Report Prepared by:

Joseph Fernandez
Michael Hutchison
Alberto A. Sagüés
Gray Mullins

FINAL REPORT

CORROSION CHARACTERISTICS OF UNPROTECTED POST-TENSIONING STRANDS UNDER STRESS

Contract No. BDK84-977-22
Final Report to Florida Department of Transportation

A. A. Sagüés
Principal Investigator
Department of Civil and Environmental Engineering

G. Mullins
Principal Investigator
Department of Civil and Environmental Engineering

UNIVERSITY OF SOUTH FLORIDA
COLLEGE OF ENGINEERING

Tampa, FL 33620
May 2014

DISCLAIMER

UNIVERSAL CONVERSION TABLE

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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **CORROSION CHARACTERISTICS OF UNPROTECTED POST-TENSIONING STRANDS UNDER STRESS**		5. Report Date May 2014 6. Performing Organization Code
7. Author(s) J. Fernandez, M. Hutchison, A. Sagüés and G. Mullins		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of South Florida (USF) Tampa, FL 33620		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDK84-977-22
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee St. MS 30 Tallahassee, Florida 32399 (850)414-4615		13. Type of Report and Period Covered Final Report 05/12/2011 - 5/12/2014 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract: An investigation was conducted to determine the effect of stress condition and environmental exposure on corrosion of post-tensioned strands during ungrouted periods. Exposures for periods of up to 4 weeks of stressed, as-received strand placed in tendon ducts embedded in concrete and sealed with caps to represent normal practice and without any trapped water did not result in any appreciable deterioration as evaluated by visual appearance, standardized mechanical tensile testing, limited reverse bend testing, and exploratory hydrogen pickup measurements. These results were observed at both an inland and a seashore test site. There was, however, notable surface rusting and indications of hydrogen pickup by the strand if water was trapped in the ducts or if the steel was exposed to moderate salt spray precipitation and especially so with both factors concurrently. Evaluation of significance of findings on current practice is presented.

17. Key Words Reinforced concrete piles, cracks, hydrogen embrittlement, corrosion, reinforcing steel, relative humidity		18. Distribution Statement No Restriction This report is available to the public through the NTIS, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 132	22. Price

ACKNOWLEDGEMENT

The authors are indebted for the assistance of numerous student participants in the University of South Florida, College of Engineering Research Experience for Undergraduates program. Valuable guidance at all stages of the project from the project manager Mario Paredes of the Florida Department of Transportation (FDOT) State Materials Office is thankfully acknowledged.

EXECUTIVE SUMMARY

Post-Tensioning strands in tendons are protected from corrosion by the presence of grout which is injected in the tendon ducts. Grouting does not take place immediately after strand placement and tensioning, so there is a period of time when the steel surface is vulnerable to corrosion unless protective action is taken. Florida Department of Transportation (FDOT) guidelines establish protection during that period by requiring appropriate closure of the duct space so moisture and aggressive agents from the external environment are prevented from reaching the steel surface. There is limited information, however, on the extent of corrosion and associated damage that may occur in the event that closure is not completely implemented or if residual water becomes entrapped in the duct space. The guidelines also establish measures for corrosion protection of the strand during transit and storage before placement in the tendon ducts. However, some unplanned environmental exposure may occur in that period, as well, with results that are not well established at present. The corrosion during those periods may have immediate consequences in the form of strand failure under tension before grouting. However, adverse effects may not become notable until much later due to delayed failure mechanisms.

The findings of previous exploratory tests (FDOT research project BDK84 977-04) showed encouraging resistance of the system to moderate amounts of corrosion during the unprotected period. However, only the unstressed condition was examined so the possible aggravation of corrosion by the presence of stress was not investigated. In particular, environmentally assisted cracking (EAC, including stress corrosion cracking, SCC, and possibly hydrogen embrittlement, HE) might develop in the tensioned strand condition but remain undetected in unstressed strand tests. Accordingly, the present investigation was conducted with the objective to determine the effect of stress condition and environmental exposure on corrosion of post-tensioned strands during ungrouted periods and to evaluate the findings as to relevance to the guidelines for corrosion control during the strand ungrouted period used by FDOT.

A field investigation was conducted, with tests in near-full-scale ducts within prestressed concrete piles containing ungrouted strand with various levels of moisture exposure, salt exposure, and with and without desiccant conducted over periods of 1- to 4-weeks. The ducts contained both stressed and unstressed strands. The piles were placed at two locations, one inland and the other at a marine shore in the north access of the Sunshine Skyway Bridge. After exposure, the strands were examined for surface rusting and hydrogen pickup and evaluated mechanically with standardized tensile tests and limited reverse bending tests.

The project findings include the following:

Exposures for periods of up to 4-weeks of stressed, as-received strand placed in the tendon ducts embedded in concrete and sealed with caps to represent normal practice and without any trapped water (closed, non-wetted condition), did not result in any appreciable deterioration as evaluated by visual appearance, standardized mechanical tensile testing, limited reverse bend testing, and exploratory hydrogen pickup measurements. These results were observed at both the inland and the seashore test sites.

Performance was similar to that indicated above, at both test sites, if conditions were the same, but the anchorage end caps were not put in place, and the anchorage area was protected from rain (open, non-wetted condition). This finding, however, must not be interpreted as an indication that capping the ends is not important, as data from a construction site indicated an instance of increased humidity during a rain event in an open duct.

For the capped condition indicated above but including a modest amount of trapped water in the capped tendon (closed, wetted condition), appreciable amounts of rust on the strand surface were observed for both test sites, starting with as little as one week of exposure. Tensile test performance was not significantly affected, but the limited reverse bending and hydrogen content test results suggested the possibility of some adverse consequences.

Application of salt deposition on the strand, simulating in the order of one-day near-seashore exposure prior to placement in the ducts, resulted in surface rust development in the closed, non-wetted condition after periods as short as one week at both test sites. The surface rusting of pre-salting was strongly enhanced when the duct was in the closed, wetted condition, especially for the 2- and 4-week exposure regimes. However, mechanical performance per the standardized tensile tests was not appreciably degraded. The exploratory hydrogen content tests, especially for the longest test exposure and the closed, wetted condition, indicated the highest hydrogen buildup for this condition. Limited reverse bending test evidence suggests the possibility of some degradation, as well, subject to more detailed examination in future work.

Limited laboratory tests confirmed the sensitivity of strand steel to hydrogen embrittlement at hydrogen levels that were larger than, but still of the order of, those measured in some of the strands exposed to the more severe testing regimes.

Placement of desiccant packets in ducts in the closed, non-wetted condition arrested much of the surface rust development when strand subject to prior salt deposition was placed in the duct, even for periods as long as 4-weeks, suggesting a possible means of controlling corrosion.

Throughout the tests there was no clear difference between the behavior observed for the stressed strands and the unstressed strands exposed in the same ducts.

While duly noting all the above conclusions, the absence of any spontaneous stressed strand failures in the test piles even after 4-weeks of sustained stress and with multiple specimens of sizeable length in the more aggressive exposure combinations, and the absence of any consistent indication of loss of strength or ductility in the tensile tests, suggest that propensity for brittle behavior was quite limited under the conditions examined.

Concerning construction practice, the results suggest that ungrouted exposures of up to two weeks as are being conducted at present have little detrimental effect, but only under conditions of strict water intrusion control and of avoidance of any salt deposition on the steel during the placement process.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Project Scope

Post-Tensioning (PT) strands in tendons are protected from corrosion by the presence of grout which is injected in the tendon ducts. Grouting does not take place immediately after strand placement and tensioning, so there is a period of time when the steel surface is vulnerable to corrosion unless protective action is taken. FDOT guidelines establish protection during that period by requiring appropriate closure of the duct space so moisture and aggressive agents from the external environment are prevented from reaching the steel surface. There is limited information, however, on the extent of corrosion and associated damage that may occur in the event that closure is not completely implemented or if residual water becomes entrapped in the duct space. The guidelines also establish measures for corrosion protection of the strand during transit and storage before placement in the tendon ducts. However, some unplanned environmental exposure may occur in that period, as well, with results that are not well established at present. The corrosion during those periods may have immediate consequences in the form of strand failure under tension before grouting. However, adverse effects may not become notable until much later due to delayed failure mechanisms (Perrin et al, 2010).

A recently completed FDOT-sponsored investigation BDK84 977-04, (Sagüés et al, 2011) addressed part of those issues by investigating how much corrosion took place during ungrouted periods of various durations. The field work in that study was exploratory, addressing only the corrosion of strands placed in the unstressed condition but otherwise simulating scenarios of interest. Tests were conducted in an inland facility (generally mild exposure) and a more severe seashore facility. Strand was exposed in ducts sealed following normal specified procedures and also in ducts not fully sealed from the outside environment, as well as ducts with intentionally trapped water with and without a corrosion inhibitor as a mitigating measure. The tests 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 adverse mechanical consequences revealed by subsequent tensile tests. There was no discernible effect from having one end of the duct continuously open to the external environment even in a seashore facility. The field test results and experience from extended exposure of ungrouted strand in California (Reis, 2007) indicated that the strand has significant tolerance, from a mechanical performance standpoint, to the presence of in-duct corrosion that may be otherwise visually striking.

The findings of those exploratory tests showed encouraging resistance to moderate amounts of corrosion during the unprotected period. However, only the unstressed condition was examined so the possible aggravation of corrosion by the presence of stress was not investigated. In particular, environmentally assisted cracking (EAC, including stress corrosion cracking (SCC) and possibly hydrogen embrittlement (HE)) might develop in the tensioned strand condition but remain undetected in unstressed strand tests (Perrin et al, 2010), (Mietz, 2002), (Isecke, 2003). SCC takes place when a particular combination exists of a corrosive environment and a susceptible material exposed to high levels of stress. Thin cracks, often multiple and branched, develop and grow causing brittle failure of the affected component. HE occurs when atomic hydrogen, resulting often from a cathodic reaction associated with a concurrent corrosion process (also known to occur under cathodic protection conditions (Hartt, 2008)), enters the metal in sufficient amounts. The hydrogen then diffuses preferentially to high stress locations and promotes brittle fracture starting there (Mietz, 2002). Both processes required high stress levels, so the damage is usually observed only in materials with yield strength high enough to support the required high stress levels (Shipilov, 2007). The high strength of posttensioned strand falls within that range. The likelihood of these phenomena increases greatly if pitting corrosion is present on the steel, because the pits act as stress concentration sites thus facilitating the initiation of cracks.

The possibility of EAC was considered in connection with 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). 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 than 94% of specified strength) in the rest.

A special case at the SFOBB 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 hard-point (irregular kink in the duct embedded in concrete) and mid-frame jacking operations. Some limited indications of EAC were seen in metallographic examination of the failed strands of the tendon at the hard-point location, as well as in some other strands. However, EAC did not appear to have played a key role in the performance of ungrouted strands in that investigation. Analysis of hydrogen content of wires from some of those strands did not show very different levels between exposed and control strands so concern for HE was alleviated. Furthermore, the extremely long ungrouted strand exposure period in that experience represented conditions that are likely to be much more severe than those encountered under normal FDOT practice. The assessment concluded based on the available evidence that, for this particular bridge and exposure conditions, extended unprotected exposure appeared to have had little impact on strand integrity other than for the special case indicated above. It was cautioned, 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 constructions projects. Caution regarding these issues has been pointed out by other collaborators in the SFOBB investigation (Lee, 2007).

The above discussion suggests that the potential for EAC and similar deterioration would be low for short ungrouted periods with properly followed current FDOT procedures. However, deviations from procedures and inadvertent environmental exposure could result in strand surface contamination and corrosion, with potentially severe consequences such as failure during the ungrouted period or delayed to a time later in service. Clearly, it was highly desirable to conduct confirmatory testing with stressed strands to supplement the exploratory work that was conducted with unstressed strands under Project BDK84 977-04. It is noted also that the experiments under that project had been conducted during late-summer, autumn months where conditions might not have been as conductive to corrosion development as they would be during the warmer and more humid summer season. Given that the unstressed strand test facilities were still available, it was desirable, as well, to continue the initial exploratory work with tests conducted during the summer months to support the validity of the previous results. The present project addressed both extending the previous work to confirm its findings for a more severe environmental regime, and to include stressed strand conditions.

1.2 Project Objectives and Research Tasks

Based on the needs indicated in the previous section, the present investigation was conducted with the following main objectives:

- Establish whether the finding from the previous investigations applied also to exposure of ungrouted unstressed strands during more aggressive summer season.
- Determine effect of stress condition and environmental exposure on corrosion of post-tensioned strands during ungrouted periods.
- Evaluate the findings as to relevance to the guidelines for corrosion control during the strand ungrouted period used by FDOT.

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 an ongoing post-tensioning construction site (Selmon Expressway), to assess actual on-site conditions. 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, the initial portion of the work consisted of using the unstressed strand exposure facilities at both the inland and seashore locations prepared for project BDK84-977-04, conducting similar tests during the warm season. The next portion of the work, involving the bulk of the effort, consisted of tests in near-full-scale prestressed concrete piles; the piles had ducts within containing ungrouted strand with various levels of moisture exposure, salt exposure and with and without desiccant were conducted over periods of 1- to 4-weeks. The piles were placed at two locations, one inland and the other at a marine shore, adjacent to the facilities used in the previous project. The after-exposure condition of the strand was determined and correlated with the test variables.

The outcome of the those tasks was analyzed to set the basis for consideration by the Department in adapting as needed its specifications and guidelines for length of the ungrouted period, and possible additional measures for corrosion control.

2 FDOT SPECIFICATIONS AND PRACTICE REVIEW

Agency specifications and literature sources have been reviewed previously in FDOT Report BDK84 977-04. A review of the current versions of FDOT specifications and practices occurred to ensure assumptions and procedures utilized in this report are valid per current practices.

Subsection 2 of the current FDOT Specification 462-7 “Tendons” (FDOT, 2013) limits the time between the first installation of prestressing steel in the duct and grouting after stressing of the strands to a maximum of fourteen calendar days (this is an increase from the previous report use of 7 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 462-8.2.1 “Duct Pressure Field Test” (FDOT, 2013) 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 1.5 psi, the air supply is turned off and pressure drop noted after one minute. Ducts may lose only 0.15 psi after one minute or 10% of the initial pressure (the addition of 10% of the initial pressure allowed for pressurization to higher pressure (~15 psi) to better find leaks, while following FDOT guidelines). 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: 462-7.4.1: Tendon duct systems (but not necessarily individual tendons) must be proof-tested for air tightness of design.
2. Specified: 462-6.5: Duct ends must be sealed from the moment of installation until strand placement.
3. Specified: 462-7.2.4: In "aggressive environment" locations, flush duct with lime treated water, and blow air to remove excess water from duct (only air was blow through the ducts, as adding lime treated water might pool in rigid area of the ducts).

Strand

4. Specified: 462-6.3: General shipping handling and storage requirements. Usual practice (but not explicitly specified): Strand comes coated with factory corrosion inhibitor (desiccant packs) in double wrapped ~>2,000 foot 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 (5b was method used).

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 14-day allowable period for ungrouted conditions per 462-7 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: 462-7.3.3.1: Strand ends to be cut out and grout caps put in place within four hours after stressing. Not specified: pressure testing immediately after grout cap placement.

3 INVESTIGATION METHODOLOGIES

3.1 Extension of Project BDK84-977-04 Experiments to Warm Season Conditions

For better organization of presentation and given the mainly confirmatory nature of this task, the details of these tests including methodology, findings and interpretation are presented separately in Appendix C of this report. The rest of this chapter addresses exclusively the main set of experiments conducted in the present project with piles to expose stressed strand.

3.2 General Experimental Approach for Stressed Strands

The test facilities were designed and constructed for exposure in an inland and a seashore facility, near the University of South Florida (USF) and Sunshine Skyway (SSK) locations respectively used in BDK84 977-04.

Each facility consisted of six reinforced concrete piles, each containing one tendon (e.g., 20 foot long) with anchors at each end. Each tendon was several (e.g., 2) 7-wire strands in the stressed condition. In addition, one unstressed strand was placed alongside the others in the same duct to provide a stress free control.

Exposure periods were 1-, 2-, and 4-weeks long. At the end of each exposure the tendons were de-tensioned and all strands in the tendon extracted for testing. The exposures were duplicated simultaneously (at the USF location) or consecutively (at the SSK location), to assess variability and reproducibility of results. In-duct relative humidity and temperature was monitored by in-place data loggers and methodology as those used in Project BDK84 977-04.

The tendons were tested in three basic conditions:

C: Normal procedure per FDOT guidelines. The strands placed in the tendon, stressed immediately, lead lengths cut out, and wedge plate caps installed to seal the interior environment. All grout vents and other openings in the closed position. Standing water and any other avoidable internal contamination was absent.

O: Normal procedure but with simulated closure deficiency and other corrosion aggravating features. Both of the wedge plate caps were removed (with a mesh in place to prevent insect intrusion) to allow for external environment interaction.

W: Normal procedure but with a control amount (e.g., 100 ml) of internal standing water to simulate a worst case moist duct event.

In addition, the following variations were implemented in selected cases:

-Salt: This suffix was added for strands exposed to a salt spray and allowed to dry overnight. This simulates the strand being exposed to the salt spray of the nearby ocean overnight

/Des: This suffix was added for ducts containing desiccant packs, which was used to help mitigate the corrosion.

-Salt/D: This suffix was added for strands exposed to a salt spray while in ducts containing desiccant packs, to determine if the mitigating effects of the desiccant would be effective on salt exposed strands.

Table 1 shows the schedule and conditions for both the USF and SSK locations. For example at the SSK location, condition C (normal procedure, closed duct), Pile 3 serves consecutively for the 1-, 2- and 4-weeks exposures, with one fresh set of strands introduced each time, testing completed at the end of operations week 7. Pile 9 is used for the salted exposure with similar conditions to Pile 7, running concurrent with the Pile 3 exposures. Similar schedule applies to conditions O and W.

Test replication is important to obtain a useful indication of variability of results and consequent appropriate interpretation of results. Therefore, in the case of the USF location, three piles tested three different conditions while the other three piles duplicated those conditions. At the SSK location, all six piles tested different conditions, with the duplication provided by the early and late summer operations.

Table 1 – Exposure/Extraction Schedule with a 6-pile Facility at each Location

Strand Tension Dates (all dates during 2013)

Extraction Dates are 7, 14, and 28 days following their respective tensioning dates.

	Beam	Condition	Duration (weeks)	Start Dates: Early Summer				Late Summer			
USF	7	C	1	19-Jun					9-Sep		
			2		3-Jul		C/Des	23-Aug			
			4			24-Jul				27-Sep	
	0	O	1	19-Jun					9-Sep		
			2		3-Jul		C-Salt	23-Aug			
			4			24-Jul				27-Sep	
	5	W	1	19-Jun					9-Sep		
			2		3-Jul		C-Salt/D	23-Aug			
			4			24-Jul				27-Sep	
	2	C	1	19-Jun					9-Sep		
			2		3-Jul		C/Des	23-Aug			
			4			24-Jul				27-Sep	
	10	O	1	19-Jun					9-Sep		
			2		3-Jul		C-Salt	23-Aug			
			4			24-Jul				27-Sep	
	6	W	1	19-Jun					9-Sep		
			2		3-Jul		C-Salt/D	23-Aug			
			4			24-Jul				27-Sep	
SSK	3	C	1	20-Jun							7-Nov
			2		2-Jul		C	22-Aug			
			4			23-Jul			26-Sep		
	4	O	1	20-Jun							7-Nov
			2		2-Jul		O	22-Aug			
			4			23-Jul			26-Sep		
	1	W	1	20-Jun							7-Nov
			2		2-Jul		W	22-Aug			
			4			23-Jul			26-Sep		
	9	C- Salt	1	20-Jun							7-Nov
			2		2-Jul		C- Salt	22-Aug			
			4			23-Jul			26-Sep		
	8	O- Salt	1	20-Jun							7-Nov
			2		2-Jul		O- Salt	22-Aug			
			4			23-Jul			26-Sep		
	11	W- Salt	1	20-Jun							7-Nov
			2		2-Jul		W- Salt	22-Aug			
			4			23-Jul			26-Sep		

3.3 Stressed Pile Design for Stressing Strands

The concept drawing of the de-tensioning pile system is shown in Figure 1. The system allows testing, removal, and evaluation of post-tension strands after each exposure period. The de-tensioning pile system provides a means of de-tensioning the strands by loosening four hex nuts.

The casting of the piles was performed at Henderson Prestress in Tarpon Springs, FL (Figures 2 through 6). Henderson Prestress provided access to a 14-inch casting bed to the University of South Florida as well as materials and labor for pile construction. After one week, the piles were removed from the casts and transported to both the inland location (USF) and the marine location (SSK). Piles were arranged in an alternating pattern to allow better access to the de-tensioning mechanism. Piles were place on two dunnage piles provided by Henderson Prestress to allow the small portion of the pile to move per the design, and the piles were made level using concrete blocks.

Once the piles were in place, a series of maintenance and cleanup steps were done (Figures 7 and 8). First, the extra prestressing strand material for the strengthening of the piles was removed. Then, the steel plates used to hold the anchor assemblies were removed from the ends where possible. The ducts were cleared out by blowing air through them to remove any water or dirt that may have entered into the ducts. The open points on the ducts were closed with plastic caps and sealed with weatherproof silicon. Rust inhibitor was applied to the exposed metal. Weatherproof silicon was applied to any joints of metal to concrete to prevent crevice corrosion. The layout of the piles at USF location is shown in Figures 9 and 10. The layout of the piles at SSK location is shown in Figures 11 and 12.

