grouting pressure test passing has effectively full compliance, as repairs are iteratively conducted until passing. Contractor is heavily invested in securing success given that grouting deficiencies costly to contractor could result otherwise.

2.2 <u>Other sources – general issues</u>

Sason (1992): This paper presents a pictorial guide for rating extent of corrosion on exposed strand. The rating method was used in this report; details are discussed later and pictures are reproduced in Appendix 2.

West (1999): In a State of the Art review the authors address temporary corrosion protection in Section 5.4.3, p 74 as cited next. Those measures reflect other sources listed in this chapter.

> "The time between stressing and grouting of internal tendons should be as short as possible to minimize the opportunity for corrosion while tendons are unprotected.
>
> - AASHTO LRFD Construction Specifications limits time to between 7 and 20 days depending upon the ambient humidity (Clause 10.4.2.2.1)
> - PTI Guide Specification for Grouting limits time to between 7 and 40 days
>
> If the time limits have been exceeded, temporary corrosion protection measures are required by both specifications. Temporary measures include:
>
> - Coat steel with water-soluble oil
> - Use vapor phase inhibitors
> - Coat steel with biodegradable soap (normally used as a coolant for metal cutting)
> - Coat steel with sodium silicate
>
> Ducts must be flushed with water immediately prior to grouting if all but the vapor phase inhibitor is used. Other options are:
>
> - Seal duct to prevent moisture entry
> - Continuous pumping of dry air through the ducts
> - Purging the duct with dry nitrogen"

ACI (2001): This is a general review of corrosion issues of prestressing steels. The 2001 version of this document was consulted here. Section 4.3.3.2 addresses temporary corrosion protection. Specific reference is made to the time limits stated for PTI (2003) elsewhere in this chapter.

AASHTO (2002): These Standard Specifications for Highway Bridges or variations thereof are often adopted by other agencies. Section 10.4.2.2.1, “Protection of steel after installation” states the permissible interval between tendon installation and grouting when no corrosion inhibitor is used. The interval is 7 days for very damp atmosphere of over saltwater (humidity>70%); 15 days for moderate atmosphere (humidity from 40% to 70%) and 20 days for very dry atmosphere (humidity <40%).

Ganz (2002): This extensive overview of post-tensioning tendon grouting practice sponsored by an industry supplier addresses delayed grouting in Item 4.5.4.5. The AASHTO Standard Specifications for Highway Bridges (AASHTO 2002) limits mentioned elsewhere in this chapter are cited. The European standard ENV 13670 (ECS 1999) is cited giving the same limits as in the review for FIB (2002) in this chapter. The use of water-soluble oils, preferably applied in the factory by the supplier (FIB 2001), is recommended for temporary corrosion protection if the delay is known or expected. The oil product Rust-Ban 310, mentioned elsewhere in this chapter, is reported to have only a low adverse effect on bond. It is indicated however that end anchorages must be free of oil. Flushing of tendons is considered bad practice in general. Dry air blowing is recommended for instances when the delay length is not known up front, on in the case of weather related continuous low temperatures.

FIB (2002): This detailed review of grouting of tendons in prestressed concrete, FIB Bulletin No. 20, discusses in Section 2.6 temporary protection of tendons before grouting. Paraphrasing that portion (with our added comments in parenthesis):

> “As a general rule, grouting should be carried out as soon as possible after the stressing of the tendons. Guidance on the maximum time is given in:
>
> - AASHTO Standard Specifications for Highway Bridges
> - UK Specification TR 47
> - ENV 13670 “Execution of concrete structures” (European standard, (ECS 1999)).
>
> ENV 13670 recommends the following:
>
> - Maximum 12 weeks between fabrication of tendon and grouting. (This appears to be from the time the strands are removed from the transport spool pack.)
> - Maximum of 4 weeks in the formwork before casting the concrete
> - Approximately 2 weeks in the tensioned condition before applying the protective measures (permanent or temporary corrosion protection)
>
> If the grouting cannot be accomplished within the above time, ENV 13670 recommends the following alternative temporary protective measures:

- Preferred option is to apply a coating of water-soluble oil of a type that does not have to be flushed out with water. Reduction of bond between the coated strand and the grout must be checked.
- Continuously blow dry air through the duct.
- In all cases, all access points to the duct, anchorages, vents and drains must be sealed to prevent the ingress of water and humidity into the duct.
- Vapor Phase Inhibitor (VPI) powder is not recommended because the dose may not be uniform and the powder is toxic. (This statement appears to not have considered CorTec VPI materials which are nontoxic and biodegradable)”

PTI (2003): These acceptance standards by a professional society provide minimum requirements for selection, design and installation of cementitious grouts. Directly relevant to this review are Sections 5.2 “Time to Grouting and Temporary Corrosion Protection” and 5.3 “Preparation for Grouting Operations” with corresponding Commentary items. Redacted quotes follow:

“Grouting should proceed as soon as possible after stressing. The time from installing tendons in the ducts in an un-stressed condition to grouting after stressing shall not exceed:

Table 2.1 – Specified Durations (PTI 2003)

Very Damp Atmosphere or over sea water (Humidity > 70%)	7 days
Moderate Atmosphere (40% < Humidity < 70%)	20 days
Very Dry Atmosphere (Humidity < 40%)	40 days

The ends of tendons shall be cut and capped within 4 hours in aggressive environments or as soon as practical in the other environments.”

The time limits indicated above are comparable but somewhat less conservative than those listed by AASHTO (2002). Additional protection measures cited include:

- Water-soluble oils
- Complete sealing of the duct
- Continuous pumping of super dry air
- Purging with dry nitrogen

Corven (2004): A recent FHWA compilation of post-tensioning tendon installation practice is presented in manual form. The manual states that grouting should be performed as soon as possible after stressing the tendons and defers to other sources, exemplified by those listed elsewhere in this chapter, for specific guidelines on exposure duration.

Fuzier (2005): This review of durability of post-tensioned tendons, FIB Bulletin No. 33, discusses temporary corrosion protection. Section 2.1.5 a defers to the prescriptions in FIB Bulletin 20 (FIB 2002) discussed elsewhere in this report . The authors explicitly indicate that grouting should be performed within 2 weeks in aggressive environments but may be delayed up to 4 to 6 weeks in benign and moderately aggressive environments. This document reports on experience in Switzerland using the water-soluble oil product Rust-Ban 310 (mentioned in the Salas (2004) review) in which un-grouted tendons were protected from significant corrosion damage for six months during winter weather. Apparently the Rust-Ban 310 did affect the bond between the grout and the tendon.

Reis (2007): An important documentation of issues and consequences of extended unprotected strand exposures is detailed in this Caltrans report of the SFOBB experience. This document by has been discussed in the Introduction Chapter of this report to which reference is made..

DelDOT (2008): This scope of services document for a bridge project exemplifies State DOT guidelines used in present day projects. The source specifies:

> "Grouting shall proceed as soon as possible after installation and stressing of the tendons. The time from installing the tendons in an unstressed condition to grouting after stressing shall not exceed the following without approval of the Department:
>
> A) Very damp atmosphere (RH > 70%) or over salt water = 7 days
> B) Moderate to dry atmosphere (RH < 70%) = 10 days"

The above represents an adaptation of broader guidelines such as those cited for AASHTO (2002) elsewhere in this chapter.

2.3 Other sources – supplemental corrosion control

Kittleman (1992, 1993): Eleven agents for lubrication and temporary corrosion protection of tendons were evaluated. The investigation included corrosion measurements and pullout tests for bond performance. While bare strand specimens corroded starting after 4 days of exposure, the lubricants offered corrosion protection for periods from 15 to 39 days. However, all unflushed lubricants except graphite essentially destroyed adhesion between strand and hardened grout. Flushing failed to significantly restore adhesion if water soluble oil lubricants were used. Stearate soap did not affect the bond.

Isecke (1997): Two organic coatings (one being Rust-Ban 310, addressed elsewhere in this chapter) were used for corrosion control with no indication of substantial risk .

Isecke (2003): Preheated air is used for moisture reduction for corrosion control of ungrouted strand for extended periods, with promising results.

Salas (2004): This publication details the conclusions of a Texas DOT research program covering a wide range of issues for corrosion protection in post-tensioned issues. Temporary corrosion protection during the ungrouted period is addressed in item 2.4.12 of the report, based on European work (Ganz 2002b) and summarized as follows.

Without further protection measures, grouting should be done in one to four weeks depending upon the climate being aggressive or benign. Emulsifiable oil/corrosion inhibitor Rust-Ban 310 was at the time of the report under test in Switzerland with apparently good temporary protection results. That product is applied at the vendor plant and should be allowed to dry prior to packaging in the spool (see the review of Fuzier (2005)). An alternative corrosion protection alternative is blowing dry air through the duct.

ASBI (2005): In this newsletter article reference is made to practices on use of corrosion inhibitors for the issue at hand. The publication states under the heading Temporary Tendon Protection against Corrosion that

> "For many years, temporary tendon corrosion protection when tendons were ungrouted for extended time periods due to cold weather was provided by Vapor Phase Inhibiting Powder (VPI Powder) blown into ducts by compressed air. This practice was abandoned about 8 years ago due to possible health hazards related to the use of the powder. A nontoxic (no health hazard) biodegradable VpCI Powder is now available from Cortec Corporation for temporary tendon corrosion protection. This powder is considered easier to apply than the oils now in use and it has only a small effect on bond between the strand and concrete".

Schokker (ca. 2005): In this progress report a summary is presented of experimental results of corrosion testing on strands with various water-soluble oils for temporary corrosion protection of strand. Bond reduction was examined quantitatively by pullout tests. Three exposure cases were examined":

- Outdoor in winter
- Controlled humidity (96% RH) and temperature (23º C)
- Partial submersion in saltwater

The authors introduced a visual corrosion rating system that, although not used in the present investigation, merit consideration for future work:

1. Excellent: as received from the manufacturer
2. Very Good: no sign of corrosion or small rust spots
3. Good: small blisters, superficial but widely spread corrosion, pitting is unusual

4. Satisfactory: small blisters, uniform corrosion or wide pitting in small areas
5. Fair: blisters, deep and/or wide pitting, interstitial corrosion
6. Poor: large blisters, trail of blisters no greater than two inches, deep and wide pitting, pitting not present on all wires, interstitial corrosion
7. Very Poor: large blisters, deep and wide pitting affecting over 70% of strand surface area, strong interstitial corrosion, visible large areas of steel section loss

Based on worst case for saltwater exposure, four water-soluble oils were recommended for follow-up testing as shown in Table 2.1:

Table 2.2 – Findings from Saltwater Tests (Schokker 2005a)

Manufacturer	Product	Corrosion Rating	Bond Reduction
Citgo	Cutting Oil NC 205	3.83	31%
Shell/Texaco	Dromus ABD 201	3.00	53%
Esso(Europe)	Rust-Ban 310	2.33	58%
Shore Chemical	Emulsifiable Cutting Oil	3.67	65%

The corrosion protection was deemed adequate but bond reduction results, showing significant loss, highlight a key concern on the applicability of oil as a means for temporary corrosion control.

Luthi (2008): Emulsifiable oil effects on bond and friction losses were investigated. Strength of bond did not decrease when tendons were coated with oil. On the contrary, in most cases the peak load was higher for specimens coated with oil than with un-oiled tendons. The authors concluded that there is no reason to flush the ducts with water prior to grouting when these oils are used for temporary corrosion protection and the oils provide up to six months protection.

Marti (2008): This source is an in-depth report on Swiss experience using Rust-Ban 310 water-soluble oil, referenced by other publications in this chapter. The paper contains an analysis of the impact of bond strength reduction on the performance of a fully bonded post-tensioned beam. The findings are based upon experimental data from large test specimens representative of an internal tendon with smooth plastic duct. The authors suggest that impact of bond loss is slight on performance of a simply supported beam so emulsifiable oils would not need to be removed before grouting the tendons. However, use of the oils is not permissible for bonded dead-end anchorages. The authors also concluded that the bond reduction from using emulsifiable oils in grouted tendons may lead to somewhat softer load-deformation response of post-tensioned members in the decompressed state. The authors also found that the dry air method, although not as effective as the use of oil, could still be recommended for temporary corrosion protection. The use of inert gas for that purpose was not recommended.

3 – FIELD INVESTIGATION AND EVALUATION

3.1 Methodology

The investigation involved two sets of field trials in custom-made exposure facilities. One of the facilities was located at the USF campus, ~ 6 miles from the nearest saltwater body, representing Inland conditions. The other, representing a Seashore location, was placed at the causeway just north of the Sunshine Skyway Bridge on land just above sea level and at ~ 20 ft from the Tampa Bay shore.