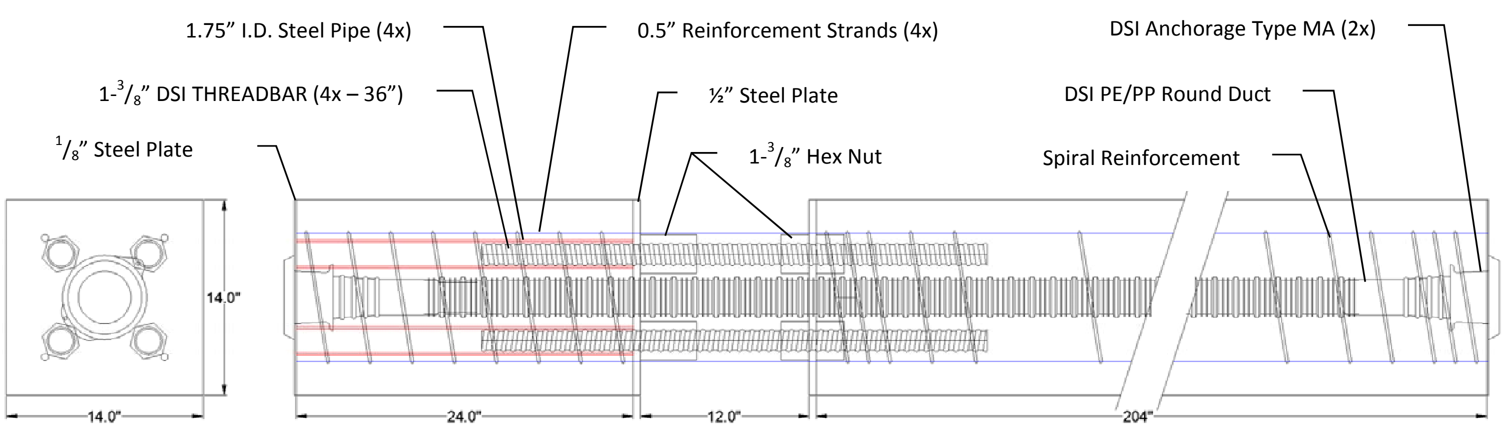


Figure 1 De-Tensioning Pile System Design. PVC and Flexible Connection Removed for Clarity

Figure 2 Setup for Casting of De-Tensioning Piles

Figure 3 Prestressing Strand for Casting of De-Tensioning Piles

Figure 4 Spiral Wire for Casting of De-Tensioning Piles

Figure 5 Concrete Pouring for Casting of De-Tensioning Piles

Figure 6 Smoothing of Poured Concrete De-Tensioning Piles

Figure 7 Cutting of Excess Strand Material

Figure 8 Cutting of Excess Strand Material

Figure 9 De-Tensioning Pile System at Inland Location (USF)

Figure 10 De-Tensioning Pile System at Inland Location (USF)

Figure 11 De-tensioning Pile System at Marine Location (SSK)

Figure 12 De-tensioning Pile System at Marine Location (SSK)

The material used was ASTM A416 7-wire steel strand. The diameter of the strand is nominally ~0.5 inches and has estimated yield strength of 270,000 psi. Steel strand was delivered on 07/18/12 rolled as shown Figure 13.

Figure 13 ASTM A416 270 Kilo-Pounds per Square Inch (ksi) Yield Strength Prestressing Steel Strand

The temporary PVC slip-cap connections were replaced with a flexible bellows connection as shown in Figure 14. Furthermore, the slip-cap connection for the RH access port was deemed inadequate for proper sealing of the ducts, and was replaced with a threaded cap, shown below in Figure 15.

Figure 14 Installed “Bellows” Connection for Pile Segment Break

Figure 15 Threaded Caps for Relative Humidity Probes Access Port

End-caps from the PT anchor body manufacturer were not compliant with FDOT specifications in terms of corrosion resistance. A custom end-cap design was proposed to provide both adequate seal and corrosion protection in lieu of employing the manufacturer's cap. The design includes a standard 4-in PVC slip cap held by a retaining bar and ring which are secured by threaded rods to the anchor body. All metallic elements of the end-cap are stainless steel. A rubber O-ring seal is machined between the PVC cap and the cast-iron wedge plate. The End Cap assembly is shown in Figure 16.

Figure 16 Custom End Cap installed on East End of Duct 6 at USF Facility

To protect the end caps and pile break steel bars/nuts from undue environmental exposure, wooden cowls fitting over the pile ends were designed, produced, and installed. Figure 17 illustrates the cowls both installed and partially removed.

Figure 17 Wooden End Cowls at USF Facility

The relative humidity (RH) probe access port was cut to a shorter height (Figures 18 & 19) to reduce the possible reflux in the ducts from the convection of air on the surface of the access port PVC tube.

Figure 18 RH Probe Access Port Tube before Height Reduction

Figure 19 RH Probe Access Port Tube after Height Reduction

In an effort to further reduce the local environment disparity between the internal duct embedded within the concrete and the portion of duct at the RH probe access port, concrete cinder blocks (Figures 20 and 21) were used to cover the access port thus relieving them from direct exposure to the external environment. At this point, no further alterations were done to the piles, and stressing of the strand commenced.

Figure 20 RH Access Port Cinder Block Covers, without Lid

Figure 21 RH Access Port Cinder Block Covers, with Lid

3.3.1 Load Cell Testing for Strands Stressing Procedure

Evaluation of the jack pressure required for appropriate strand stressing and determination of stressing procedure was performed on 07/25/12. A strand sample was paid out from the delivered spool and stressed to various levels. The load cell and jack used, as well as the testing setup are illustrated below in Figures 22, 23 & 24.

Figure 22 Load Cell Setup for Stressing Operation Test

Figure 23 Hydraulic Jack Setup for Stressing Operation Test

Figure 24 On-Site Testing Evaluation Setup for Stressing Operation Test

Colored electrical tape (yellow – see Figure 22) was used to measure slippage of the strand. The load cell was placed at the dead end and used to measure the force applied to the strand so as to calibrate the hydraulic system. The calibration consisted of measuring the force on the strand as function of the hydraulic system pressure. The force on the strand was divided by the nominal cross-sectional area of the strand (0.144 inches^2) to obtain the stress on the strand, and plotted as function of the pressure from the hydraulic system. The plot was found to be highly linear as expected. The ratio of the stress on the strand to pressure in the hydraulic pump was found to be 0.0304 ksi/psi. Elongation measurements were in general agreement with the stress levels thus estimated. The jack was fitted with a custom collar to ensure adequate wedge set. Applying pressure to obtain a strand stress of 229.2 ksi and removing jack pressure resulted in a final stress of 220.8 ksi or 0.82 f_{pu}. It was decided to use for the regular stressing procedures an initial pressurization of 1,000 psi to remove any slack from the strand, and then increase the pressure to 8,000 psi (a nominal stress of 243.9 ksi, or 0.90 f_{pu}) so that upon removal of the pressure and subsequent wedge set a final stress level of about 0.87 f_{pu} would exist. While the code recommended jacking load should not exceed 0.94 f_{py} or 0.8 f_{pu}, (which should then result in a final stress of 0.7 f_{pu}), all specimens were jacked to a level high enough to overcome large wedge seating losses (due to short strands) and to leave the strand at a higher than normal stress during the exposure ($>0.8f_{pu}$ instead of $0.7f_{pu}$). This resulted in a more aggravated stress state that offered a greater opportunity of revealing any adverse effect of stress-corrosion interactions during the ungrouted period.

3.3.2 Pile/Duct Integrity Testing for Stressed Strands

In order to verify the validity of the seal offered by the end caps and flexible bellows connections, a vacuum test was performed on Duct 6 at the USF facility. A threaded cap with a small hole was placed over the RH access port, and a vacuum hose was attached to the cap at the hole, then vacuumed down to 15 inches Hg, and the vacuum level was subsequently measured (see Figure 25) .The results of the test showed that the duct can hold vacuum pressure, indicating a sealed system with the bellows and custom end caps.

Figure 25 Vacuum Hose Attached to RH Access Port for Vacuum Pressure Testing

Procedure

Although initial vacuum tests on selected ducts showed them holding favorable vacuum levels, further investigation revealed that several other ducts showed significant pneumatic leakage. The testing procedure shifted from vacuum to pressure testing (applying 15 psig of pressure) in order to facilitate more rapid leak detection. Leak location was determined using a spray bottle of liquid soap and water. Soap bubbles formed at leak sites, which were then subsequently cleaned of solution and repaired.

Repair

Following each pressure test, identified leaks were repaired by removing old sealant material (if necessary) and resealing the leak location with exterior silicone caulking under duct pressure. As larger leaks were repaired in each previous test, smaller leaks became visible and were addressed in turn. Other leak repairs included: tightening flexible expansion connection bellows and securing end cap seals. These procedures were conducted multiple times as needed until the leak rate in all piles decreased to less than 10% pressure loss per minute. This leak rate threshold is comparable to that stated in FDOT Specification 462-8.2.1 which "allows leak rates less than 0.15 psi over a one-minute interval when the ducts are pressurized to 1.5 psi (or a loss of less than 10%)" (FDOT, 2013).

3.3.3 Atmospheric Salt Deposition and Relative Humidity (RH) Analysis

In lieu of an external strand exposure to the environment, the 'exposed to the environment' strands were subjected to a controlled laboratory salt spray delivery, thus eliminating the need to circumvent rainfall events in an external environmental exposure. The atmospheric chloride deposition rate was measured at both facilities using a wet candle method conforming to ASTM G140 specifications; the SSK facility wet candle setup is shown in Figure 26.

Figure 26 Wet Candle Setup for Determining Atmospheric Cl^- Deposition Rate at SSK Facility

Duplicate wet candles were exposed for 7 to 8 periods of ~30 days over about 1 year at both facilities. Following exposure, chloride content was determined via ASTM testing method D4458. Chloride content was determined and the atmospheric chloride deposition was estimated. The average, highest and lowest results measured are listed below in Table 3. As expected, exposure at the inland USF location was minimal. The values for the SSK facility were much larger in comparison, but not as severe as encountered at other Florida near-shore locations (Montgomery, 2012). The range of values found in the (Montgomery, 2012) document varied from 75 to 2550 mg Cl^- m^{-2} day^{-1} and another analysis from (Echevarria, 2012) showed a range from 100 to 400 mg Cl^- m^{-2} day^{-1}. However, both of the measurements from these sources were performed on the Atlantic side of Florida, which may differ from conditions in the Gulf of Mexico side. Also, (Echevarria, 2012) values for sites away from the ocean but near a water way, 100 to 200 mg Cl^- m^{-2} day^{-1} were closer to our measured values. Based on those results and to create a somewhat more conservative effect, the salt spray mixture and exposure for the laboratory spray was formulated to simulate a somewhat larger precipitation of 100 mg Cl^- m^{-2} day^{-1} (chosen as a lower end value which may be more realistic for the Gulf region). The mixture was prepared by mixing distilled water with synthetic seawater to achieve the target chloride level. Appendix B describes the protocol used.

Table 2 – Atmospheric Chloride Deposition Estimation for Both Testing Facilities via Wet Candle Method (mg Cl^{-} m^{-2} day^{-1}); Average and (Minimum - Maximum)

USF		
Month(s) of Testing	Average ppm of Cl	mgCl/m^2 day
2012 October	0.3	0.5
2013 January	0.2	0.3
2013 March	0.3	0.5
2013 April	0.6	1.0
2013 June	0.2	0.3
2013 July	0.2	0.3
2013 August & September	0.1	0.1
Average	0.3	0.4
Range	0.1 - 0.6	0.1 - 1.0
SSK		
Month(s) of Testing	Average ppm of Cl	mgCl/m^2 day
2012 September	13.8	23.0
2012 October	31.5	52.5
2013 January	24.6	41.0
2013 March	9.2	15.3
2013 April	25.3	42.2
2013 June	3.8	6.3
2013 July	8.2	13.7
2013 August & September	12.6	10.5
Average	16.1	25.6
Range	3.8 - 24.6	6.3 - 52.5

Based on the concern of high RH in the piles, arrangements to measure the RH in post-tension ducts inside a bridge deck system currently under construction were made. The Tampa, FL Selmon / I-4 connection uses post-tension box girder segments, and as there was a pause in the construction (typical of construction practices), we were able to put RH probes in various ducts of different box girder segments, both at the casting yard and at the construction site. Appendix A is a report summarizing the findings, which indicated that the internal environment in all of the test piles ducts was at a generally higher RH (~ 10 to 20 % higher) than those of an actual construction post-tension system in the area.

Initial tests with desiccant packs placed inside the caps at each end of the ducts have shown that effective moisture removal can take place. Desiccant packs were used to condition the ducts that were used to tests in the dry and closed condition. The second exposure set at the USF location evaluated the potential benefit of having desiccant packs inside the end caps if extended ungrouted periods are anticipated.

The relative humidity measured (using Omega OM-EL-USB-LCD RH and Temperature recording probes) in representative piles after drying with desiccant is shown in Figures 27-30. These results were comparable to the ones obtained at the Selmon Expressway site and therefore the closed and open duct conditions of the test piles are similar to actual construction conditions.

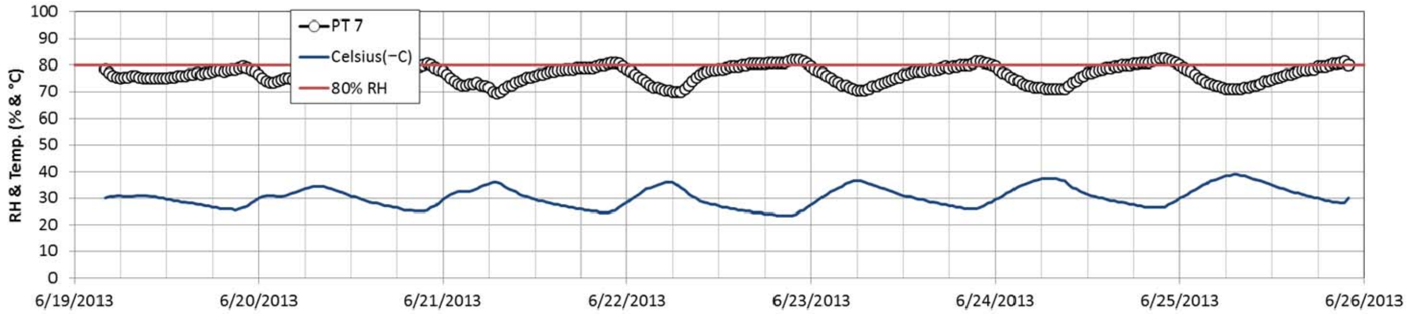


Figure 27 Closed USF Duct RH (Red Line is 80% RH)

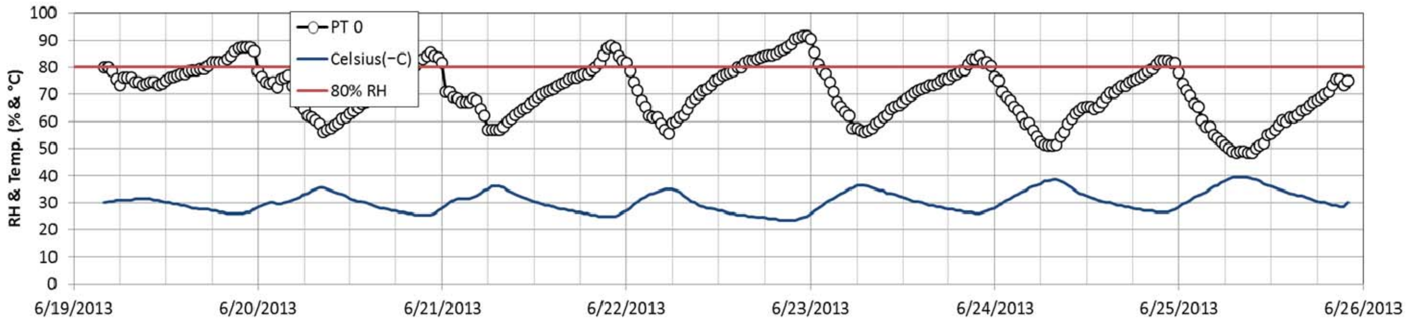


Figure 28 Open USF Duct RH (Red Line is 80% RH)

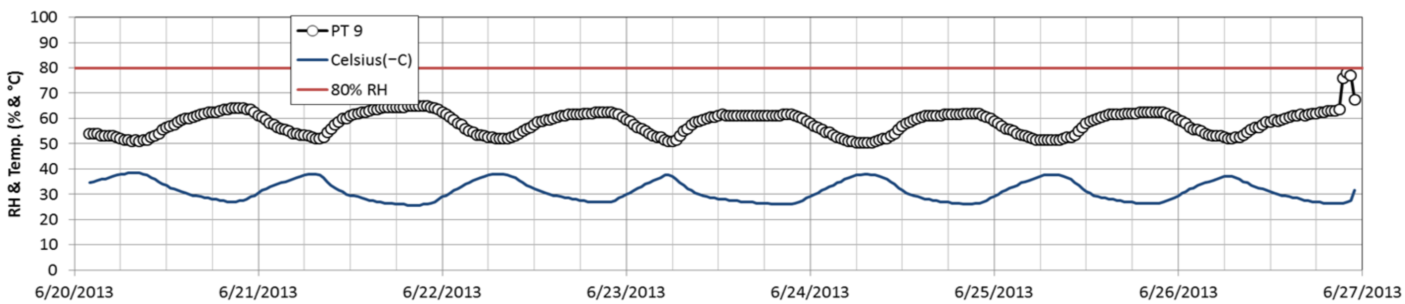


Figure 29 Closed SSK Duct RH (Red Line is 80% RH)

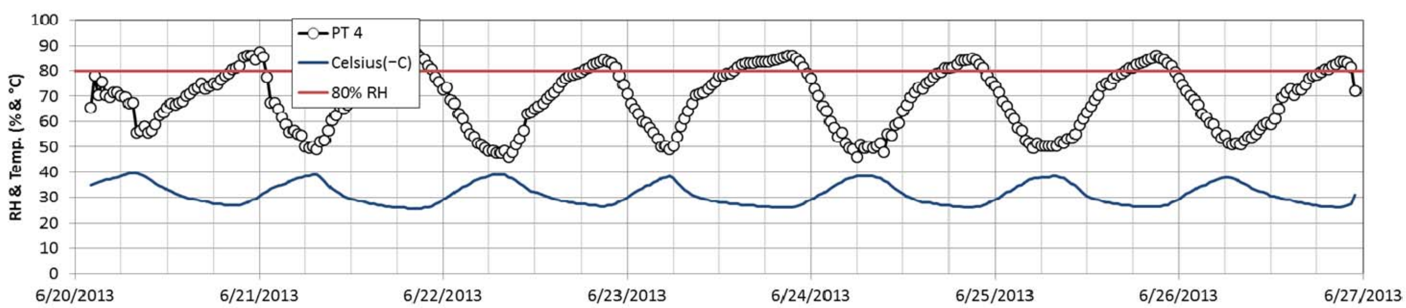


Figure 30 Open SSK Duct RH (Red Line is 80% RH)

3.4 Experimental Procedure

3.4.1 Stressing Strand Procedure

Specimens of strand were unwound from the spool and cut into 23 foot lengths. Once a specimen was cut from the spool, it was laid on the examining table, encoded with the appropriate paint labeling (as documented in Appendix B) and photographed on both sides. A measuring tape was placed alongside each strand, and detailed photos of each ~1 foot of strand were taken. Once preparation of a set of specimens for either the USF or Sunshine Skyway locations was completed, the specimens were bundled together (care was taken to separate salted from unsalted strands to prevent cross contamination), covered to prevent salt or dirt from depositing at the surface, and stored until placement and stressing commenced. After a set of specimens was placed / stressed, exposed to specific conditions and relaxed, the specimen was photographed again as before to document changes in the surface of the strand due to conditions exposure and stressing.

Selected sets of specimen strands were sprayed with salt solution per the protocol stated in Appendix B, one day prior to being stressed and they were bundled separately from unsalted strands and transported in a separate container. Only pre-salted strands were transported in the container used only for salted specimens, to ensure no cross-contamination to the strands that were non-pre-salted.

For placement in the piles the strands were removed from their storage container pushed through the ducts, crossing the two stressed strands by appropriate placement in the wedge plates at opposite ends. Thus, a crossover overlap contact was created somewhere near the center of the pile, that contact was introduced to increase the chances of crevice effects or adverse condensation of moisture in the area of contact. The wedge pieces were then placed on both ends of the strands to be stressed and tightened down by hand. The unstressed control strand was placed in the duct, through the wedge plate holes, but no wedge pieces were placed on them. The stressing of the strands was performed one strand at a time using the mono-strand jack as shown in Figure 31 for the two stressed strand in each pile. Stressing was performed by placing the jack at the end of the pile furthest away from the pile segment break and once stressed the excess strand length was cut away. Examples of the stressed and capped piles are shown in Figures 32 and 33 for the USF and SSK facilities, respectively. Detailed stressing procedures are given in Appendix B.

Figure 31 Mono-Strand Jack Used to Stress Strand

Figure 32 Stressing Strand at USF

Figure 33 Stressing Strand at SSK

3.4.2 Mechanical Testing

The strand tested in this project (7-wire strand A416 270 ksi) was specified to pass the tensile testing method detailed in ASTM A1061/A1061M in terms of yield strength, elongation, and breaking strength. The testing performed here was to determine to what extent strand in the post-exposure condition would satisfy that specification. Removing the de-stressed strands from the piles involved cutting them from the wedge plates, and relabeling them on site. The strands were then brought to the laboratory at USF, where they were then photographed and cut into segments for mechanical testing. A 50” segment was cut from the center of each strand specimen for tensile testing. To improve gripping silicon carbide powder was glued 8” from the ends of the 50” specimen using diluted Elmer’s™ glue as detailed in Figure 34. These specimens were then transported to the FDOT State Material Office for tensile testing using the pull testing machine and setup shown in Figure 35. Once the tensile test was complete (the specimen normally broke at the center point between the grips shown in Figure 35), the two separate specimen pieces (as represented in Figure 36) were secured together and transported back to USF for analysis and storage.

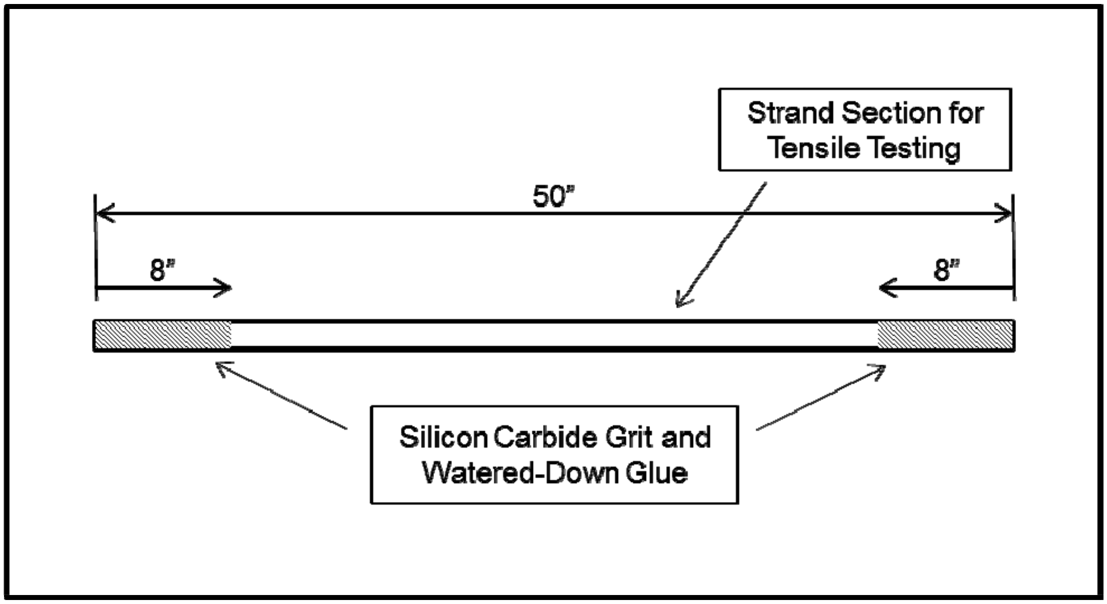


Figure 34 Section of Stand Used for Tensile Testing

Figure 35 Typical Strand Placements in Tensile Testing Machine at the FDOT SMO

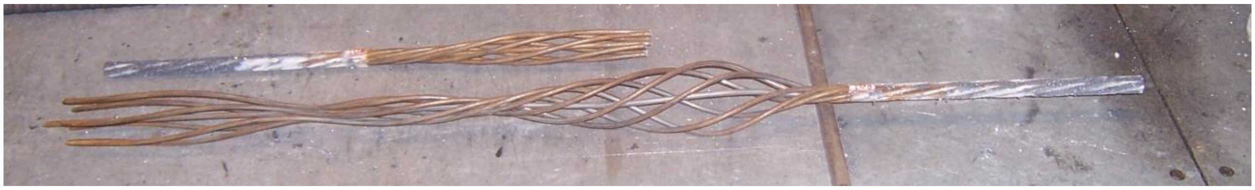


Figure 36 Typical Strand after Tensile Testing

3.4.3 Hydrogen Concentration Measurement

The procedure for the measurement of the hydrogen concentration consisted of outgassing in a vacuum system. Figure 37a and 37b shows a diagram and a photograph of the vacuum system setup respectively. Specimens for this test consisted of a set of four 2” pieces from the outer wires for each strand. Each piece was glass-bead blasted to ensure that there was no surface rust which during outgassing can produce water vapor and falsely increase the hydrogen concentration reading. Then the pieces were placed together in a 0.5 inch internal diameter quartz tube, sealed at the end closest to the specimens and with the other end connected to the vacuum system. The vacuum system was then sealed and pumped down to about 0.05 Torr with a mechanical vacuum pump. A valve was closed isolating the pump from the rest of the sealed vacuum system, which had a total volume of 824 cm^3. Measurements of the system pressure were taken using a McLeod gauge every minute to establish the value of the leaking rate. After five minutes, a tube furnace set at a temperature of 480 ^oC was slid over the quartz tube end containing the specimen; the rest of the system remaining at room temperature. Measurements of the system pressure were taken every minute for at least another 35 minutes. The pressure gauge data was corrected for parallax and point of view errors using electronic camera photos taken at each measurement. A photo pixel counting program was used to accurately conduct those corrections.

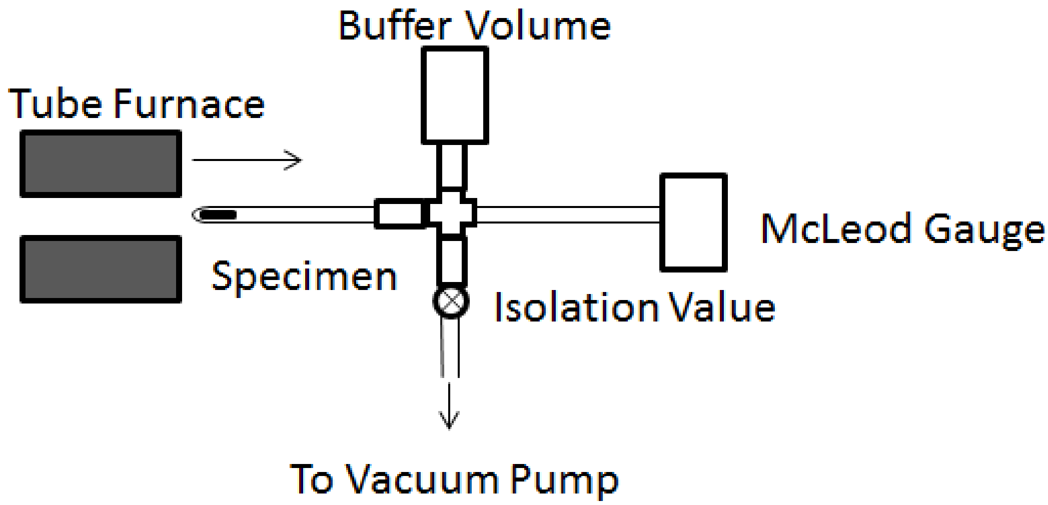


Figure 37a Diagram of Hydrogen Concentration Measurement Setup

Figure 37b Hydrogen Concentration Measurement Setup

The temperature of 480 ^{o}C was chosen as a temperature at which only Hydrogen would be expected to be outgassed from the specimen in the time frame of the tests. The pressure versus time data were plotted as exemplified in Figure 38. The results showed an initial pre-heating increase in pressure corresponding to the leak rate of the system, an intermediate period where the bulk of the outgassing took place, and a terminal stage of return toward the baseline leak rate. The increase in pressure associated with outgassing was assumed on first approximation to follow single time constant τ kinetics of the form

$$\Delta P(t) = Po\ (1\text{-}exp^{-(t-to)/\tau}) \qquad (1)$$

where
$P(t)$ is the pressure corresponding to the amount of hydrogen outgassed into the chamber volume V,
t is the time since the start of the experiment,
to is as defined next,
and Po is the terminal pressure increase in the system as a result of the outgassing.

The increase is a function of effective time (t-to) since the moment when the specimen achieved the outgassing temperature, and for t < to, $\Delta P(t)$ is assigned a value of zero. Per the above, at any given time the total pressure is then assumed to be given by

$$P_{TOTAL}(t) = P_I + P_L(t) + \Delta P(t) \qquad (2)$$

where
$P_L(t) = L_R * t$, L_R being the leak rate
P_I is the initial pressure

The pressure versus time data was then compared with the $P_{TOTAL}(t)$ modeled per Eq. (2) with the values of to, τ, L_R, P_I and Po as adjustable parameters. The sum of the squared differences between model and measured data was treated as a minimization variable. The values of the parameters, in particular Po, for minimum condition were then obtained by use of the SOLVER function in an Excel spreadsheet. The value of Po was used, assuming ideal gas behavior, to estimate the outgassed hydrogen concentration C_H which with the choice of units indicated below is in weight parts per million, (ppmw) by:

$$C_H = (MW_H * Po * V) / (q * m_{STEEL} * R * T) \qquad (3)$$

where
MW_H is the molecular weight of Hydrogen, 2.016 g/mol,
Po is the total pressure change (in Torr) over the entire outgassing measurement.
m_{STEEL} is the mass of the steel specimen in grams,
R is the gas constant 8.314 J/mol-K,
V is the volume of the system in cm^3,
T is the absolute room temperature in K (assumed to be 298 K),
and q is a constant used to convert the pressure from Torr to Pa, 133.322 Torr/Pa.

The values of the other parameters were used only to verify plausibility of the outcome. L_R was found to be close to the visually estimated initial leak rate; to was found to be in the order of two minutes after furnace move, consistent with the expected warm up time of the specimen; τ was in the order of several minutes consistent as well with the expected diffusivity of Hydrogen at the operating temperature and typical diffusivity values (Enos, 2002), and P_I was close to the observed initial pressure.

An uncertainty analysis of the test outcome was performed by first taking the pressure data for t > 20 min (corresponding to the terminal pressure-time slope where pressure increases quite linearly with time) from six different randomly selected specimens. Then for each specimen the data were linearly de-trended and the standard deviation was calculated. That standard deviation is thus representative in each case of the random scatter of the pressure data around a nominal true value at a given time. The average of those standard deviations, σ_a = 0.006 Torr, was then calculated as an overall typical value for these experiments. Simulated data sets were then created by constructing ideal pressure evolution tables at 1 minute intervals using Eqs. (1-3) with parameters to = 6 minutes, τ = 6 minutes, L_R = 0.01 Torr /minute , P_I = 0.05 Torr, m_{STEEL} = 20 g, V = 700 cc, T = 298 K and Po corresponding to C_H values ranging from 0.01 to 1 ppmw. The ideal pressure value for each time in each set was then added an individually randomized simulated normally-distributed scatter contribution with standard deviation σ_a. The procedure was repeated 10 times for each set, effectively simulating the data of a group of 10 replicate experiments. The simulated data sets were then processed by the same program used to interpret the laboratory data, yielding a group of estimated C_H values. The standard deviation of that group was then calculated and the result was named σC_H. The entire procedure was performed twice to obtain a richer field of simulated results. The value of σC_H was found to be in the order of 0.04 ppmw, and to not vary systematically with the initially assumed value of C_H within the 2-order of magnitude range assumed above. The value of 0.04 ppmw was consequently deemed to be the approximate detection limit and representative of the random error of the test method.

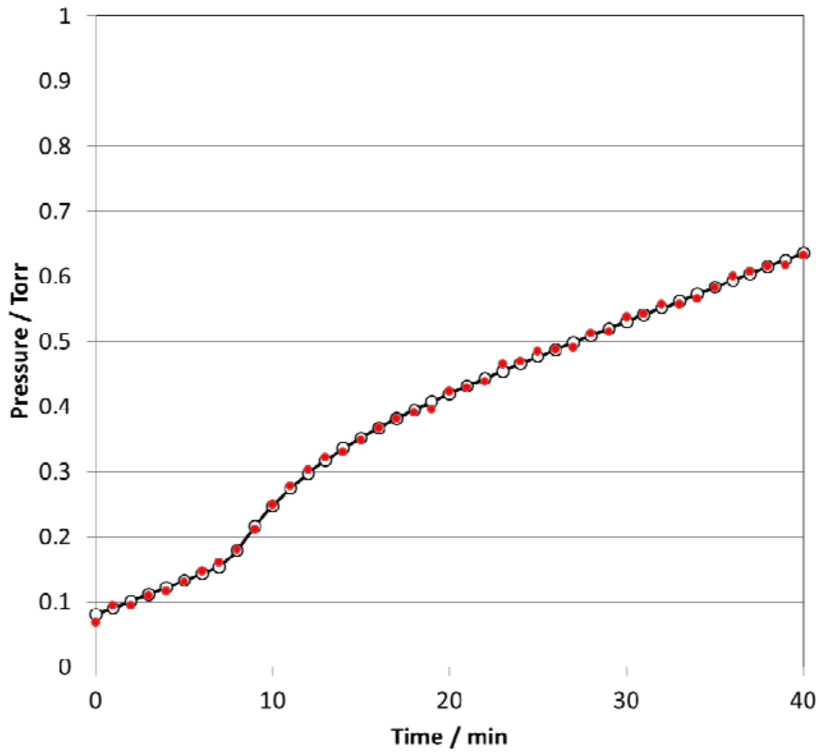


Figure 38 Hydrogen Concentration Calculations from Measurements. Example for Specimen 89a. Parameter Fit Values: to = 7.53 Minutes, Po = 0.08 Torr, τ = 3.99 Minutes, L_R = 0.01 Torr/ Minute, Hydrogen Concentration Value 0.55 ppmw. Red Symbols: Data; Black Symbols: Model Fit

3.4.4 Hydrogen Charging

Testing of strand specimens for HE susceptibility was performed using hydrogen charging with a solution of 875 ml of DI water, 125 ml of Sulfuric Acid (H_2SO_4), and 0.5 grams of Antimony Trioxide (Sb_2O_3) [as a hydrogen recombination poison] while cathodic polarization with an impressed cathodic current density of about 0.05 A/cm^2 took place at room temperature (25 ^oC). The setup is shown in Figure 39.

The stressing of the specimens while being charged was implemented by bending the specimens on a 1 in mandrel into a "U" shape and maintaining that shape using a pre-drilled brace plate (Figure 40), to create conditions that can lead to HE. Details of the bending procedure are given by (Fernandez, 2011). Bending the specimens 180^o deformed them plastically as well as elastically, ensuring the yield strength of the material was exceeded thus creating the highest stress levels and likely increasing sensitivity to HE. The solution immersion line was ~ 1 inch from the bottom of the specimen. The specimens were initially charged for as much as 24 hours at lower polarization (0.01 A/cm^2), but shorter charging times while ensuring hydrogen charging sufficient to induce delayed failure was desired. It was discovered through numerous iterations, that delayed failure due to HE could be routinely achieved by charging the specimens for as little as 25 minutes at 0.05 A/cm^2. This combination was chosen for the subsequent tests as it reduced the testing time and was sufficient to initiate HE-induced cracking and mechanical failure as desired.

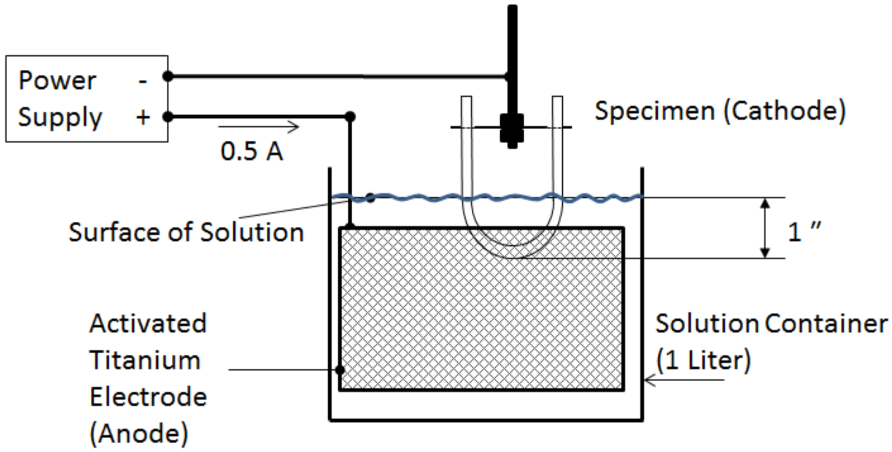


Figure 39a Diagram of Hydrogen Charging Setup with Variable Power Source

Figure 39b Hydrogen Charging Setup with Variable Power Source

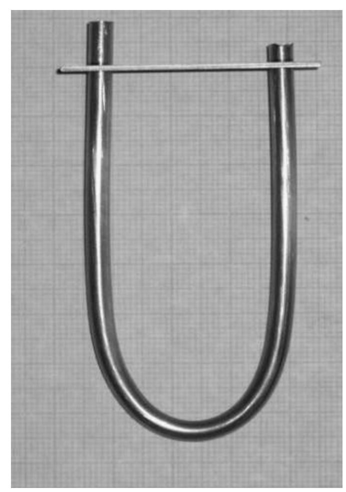


Figure 40 Stressed "U" Bent Specimen. Grid in mm

An introductory description of this type of test is given in (ISO 7801, 1984). A modified version of the reverse bending test was implemented here. The setup used is shown in Figures 41a and 41b. The test started with the insertion of the test piece with the bending handle vertical, through the center of the bending handle and fastened to it with two screws. The lower end of the test piece was held between the grips so that the test piece was perpendicular to the axes of hardened steel cylindrical supports 5/8 inch in diameter. A spacer was used during placement to ensure that there is 1” between the bottom of the bending handle and the top of the cylindrical pieces. In Bend #1, the test piece was bent counterclockwise until the handle was horizontal at a 90° angle from the initial vertical position and then returned to the vertical position. In Bend #2 the piece was bent clockwise until the handle was horizontal, and then returned to the vertical position. Bend #3 was conducted as done for Bend #1 and so on. This pattern of counterclockwise and clockwise bending continued until complete fracture of the test piece occurred and the Bend # for that event was recorded as the test outcome for that specimen. Bending occurred at a uniform rate without shock, not exceeding one bend per second.

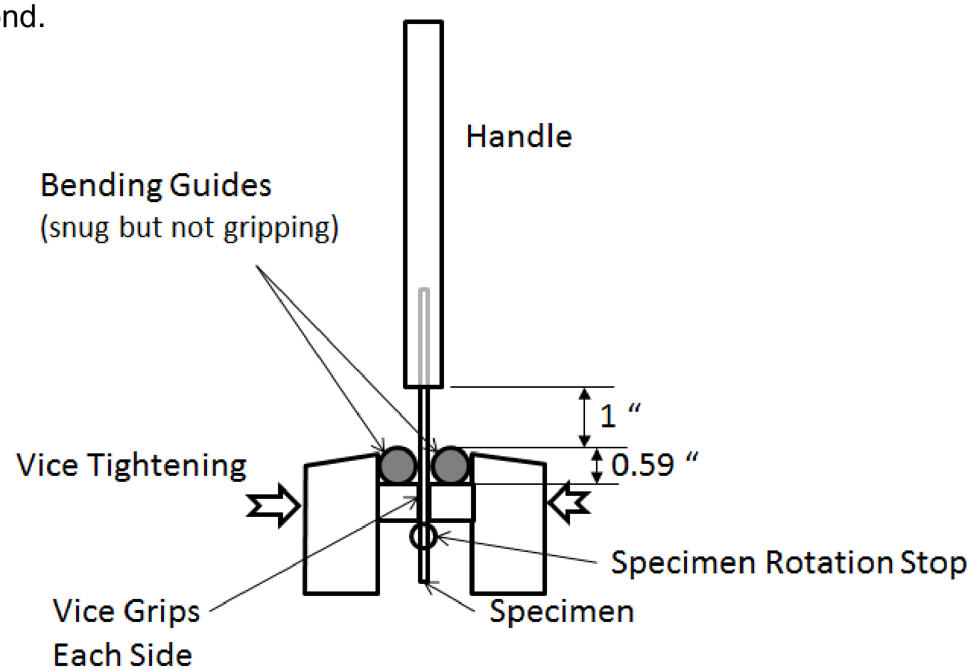


Figure 41a Diagram of Reverse Bending Setup

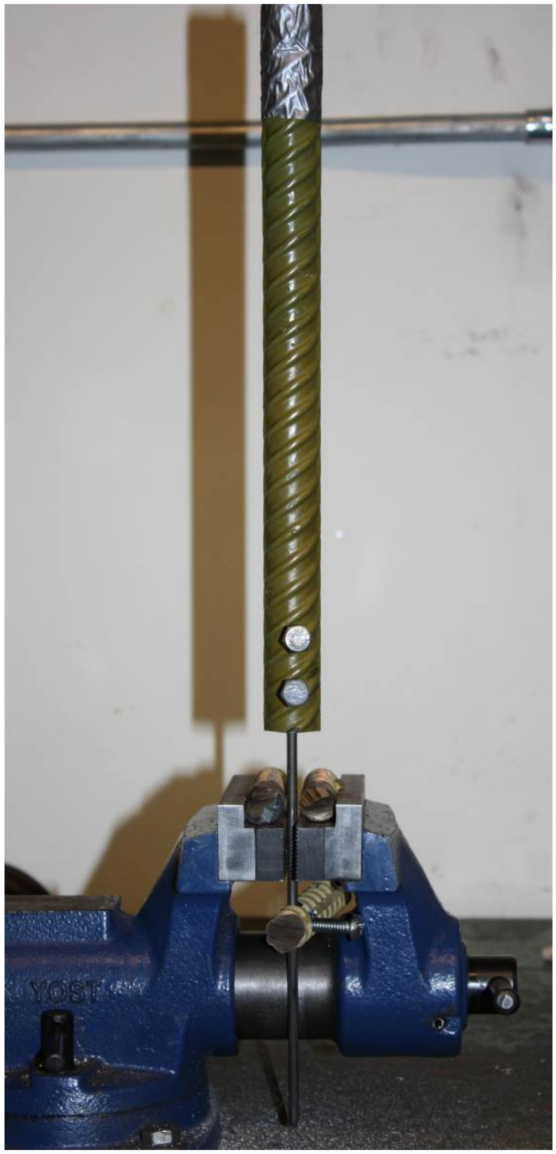


Figure 41b Reverse Bending Setup

3.4.6 Additional Assessment

Specimens from strands exposed in the piles both at USF and SSK were cut from the exposed strand for determination of condition per the pictorial pitting scale per (Sason, 1992), similar to the assessment used in the previous, unstressed ungrouted strand project (BDK84 977-04). Both an outer wire and the king (that is, the straight, center wire in a 7-wire strand) wire of various strands exposed to various conditions were visually examined in their state just after the exposure, and after light mechanical cleaning, to further determine the degree of corrosion discoloration and of any visible pitting. Specimens were assigned a rating based on the scale (1 being the lowest degree of distress), noting that a value of 4 or higher would indicate that the strand may be subject to rejection for use in prestressing per the criteria presented by (Sason, 1992). Where no corrosion was observed, that set of time exposed and condition was labeled 1 (no corrosion). In cases of light corrosion, it was labeled 2 or 3 and for very corroded specimens, the indication was 4

4 RESULTS AND DISCUSSION

4.1 Extension of Project BDK84-977-04 Experiments to Warm Season Conditions

The results and discussion are presented in Appendix C.

4.2 Stressed and Control Unstressed Strand Results

Table 3 indicates the after-exposure appearance of the as-retrieved (but prior to any surface cleaning) strand exposed for various time-and-condition sets in both the inland (USF) and Seashore (SSK) locations. Where no corrosion was observed, that set was labeled “NC” (no corrosion). In cases of light corrosion, the set was labeled “LR” (light rust). For very corroded appearance the indication was “VR” (very rusted).

Selected wires from various strands representative of the conditions tested were cleaned and inspected. Table 4 indicates the condition of wires from the strands after cleaning. Table 4 is a summary of the more detailed results presented in Table 5, constructed using the rating scale developed by (Sason, 1992). Results in Table 5 are shown in pairs; the top value corresponds to a stressed strand and the bottom to an unstressed strand in the same duct with the same exposure regime. Pile numbers and exposure regimes are keyed to the listing in Table 1.