The test arrangement simulated environmental conditions that steel strand may encounter in a post-stressing, pre-grouting condition. Much of the metal loss due to electrochemical corrosion phenomena can take place on steel relatively independent of the mechanical stress state. Some corrosion modes such as stress corrosion cracking (SCC) or hydrogen embrittlement (HE) become evident only in the stressed strand. However, evaluation of corrosion with simultaneous stressed condition is highly resource intensive. Following planning discussions with project management and in consultation with FDOT Office of Construction, the testing scope was limited to exposing strand in the unstressed condition only, followed by post-exposure mechanical strength determination of selected strands. This approach serves as a useful first stage to reveal regimes that would result in clearly unacceptable corrosion levels, or in conspicuous corrosion pits or other precursor deterioration that could induce corrosion modes that would be manifested under stress. Tests with simultaneous environmental exposure and application of stress are deferred to a future investigation contingent on resource availability.

The test was planned under the assumption that in a construction environment the strands are always promptly stressed after placement, and that the strand ends are cut and the grout caps put in place promptly as well. The use of actual anchor heads in the tests to simulate leakage through those was deemed to yield only minor benefit compared with cost and complexity involved. Instead, to simulate normal tendon termination the test assemblies used temporary duct-ending caps further sealed with duct tape on the perimeter.

Each test facility (see Figure 1) consisted of eight 3-inch diameter, 20 ft long alternatively corrugated/smooth ducts. The corrugated part of the ducting was polyethylene / polypropylene (PPEX3, 3-inch internal diameter, 3.6 in external, representative of the material used in FDOT projects). Corrugated duct allowed the opportunity for water/contaminants accumulation as may be encountered in actual construction. Corrugated ducting was chosen also at it is used by FDOT exclusively for internal tendons, which are in the majority in current construction practice. The smooth portions of the ducts were 3-inch Schedule 40 Harvel™ clear PVC pipe to allow for external visual inspection. The assemblies had a sag in the center as detailed in the elevation profile in Figure 1 to increase opportunity for water accumulation resembling a field installation.

A hinged sloping roof covered the entire duct length including both end caps, with an overhang of about 2 ft at the ends. The top of the roof was covered with building insulation 1 in thick, with reflective aluminum film on the outside. Sides and ends were freely exposed on the entire perimeter. The hinged roof was lifted during assembly and inspection.

Per test planning discussions the tests simulated the corrosion conditions present in ducts under various levels of corrosion severity and one protective measure. Those conditions were: sealed under optimal conditions, improper sealing, sealed with some entrapped water, and sealed with entrapped water as well as containing a vapor-phase corrosion inhibitor. Table 3.1 gives further detail and designations for each case.

Table 3.1 – Field Exposure Conditions

Designation	Test Condition
DCN	**D**ry duct (no free water inside) assembled under ambient conditions. Both ends **C**losed. **N**o corrosion inhibitor. .
DON	**D**ry duct but with simulated improperly sealed condition, by leaving one end cap out (a bug mesh was placed instead). One end **O**pen. **N**o corrosion inhibitor.
WCN	**W**et duct (intentionally trapped water inside) assembled under ambient conditions with the addition of sufficient potable water to produce an internal atmosphere at 100% relative humidity. Both ends **C**losed. **N**o corrosion inhibitor.
WCI	**W**et duct assembled under ambient conditions plus the addition of sufficient potable water to produce an internal atmosphere at 100% relative humidity. Both ends **C**losed. Fogging with a water-based vapor phase corrosion **I**nhibitor.

The facilities were lined up in a North-South direction. The ducts were laid out starting from the E side of the double enclosure in the order [DCN] - [DON] - [WCN] - [WCI] - [DCN] - [DON] - [WCN] - [WCI] so each condition was tested in duplicate.

Each duct initially contained 5 strands complying to ASTM A416 - 09, Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete 0.6-in diameter (strand No. 15), 7 wire, Grade 270. An 8 in spike hot-dipped galvanized steel nail (3/8 in diameter wire) was clamped at each ends of each 5-strand assembly in a manner representative of electrochemical coupling that may occur with the anchor body. Each duct contained 4 grout vent caps with ball valves.

The duplicate ducts for conditions [DCN] and [DON] each contained an Omega OM-EL-USB-2-LCD temperature and relative humidity logging device in an airtight chamber connected to the duct through one of the vent cap valves, kept open to the chamber.

All strands were photographed front and back at high resolution covering the entire length before placement in the ducts. One strand from each duct was removed after 1 week, 2 weeks, 4 weeks and 8 weeks from placement day which was 9/6/10 and 11/9/10 for the Inland and Seashore facilities respectively. One additional strand was left in place for each duct at each facility for a longer interval pending future visits by FDOT personnel. The removed strands were not reintroduced and kept in an air conditioned laboratory. There initial inspection and re-photographing front and back of the extracted strands was made in the as-extracted condition with no alteration, except for lightly brushing and vacuuming loose inhibitor material in the strands exposed to inhibitor. Afterwards, for all removed 8 week exposure samples from both test facilities, the surface of the strand was brushed with a fine metal wire brush and steel wool (more thoroughly in the case of strands with conspicuous rust) to better reveal any metal loss. The strands thus cleaned were photographed again. The strands extracted from the Seashore facility were cut into 4 equal length pieces labeled A, B, C and D counting from one end. 50-in lengths of pieces C and D of each strand were tested mechanically per ASTM A 1061/A 1061M – 09, Standard Test Methods for Testing Multi-Wire Steel Strand to obtain strength and ductility results. The fracture surfaces were inspected visually for signs of embrittlement.

Visual appearance of the strand on removal was assigned a Visual Corrosion Rating (VCR) based on the method described by Sason (1992), using reference pictures exemplifying increasing levels of corrosion damage. This system was used for the San Francisco Bay Bridge Overpass investigation (Reis 2007) (Sason 1992). The VCR assignment, based on the pictures reproduced in Appendix 2, was as follows:

1. Little or no corrosion, acceptable.
2. Some amount of surface corrosion, acceptable.
3. More corrosion but still acceptable.
4. More corrosion, borderline.
5. Excessive corrosion, visible pitting, cause for rejection.
6. Further excessive corrosion, visible pitting, cause for rejection.

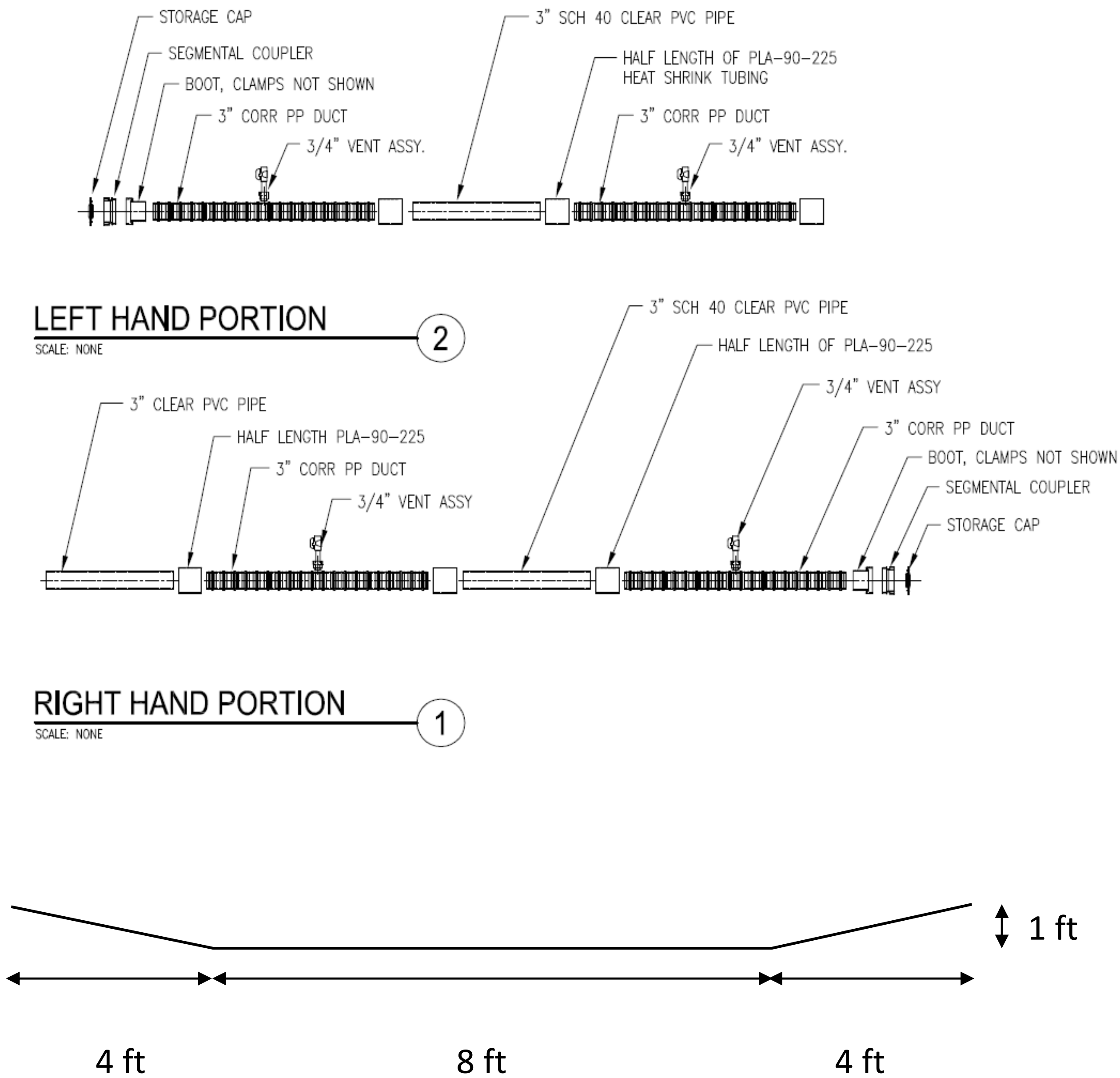

Figure 1 A - Test Facility Duct Construction and Elevation Profile (Approximate)

Figure 1 B - Test Facility During Construction. Inland Facility (USF Campus), West Side Seen from North, Showing Ducts From Left to Right: [DCN] - [DON] - [WCN] - [WCI]. Hinged roof is lifted.

Figure 1 C - Inland Facility (USF Campus), seen from N at the time of the 1-week inspection; hinged roofs lifted.

3.2 Results and Discussion

The environmental conditions recorded by the temperature and humidity gauges in DCN and DON exposure tubes are shown as function of time in Figure 2[2]. Conditions in the WCN and WCI tubes are expected to have had the same temperature as recorded for the other tubes and relative humidity near 100%.