Table 3 - General State of Corrosion As-Extracted by Location and Exposure Conditions of Strands in the Test Piles (See Table 1 for detailed test conditions)

Duct Condition	Strand Starting Condition											
	As Received						100 mg Cl/m^2					
	Inland			Seashore			Inland			Seashore		
	1wk	2wk	4wk	1wk	2wk	4wk	1wk	2wk	4wk	1wk	2wk	4wk
Closed, Normal	NC	NC	NC	NC	NC	NC	LR	LR	LR	LR	LR	LR
Open	NC	NC	NC	NC	NC	NC				LR	LR	LR
Closed, Wet	VR	VR	VR	VR	VR	VR				VR	VR	VR
Closed, Desiccant	NC	NC	NC				NC	NC	NC			

Table 4 - General State of Strands after Cleaning by Location and Exposure Conditions of Strands in the Test Piles (See Table 1 for detailed test conditions)

Duct Condition	Strand Starting Condition											
	As Received						100 mg Cl/m^2					
	Inland			Seashore			Inland			Seashore		
	1wk	2wk	4wk	1wk	2wk	4wk	1wk	2wk	4wk	1wk	2wk	4wk
Closed, Normal	1	1	1	1	1	1	2	2	2	2	2	2
Open	1	1	1	1	1	1				2	3	3
Closed, Wet	1	1	2	1	1	2				2	3	4
Closed, Desiccant	1	1	1				1	1	1			

Table 5 - Summary of Ratings

Case # and Specimen ID	Pile Number	1 Week	2 Week	4 Week	Salted?	Wet	Open	Closed	Location	Sason Value	Pitting?
106a	11			X	Y	X			SSK	4	Y
108a	11			X	Y	X			SSK	4	Y
88a	11		X		Y	X			SSK	3	N
90a	11		X		Y	X			SSK	3	N
70a	11	X			Y	X			SSK	2	N
72a	11	X			Y	X			SSK	2	N
97a	1			X	N	X			SSK	2	N
99a	1			X	N	X			SSK	2	N
79a	1		X		N	X			SSK	1	N
81a	1		X		N	X			SSK	1	N
61a	1	X			N	X			SSK	1	N
63a	1	X			N	X			SSK	1	N
46a	5			X	N	X			USF	2	N
48a	5			X	N	X			USF	2	N
37a	5		X		N	X			USF	1	N
39a	5		X		N	X			USF	4	Y
10a	5	X			N	X			USF	1	N
12a	5	X			N	X			USF	1	N
103a	8			X	Y		X		SSK	3	N
105a	8			X	Y		X		SSK	2	N
85a	8		X		Y		X		SSK	3	N
87a	8		X		Y		X		SSK	2	N
67a	8	X			Y		X		SSK	2	N
69a	8	X			Y		X		SSK	2	N
94a	4			X	N		X		SSK	2	N
96a	4			X	N		X		SSK	2	N
76a	4		X		N		X		SSK	1	N
78a	4		X		N		X		SSK	1	N
58a	4	X			N		X		SSK	1	N
60a	4	X			N		X		SSK	1	N
49a	0			X	N		X		USF	2	N
51a	0			X	N		X		USF	2	N
31a	0		X		N		X		USF	2	N
33a	0		X		N		X		USF	2	N
13a	0	X			N		X		USF	1	N
15a	0	X			N		X		USF	1	N
100a	9			X	Y			X	SSK	1	N
102a	9			X	Y			X	SSK	2	N
82a	9		X		Y			X	SSK	2	N
84a	9		X		Y			X	SSK	2	N
64a	9	X			Y			X	SSK	2	N
66a	9	X			Y			X	SSK	2	N
91a	3			X	N			X	SSK	1	N
93a	3			X	N			X	SSK	1	N
73a	3		X		N			X	SSK	1	N
75a	3		X		N			X	SSK	1	N
55a	3	X			N			X	SSK	1	N
57a	3	X			N			X	SSK	1	N
52a	7			X	N			X	USF	1	N
54a	7			X	N			X	USF	1	N
34a	7		X		N			X	USF	1	N
36a	7		X		N			X	USF	1	N
16a	7	X			N			X	USF	1	N
18a	7	X			N			X	USF	1	N

Figures 42, 43, 44, and 45 show a representative direct comparison between the as-received condition of the strands and the same location on the strands after exposure.

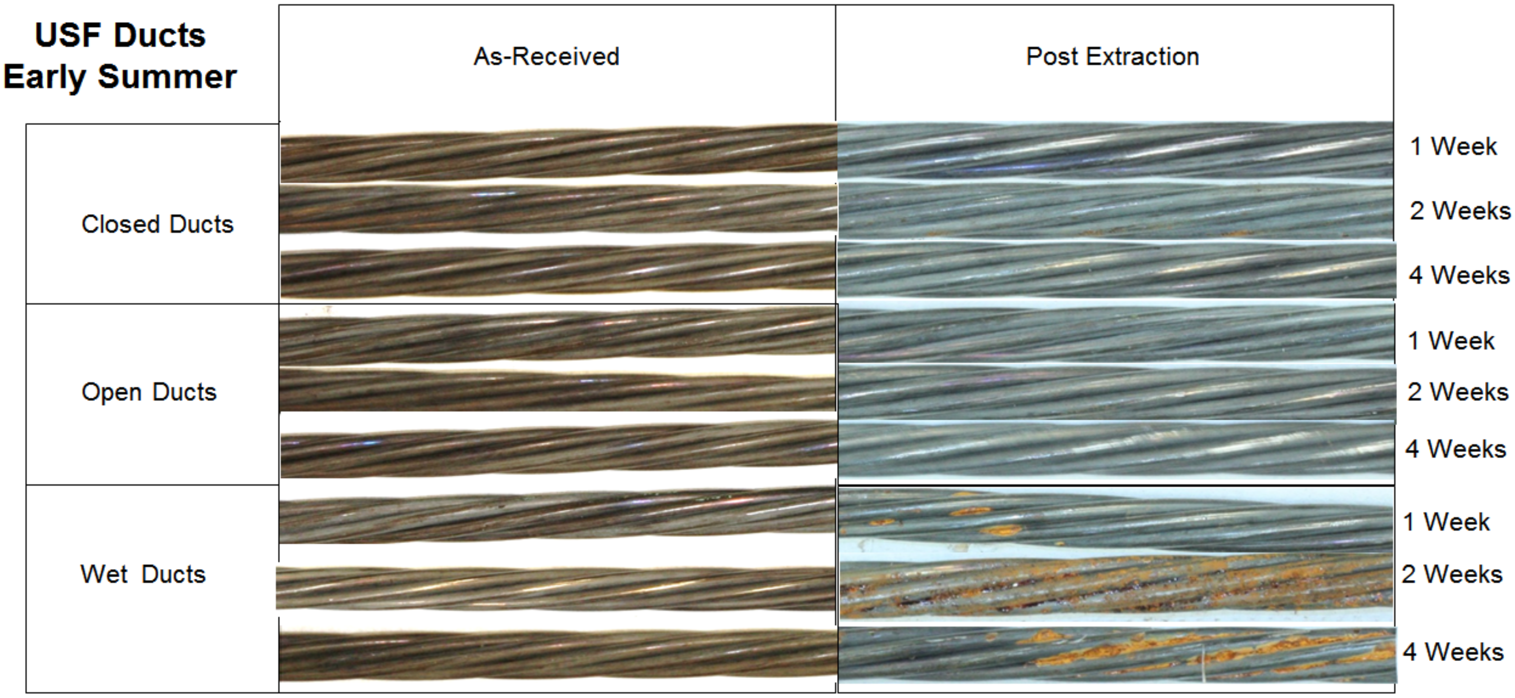


Figure 42 USF Early Summer Strand Surface Comparison

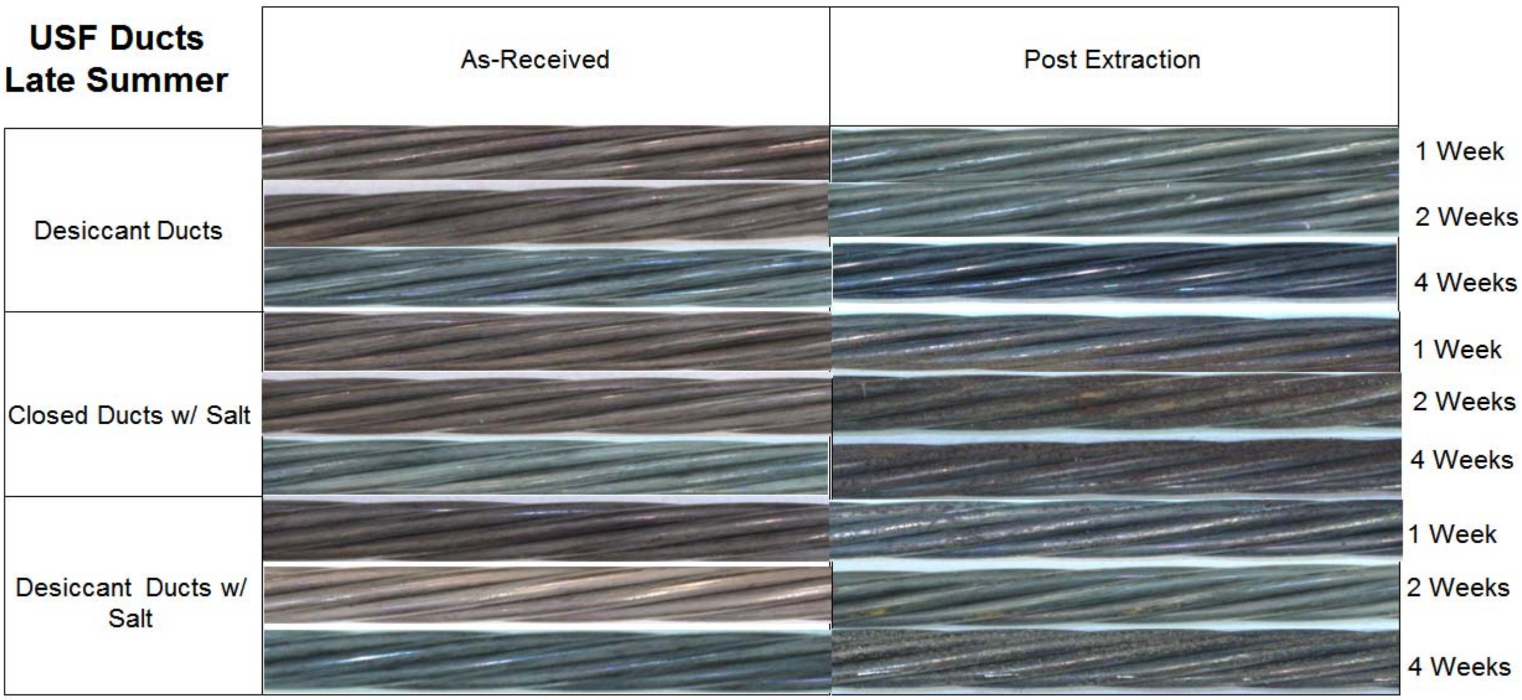


Figure 43 USF Late Summer Strand Surface Comparison

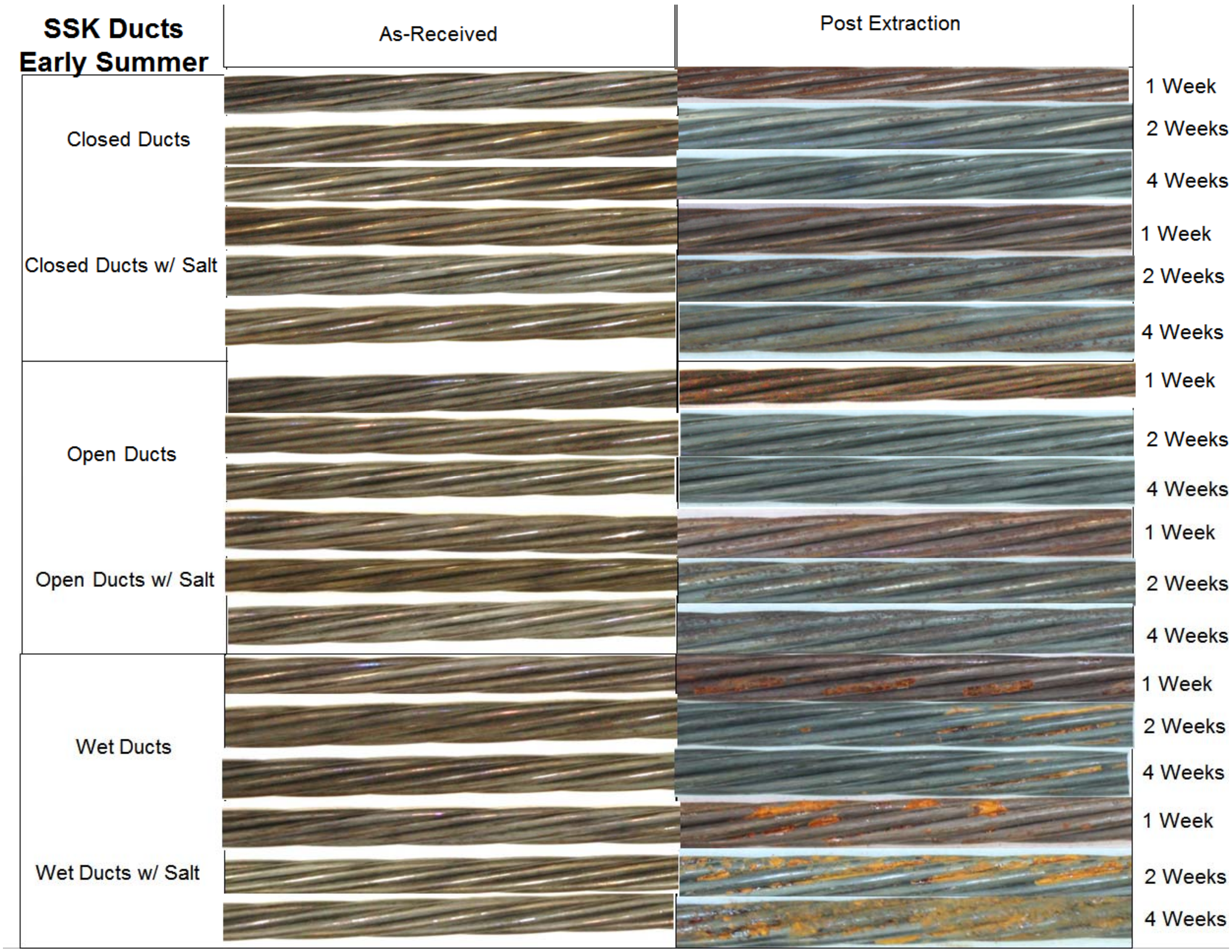


Figure 44 SSK Early Summer Strand Surface Comparison

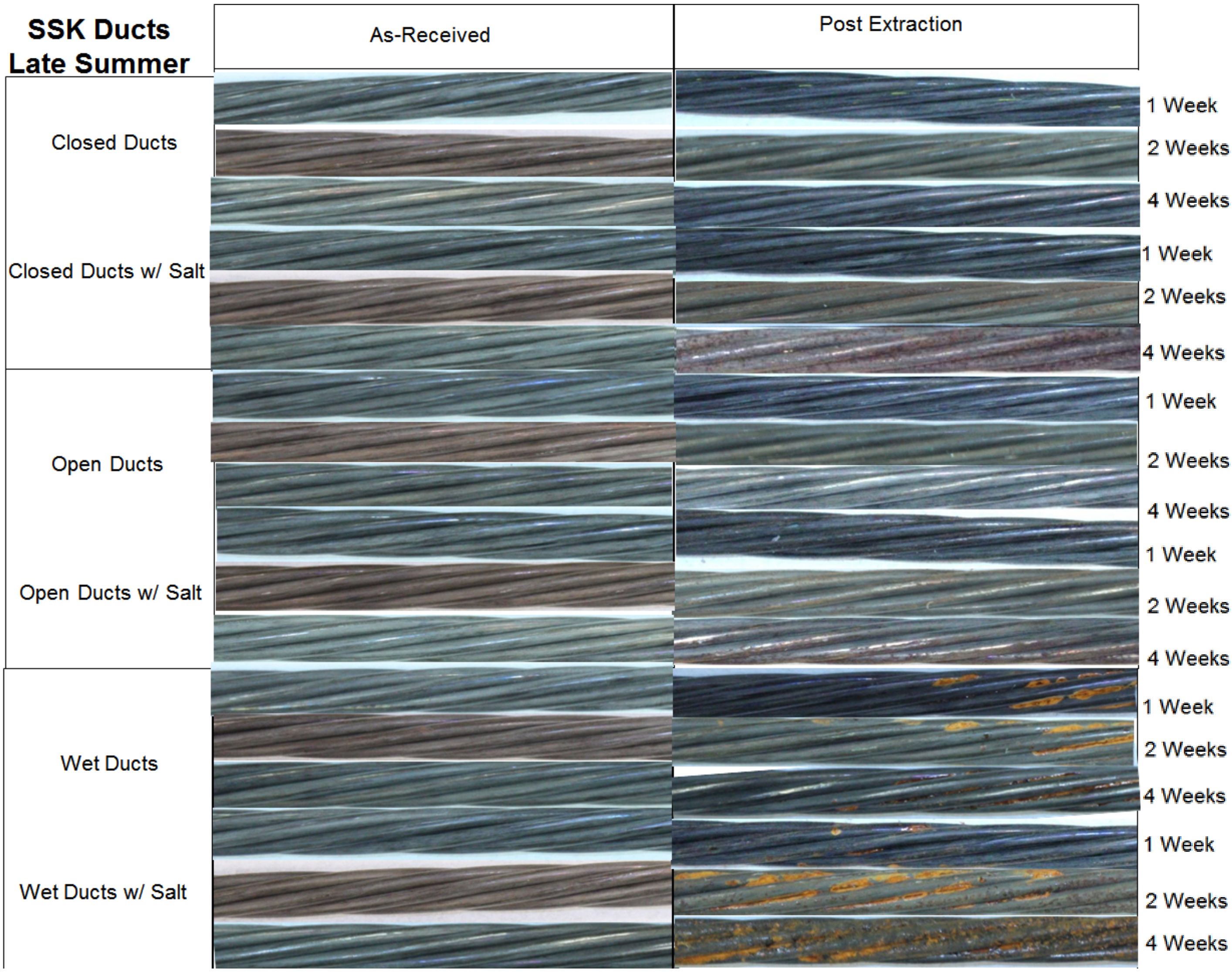


Figure 45 SSK Late Summer Strand Surface Comparison

Examination of Tables 3, 4 and 5, Figures 42-45 and consideration of the test circumstances reveals the following main findings:

- At both the inland and seashore sites exposures in closed ducts without trapped water or prior exposure to salt did not result in any conspicuous rusting for up to 4-weeks of ungrouted exposure.

- Exposure in open ducts without any initial trapped water or pre-salting also did not result in any clearly identifiable surface rusting for up to 4-weeks of ungrouted exposure.

- Trapped water in the ducts was a major factor in inducing visible surface corrosion, even after just one week of ungrouted exposure.

- In the presence of trapped water, pre-salting that simulates exposure of unprotected strand for a period in the order of one day, was a further aggravating factor in inducing the appearance of visible rust in as little as one week of ungrouted exposure.

- Pre-salting also induced visible surface rust, although lighter than in the presence of trapped water, even in the case of otherwise normally closed ducts, even after just one week of ungrouted exposure.

- Pre-salting, however, did not result in clearly visible rust in otherwise normally closed ducts, even after 4-weeks of ungrouted exposure, if desiccant packets were placed inside the duct at the beginning of the exposure.

- While Figures 42-45 show only stressed strand specimens, examination of the unstressed companion strands exposed similarly in the same ducts, supplemented by the data on unstressed strands in Appendix C, revealed essentially the same trends as those of the stressed strands, indicating that the stress condition did not play any major factor in the development of surface rust or corrosion loss under the test conditions examined.

- The visible manifestations of rust, even in the “Very Rusty” condition were not associated with dramatic metal loss, as manifested by ratings not exceeding 4 (Sason, 1992) upon surface cleaning even for the most conspicuous rusting cases.

4.3 Mechanical Testing Results

Appendix D gives the mechanical testing data obtained for all 216 specimens. The mechanical tests show that none of the strands validly tested failed to meet the ASTM requirement for Load at Failure (Figure 46), Load at 1% Extension (Figure 47), or Total Elongation (Figure 48). It is noted that of the 216 strands tested, 9 of them had slip occur in the grips during their test, invalidating those results (shown as red filled squares). Based on the evidence examined, there was no significant and clear differentiation either in tensile test behavior between stressed and unstressed companion strands. Test performed with 4 specimens cut from as-received, never exposed strand (blue symbols in the figures) showed no differentiation from the exposed specimens. Figures 49 through 51 show the same information as Figures 46 through 48 but aim to reveal possible differences between the stressed strand data and the unstressed strand data. Figures 52 through 54 show a comparison between the salted and wet, unsalted and wet, and unsalted and closed (dry) conditions. These figures were each focused on a relatively small range of values around the median to better uncover possible differentiation between conditions. The graphs showed only minor deviations between the distributions sampled, and not following any clearly established systematic pattern. For example, while the median value of load at 1% extension (Figure 53) was slightly greater for the unsalted wet than for the salted wet specimens - a possibly expected outcome, an opposite and comparable minor difference was observed in the total elongation values (Figure 54). It was thus concluded that those apparent minor differences reflected only natural scatter of results. It is noted that in the tests detailed for unstressed strands during the warm season (Appendix C) there was also very little differentiation in the behavior for the different test conditions, with the exception of the exceptionally long exposure (9 months) cases in the more aggressive exposure regimes.

In general, the mechanical testing results show that none of the strands exposed in the test piles, even in the most severe test conditions (ungrouted for 4-weeks with salt previously sprayed on them and water placed in the duct) would have failed to qualify per the ASTM tensile testing requirements. Caution applies, however, as to the possibility of failure modes not directly addressed by the ASTM testing procedure, such as hydrogen embrittlement, discussed later on.