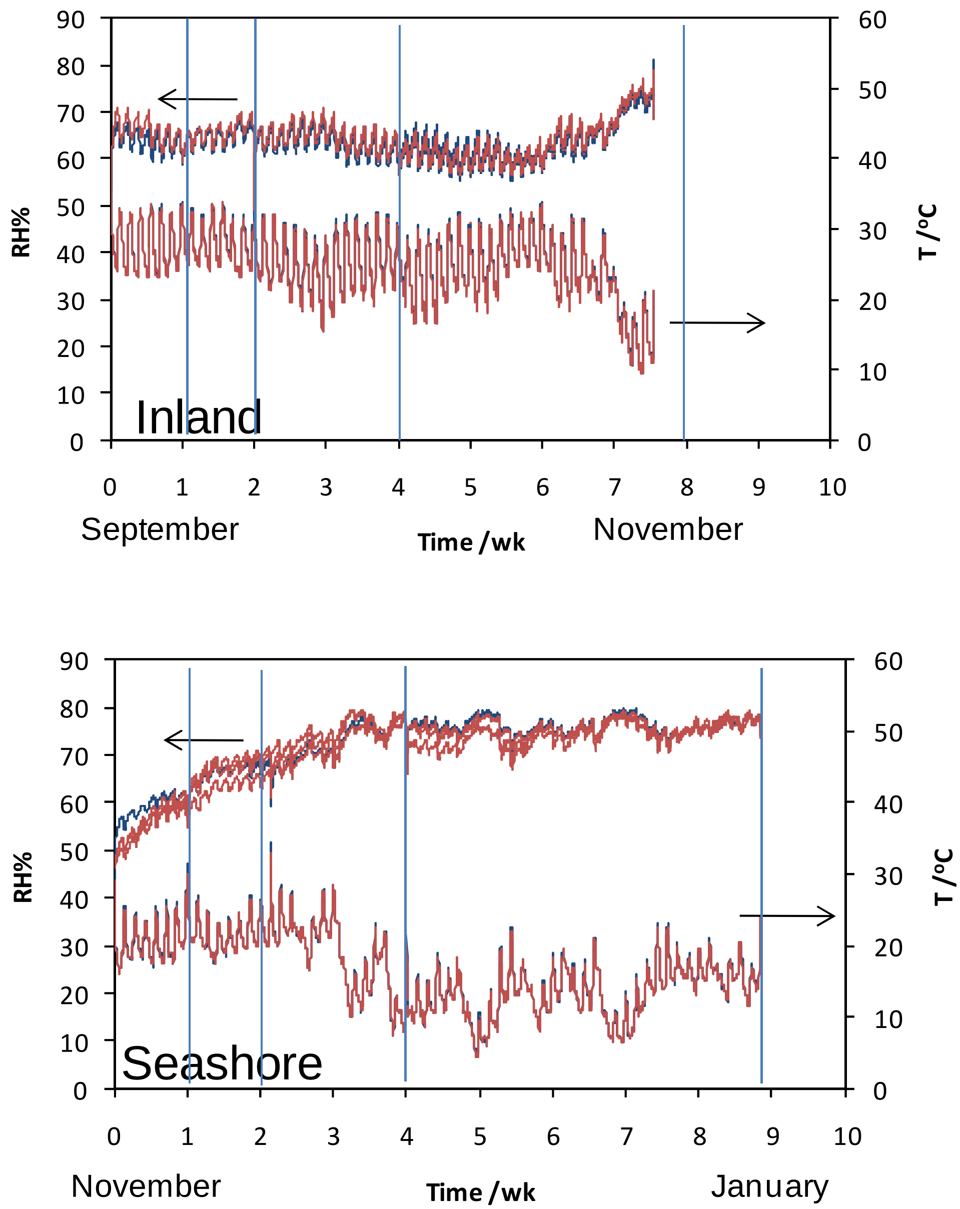

Figure 2 – Environmental conditions in DON (red) and DCN (blue) tubes. Results from duplicate probes. Sample extractions occurred at the time indicated by the vertical lines. See Table 3.1 for condition exposure code.

[2] Inland facility data for the last half week not processed for this report.

Sample extractions took place at the moments indicated by the vertical lines in Figure 2, within 1 day of the target times for the 1, 2 and 4 week exposures and within 6 days of target date for the 8 week exposures. The range of observed temperatures are as expected for the reflective roof and side-ventilated conditions of the facilities, and for the time of the year (Fall for the Inland and, late fall/early winter for the Seashore facilities respectively).There was some but not extensive rainfall during the test periods. Recorded RH values were surprisingly similar within each facility for the open (DON) and closed (DCN) tubes. Diurnal RH cycles were moderate (typically with changes not exceeding ~10 units) in both facilities. In the Inland facility the DON/DCN RH values were relatively low, staying below 70 % for much of the time. In contrast, the Seashore facility had DON/DCN RH that between 70% and 80% for much of the last 4 weeks of exposure. That range is of potential significance as it approaches the condition (typically >80% RH) where a sustained water film may form on the surface of steel.

Photographs showing the portions of the extracted segments having the greatest visual indications of corrosion are shown in Appendix 3. The rating numbers correspond to the place showing the greatest signs of corrosion on the entire length of the strand segment extracted at the indicated exposure time. Based on that record, Table 3.2 summarizes the VCR observations for both test facilities.

Table 3.2 – Visual Corrosion Ratings per Section 3.1 and Appendices 2 and 3 for strands extracted from each facility after the indicated time of exposure. See Table 3.1 for condition exposure code. Dual entries indicate intermediate value.

CONDITION (DUPLICATE E-W)		INLAND (USF)				SEASHORE (SS)			
		1wk	2wk	4wk	8wk	1wk	2wk	4wk	8wk
DCN	E_1	1	1	1	1	1	1	1	1
	W_5	1	1	1	1	1	1	1	1
DON	E_2	1	1	1	1	1	1	1	1
	W_6	1	1	1	1	1	1	1	1
WCN	E_3	1	2-3	2	2-3	1	2	2-3	3-4
	W_7	1	1	2-3	2-3	1	2	1	2-3
WCI	E_4	1	1	2	2	1	1	1	2-3
	W_8	1	1	2	2	1	1	1	2

Results of mechanical tests of exposed strands, available for the Seashore facility at time of preparation of this report, are summarized in Figure 3.3, keyed to exposure condition and time.

As can be appreciated from Table 3.2 and the figures in Appendix 3, visual manifestations of corrosion have been nearly insignificant for up to 8 weeks at both facilities for the DCN and DON conditions (no entrapped water, both-ends-closed; no entrapped water, one-end-open; respectively). The exposed strands had essentially the same appearance as that of the initial, as-received material. The 1, 2 and 4-week appearance for these conditions was nearly the same as for 8 weeks. It is noted that some superficial rust spots where found on the as-received strand. Those spots were documented in the pre-exposure photographs and disregarded accordingly when assigning a VCR in the post-exposure observations.

In contrast, for both facilities significant rust developed after 2 weeks exposure for the WCN and WCI conditions (entrapped water and both-ends-closed, no-inhibitor and with inhibitor respectively)[3]. The rust was visible mainly on the strand portion that was under the water injection ports. Rust development was somewhat less evident on the strands with applied inhibitor, although part of that visual difference may have resulted simply from the surface being partially covered by caked-on inhibitor dust. As noted in examinations by Caltrans after long term exposure of ungrouted strand in San Francisco Bay, the actual metal loss as observed in the cleaned surface can be much less than it would appear from the presence of conspicuous rusting. That was also the case here, as can be seen in the close up pictures of cleaned surfaces in Appendix 4, showing that the worst pitting observed (Seashore facility, wet ducts) was generally shallow. Consequently, the VCR rating for exposure in the wet ducts was with one exception deemed to be 3 or less, thus receiving an “acceptable” classification per Appendix 2. The exception was for WCN, 8 weeks at the Seashore site, and even in that case the VCR was deemed to be between 3 and 4, hence corresponding to only a marginally condition per Appendix 2.

The mechanical test results (Figure 3) showed no evidence of significant adverse effects of the field exposures. All strands, regardless of the exposure condition and duration, amply met the ASTM A416 strength requirements, and with one exception (where the elongation fell short by only 0.1%) also met the elongation requirements. The data shown by the grayed column corresponded to a test with grip slippage and was not considered. Statistical evaluation of the results was performed to reveal possible differences between the results from the various exposure conditions (Figure 4). The evaluation showed no consistent differences between the mechanical test results of “C” strand segments (see Section 3.1), which were from the central portion of each strand and thus tended to show more rust in the wet ducts, and those “D” segments which were near the end. Likewise, no clear differentiation was found between the results from the dry and wet ducts. Inhibitor presence did not appear to have resulted in differentiation of mechanical behavior either. Examination of the

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[3] The extent of rust formation in these conditions after one week appeared to be minimal; however, the amount of moisture in the ducts within the first week, especially at the Seashore facility, may have been lower than intended. Modifications to the ducts were made at both test facilities by the first week to ensure water retention and minimal leakage.

fracture surfaces and plastic necking zone of selected wires near the fractures showed no conspicuous indication of unusual features that may have suggested embrittlement. It is cautioned that the tensile test is limited in nature and cannot assess fatigue resistance or the presence of delayed cracking modes. Some of those aspects are the subject of planned future work.

In summary the above observations as a whole indicate that for the seasonal periods investigated, and for either the Inland or Seashore exposure regime, there was no significant corrosion or adverse mechanical effect (for the properties evaluated by the tensile test) over an 8-week exposure period for ungrouted strand in both the closed and open ducts that had no intentionally trapped water. Water intentionally trapped in closed ducts resulted in conspicuous visible corrosion and shallow pitting after about 2 weeks of exposure. The presence of a vapor-phase corrosion inhibitor in the wet ducts was associated with somewhat less conspicuous, but not dramatically reduced, corrosion.

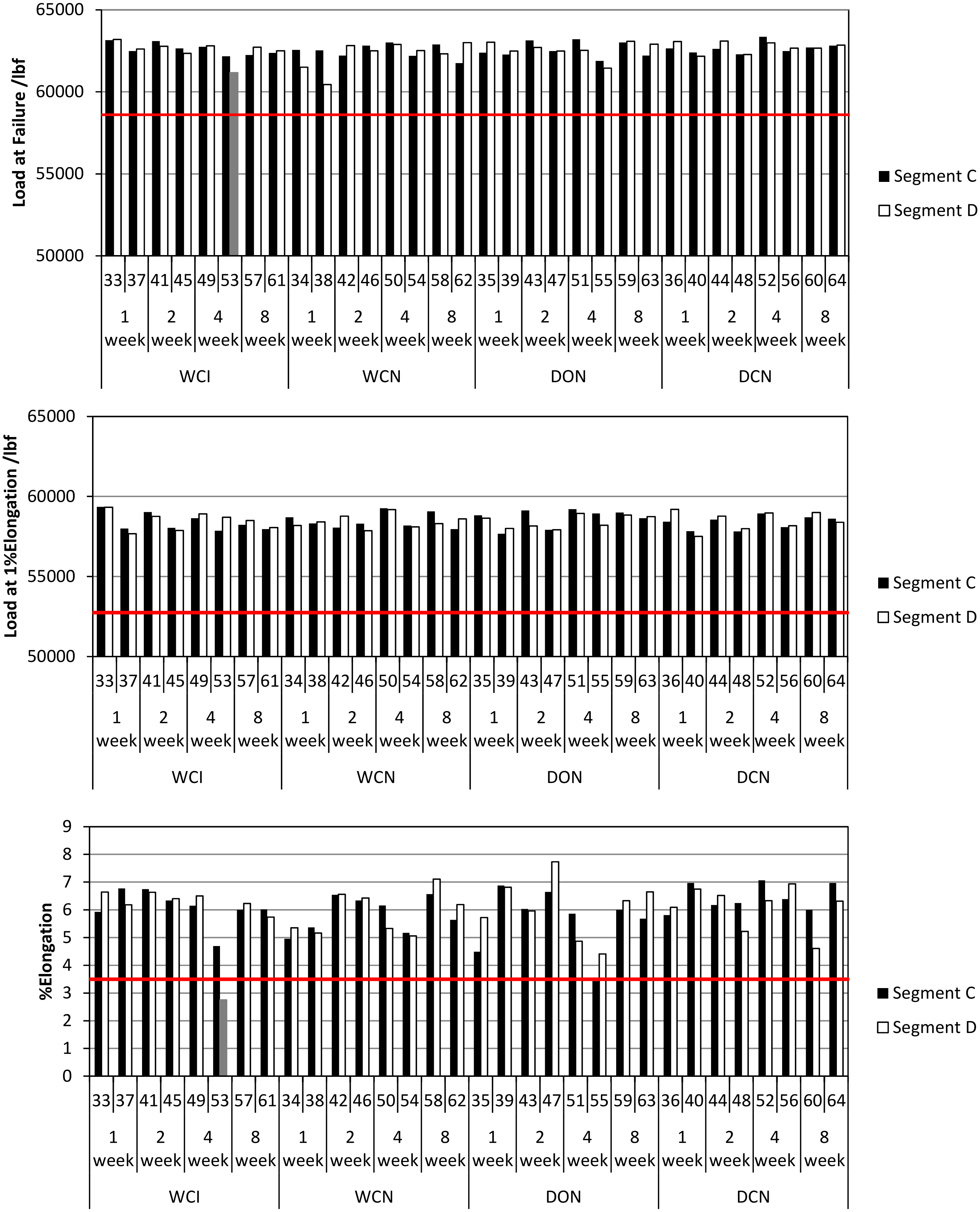


Figure 3 – Mechanical properties of extracted strands from the Seashore facility. Red lines indicate requirements per ASTM A416 – 09. See Table 3.1 for condition exposure code. Grayed columns denote grip slippage in one test.