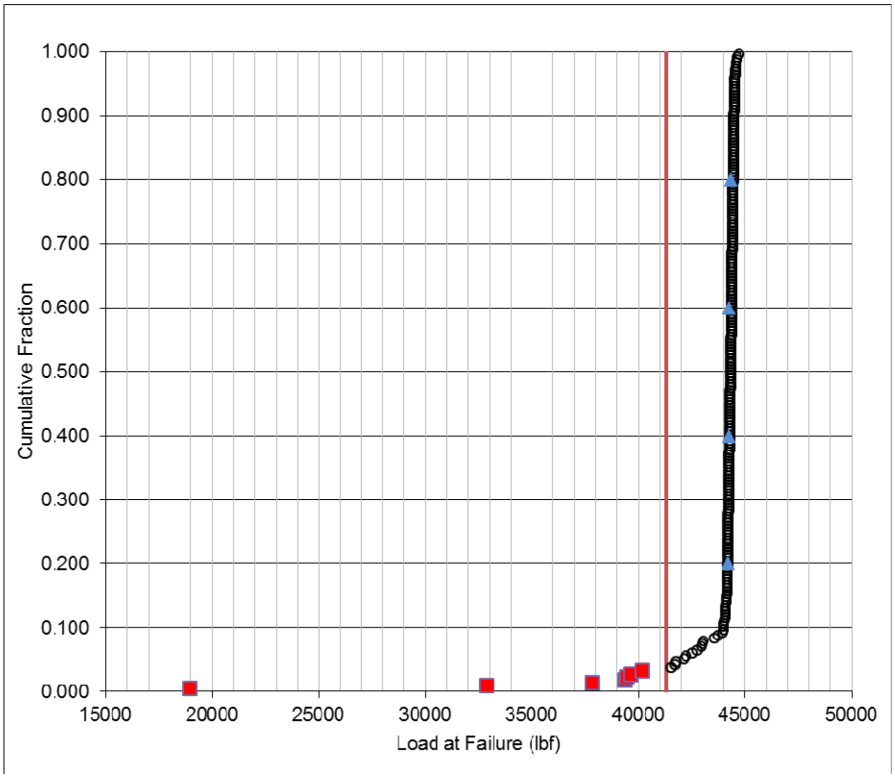


Figure 46 Cumulative Fraction of Load at Failure. Red Line Indicates Specification Requirement. Red square symbols are indicative of invalid tests. Blue Symbols are for Unexposed Controls

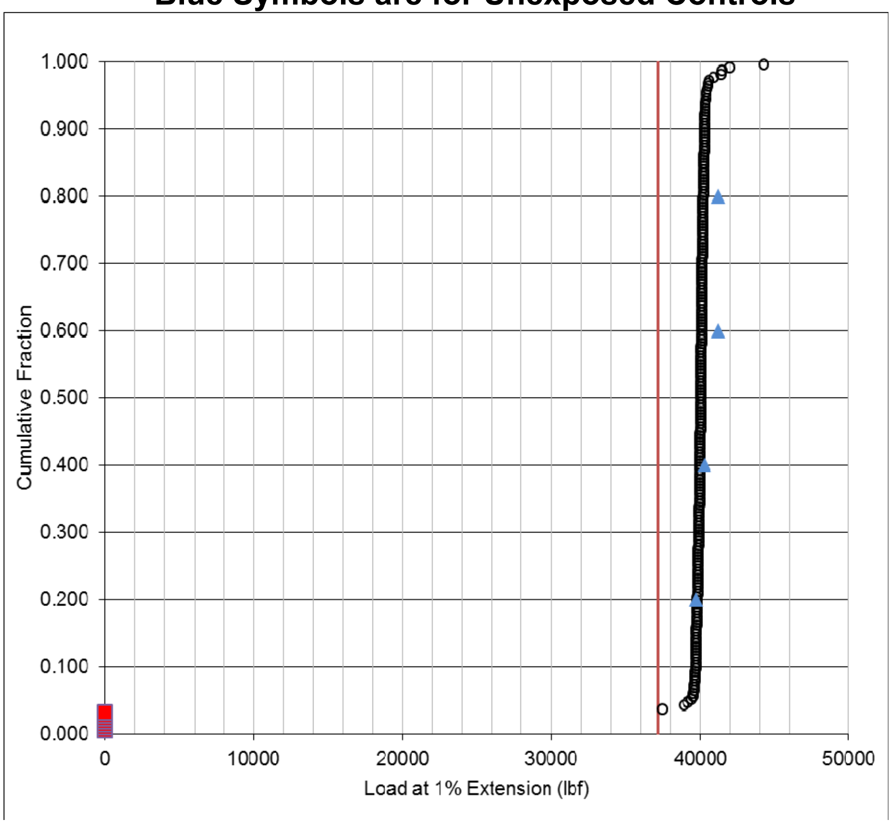


Figure 47 Cumulative Fraction of Load at 1% Extension. Red Line Indicates Specification Requirement. Red square symbols are indicative of invalid tests. Blue Symbols are for Unexposed Controls

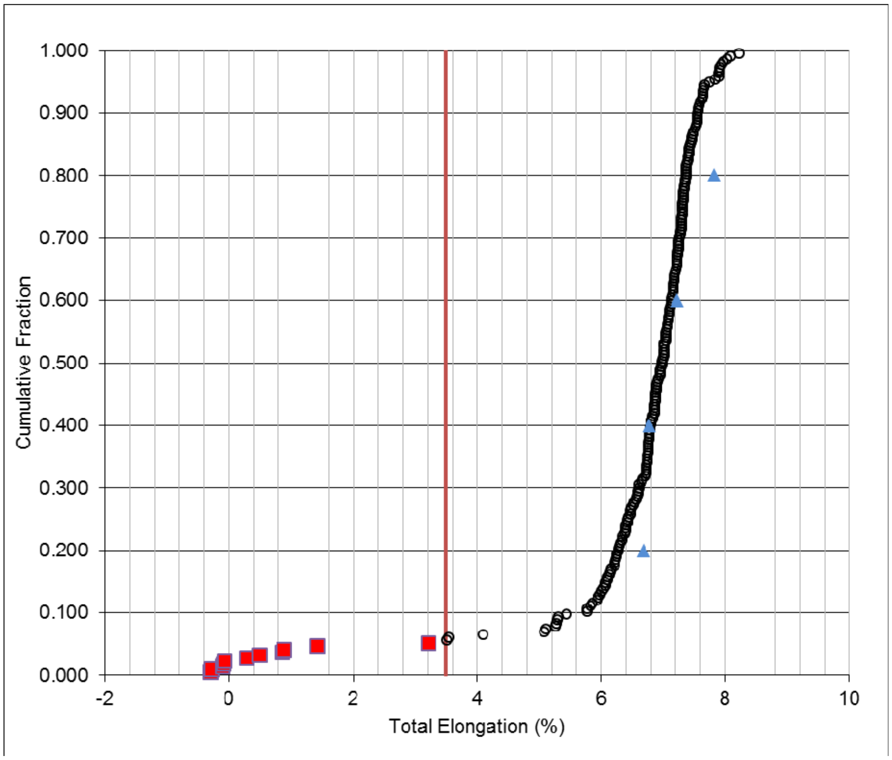


Figure 48 Cumulative Fraction of Total Elongation. Red Line Indicates Specification Requirement. Red square symbols are indicative of invalid tests. Blue Symbols are for Unexposed Controls

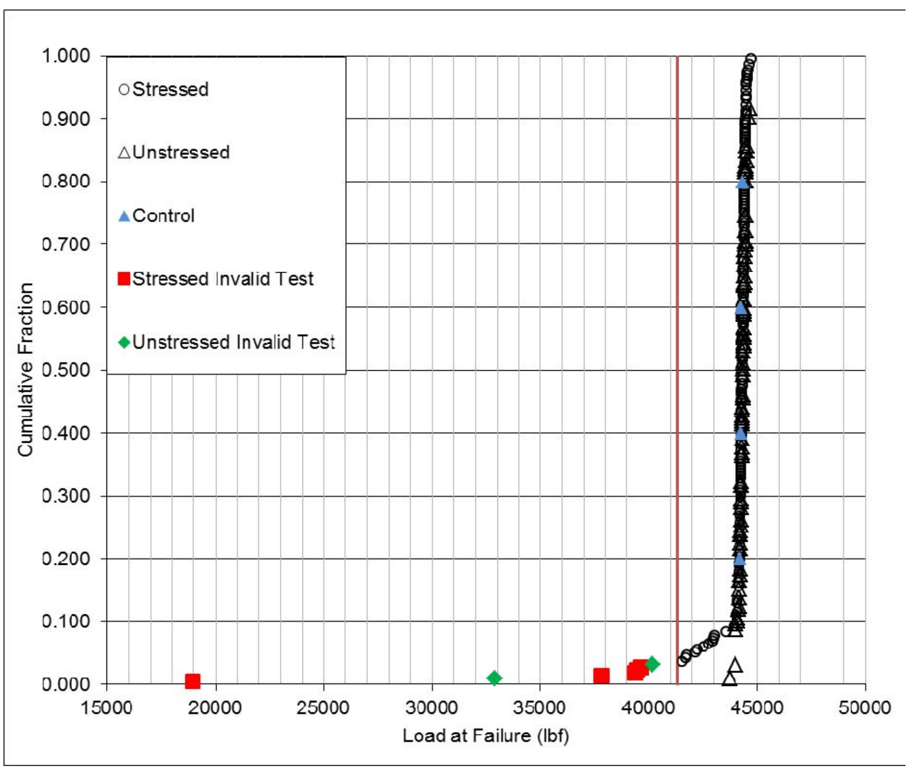


Figure 49 Cumulative Fraction of Load at Failure by Stressed and Unstressed. Red Line Indicates Specification Requirement

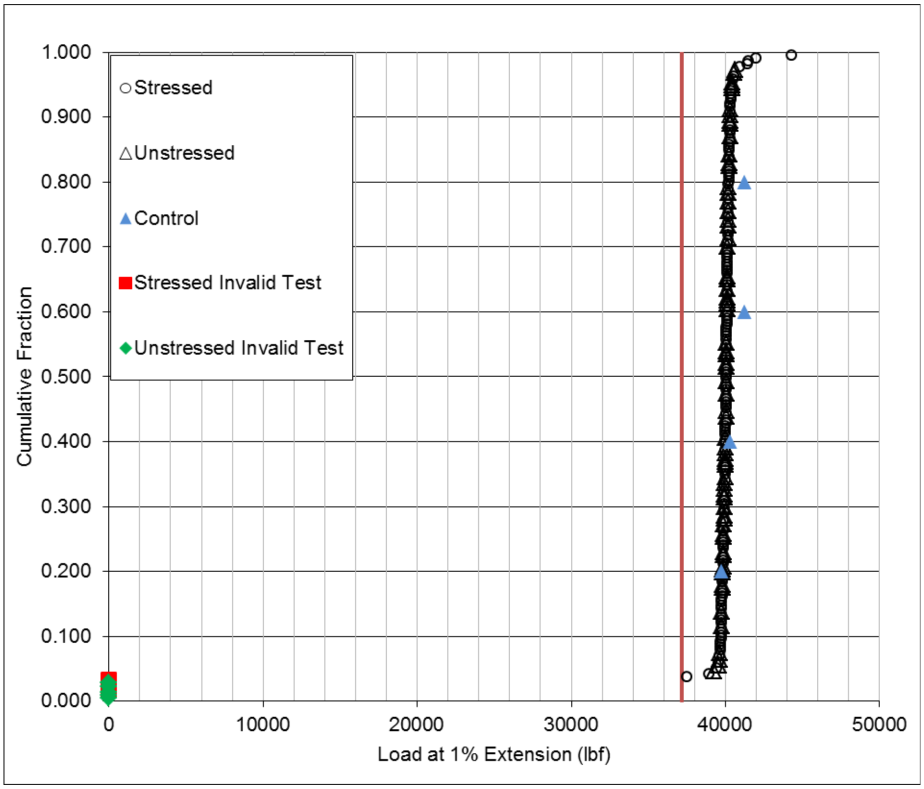


Figure 50 Cumulative Fraction of Load at 1% Extension by Stressed and Unstressd. Red Line Indicates Specification Requirement

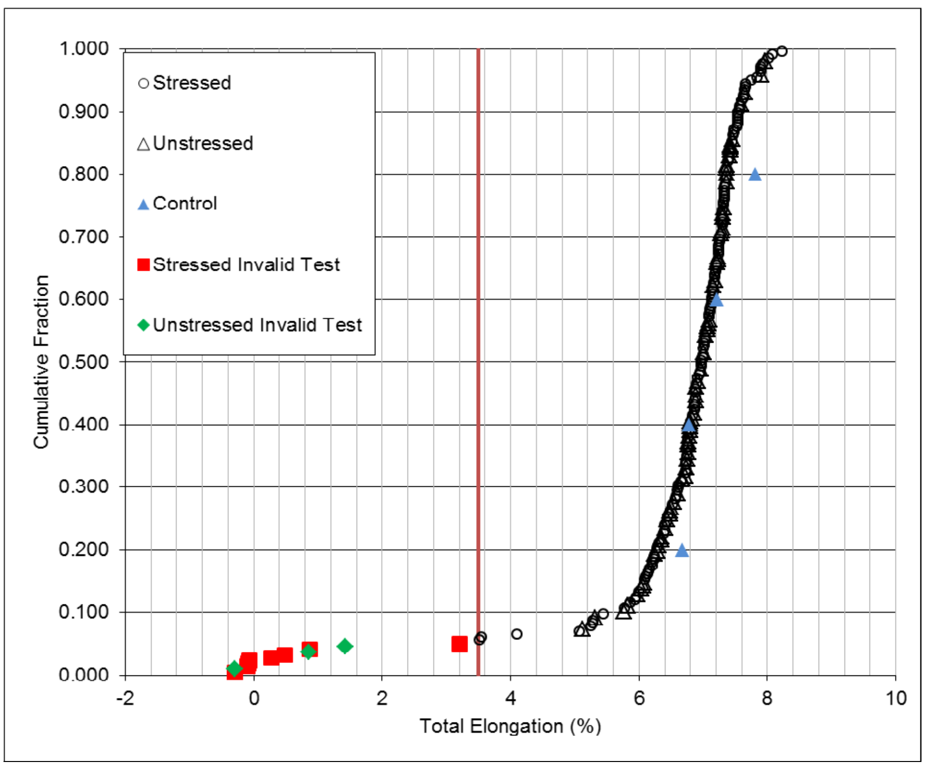


Figure 51 Cumulative Fraction of Total Elongation by Stressed and Unstressed. Red Line Indicates Specification Requirement

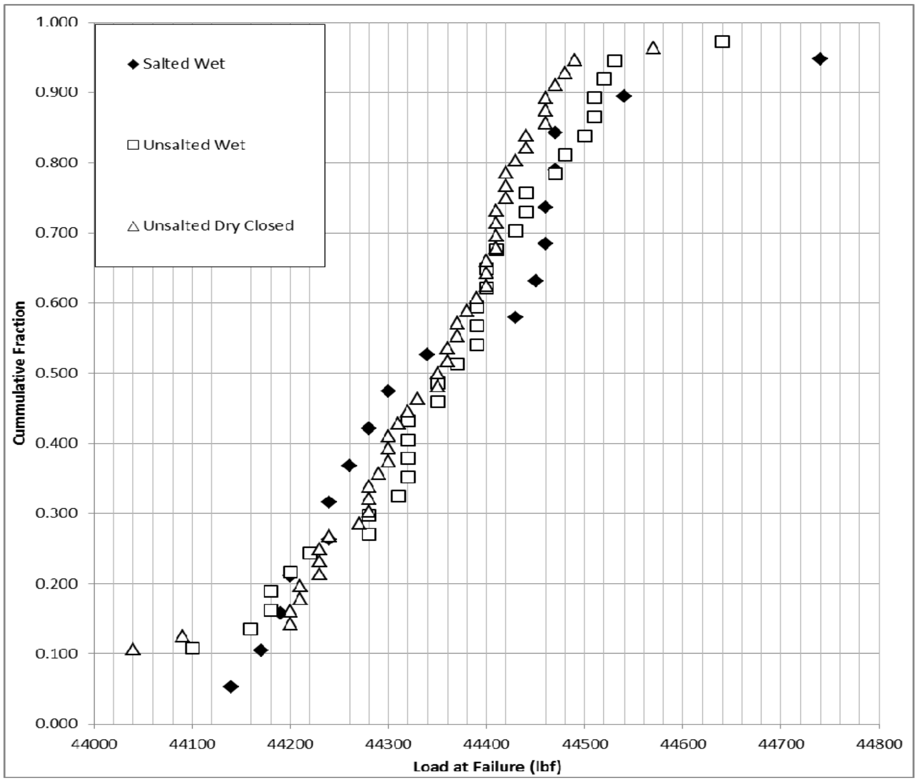


Figure 52 Cumulative Fraction of Load at Failure Comparison

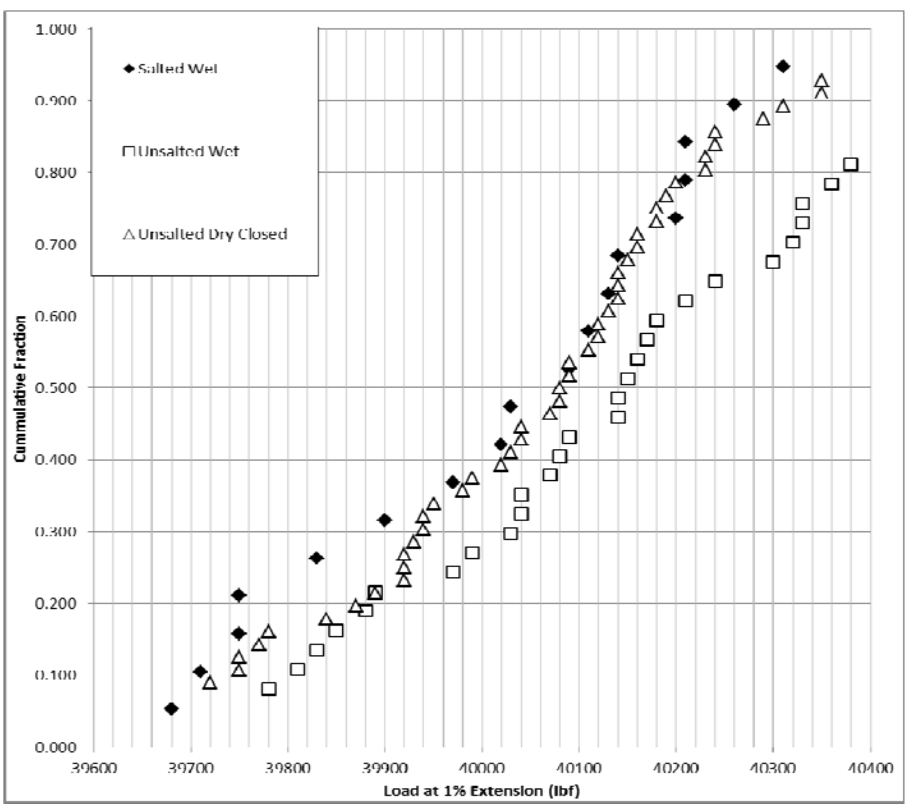


Figure 53 Cumulative Fraction of Load at 1% Extension Comparison

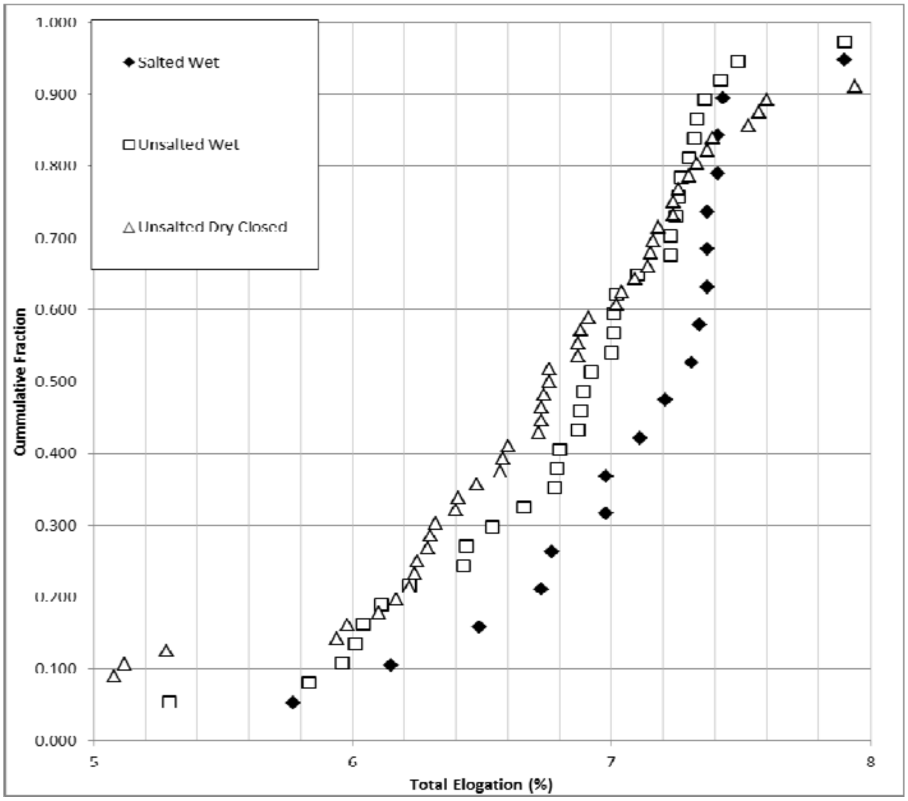


Figure 54 Cumulative Fraction of Total Elongation Comparison

4.4 Hydrogen Concentration Results

The hydrogen concentration measurements for unexposed, exposed and purposely charged specimens are shown in Figure 55. It is emphasized that the hydrogen concentrations values indicated there are subject to verification in future investigations (especially concerning the possibility of artifacts that may lead to falsely high indications of hydrogen content), and that values below ~0.04 ppmw (roughly in the order of the sensitivity of the test) are nominal indications of the experimental test curve fitting procedure and not distinguishable from zero content. Starting from the left of the chart, the first set of four values are for strand specimens cut directly from the spool and kept in an air conditioned environment until tested, showing essentially no detectable hydrogen content with the test as performed. The next set of data shows the hydrogen concentrations of three specimens electrochemically charged in the laboratory using the hydrogen charging method described earlier. The “Individually Charged” and “Together Charged” specimens were charged in the unstressed condition. The Bent/Broken specimen was charged in the stressed condition for 25 minutes (a condition that resulted in hydrogen-induced cracking as shown later). All the charged specimens showed concentrations in the order or 0.5 to 2 ppmw hydrogen, clearly much higher than that of the as-received controls.

The remaining specimens were cut out of field-exposed strands in conditions representative of the variety of exposure regimes used. Specimens are designated by a code block indicating the exposure condition (e.g., CWS2 means Closed Wet Salted, 2-weeks) plus the specimen ID. While the data set is limited and shows significant variability, some trends may be discerned from the results. Most importantly, the measured hydrogen concentrations of the specimens exposed to the most severe regime (salted and wet environment) were on average relatively close to the concentration of the hydrogen-charged specimens, which exploratory tests indicate are prone to hydrogen embrittlement in severe bending regimes (see next section). In contrast, the specimens exposed to the mildest conditions in the set from the point of view of visual appearance indicated earlier on (open unsalted) had concentrations measurement values close to those of the unexposed controls.