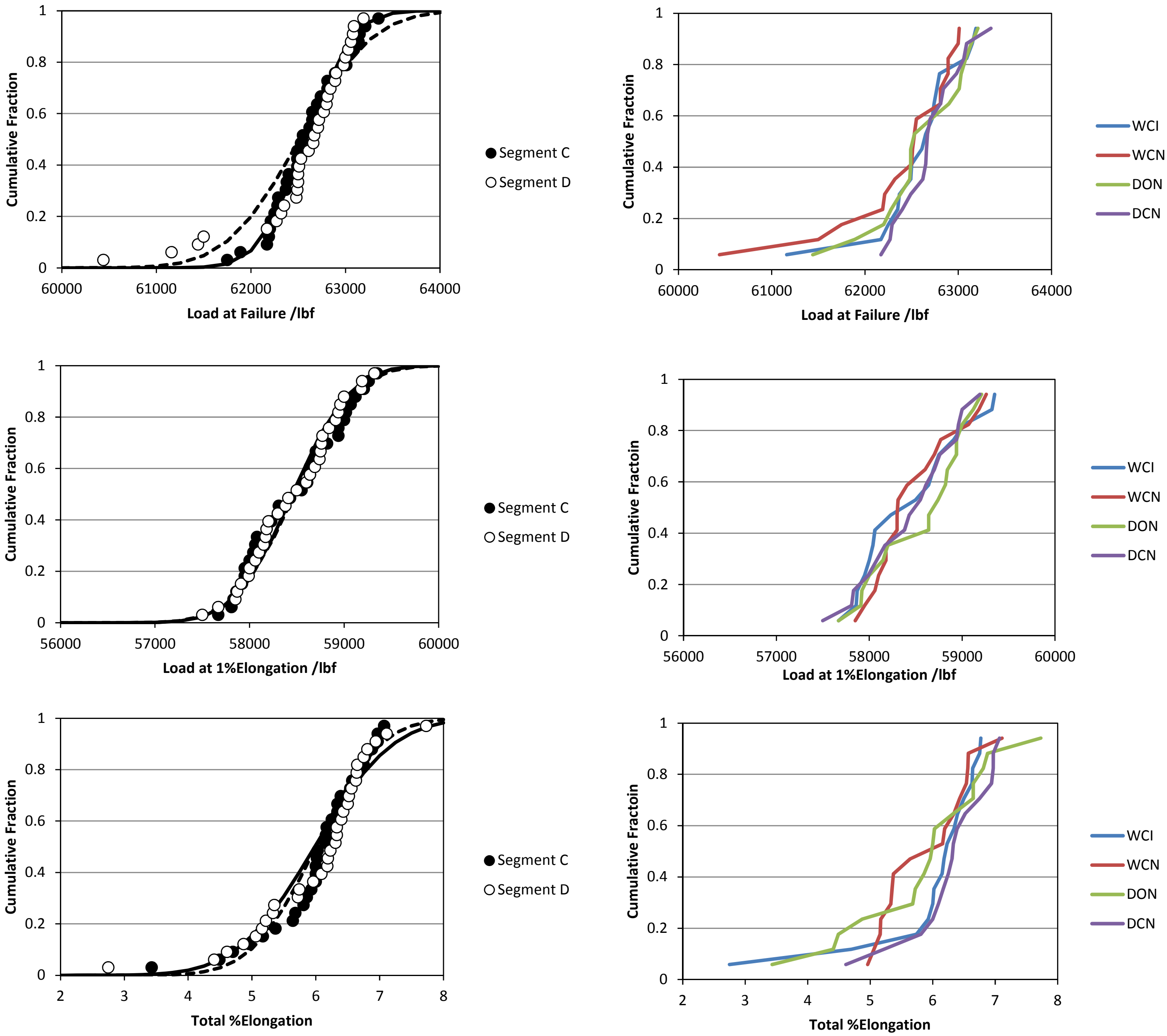


Figure 4 – Cumulative distribution of results of mechanical properties tests, showing no consistent differentiation between results from the various exposure conditions or the location of the strand segment in the exposure duct.

3.3 Interpretation of Findings from Documentary Review and Field Evaluation

The documentation and experience review indicate that a 7-day limit for the ungrouted strand condition, similar to that currently adopted by FDOT, is recommended often by U.S. and other agencies. However, allowable periods of up to 40 days are proposed for environmental conditions that are deemed to be not aggressive. Corrosion inhibitor injection and oil coatings are the approaches most often listed as the means of addressing cases when the limit is to be exceeded. However, negative aspects cited for inhibitor or oil use are associated with potential loss of bond or questionable corrosion control efficiency.

While it is recognized that prolonged exposure of corrosion of strand in the ungrouted condition is undesirable, the actual adverse consequences of that exposure may be limited. The Caltrans experience with the SFOBB project offered instances of unintended extraordinarily long exposure (e.g. > 1 year) of ungrouted stressed strand to conditions that included retained water in the ducts. Even in those highly adverse conditions corrosion development was moderate and mechanical strength was on the whole retained, with no documented cases of strand failures in normal mechanical conditions. The field tests in this project, performed only with unstressed ungrouted strand, showed conspicuous corrosion only if water in liquid phase form had been contained in closed ducts. Even in those cases the corrosion was mostly in the form of shallow pits after 8 weeks of exposure, with no adverse mechanical consequences that could be revealed by subsequent tensile tests. There was no discernable effect from having one end of the duct continuously open to the external environment (although sheltered from direct rainfall), even in the Seashore facility only ~50 ft from the bay water at low elevation.

The field tests were conducted under mostly moderate Florida Fall conditions that did not include extremely high RH that may be encountered in summer, or occasional freeze (with potential for associated in-duct water condensation) during winter. More importantly, the strands were not stressed so the effect of potential sources of degradation such as SCC or HE could not be directly assessed. Nevertheless, the field test results suggest that in the absence of free water in the ducts there is little potential for corrosion even in ducts not fully sealed from the external environment. Water presence in the ducts resulted in clear signs of strand corrosion after 2 weeks of exposure, regardless of corrosion inhibitor presence. It should be noted however that the tests, along with the Caltrans experience suggest that the strand has significant tolerance, from the standpoint of mechanical performance as evaluated in a tensile test, to the presence of in-duct corrosion that may be otherwise visually striking.

The above observations suggest that the presence of free water in the ducts was more important than the external environmental regime (Inland, Seashore) as a factor in the development of in-duct corrosion of ungrouted strand. When corrosion developed in the presence of trapped water, the consequences were limited even after 8 weeks exposure in the field tests, and even after longer periods in the Caltrans experience. These findings indicate that some relaxation of the blanket 1-week limit in the present

FDOT guidelines may merit consideration while retaining a generally conservative approach to corrosion control. Possible approaches for discussion include:

1. Retaining the current 1-week limit if no assurance can be made that free water is absent from the duct and the strand surface at the time of strand placement and tensioning.

   Rationale: Conspicuous corrosion development was observed in the field tests with free water in duct after 2 weeks. Pending future testing, that corrosion is for now conservatively assumed to have potentially detrimental effects that may not have been revealed in the unstressed exposure conditions used. Note that per Appendix 1, water on strand surface (from severe environmental condensation) could cause superficial corrosion, and also could significantly contribute to water balance inside the duct.

2. Extending the limit to 2 weeks if assurance of a fully dry duct and strand surface at the time of strand placement and tensioning can be provided.

   Rationale: An extension to 2 weeks is thought to be the minimum that would have significant positive impact in facilitating construction operations. Unaltered visual surface condition after 2 weeks in the field tests with ducts without entrapped water suggests no detrimental effects even in the stressed condition.

3. Extending the limit to 4 weeks for inland locations (“Moderately Aggressive” classification per FDOT Structural Design Guidelines) where the possibility of salt contamination of strand surface of duct interior is low.

   Rationale: While the field tests showed little indication of environmental effects, evidence from the literature on atmospheric corrosion suggests some measure of relaxation for absence of environmental chloride applies may still apply. Unaltered visual surface condition after 4 weeks in the field tests with ducts without entrapped water suggests no detrimental effects even in the stressed condition.

4. Not relying on a vapor corrosion inhibitor as a primary remedial measure.

   Rationale: Corrosion development in the wet ducts took place in the field tests even in the presence of substantial amounts of inhibitor. Any mitigating effect of the inhibitor was not pronounced.

Further potential guideline change considerations should be contingent on the development of additional evidence. A relatively easy test could be made by exposing a new set of strands, with the existing facilities, during the summer. Consideration should be given to the more resource intensive evaluation of the behavior of stressed strands in ungrouted ducts.

4 – CONCLUSIONS

1. Literature review indicated that a 7 day limit for the ungrouted strand condition, similar to that currently adopted by FDOT, is often specified by transportation agencies. However, allowable periods of up to 40 days are proposed for environmental conditions that are deemed to be not aggressive. Corrosion inhibitor injection and oil coatings are the approaches most often listed as the means of addressing cases when the limit is to be exceeded, but there are negative factors, including loss of bond, associated with their use.
2. Field tests with unstressed ungrouted strand showed conspicuous corrosion only if free water had been contained in closed ducts. Even in those cases the corrosion was mostly in the form of shallow pits after as much as 8 weeks of exposure, with no clear loss of strength revealed by subsequent tensile tests. There was no discernable effect from having one end of the duct continuously open to the external environment even in a seashore facility. Inhibitor presence had no well-defined effect on mitigating corrosion.
3. The field test results and experience from extended exposure of ungrouted strand elsewhere indicated that the strand has significant tolerance, from the standpoint of mechanical performance as evaluated by the tensile test, to the presence of in-duct corrosion that may be otherwise visually striking.
4. Possible approaches for consideration in updating FDOT exposure duration guidelines include extending the current limit to 2 weeks and 4 weeks depending on environmental classification, if assurance can be made that in-duct or on-strand free water is absent.

5 – REFERENCES

AASHTO (American Association of State Highway and Transportation Officials) (2002) "Standard Specifications for Highway Bridges", 17th Ed., AASHTO, Washington D.C.

ACI (American Concrete Institute) (2001) "ACI 222.2R-01, Corrosion of Prestressing Steels - Report by ACI Committee 222." Farmington Hills, MI.

ASBI (American Segmental Bridge Institute) (2005). "Temporary tendon protection against corrosion " ASBI Newsletter *Segments*, 46, Spring.

Bricker, M. D., and Schokker, A. J. (2005) *Corrosion from bleed water in grouted post-tensioned tendons*, Portland Cement Association, Skokie, Ill.

Corven, J. (2001) "Mid Bay Bridge Post-Tensioning Evaluation", Final Report, Florida Department of Transportation, October. Available under "Post Tensioning" in http://www.dot.state.fl.us/structures/

Corven, J., and Moreton, A. (2004) *Post-tensioning Tendon Installation and Grouting Manual*, Federal Highway Administration. Office of Bridge Technology, Washington, D.C.

DelDOT (Delaware Dept. of Transportation) (2008) Scope of services package for Indian River Inlet Bridge, Part 4, Special Provisions. Available at http://www.deldot.gov/

ECS (European Committee for Standardization) (1999) "Execution of concrete structures", Final Draft of European Pre-Standard pr ENV13670-1, Annex D, European Committee for Standardization (CEN), Brussels *(as cited by Ganz (2002).*

FDOT (Florida Department of Transportation) (2002-2004) "New Directions for Florida Post-Tensioning Bridges", Volumes 1 through 10B, Available under "Post Tensioning" in http://www.dot.state.fl.us/structures/

FDOT (Florida Department of Transportation) (2008a) Specifications and Estimates Office, Florida Department of Transportation "Standard Specification for Road and Bridge Construction". The review presented here is based on the 2007 (Rev 2008) version. Updated references available at ftp://ftp.dot.state.fl.us/LTS/CO/Specifications/SpecBook/2010Book/2010Master.pdf

FDOT (Florida Department of Transportation) (2002-2004) (2008b) Structures Design Office, Florida Department of Transportation, "Structures Manual", Tallahassee. Review based on the 2008 version. Updated references available at http://www.dot.state.fl.us/structures/

FIB (Federation International du Beton), FIP(Fédération Internationale de la Précontrainte), (2001) "Factory applied corrosion protection of prestressing steel : state-of-art report", FIB, Lausanne.

FIB (2002) (Federation International du Beton), FIP (Fédération Internationale de la Précontrainte), CBE (Comite Euro-International du Beton) “Grouting of tendons in prestressed concrete: guide to good practice, FIB Bulletin No. 20”, FIB, Lausanne.

Fuzier, J.-P., Ganz, H.-R., and Matt, P. (2005) "Durability of post-tensioning tendons - FIB Bulletin No. 33”, FIB, Lausanne.

Ganz, H. R., and Vildaer, S. (2002). "Grouting of Post-Tensioning Tendons, VSL Report Series 5", VSL International, Lyssach.

Ganz, H.R. (2002b) “Recent Developments in the Protection of Prestressing Steels”, Proceedings of the first fib Congress: Concrete Structures in the 21st Century, Session 7, Osaka, Japan, 2002.

Hartt, W., Poeydomenge, A., Stauder, A. and Scannell, W.(2008) "Long-term effects of cathodic protection on prestressed concrete bridge components", Report No. FHWA-RD- 98-075, Published by NTIS, April.

Isecke, B., Mahlcke, W., Mietz, J., and Ruckert, J. (1997). "Temporary corrosion protection of prestressing steels with film forming coatings." *Materials and Corrosion-Werkstoffe Und Korrosion*, 48(9), 613-623.

Isecke, B., Mietz, J., and Schutt, K. (2003). "Temporary corrosion protection of prestressing steels in non-injected ducts." *Materials and Corrosion-Werkstoffe Und Korrosion*, 54(6), 413-418.

Kittleman, W. M. (1992). "Evaluation of emulsifiable oils for lubrication and temporary corrosion protection of seven-wire strand. M.S. Thesis" University of Texas at Austin.

Kittleman, W.M., Davis, R.T., Hamilton, H.R., Frank, K.H., and Breen, J.E (1993). “Evaluation of Agents for Lubrication and Temporary Corrosion Protection of Post-Tension Tendons” Research Report CTR 0-1264-1. Center for Transportation Research, The University of Texas at Austin, August, 104 pp.

Lee, S.K. and Virmani, Y.P. (2007), "Laboratory Evaluation of Post-Tensioning Strand Samples Removed from San Francisco-Oakland Bay Bridge Skyway Seismic Replacement Project", Appendix A in in Reis (2007).

Luthi, T., Diephuis, J. R., Icaza, A., Breen, J. E., and Kreger, M. E. (2008). "Effects of Duct Types and Emulsifiable Oils on Bond and Friction Losses in Posttensioned Concrete." *Journal of Bridge Engineering*, 13(1), 100-109.

Marti, P., Ullner, R., Faller, M., Czaderski, C., and Motavalli, M. (2008). Temporary corrosion protection and bond of prestressing steel." *Aci Structural Journal*, 105(1), 51-59.

Mietz, J., and Isecke, B. (2002). "Assessment of test methods for evaluation stress corrosion cracking susceptibility of prestressing steels." *Materials and Corrosion-Werkstoffe Und Korrosion*, 53(6), 373-384.

Mietz, J., Burkert, A., Lehmann, J., Burkert, A., and Eich, G. (2008). "Galvanised constructional elements in contact with prestressing steel tendons." *Materials and Corrosion-Werkstoffe Und Korrosion*, 59(2), 131-138.

Mietz, J., Fischer, J., and Isecke, B. (1999). "Stress corrosion cracking of prestressing steels." *Materials and Corrosion-Werkstoffe Und Korrosion*, 50(9), 535-540.

Pielstick, B. and Peterson, G. (2002) "Grouting of bridge post-tensioning tendons training manual", Florida Department of Transportation, Tallahassee FL.

Podolny, W., Cox, W., Hooks, J., Miller, M., Moreton, A., Shahawy, M., Edwards, D., Madani, M., Montgomery, R. K., Pielstick, B., and Tang, M.-C. (2001) "Performance of concrete segmental and cable-stayed bridges in Europe." U.S. Dept. of Transportation, Federal Highway Administration, International Technology Exchange Program, [Office of International Programs, Washington, D.C., 89.

Powers, R.G., Sagüés, A.A., Virmani, Y.P. (2002) "Corrosion of Post-Tensioned Tendons In Florida Bridges", Proceedings, 17th. U.S.-Japan Bridge Engineering Workshop, Nov. 12-14, 2001, Public Works Research Institute, Japan, Technical Memorandum of PWRI No. 3843, Hiroshi Sato, Ed. pp. 579-594, PWRI, 2002.

PTI (Post-Tensioning Institute) Grouting Specifications Committee (2003) "Specification for Grouting of Post-Tensioned Structures", PTI Guide Specification, 2nd. Ed, PTI, Phoenix, Arizona, April.

Reis, R. E. (2007) "Corrosion evaluation and tensile results of selected post-tensioning strands at the SFOBB Skyway seismic replacement project" Phase II Report, Caltrans, Sacramento, CA, September, 2007.

Sagüés, A.A. (2006) " Posttensioned Grouted Tendons" p. 570 in "Corrosion: Environments and Industries", Volume 13C, ASM Handbook, ASM International, Metals Park, OH.

Sagüés, A. (2007) "Corrosion of post-tensioned strands at SFOBB Skyway replacement project", Appendix B in Reis (2007).

Salas, R. M., Schokker, A. J., West, J. S., Breen, J. E., and Kreger, M. E. (2004). "Conclusions, recommendations, and design guidelines for corrosion protection of post-tensioned bridges." University of Texas at Austin, Center for Transportation Research ; Available through National Technical Information Service, Austin, TX; Springfield, Va., 100.

Salas, R. M., West, J. S., Schokker, A. J., Breen, J. E., and Kreger, M. E. (2003). "Long-term post-tensioned column exposure test specimens : final evaluation." Center for Transportation Research, Texas. Dept. of Transportation, Austin, TX; Springfield, Va.

Salas, R. M., Schokker, A. J., West, J. S., Breen, J. E., and Kreger, M. E. (2008). "Corrosion risk of bonded, post-tensioned concrete." *PCI Journal*, 53(1), 89-107.

Sanchez, J., Fullea, J., Andrade, C., and Alonso, C. (2007). "Stress corrosion cracking mechanism of prestressing steels in bicarbonate solutions." *Corrosion Science*, 49(11), 4069-4080.

Sason, A.S. (1992) "Evaluation of Degree of Rusting on Prestressed Concrete Strand," *PCI Journal*, V.37, No. 3, May-June, pp. 25-30.

Schokker, A. J., Koester, B. D., Breen, J. E., and Kreger, M. E. (1999). "Development of high performance grouts for bonded post-tensioned structures." Research report, Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin; Available through National Technical Information Service, [Austin, Tex.] [Springfield, Va., xi, 56 p.

Schokker, A., Salcedo, E., and DeSalvo, J. (ca. 2005). "Temporary Corrosion Protection for Strand and Influence of Vibration During Setting of Grout." Powerpoint presentation available at www.asbi-assoc.org/

Staehle, R. and Little, B. (2002) " Corrosion and stress corrosion cracking of post tension cables associated with fungal action", p.33 in *Microbiologically Influenced Corrosion* ,Proceedings of Corrosion/2002 Research Topical Symposium, NACE International, Houston,.

Wang, H., Sagüés, A.A. and Powers, R.G. (2005a) "Corrosion of the Strand-Anchorage System in Post-Tensioned Grouted Assemblies" Paper No. 05266, Corrosion/2005, NACE International, Houston.

Wang, H and A. A. Sagüés, A.A. (2005b) “Corrosion of Post-Tensioning Strands”, Final Report to Florida Dept. of Transportation, Report No. BC353-33, 47 pp., Nov 1.

West, J. S., Larosche, C. J., Koester, B. D., Breen, J. E., and Kreger, M. E. (1999). "State-of-the-art report about durability of post-tensioned bridge substructures." Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin ; Available through National Technical Information Service, Springfield, Va., Austin, TX.

APPENDIX 1 - Visit to Strand Manufacturing Site.

MEMORANDUM

Date: February 22, 2010 (per revisions following initial 1/22/10 draft).
From: A. Sagüés
To: M. Paredes, F.C. Karins

Subject: 1/21/10 visit to Insteel Wire Products strand plant, 1 Wiremil Road, Sanderson, Fl 32087. Conducted under FDOT Project BDK84 977-04: “Corrosion Characteristics of Post-Tensioning Strands in Ungrouted Ducts” (USF # 2104111900).

The visit was conducted by Mario Paredes, FDOT and Alberto Sagüés, USF, and hosted by Donnie Sapp, General Manager, Phone (904) 275 2100, dsapp@insteel.com .

We toured the facilities for wire stock cleaning, wire drawing and stranding, strand epoxy coating, and quality control lab. The following reflect direct observations to our best recollection and information provided by Mr. Sapp:

The plant produces about 50,000 tons/year of strand at present, twice as much in the pre-slump period. Will have to look into what fraction of that production goes to FDOT projects.

The Sanderson plant is the only Florida strand plant active at present.

The plant recently produced $240x10^3$ psi strand out of Enduramet 33, a non-magnetic Mn austenitic alloy, for a U.S. Navy project. Some of that strand was still at the plant. It was made using wire already drawn to the needed sizes.

For normal operation the plant receives spools of 7/16 in carbon steel wire from a steel supplier, mostly Charter Steel.

The as-received rod has mill scale. It is brought in spool form into the cleaning house. The mill scale is removed in an HCL bath and phosphate coated (Figure A1.1). The wire in the spool has a rough, milky external appearance with apparently some phosphate on the surface (Figure A1-2). The cleaning building is ventilated with outside air. In the day of the visit, RH was near 100% with heavy rain at times.

The descaled and phosphated wire is brought into the drawing area. There the wire is drawn in several die steps from 7/16 in to 0.166 in (Figure A1.3). A dry lubricant powder resembling laundry detergent (Figure A1.4), sodium stearate, facilitates drawing. Calcium-based lubricant has not been used since the 1980's.

After drawing, the wire is made into 7-wire strand by a regular twisting process (Figures A1.5 and A1.6). The strand after this step is called "green strand" and has not yet stress-relieved.

The next step is stress-relief which consists of heating the strand for a few seconds at a proprietary process temperature. The strand, still hot, is rinsed with fresh water which evaporates dry and nearly completely removes any residual sodium stearate left over from the drawing steps.

The stress-relieved strand is wound into coil spools immediately afterwards. Normally the coils are covered for shipping with a wrap-around tarp that covers the outer perimeter and sides of the spool, but leaves the inner perimeter exposed (Figure A1.7). If the customer[4] specifies it, special wrapping is made. Figure A1.8 shows one spool with special wrapping that was present in the preparation area. That spool had the inner perimeter covered with plastic and what appeared to be humidity control or inhibitor packets inside. It is noted that the wrapping in this spool resembles that specified under Section 462-6 of the FDOT Standard Specifications for Road and Bridge Construction. Mr. Sapp is being contacted as to identification of the type of inhibitor that may be most commonly used by the plant for special wrapping.

The drawing/stranding/stress relief trains are all in a large non-air conditioned building ventilated with outside air. On the day of the visit the freshly produced spools had, before covering, extensive dew condensation due to the high atmospheric humidity. The strand on the outer perimeter showed many red spots; upon finger rubbing of the surface much of the red color disappeared by small superficial red spots remained (Figure A1.9). Mr. Sapp indicated that deeper in the spool there is no coloring.

Mr. Sapp indicated that normal storage of spools is indoors and that the spools are taken outside just before shipping. He estimated that typical wait times between production and shipping are about 2-4 weeks, although in some instances a period of as much as a few months may have elapsed. On the day of the visit some spools with their wrap-around tarp were in the yard being loaded onto flatbed trucks (Figure A1.10). Heavy rain took place periodically.

The plant also regularly produces epoxy-coated strand in various sizes.

[4] The plant produces and ships materials per the customer specifications. The customer (e.g. a builder) is the party that assumes contractual responsibility with its client (e.g. a State agency) to provide material with specific properties and shipping requirements.

Figure A1.1 - Last cleaning step.

Figure A1.2 - Phosphated and neutralized final surface appearance.

Figure A1.3 - Wire drawing train.

Figure A1.4 - Sodium stearate lubricant.

Figure A1.5 - Green stranding train

Figure A1.6 - Regular stranding procedure

Figure A1.7 - Normal wrapping for shipping

Figure A1.8 - Special wrap

Figure A1.9 - Outer spool surface before wrapping. High humidity conditions in day picture was taken, superficial rust visible. Central region was finger-rubbed to spread out condensation deposit.

Figure A1.10 - Spools placed outside awaiting shipping in rainy day.

APPENDIX 2 – Surface condition reference pictures used to assign a Visual Corrosion Rating to strand extracted from the exposure test facilities.

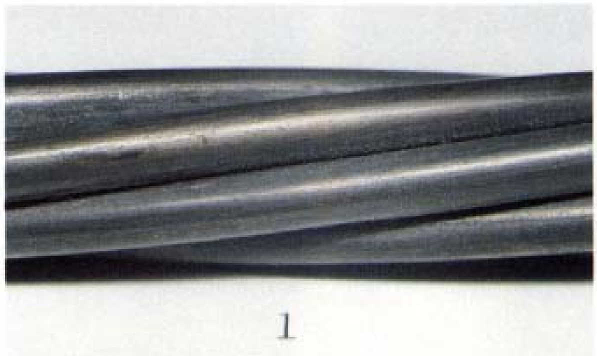


Photo 1. Strand surface before cleaning.