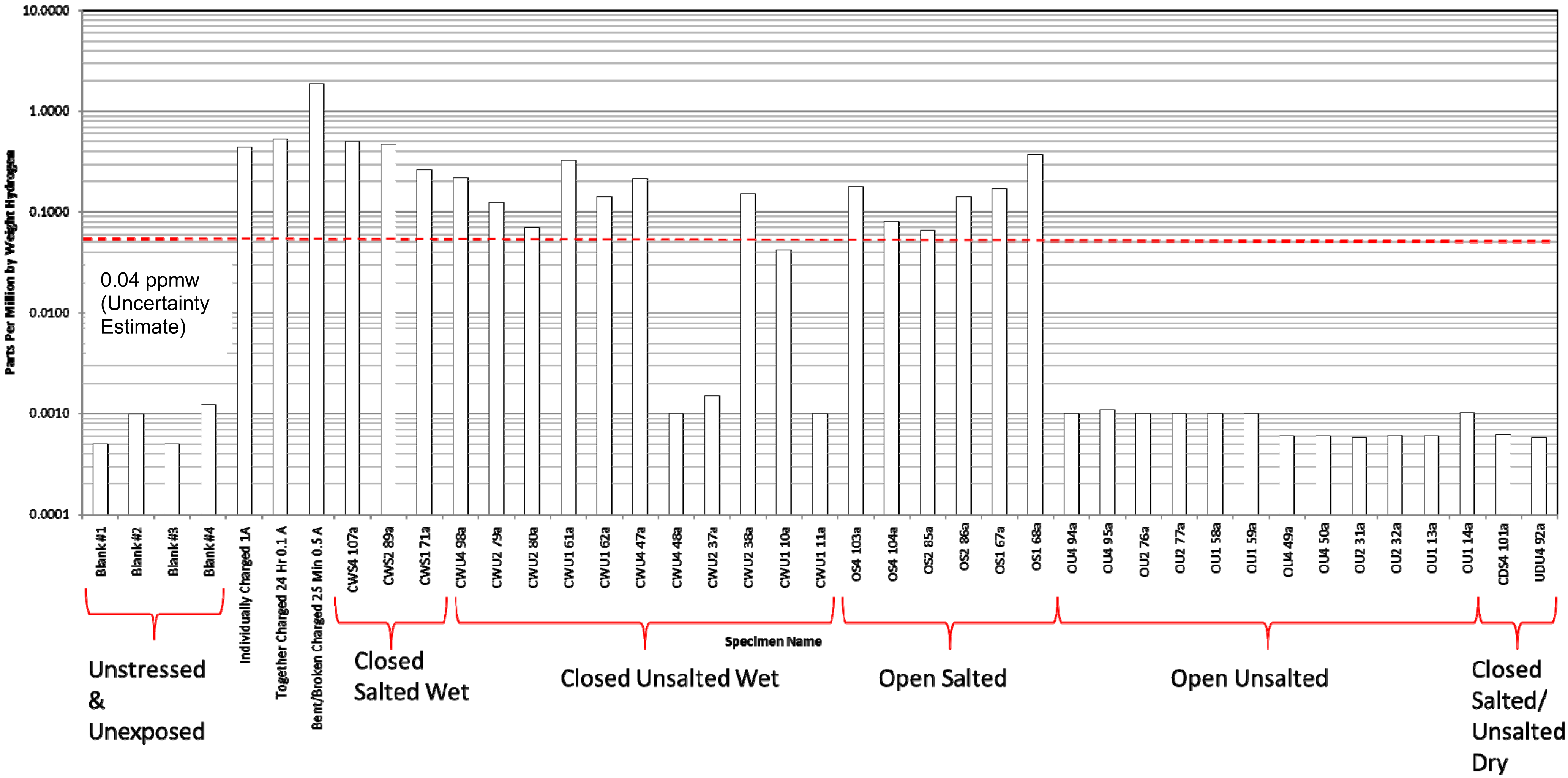


Figure 55 Hydrogen Concentration Test Results

4.5 Hydrogen Charging Mechanical Effects

Experiments on the mechanical performance of hydrogen-charged specimens have been largely exploratory to date so only limited observations apply. The most conclusive results have been with specimens charged to conditions that resulted in measured hydrogen concentrations between ~0.4 to 2 ppmw, noted in the previous section. When those specimens were charged in the U-bend configuration, several instances of spontaneous fracture took place. The specimens were charged typically for 25 minutes at the indicated current levels and afterwards placed into an alkaline solution with pH>13 simulating a concrete pore solution (SPS) environment. In some instances near the end of the 25-minute charging period incipient cracks were noted, followed by spontaneous full fracture within about 2.5 hours of placement in the SPS. The phenomenon has the typical characteristics of delayed-cracking hydrogen embrittlement and the hydrogen levels are consistent with those observed elsewhere to have promoted hydrogen embrittlement in strand steel (Enos, 2002).

Figures 56, 57 and 58 illustrate respectively a tentative sequence of events proposed to explain the fracture morphology and examples full fracture and initial cracking. In the U-Bend configuration used brittle cracks initiate normal to the tensile stress in the outer fibers of the bent specimen and then quickly transition into a shear mode that runs parallel to the drawing direction, possibly along deformed grain boundaries or favoring the pearlite or pearlite-ferrite interfaces.

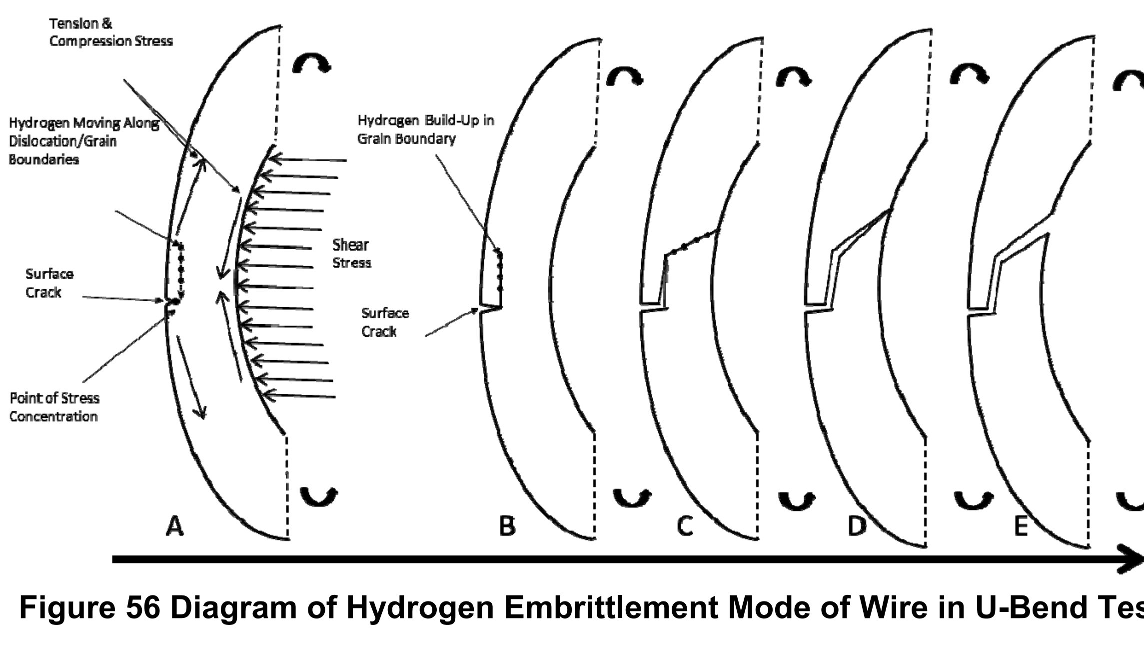


Figure 56 Diagram of Hydrogen Embrittlement Mode of Wire in U-Bend Test.

Figure 57 U-Bend Specimen Failed Due to Delayed Failure Hydrogen Embrittlement

Figure 58 Cracking on Wire U-Bend Specimen

It is emphasized that these tests involve a very severe level of stress, a loading configuration quite different from the straight tensile loading encountered in a tendon, and a very high cathodic current density that promotes the development of similarly enhanced transient hydrogen concentrations near the metal surface. Hence the results should not be interpreted as being directly indicative of a similar risk of brittle failure in the strand exposed to the more aggressive field conditions noted in Figure 55. Indeed, the absence of any spontaneous stressed strand failures in the test piles even after 4-weeks of sustained stress and with multiple specimens of sizeable length in the more aggressive exposure combinations, and the absence of any consistent indications of loss of strength or ductility in the tensile tests, suggest that propensity for brittle behavior is quite limited under the conditions examined. Nevertheless, the experiments verified that hydrogen embrittlement is a possible mode of failure in stressed strands, and that a measure of caution is in order when exposure severity (e.g., more than 2-weeks exposure in aggressive conditions) leads to measured hydrogen levels approaching those observed to make brittle failure possible, albeit in highly severe conditions.

4.6 Reverse Bending Testing Results

The reverse bending test was run on both king and non-king wires removed from the exposed strands. This test was conducted as it may assist to reveal the adverse effect of surface irregularities such as minor pitting, or incipient cracking induced by hydrogen embrittlement or other environmentally assisted cracking mode, that may not have clearly degraded the performance in the standardized tensile test. The repeated severe bending procedure would allow those defects to grow via induced low cycle fatigue and result in early cracking on cyclic bending, thus acting as a sensitive indicator of otherwise hard to detect damage (ISO 7801, 1984).

Four control specimens were also tested for comparison. Figure 59 shows the data for the king wire, which is straight, tested using the reverse bending method. The average value of seven, 90 degree bends before break, with little variation in all cases, indicated little effect on the king wire for the various conditions of exposure tested.

Non-king wires were also tested using the reverse bending method (Figure 60), as the outer wires of the strand could be expected to have experienced more general and localized corrosion than the king wire. However, the outer wires are deformed in a helical pattern that makes the reverse bend test harder to implement reproducibly due to unintended twisting and slipping. Accordingly, there was much more variability in the results than in the king wire tests, as it is evident in Figure 58, especially for one of the tests which yielded 26 bends to failure and for which slippage was clearly noted during the test. Within the limitations highlighted by that variability, the results again do not show dramatic differentiation between the different exposure regimes or with unexposed specimens. It should be noted, however, that some of the bend counts for the salted conditions with 2- to 4-week exposures tended to be among the lowest values observed, while specimens exposed to only 1- to 2-weeks in the same or other environments tended to yield higher bend counts. The data available are not sufficient to conclude whether these are valid trends.

In general, considering the inherent scatter of the reverse bending test results, those did not reveal any strong and consistent degradation that could be well correlated with the exposure regimes evaluated. Caution is in order, however, as to the possibility of increasingly greater deterioration as the length of exposure increases. These observations merit more detailed examination in follow up work, either by modifying the test methodology to reduce scatter, or by testing a larger number of the archived specimens.

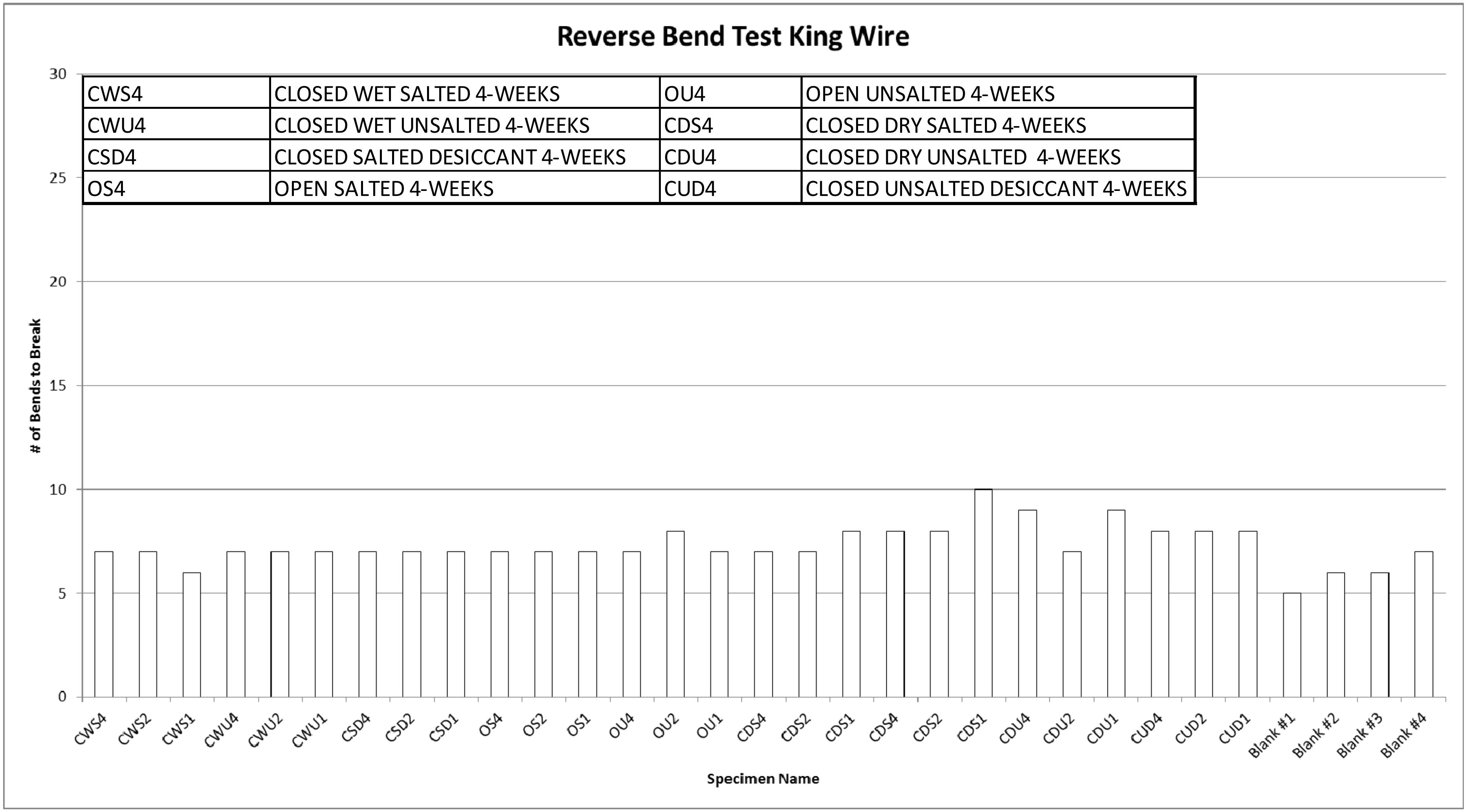


Figure 59 Reverse Bend Test Results for King Wire Testing

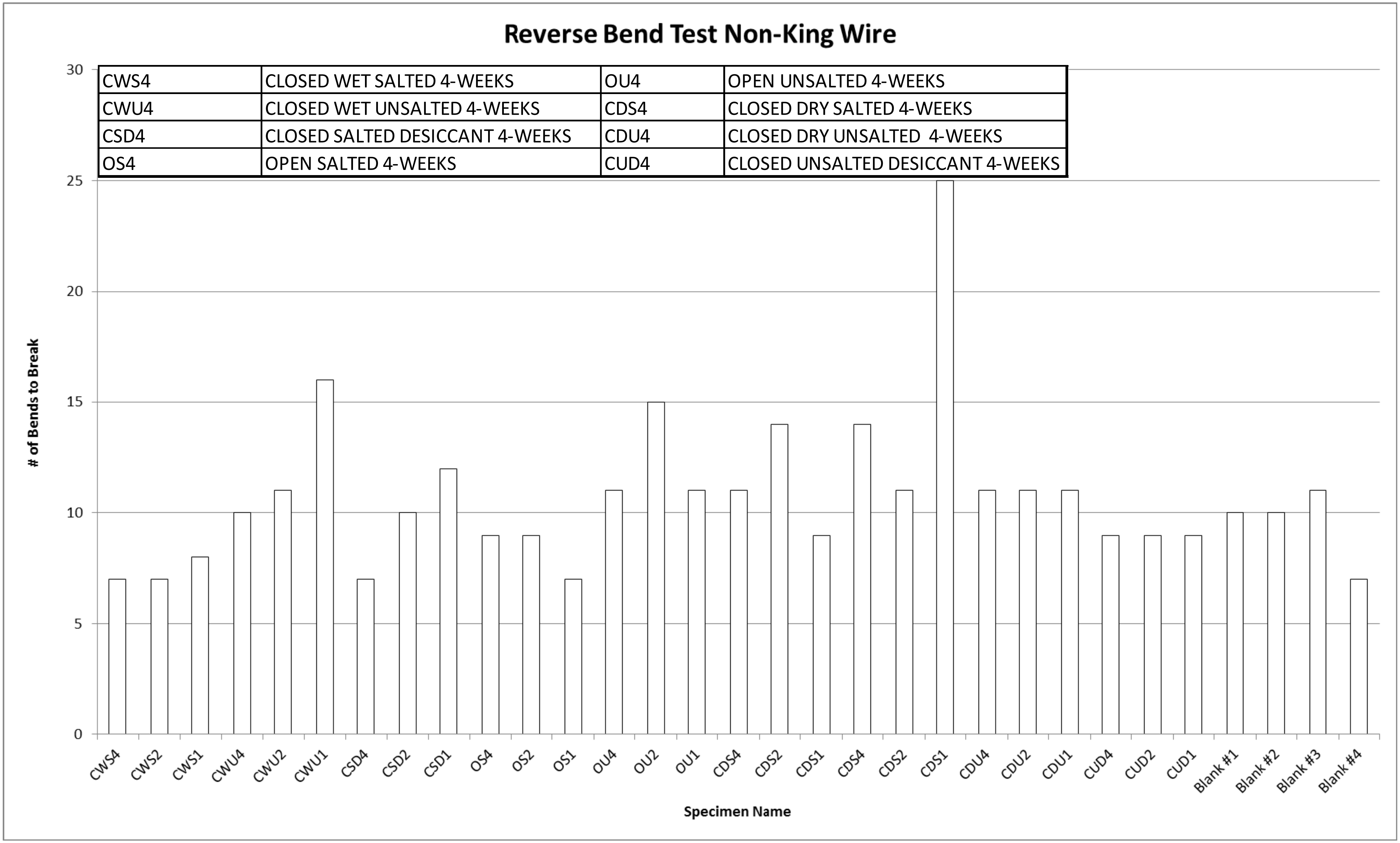


Figure 60 Reverse Bend Test Results for Non-King Wire Testing

4.7 Additional Assessment Results

Figures 61 and 62 exemplify wire appearances before and after light surface cleaning, resulting in ratings of 2 and 4 respectively. The picture scale used is given in (Sason, 1992). The summary of all results are shown previously in Table 5.

Figure 61 Specimen 97a 4 Week not Salted but Wet Exposed (Top) and after Cleaning (Bottom)

Figure 62 Specimen 106a 4 Week Salted and Wet Exposed (Top) and after Cleaning (Bottom)

4.8 Overall Observations

As detailed in Appendix C, the extension of the previous work conducted under Project BDK84 977-04 (Sagüés et al, 2011), where only unstressed strands were evaluated, to warm season conditions yielded results generally in agreement with the initial study and served to further validate those findings. The present investigation results from piles containing stressed strands have in turn generally extended the applicability of those earlier findings when in the presence of working stress levels.

As in the prior unstressed strand work, it was found in the pile tests that, in the presence of stress, corrosion in the ungrouted condition tended to be inconsequential, even over periods of up to 4 weeks, if the ducts did not contain entrapped water and the strand surface was not compromised. The pile tests also revealed that appreciable corrosion could rapidly develop in the presence of even a modest amount of trapped water, or if the surface of the strand experienced saltwater precipitation to an extent comparable to that obtained after one day of unprotected exposure near the seashore, and especially with a combination of both factors. The corrosion under those circumstances was not enough to seriously affect the ability of the material to pass the requirements of a standardized tensile test, but limited additional testing in a severe reverse bending mechanical regime and for the presence of hydrogen suggested that some adverse lasting effects could be developing under the more aggressive regimes evaluated. Surprisingly, there was little difference in results between closed and open ducts in the non-wetted and non-pre-salted strand conditions, but it must be recalled that cowls prevented direct rain exposure of the anchors in the test piles. Moreover, a rain event at the construction site that was visited (see Appendix A) was noted by the humidity test gauge inside a duct. Hence, the results of the pile tests in this regard must not be interpreted as an indication that capping the ends is not important.

It is to some extent reassuring (and consistent with the earlier work) to note that, throughout the pile tests, there was no clear difference between the behavior observed for the stressed strands and the unstressed strands exposed in the same ducts. Moreover, as noted earlier in the report, the absence of any spontaneous stressed strand failures in the test piles even after 4-weeks of sustained stress and with multiple specimens of sizeable length in the more aggressive exposure combinations, and the absence of any consistent indication of loss of strength or ductility in the tensile tests, suggest that propensity for brittle behavior was quite limited under the conditions examined.

Concerning construction practice, the results suggest that ungrouted exposures of up to two weeks as are being conducted at present have little detrimental effect, but only under conditions of strict water intrusion control and of avoidance of any salt deposition on the steel during the placement process. Longer exposures may still be possible without adverse effect, but the results showed that the effect of aggravating factors such as water intrusion or salt contamination of the tendon surface intensified with length of exposure, so tolerance to deviations from ideal practice would be reduced accordingly. The results also provided encouraging indication that the temporary use of desiccant in the caps may mitigate the adverse effect of having salt contamination on the steel surface.

5 CONCLUSIONS

1. Exposures for periods of up to 4-weeks of stressed, as-received strand placed in tendon ducts embedded in concrete and sealed with caps to represent normal practice and without any trapped water (closed, non-wetted condition), did not result in any appreciable deterioration as evaluated by visual appearance, standardized mechanical tensile testing, limited reverse bend testing, and exploratory hydrogen pickup measurements. These results were observed at both the inland and the seashore test sites.

2. Performance was similar to that indicated above, at both test sites, if conditions were the same but the anchorage end caps were not put in place, and the anchorage area was protected from rain (open, non-wetted condition). This finding, however, must not be interpreted as an indication that capping the ends is not important, as data from a construction site indicated an instance of increased humidity during a rain event in an open duct.

3. For the capped condition indicated above but including a modest amount of trapped water in the capped tendon (closed, wetted condition), appreciable amounts of rust on the strand surface were observed for both test sites, starting with as little as one week of exposure. Tensile test performance was not significantly affected, but the limited reverse bending and hydrogen content test results suggested the possibility of some adverse consequences.

4. Application of salt deposition on the strand, simulating in the order of one-day near-seashore exposure prior to placement in the ducts, resulted in surface rust development in the closed, non-wetted condition after periods as short as one week at both test sites. The surface rusting of pre-salting was strongly enhanced when the duct was in the closed, wetted condition, especially for the 2- and 4-week exposure regimes. However, mechanical performance per the standardized tensile tests was not appreciably degraded. The exploratory hydrogen content tests, especially for the longest test exposure and the closed, wetted condition, indicated the highest hydrogen buildup for this condition. Limited reverse bending test evidence suggests the possibility of some degradation as well; subject to more detailed examination in future work.

5. Limited laboratory tests confirmed the sensitivity of strand steel to hydrogen embrittlement at hydrogen levels that were larger than, but still in the order of, those measured in some of the strands exposed to the more severe testing regimes.

6. Placement of desiccant packets in ducts in the closed, non-wetted condition arrested much of the surface rust development when strand subject to prior salt deposition was placed in the duct, even for periods as long as 4-weeks, suggesting a possible means of controlling corrosion.

7. Throughout the pile tests there was no clear difference between the behavior observed for the stressed strands and the unstressed strands exposed in the same ducts.

8. While duly noting all the above conclusions, the absence of any spontaneous stressed strand failures in the test piles even after 4-weeks of sustained stress and with multiple specimens of sizeable length in the more aggressive exposure combinations, and the absence of any consistent indication of loss of strength or ductility in the tensile tests, suggest that propensity for brittle behavior was quite limited under the conditions examined.

9. Concerning construction practice, the results suggest that ungrouted exposures of up to two weeks as are being conducted at present have little detrimental effect, but only under conditions of strict water intrusion control and of avoidance of any salt deposition on the steel during the placement process.

REFERENCES

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

ASTM International, *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressing Concrete, ASTM A416*, 2006.