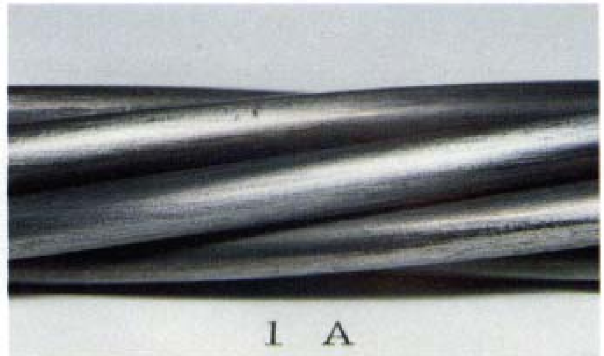


Photo 1A. Strand surface after cleaning.

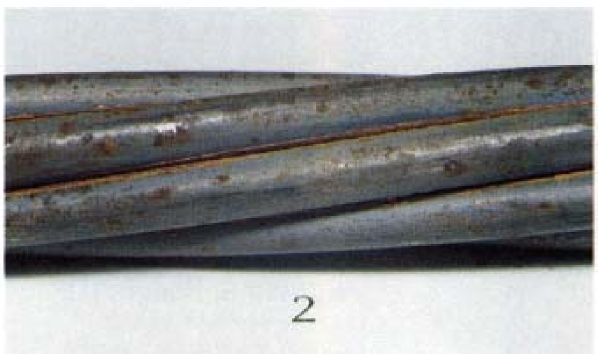


Photo 2. Strand surface before cleaning.

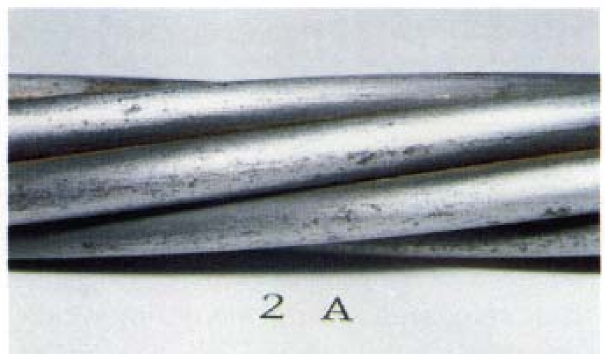


Photo 2A. Strand surface after cleaning.

Photo 3. Strand surface before cleaning.

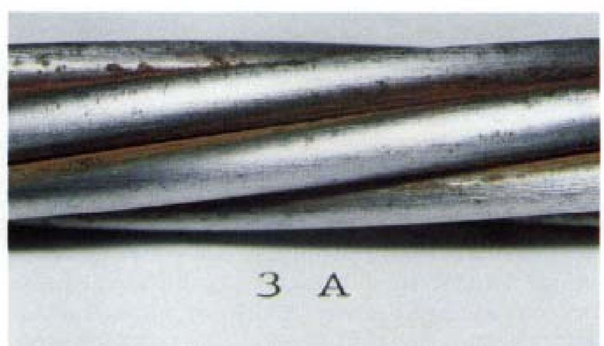


Photo 3A. Strand surface after cleaning.

Figure A2.1 – Photos 1/1A (little or no corrosion, acceptable), 2/2A (some amount of surface corrosion, acceptable) and 3/3A (some amount of surface corrosion, acceptable) used per Reis (2007). Pictures reproduced from Sason (1992) by kind permission from The Precast Prestressed Concrete Institute (PCI).

Photo 4. Strand surface before cleaning.

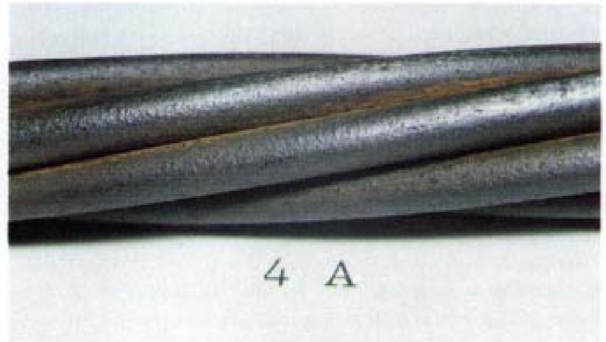


Photo 4A. Strand surface after cleaning.

Photo 5. Strand surface before cleaning.

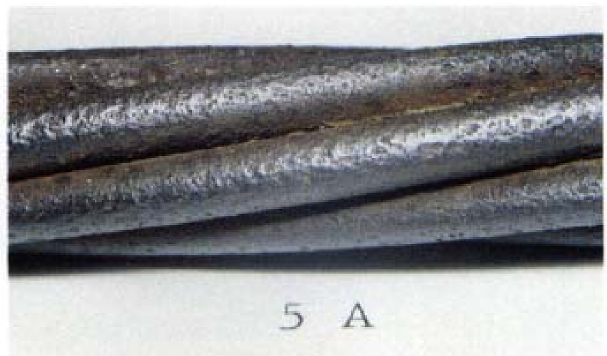


Photo 5A. Strand surface after cleaning.

Photo 6. Strand surface before cleaning.

Photo 6A. Strand surface after cleaning.

Figure A2.1 – Photos 4/4A (borderline condition), 5/5A (excessive corrosion with visible pitting, cause for rejection) and 6/6A (excessive corrosion with visible pitting, cause for rejection) used per Reis (2007). Pictures reproduced from Sason (1992) by kind permission from The Precast Prestressed Concrete Institute (PCI).

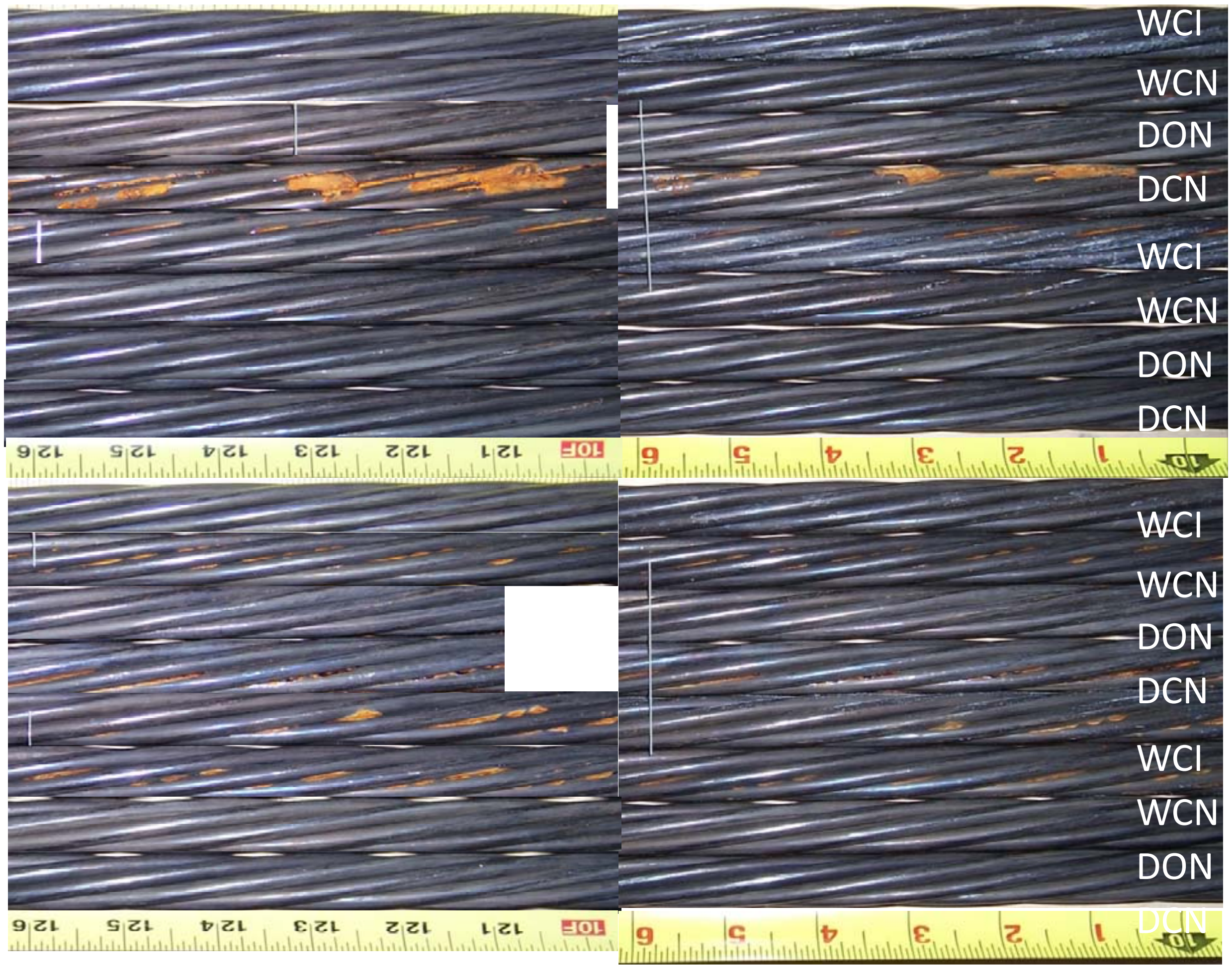
APPENDIX 3 - Photographic record of strands exposed in the test facilities.

Notes common to all pages:

- Each page contains pictures of one side of the strand (top frames) and of the other side of the same strand (bottom frames).
- The lower and upper 4 strands in each frame correspond to the E and W ducts respectively, identified per the nomenclature in Section 3.1.
- An ~ 7 in long segment has been selected for each extracted strand, showing the location with the greatest amount of visual corrosion signs in the entire ~20 ft exposure length (frames labeled As Extracted). For those pictures the surface was undisturbed except for lightly brushing of inhibitor dust or paste if present.
- The corresponding segment in the Initial strand condition prior to placement in the test facility is shown in the frames so labeled.
- For the 8-week extractions the strand surface was cleaned by brushing brushed with a fine metal wire brush and steel wool, more thoroughly in the case of strands with conspicuous rust. The corresponding pictures are labeled After Cleaning.
- The ruler markings in inches are shown for scaling purposes and do not imply that the same location respective to the strand end is shown in all segments.

Figure A3.1 - Inland – 1 week exposure.

Initial As-Extracted



Note rust was in the present in the As-Extracted condition was already present initially so it is not credited to exposure.

Figure A3.2 - Inland – 2 week exposure.

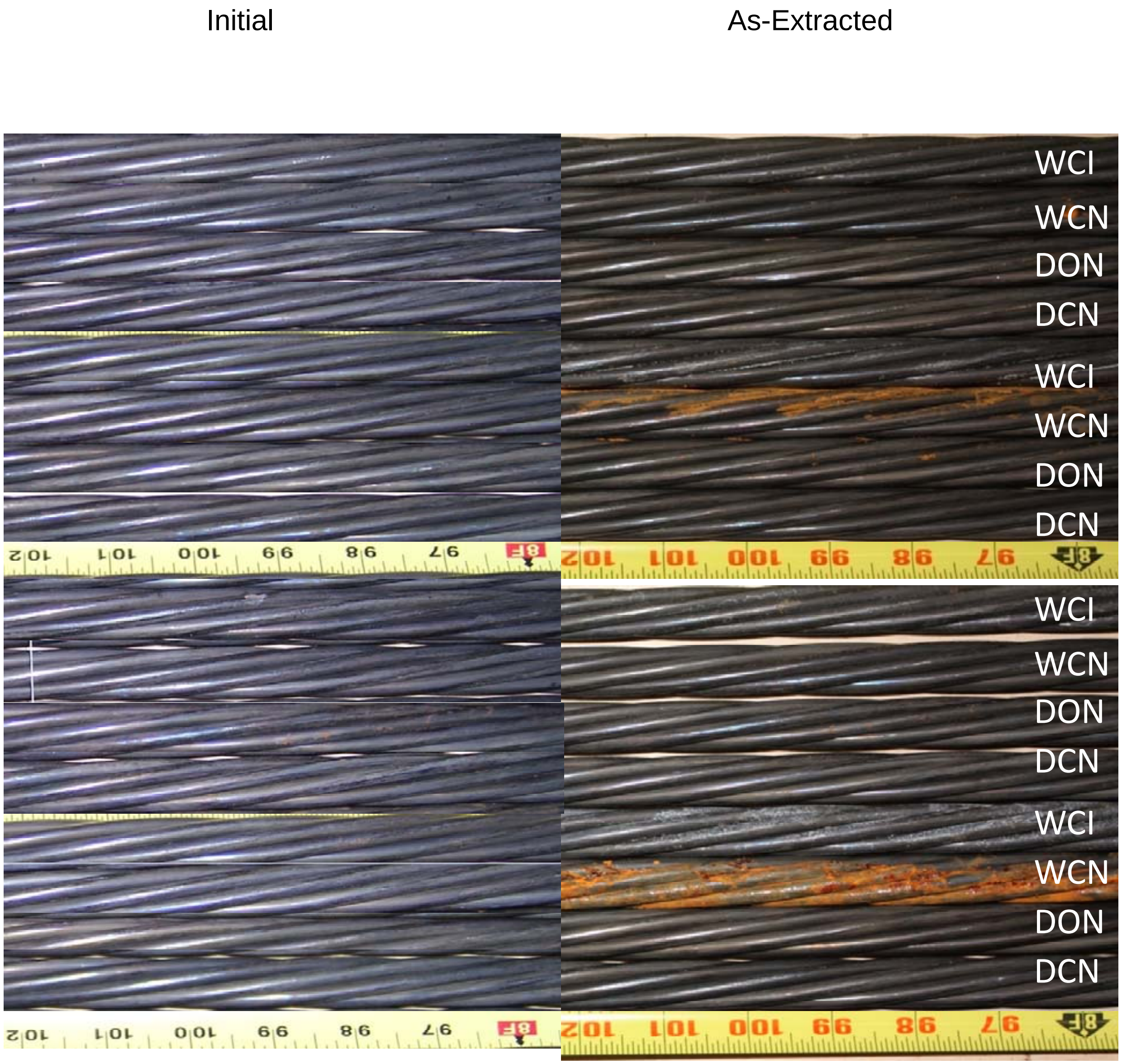


Figure A3.3 - Inland – 4 week exposure.