Corven, J. *Mid Bay Bridge Post-Tensioning Evaluation*, Final Report, Florida Department of Transportation, Corven Engineering, Inc. Tallahassee, FL, October 2001

Corven, J. *New Directions for Florida Post-Tensioning Bridges*, Volumes 1 through 10B, Final Report, Florida Department of Transportation, Corven Engineering, Inc. Tallahassee, FL, 2002-2004

Echevarria, V., " Concrete Diffusivity and its Correlation with Chloride Deposition Rate on Concrete exposed to Marine Environment", Masters of Science Thesis at Florida Atlantic University, Boca Raton, FL, December 2012.

Enos, D. G., and Scully, J. R. "A Critical-Strain Criterion for Hydrogen Embrittlement of Cold-Drawn, Ultrafine Pearlitic Steel", Metallurgical and Materials Transactions, Volume 33A, Pages 1-16, 2002.

FDOT (Florida Department of Transportation) Specifications and Estimates Office, Florida Department of Transportation *Standard Specification for Road and Bridge Construction*. Updated references available at http://www.dot.state.fl.us/structures/ Melbourne, FL : Florida Institute of Technology, 2013.

FDOT (Florida Department of Transportation) Structures Design Office, Florida Department of Transportation, *Structures Manual*, Tallahassee. Updated references available at http://www.dot.state.fl.us/structures/ Melbourne, FL : Florida Institute of Technology, 2008.

Fernandez, J. "Stress Corrosion Cracking Evaluation of Candidate High Strength Stainless Steels for Prestressed Concrete", Master's Thesis, University of South Florida, Tampa, FL, December 2011.

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

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

ISO 7801 " Metallic Materials-Wire-Reverse bend Test", International Standard Organization Report ISO 7801-1984, 1984.

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

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

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

Montgomery, E., Curran, J. C., Calle, L. M., Kolody, M.R., "Time Scale Correlation between Marine Atmospheric Exposure and Accelerated Corrosion Testing", NASA Kennedy Space Center Report Number KSC-2012-049 , August 2012.

Perrin, M., Gaillet, L., Tessier, C. and Idrissi, H, "Hydrogen Embrittlement of Prestressing Cables" Corrosion Sci. Vol. 52, pp. 1915-1926, 2010.

Powers, R.G., Sagüés, A.A., Virmani, Y.P. "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.

Reis, R., "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., "Corrosion of post-tensioned strands at SFOBB Skyway replacement project", Appendix B in Reis 2007.

Sagüés, A., Karins, F.C. and Lau, K. *Corrosion characteristics of post-tensioning strands in ungrouted* ducts (Final Report for FDOT Project BDK84 977-04). Melbourne, FL : Florida Institute of Technology. Editorial Review for FDOT Research Report BDK84-977-22, 2011.

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

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

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

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

Shipilov, S.A. “Solving Some Key Failure Analysis Problems using Advanced Methods for Materials Testing”, Engineering Failure Analysis 14 , p. 1550, 2007.

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

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

West, J. S., Larosche, C. J., Koester, B. D., Breen, J. E., and Kreger, M. E. "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, 1999.
.

APPENDICES

Appendix A: Selmon / I-4 RH Measurements and Comparisons to Testing Piles Used for Stressed Strand Testing

Site visit and testing was conducted by Michael Hutchison under the supervision and assistance of *PCL/AW, A Joint Venture.* This visit was part of an investigation of the duct environment in post-tensioned (PT) bridges prior to grouting. Relative humidity (RH) and temperature were measured in 11 ducts which would become permanently part of the Selmon / I-4 connector bridges. Four (4) visits in total were conducted to both place probes and subsequently remove them. The visits were on May 8th, 14th, 21st, and 22nd, 2013. Probes were placed within PT ducts in three (3) locations: a constructed span (10-8), a cantilevered span (10-11) and in two segments still in the casting yard (also 10-11). Figure A1 shows a typical box girder section prior to placement. Figure A2 illustrates the approximate locations of ducts within a typical box girder segment and also which ducts had probes inserted. Probe placement was determined based on duct availability and accessibility.

Figure A1 Typical box girder segment resting on ground beneath span 10-11 Note some ducts left uncapped. No RH probes were placed in this segment, pictured only for overall appearance information

Only one significant rain event took place during the testing period, on the afternoon of 5/20. The event is noted by an arrow in the time records.

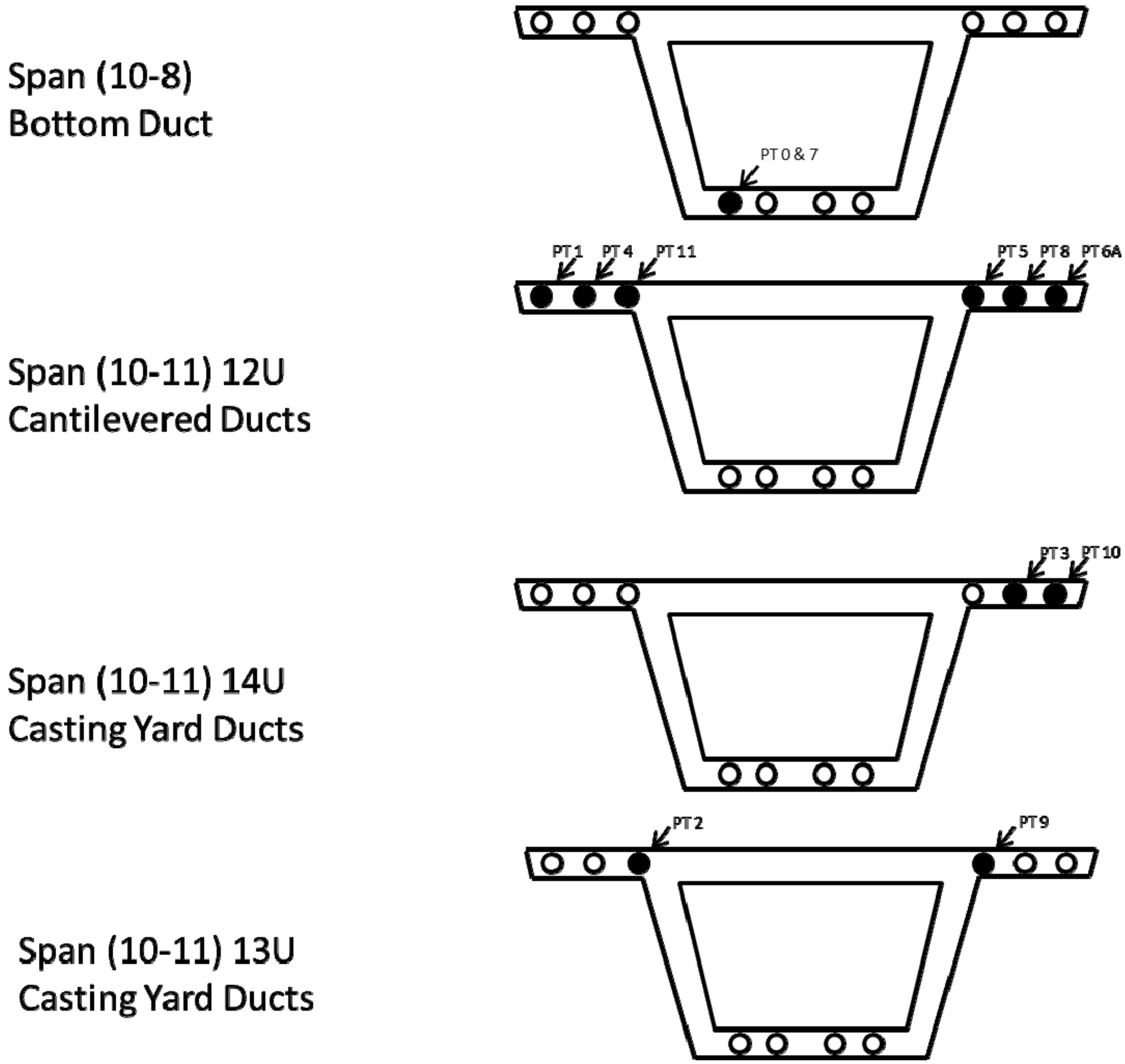
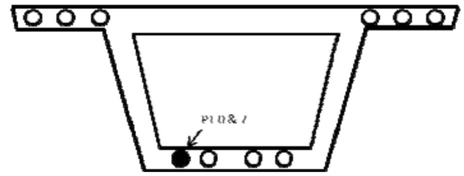


Figure A2 Probe placement and duct locations within typical box girder segments

Completed Duct (10-8)

Span (10-8)
Bottom Duct



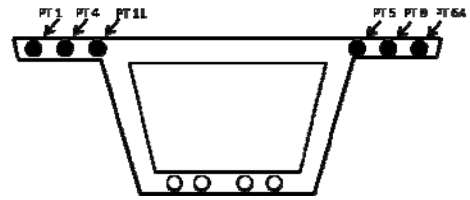
Two probes, placed in span 10-8, were placed together next to each other in a completed duct with permanent plastic caps and awaiting strand placement. Probes installed were PT 0, and PT 7. Figure A3 shows the end cap inside of which the probes were placed. Figure A4 shows the labeling of the segment within the span, which was already placed at its service elevation.

Figure A3 Permanent plastic end cap and grouting port in span 10-8

Figure A4 Spray paint used by *PCL/AW* for identification of segment location and casting date

Cantilever Ducts (10-11)

Span (10-11) 12U
Cantilevered Ducts

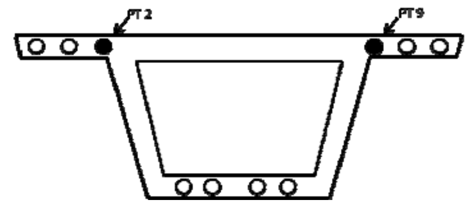


Ducts monitored in span (10-11) were from the upper row of a cantilevered section in segment 12U, already at service elevation. The probes used in this area were: PT 6A, 8, 5 11, 4, & 1. The probes were placed in the interior section of the duct that would become coupled to a nearby segment later during construction. Ducts were sealed with temporary plastic caps. Figure A5 shows the bottom portion of an adjacent cantilevered section. The caps used to seal the cantilevered ducts were identical to the one seen in Figure A5.

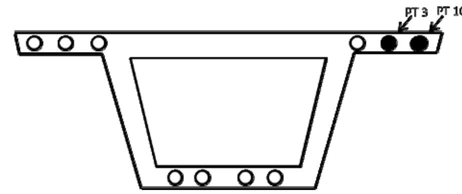
Figure A5 Uncapped PT strand ducts in partially constructed span (10-11). Probes not placed in this segment

Casting Yard Ducts (10-11)

Span (10-11) 13U
Casting Yard Ducts



Span (10-11) 14U
Casting Yard Ducts



Two (2) box girder segments from the casting yard, both to be installed in span (10-11), were chosen for probe insertion. These segments were still on the ground. During span erection, these segments were to sequentially follow the cantilevered segment mentioned previously. The upper ducts near the inside of the segment wings (left side in Figure A6) had probes positioned within to emulate similar concrete cover as in experiments that are part of an ongoing investigation at USF. Segment 13U (PT 2 & 9) had probes placed within PT strand ducts, where segment 14U had probes placed in PT bar ducts (PT 3 & 10). Some ducts were found to have the caps open upon inspections (Figure A7).

Figure A6 PT strand (left) and PT bar ducts (right) with temporary end caps in casting yard (14U, used for PT bar duct RH record). Note uncapped duct in nearby segment. No picture for 13U

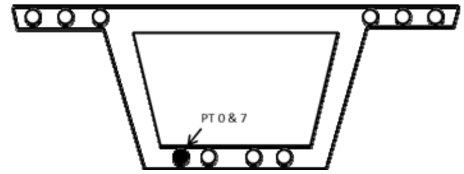
Figure A7 Uncapped PT strand duct in casting yard segment (14U, no probes placed in this duct)

Relative Humidity and temperature were measured with Omega 'OM-EL-USB-2-LCD' RH and Temperature recording probes, which acquired data at 30-minute intervals. Prior to duct placement all probes were placed successively in two (2) chambers with saturated salt solutions for calibration. The saturated solutions of sodium chloride (NaCl) and potassium chloride (KCl) in small sealed containers create an environment of fixed relative humidity of ~76% and ~86% RH, respectively, provided that temperature and pressure remain relatively constant. The probes were then calibrated against these fixed points by adding or subtracting the appropriate amount to the raw records. All data presented below are after calibration. The probes were interrogated via a USB port after extraction from the ducts. Dates are marked at midnight, the beginning of that day.

Results are presented in Figures A8 through A20 for each element monitored. Relative humidity (%) is plotted in black and temperature (°C) in red, both on the same scale. The green horizontal line denotes 80% RH, a value commonly associated with conditions that would cause deposition of a moisture film on the steel surface (if it were in place) capable of causing visible corrosion.

Completed Duct (10-8) - RH

Span (10-8)
Bottom Duct



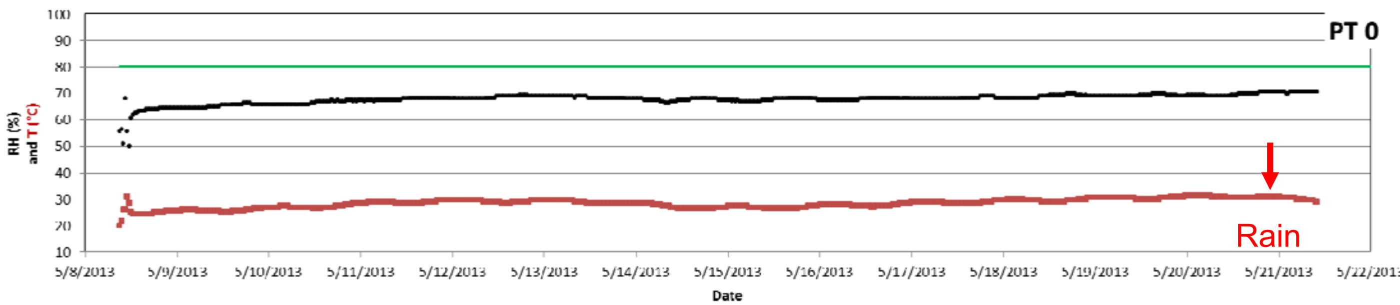


Figure A8 RH of probe PT 0 in completed duct (permanent cap)

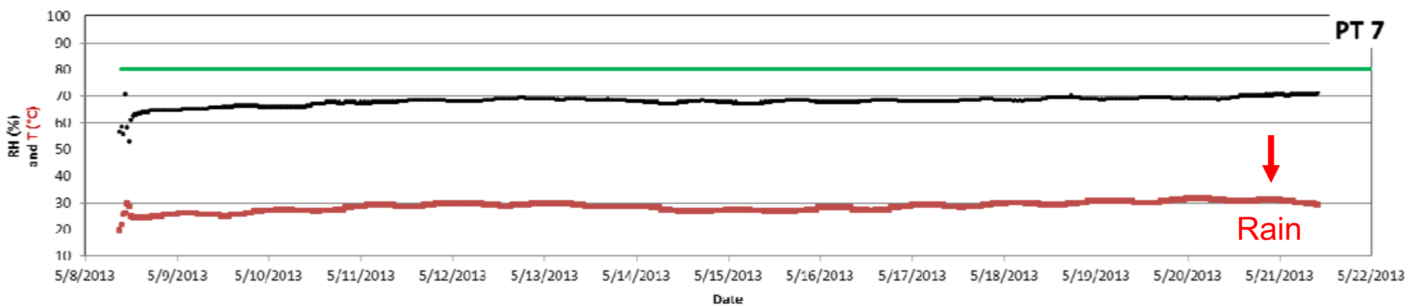
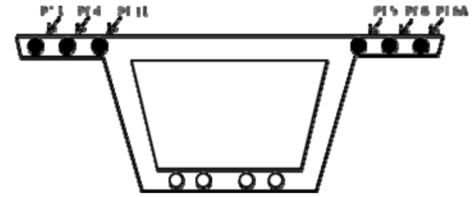


Figure A9 RH of probe PT 7 in completed duct (permanent cap)

The RH in this duct never exceeded 75% RH and stayed stable within a small range of variability. The temperature also remained mostly constant, varying marginally from day to night. Bottom ducts are not only insulated by their concrete cover, but the shade from the above deck and the air in the crawlspace above also serve as insulation. This insulation is evidenced by the lack of fluctuation in temperature from day to night.

Cantilever Ducts (10-11) – RH

Span (10-11) 12U
Cantilevered Ducts



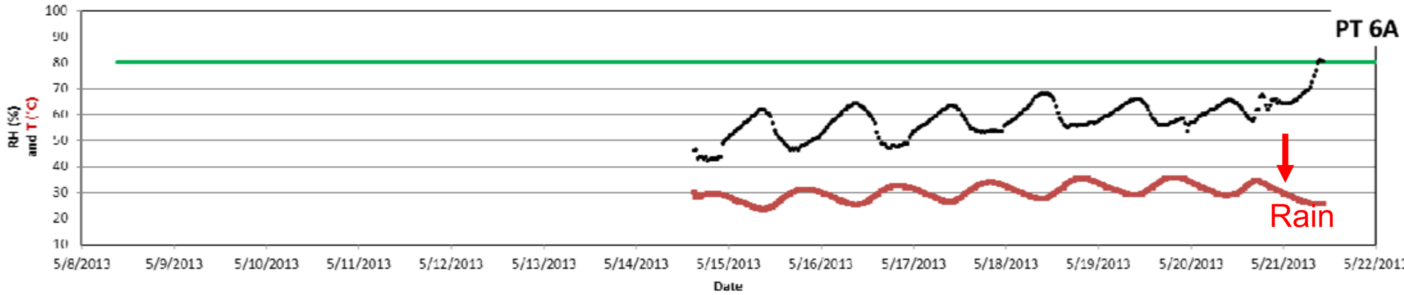


Figure A10 RH of probe PT 6A in cantilevered duct

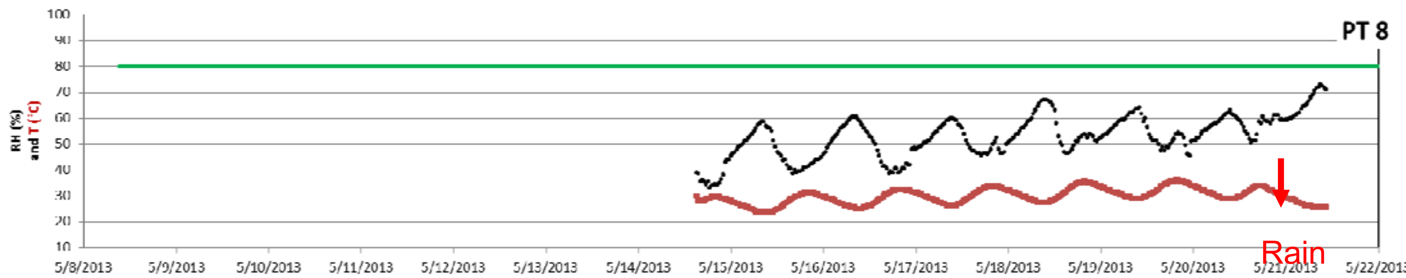


Figure A11 RH of probe PT 8 in cantilevered duct

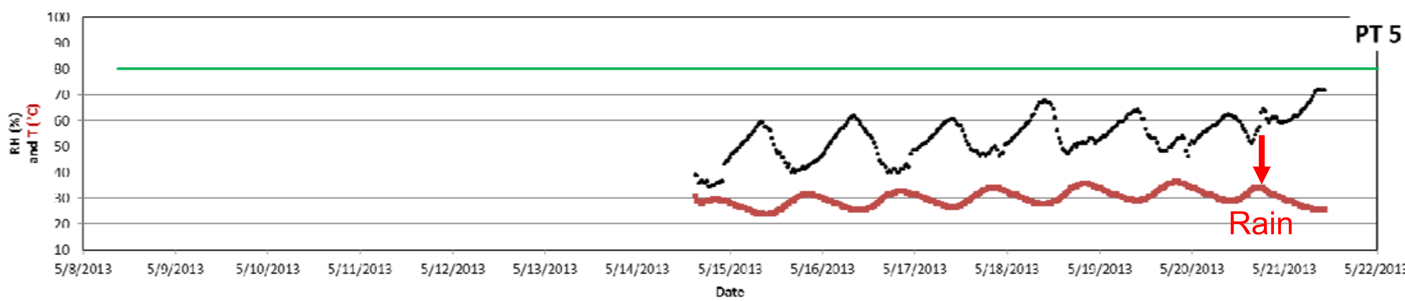
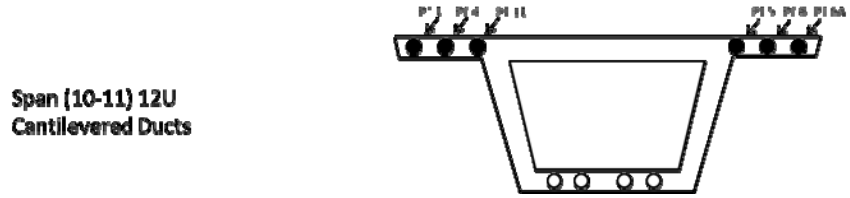


Figure A12 RH of probe PT 5 in cantilevered duct



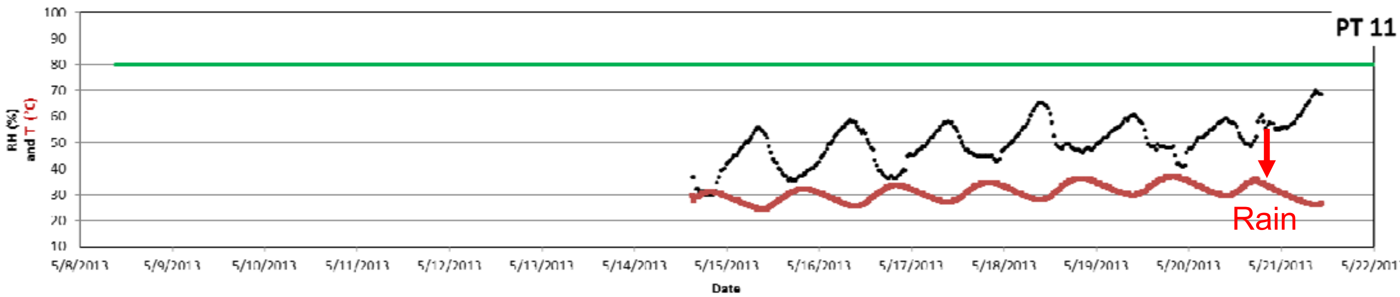


Figure A13 RH of probe PT 11 in cantilevered duct

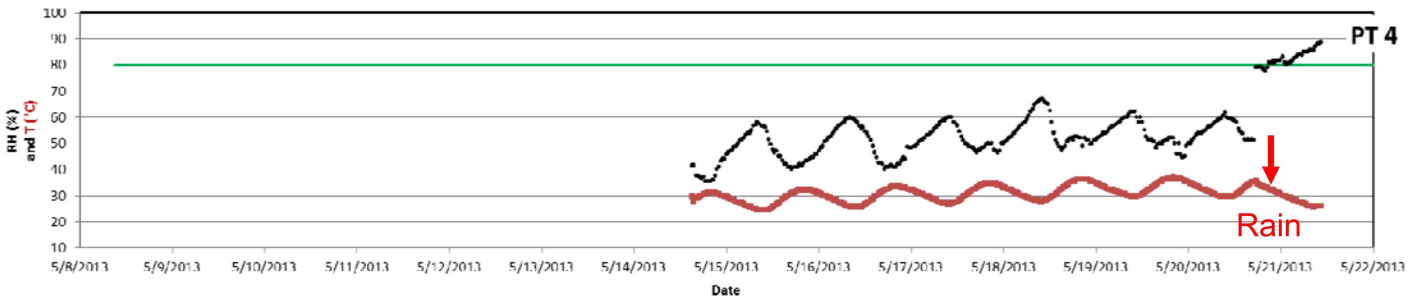


Figure A14 RH of probe PT 4 in cantilevered duct (visible moisture on extraction)