Initial As-Extracted

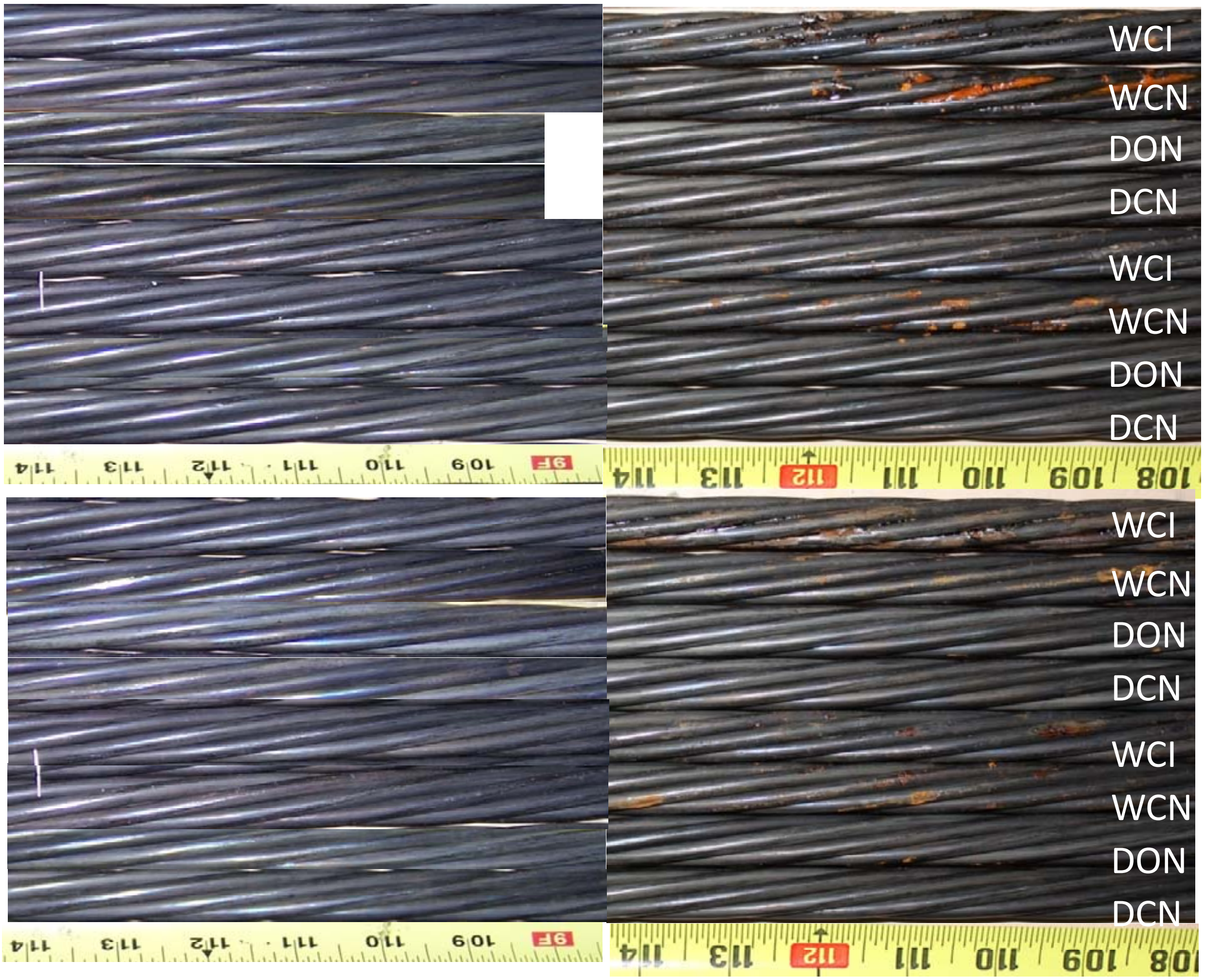


Figure A3.4 - Inland – 8 week exposure.

Initial | As-Extracted | After Cleaning

Figure A3.5 - Seashore – 1 week exposure.

Initial

As-Extracted

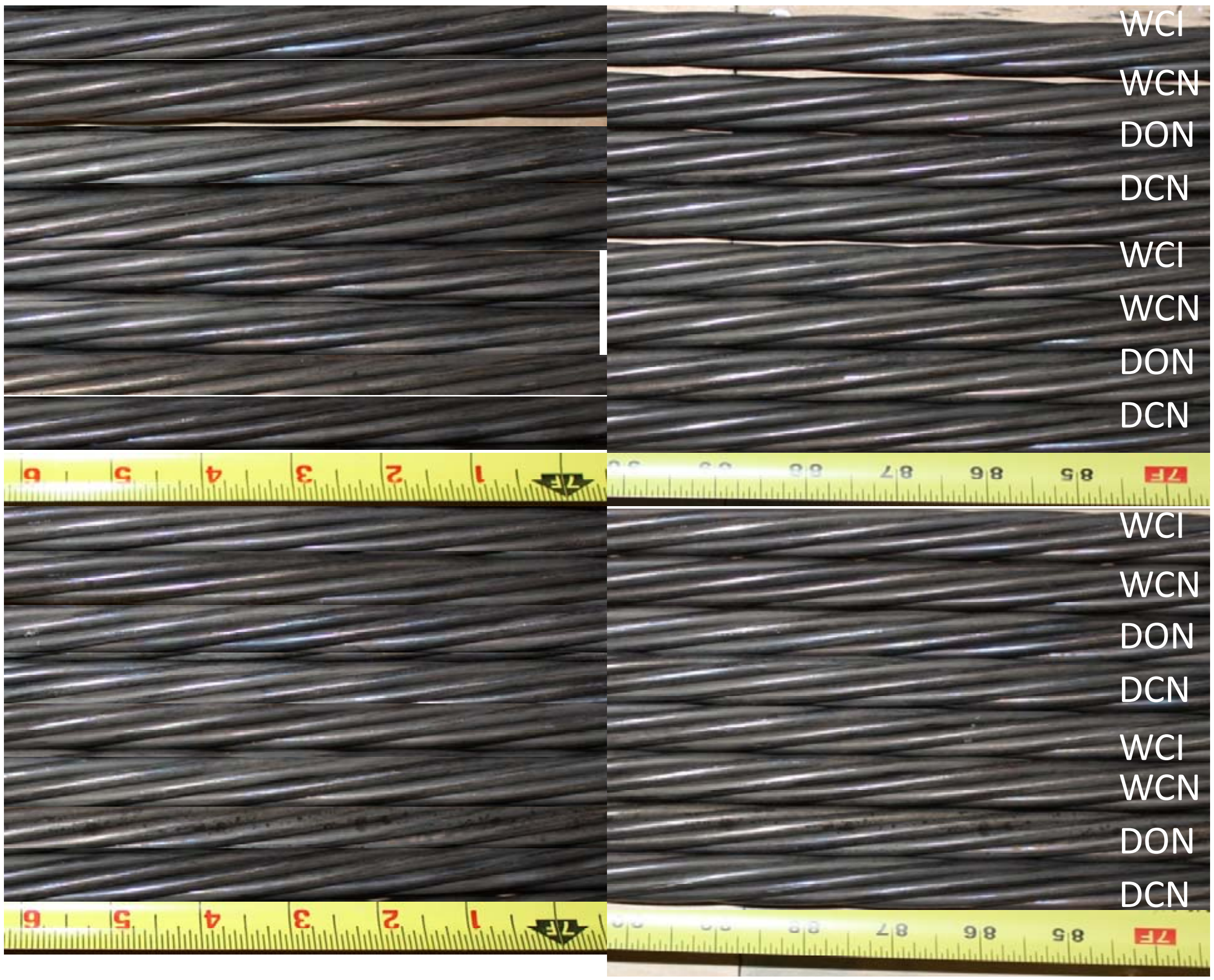


Figure A3.6 - Seashore – 2 week exposure.

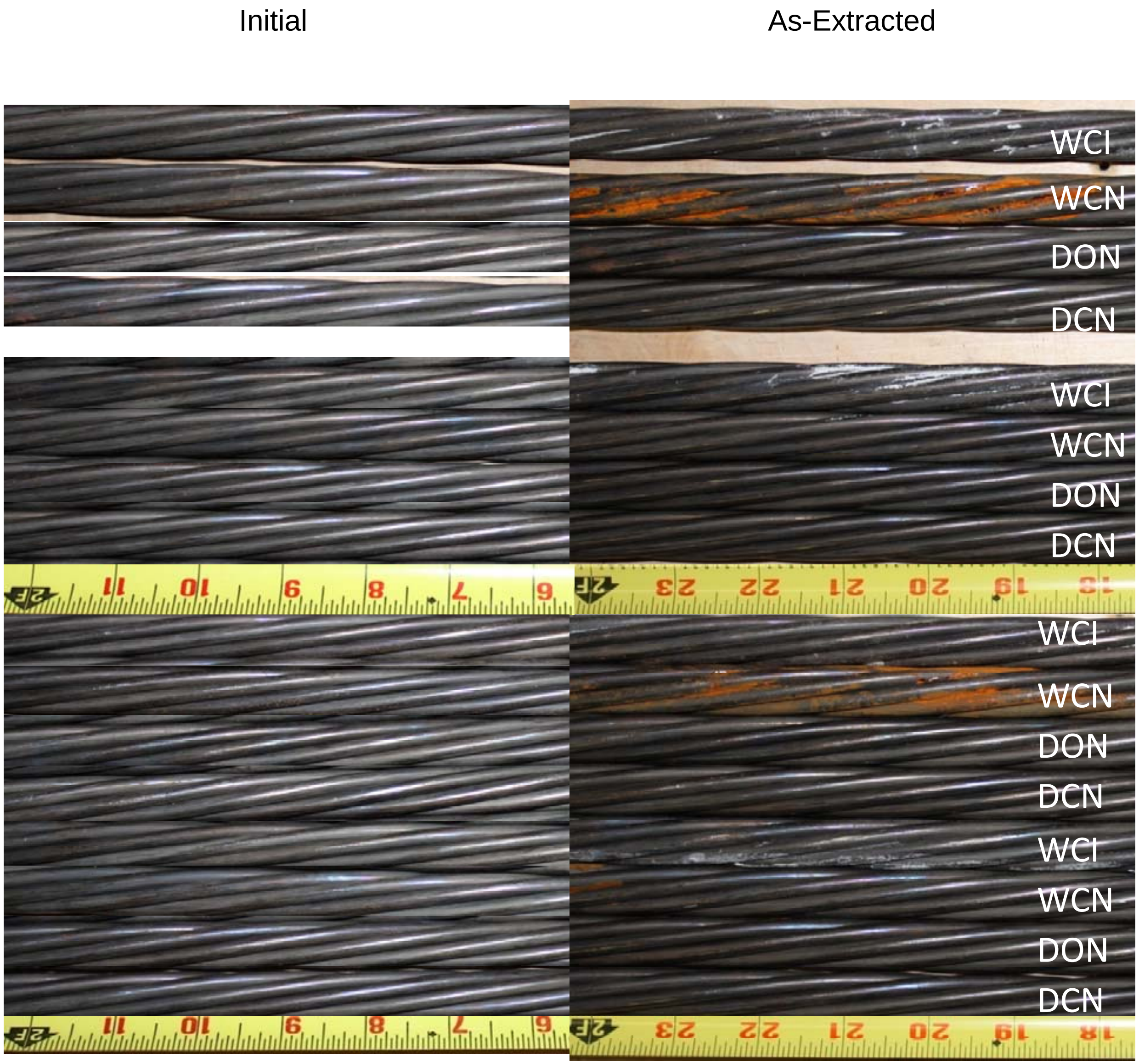


Figure A3.7 - Seashore – 4 week exposure.

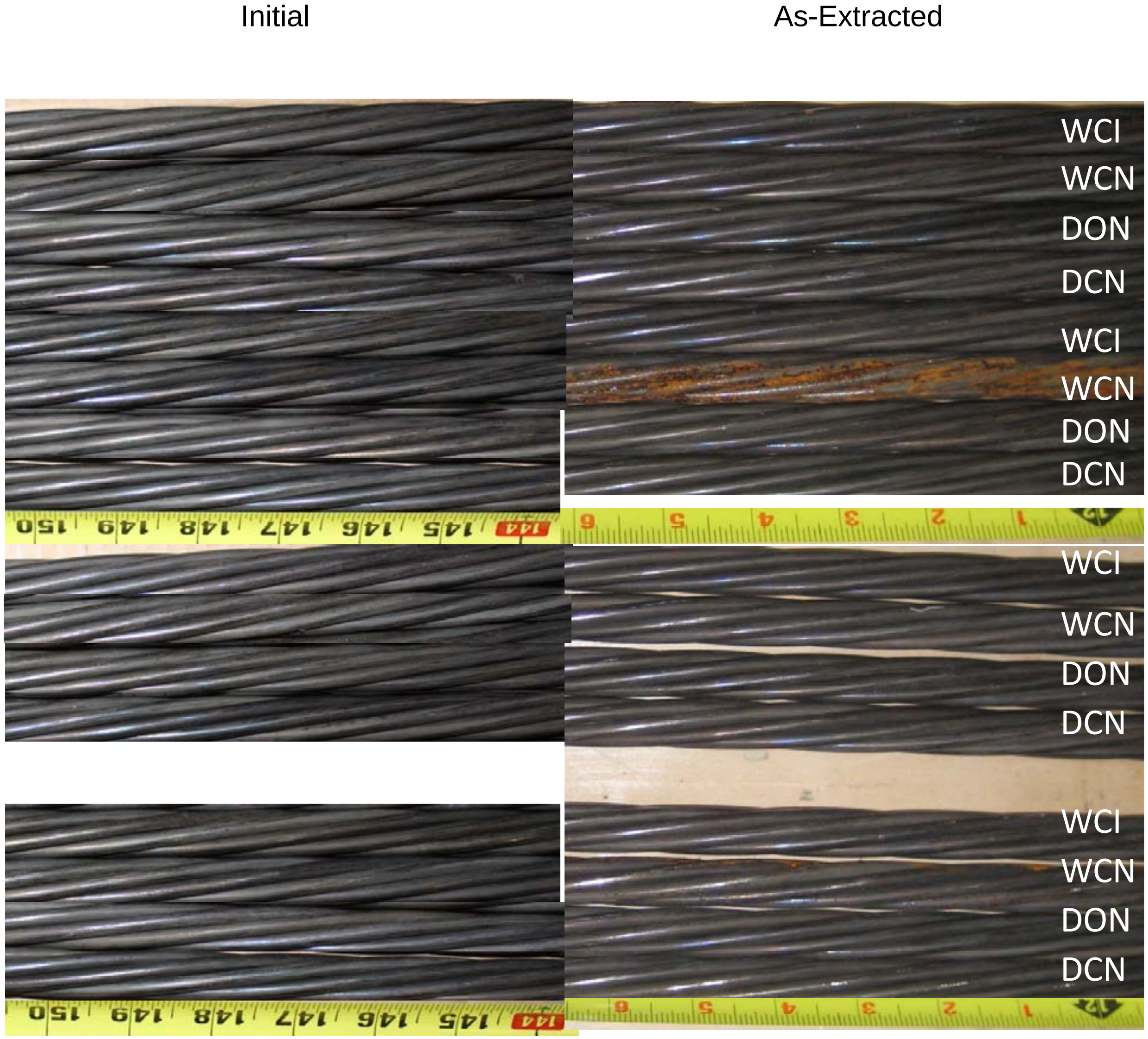


Figure A3.8 - Seashore – 8 week exposure.

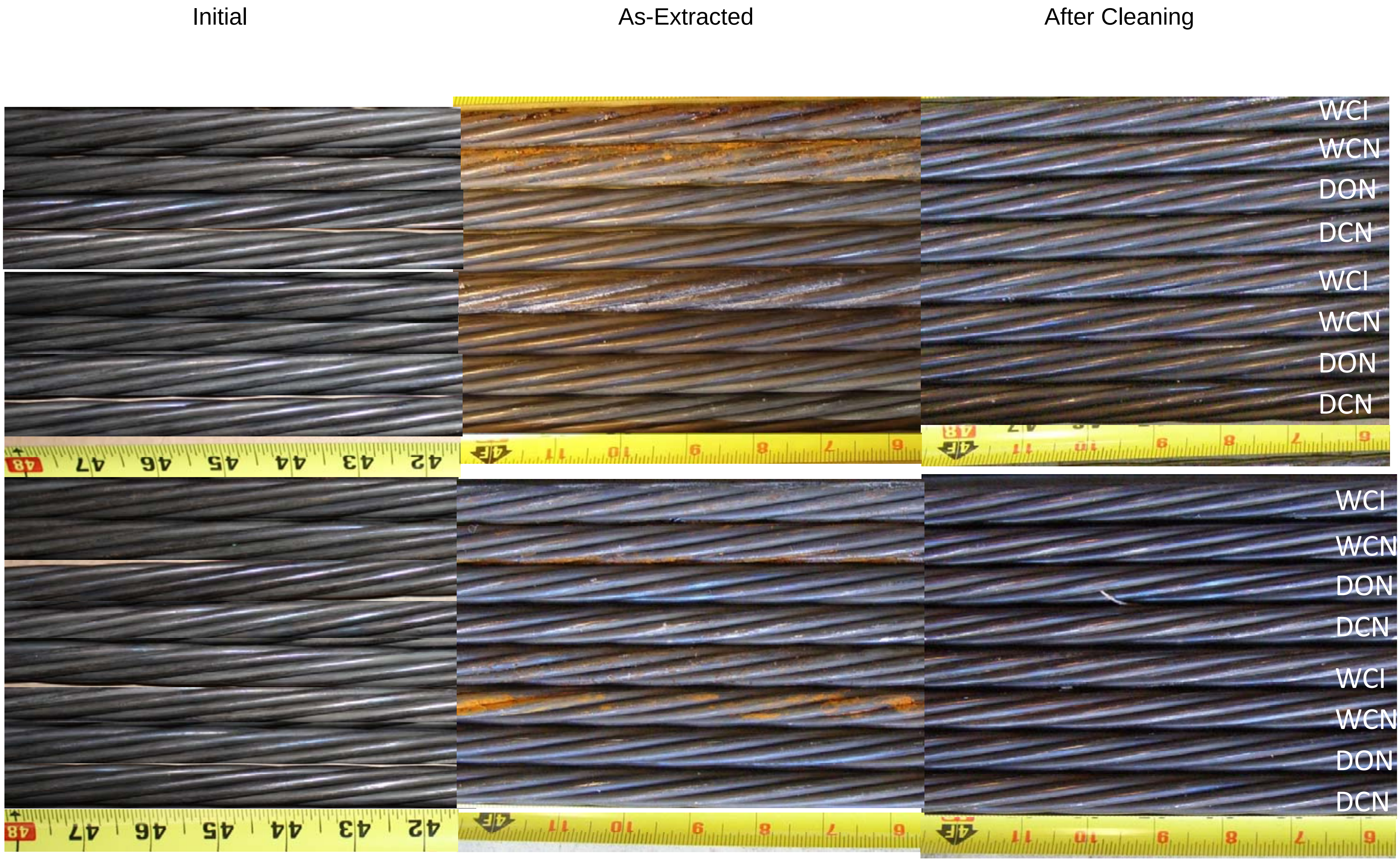


Figure A3.9 - Most severe pitting observed (Seashore facility) – Set 1

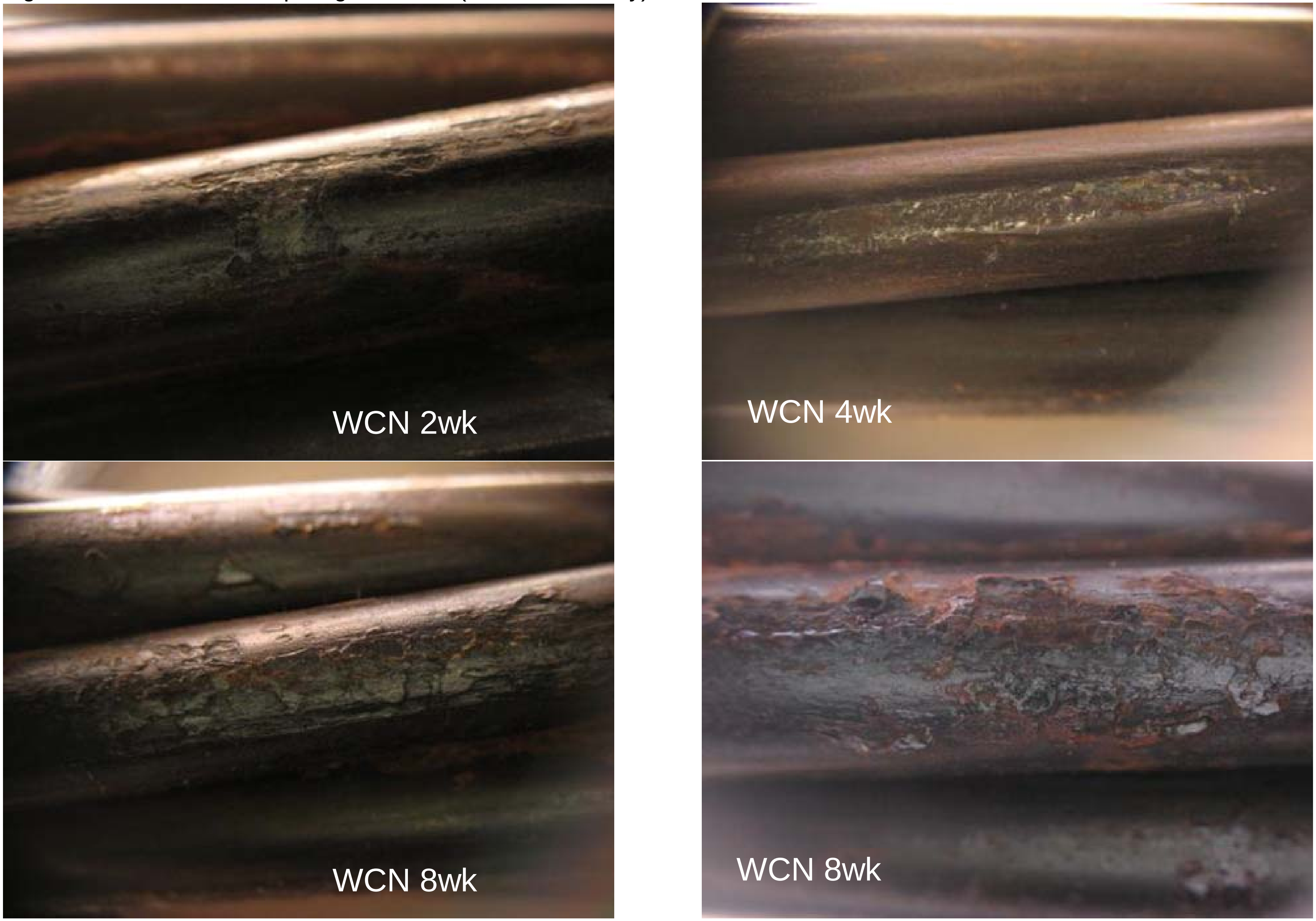


Figure A3.10 - Most severe pitting observed (Seashore facility) – Set 2