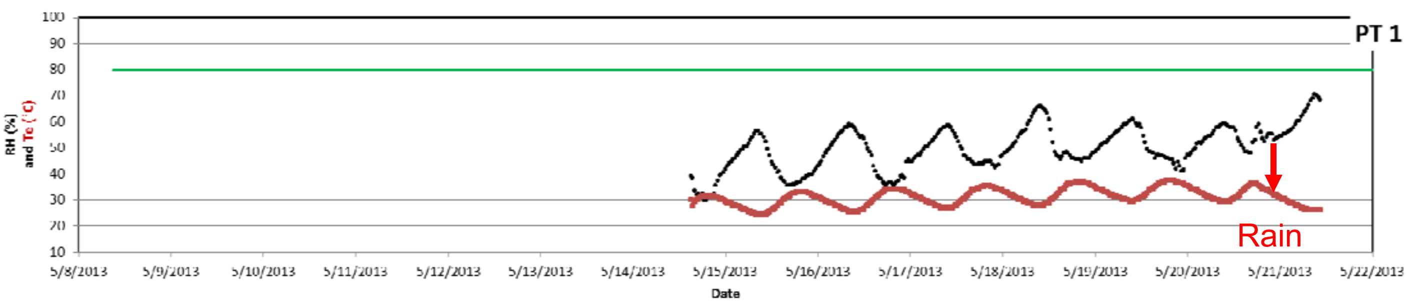
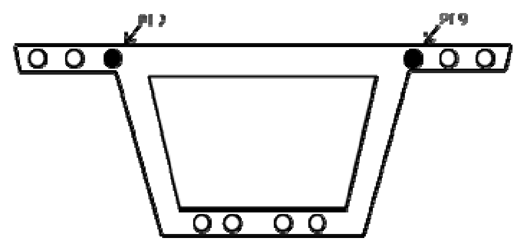


Figure A15 RH of probe PT 1 in cantilevered duct

The RH in the ducts of the cantilevered section was subjected to large cyclic daily fluctuations. For most of the monitoring period, as the temperature dropped during the night the RH in the ducts increased to its cycle maximum and conversely, when the temperature increased during the day, the RH decreased, following typical behavior expected from a system without much condensed water. Most ducts maintained a RH below 75%, with the exception of PT 6A and especially PT 4 near the end of the measurement timeframe, for which marked increases in RH coincided with a rain event. In PT 4 the RH increase was accompanied by visible condensed moisture presence at the time of probe extraction, suggesting liquid water intrusion that would have resulted from a particularly poor seal by its temporary cap.

Casting Yard Ducts (10-11) – RH



Span (10-11) 13U
Casting Yard Ducts

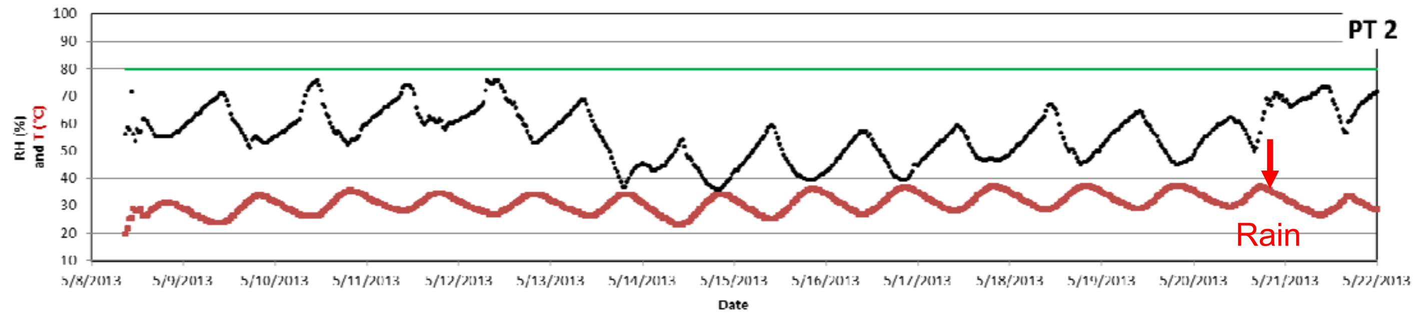


Figure 17 RH of probe PT 2 in casting yard strand duct (14U)

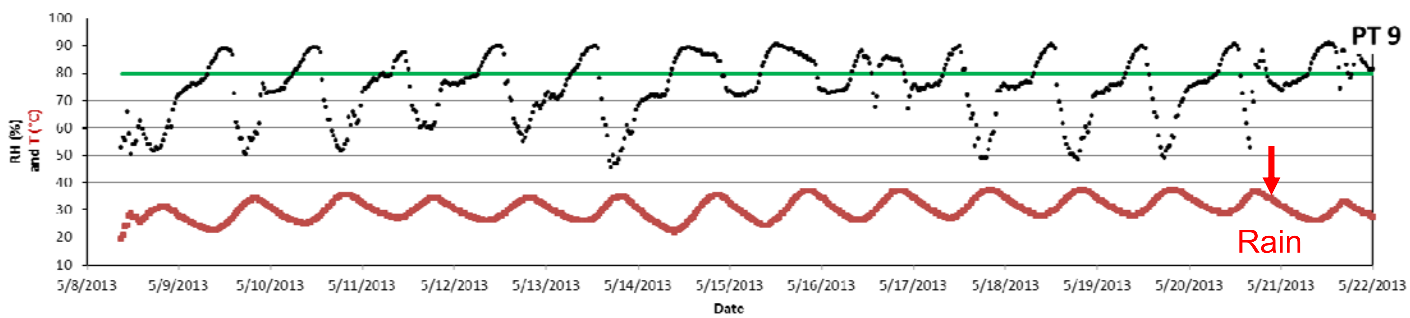
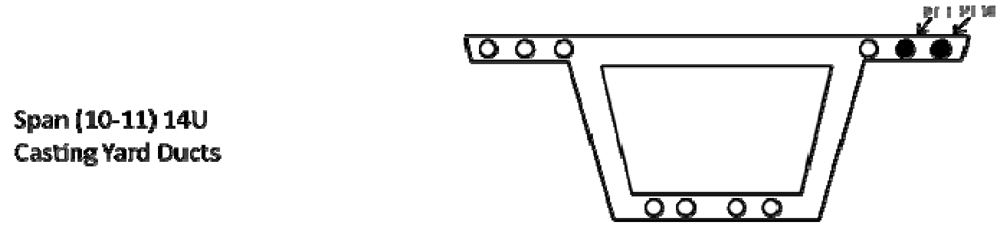


Figure A18 RH of probe PT 9 in casting yard strand duct (13U)

Segment 13U had two probes (PT 2 & 9) placed in two different PT strand ducts at either side of the deck segment. The RH values, expected to be similar, showed a clear differentiation, despite having identical sealing methods, duplicate environments, and sharing the same segment. The RH readings from the probe in PT 9 peaked regularly above 80% while those from PT 2 showed significantly drier conditions. This difference indicates that otherwise similar ducts, regardless of care and handling, may still have quite distinct internal environments. Imperfect duct sealing and water intrusion could both be responsible for this disparity.



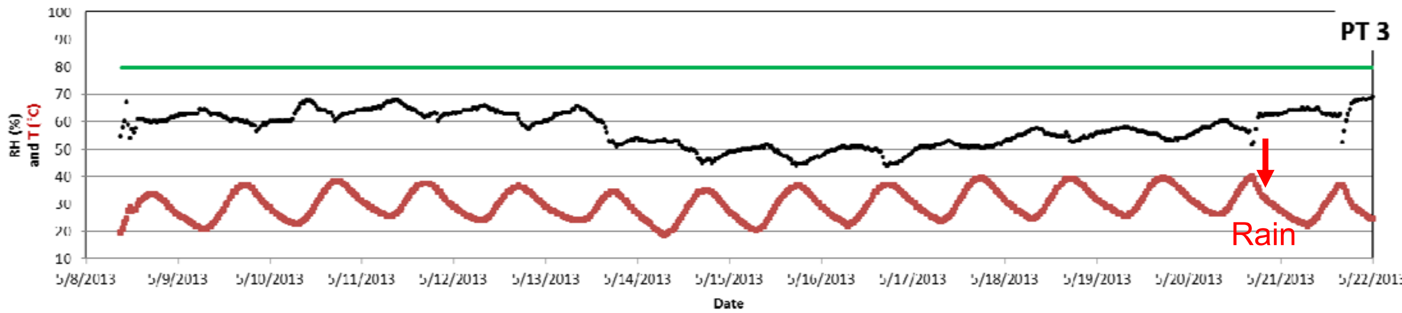


Figure A19 RH of probe PT 3 in casting yard bar duct (13U)

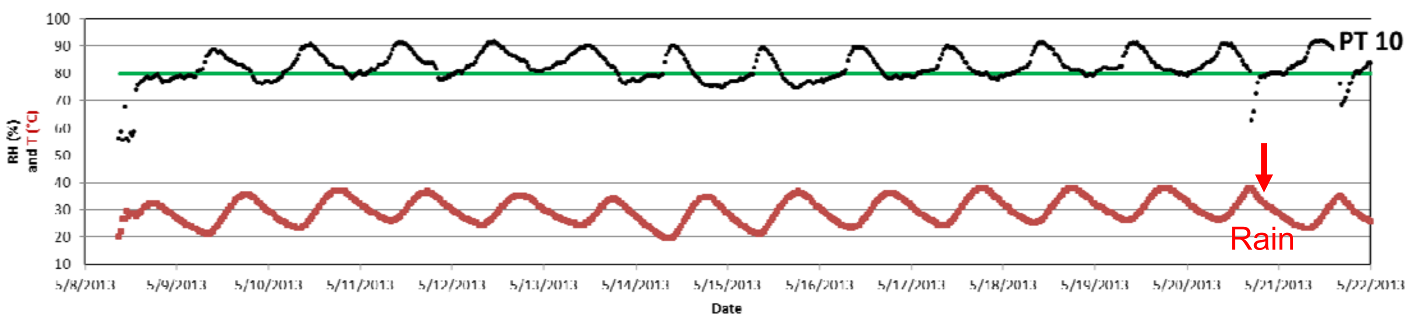


Figure A20 RH of probe PT 10 in casting yard bar duct (14U)

PT bar ducts in Segment 14U, (PT 3 & 10) also showed disparity (as in 13U) between seemingly identical ducts. Again one of the probes (PT10) showed high humidity levels while the other indicated much drier conditions. The high humidity cases appear to indicate that the seal offered by the duct caps was insufficient in those cases and rainwater accumulation was taking place. It is noted that fluctuations in RH seem to be more pronounced in the larger diameter strand ducts than in the smaller PT bar ducts.

Appendix B: Stressing Procedures, Salting Procedures and Specimen Labeling and Preparation

<u>Labeling, Exposure, and Stressing Procedures Developed</u>

The system of labels for the strand specimens was developed and implemented. Figure B1 shows the diagram of the color-coded labeling system.

As shown below

- Enamel Paint within 2” of dead end
- Higher number ducts will be denoted with base 5 (rather than base 10) e.g., PT 7 will have a yellow stripe with a red stripe (5+2=7).
- ‘Top’ location for photography purposes – Notch at dead end

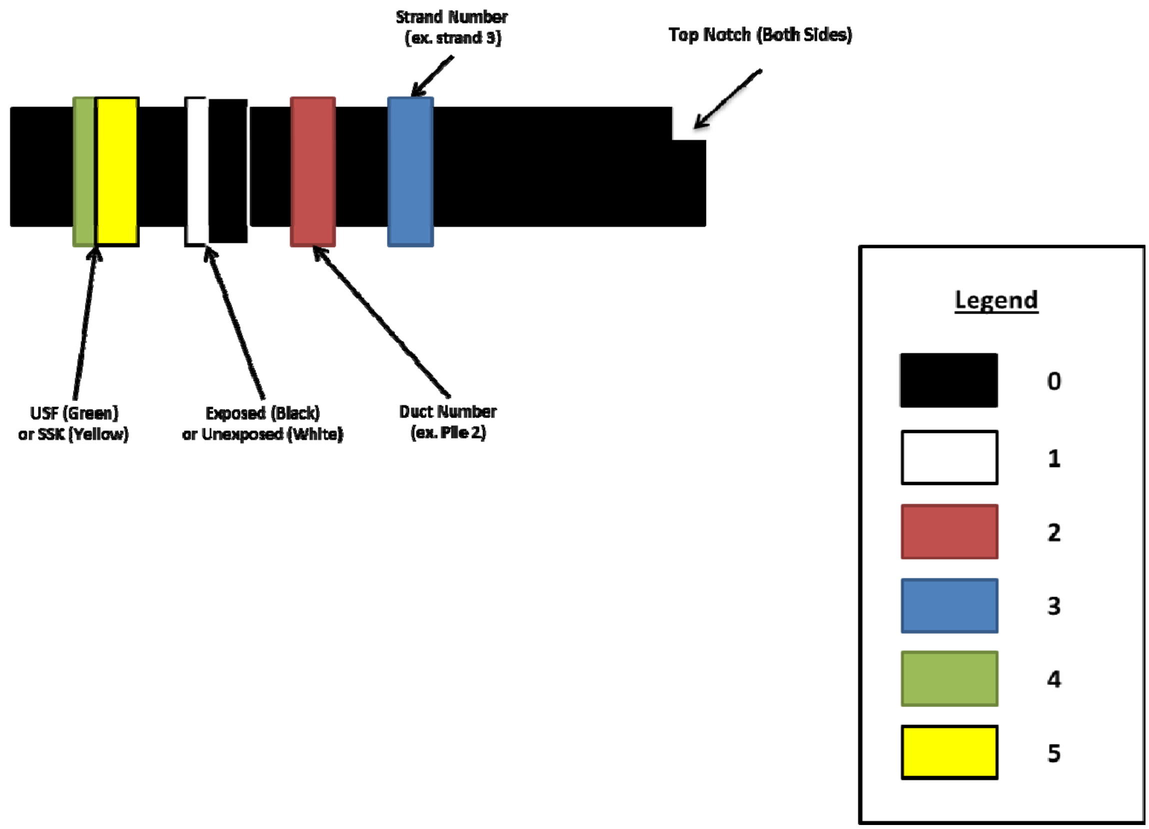


Figure B1 Diagram of Color-Coded Specimen Strand Labeling System

For specimens to be exposed at the Sunshine Skyway (SSK) location in half of the piles the strands will be exposed to a simulated salt spray precipitation equivalent to having left the strands exposed to the atmosphere (no rain) for one day. The target chloride deposition level was set to approximately 100 mg Cl^{-} m^{-2} day^{-1}, reflecting the values determined earlier using the wet candle method.

Application of Salt Exposure Spray

A synthetic sea water solution was prepared, mixing as directed to produce a salt water spray solution. The salting protocol to follow is:

- Prepare simulated sea water solution by mixing 3.5 grams of solid synthetic sea water powder per 100 g of sea water solution (weight 3.5 grams of powder in 100 ml beaker, and add DI water to 100 ml level) .
- Place protective surface (paper towel) on table on floor, which is 0.6 meter wide, 7 m long.
- Lay out strand exposure group touching side by side (~ 0.15 m wide band) on covered table.
- Place 0.1 x 0.2 m pre-weighed & record to 0.1 mg or better precision, aluminum foil piece, near center of strand group, next to strands.
- Fill spray bottle with 18.4 g simulated seawater solution.
- Spray strand bundle and base surface from a height of 60 cm, over a width of 50 cm so as to cover evenly central 0.5 m of surface and bundle (area ~3.5 m^2).
- Repeat spraying back and forth along strands until bottle is empty.
- Allow aluminum foil to dry for 10 minutes. Place foil in oven at 105 ^{o}C for 10 minutes. Remove from oven and close foil on center to avoid hygroscopic water pickup.
- Record the weight of the foil in balance to 0.1 mg precision. The difference in values between initial weight and final dry weight is the actual amount of salt weight deposited on the foil.
- Using foil surface area versus weight of salt measured to determine approximate amount of salt applied to surface of strands (it should be ~2 mg of salt to show 100 mg Cl^{-} m^{-2} day^{-1}). On conversion to chloride ion only it should correspond approximately to the target value.

Stressing Procedure

The step-by-step stressing procedure that will be used for both the USF and Sunshine Skyway Pile locations is as follows:

- For applicable strands, expose to simulated salt solution (details above)

- Transport Strands to Location
- Remove Cowls, End Caps, RH probes and loosen bellows for all piles
- Set block separation at 12” using template for all piles
- Using electrical tape, cover the end of the strands which will be inserted
- Feed the strands through the duct ensuring strands overlap
- Lubricate the inside wedge plate surfaces with graphite/oil (to ease removal of wedge pieces)
- Lubricate and Install wedge pieces (graphite/oil, 2 for each strand)
- Once all strands are in place, place wedge plates and ensure strands have braiding
- Double check all steps and strand setup
- Ensure all parties are at a safe location and begin stressing ~85% GUTS (8000 psi –jack pressure)
- Add protective sleeves to strand ends (for cutting)
- Cut off strand ends to <2” exposed from the wedge plate surface with an angle grinder
- Repeat for all strands
- Spray 100 cc of DI water in wet ducts through RH port with finger sprayers
- Retighten bellows; replace end caps, RH Probes and covers, and cowls.

Appendix C: Extension of Project BDK84-977-04 Experiments to Warm Season Conditions

C.1 Testing Platform Design

Two facilities were available from the previous investigation (Sagüés et al., 2011) and used for the present unstressed strand study. The facilities were designed to house eight (8) full sized ducts currently used in practice albeit shorter in length than PT duct used in actual bridges. Each facility consists of a hinged roofing enclosure which house eight (8) ducts each. The ducts were sheltered from direct rain on the top and sides, but open to the outside at the ends. The duct segments consisted of polypropylene corrugated sections (PPEX3 3-in internal diameter, 3.6-in external diameter) and transparent polyvinyl chloride (PVC) sections (3-in Sch-40 Harvel™ Clear PVC). The transparent portions were added for in situ visual inspection. Ducts were approximately 20 feet in length and the roof enclosure extended two feet on each side, Figure C1 and Figure C2 display the facility design. Duct sections contained a sag in the center to reproduce conditions used in external PT tendons which have intentional sags secured by deviator blocks. Four vent ports (used in construction for grouting purposes) for each duct was installed at fifth points. One of these central vent ports for each duct housed a relative humidity and temperature probe (Omega OM-EL-USB-2-LCD) as shown in Figure C3.

Figure C1 USF Duct Facility in the Open Position

Figure C2 SSK Duct Facility in the Closed Position - Sunshine Skyway Bridge Main Span and Generator Control Room in the Background

Figure C3 Relative Humidity & Temperature Probe Housings Attached to Ducts via Vent Port and Secured with Wood Boards and Zip-Ties

The other would house a separate water reservoir for the ducts which required it. Water level was marked and refilled as needed, as seen in Figure C4.

Figure C4 Water Reservoir Attached via Vent Port (left) and Closed Vent Port Covered with Bug Shield (Right)

A galvanized nail was attached via a stainless steel hose clamp (Figure C5) to simulate the effects (if any) of a galvanized anchorage system on the corrosion propagation of the strands.

Figure C5 Strand Group Ready for Duct Insertion with Galvanized Spike Secured with Stainless Steel Hose Clamp

The two facilities were located at the University of South Florida and by the North abutment of the Sunshine Skyway Bridge in St. Petersburg Florida; the former to represent a milder inland environment and the latter, a more aggressive shoreline environment. Four ducts conditions duplicated at both facilities, realistic of what may occur during bridge erection, were simulated. ‘Dry’ ducts indicate that there was no water added to the ducts and were kept dry with the exception of moisture from the outside air in those ducts which were exposed to the external environment. ‘Wet’ ducts indicate that the duct was kept at 100% relative humidity through an attached water reservoir and additionally ~100 cc of deionized water was intentionally splashed in the center two vent ports (50 cc each port) of those ducts at the beginning of the experiment. The duct conditions used are listed in Figure C1.

Table C1 Duct Environment Conditions

Duct	Dry / Wet	Sealed / Open
Ducts 1 & 5	Dry	Sealed – Both Ends
Ducts 2 & 6	Dry	Open - 1 End
Ducts 3 & 7	Wet	Sealed - Both ends
Ducts 4 & 8	Dry	Open – 2 ends

At the beginning of the experiment five strands were placed in each of the ducts. One strand from each duct was then extracted after one, two, four, and eight week exposures. The duration periods were intended to straddle a plausible range of exposures, with the 8-week period as a somewhat extreme value. In addition, an opportunity arose to investigate the effects of very prolonged exposure whereby one strand in each duct, left over from the previous project (Sagüés et al., 2011) and with a total exposure time of 9-months was present at the beginning of the experiment. Those strands were removed for testing before commencing the present exposures. Some of the 9-month wet exposed strands were in ducts with a vapor-phase inhibitor. As the results both from the previous study and the present concur that inhibitor presence had no “well-defined effect” on the corrosion propensity for those strands (Sagüés et al., 2011), the results from all 9-month wet exposed strands will be designated as such without specifying whether inhibitor was present or not.

C.2 Results and Discussion

C.2.1 Visual Appearance

The results from photographic documentation of the strand both in the initial, as extracted and cleaned condition are presented in Section C.2.2. The corrosion observed on the ends of the strands did not appear to have been influenced by the presence of the galvanized spike.

Since conspicuous corrosion was observed only in the wet ducts and the longest term exposures (especially for the supplemental 9-month exposed samples that became available from the previous investigation), detailed observations addressed mainly those conditions. Wire samples taken from the supplemental 9-month wet exposed strands showed conspicuous localized corrosion

The prevailing evidence obtained in the present unstressed study did not show major disparity with results acquired within the prior investigation (Sagüés et al., 2011). The prior investigation was conducted in the late fall and early winter months, where the present work was conducted in the late summer. In the previous study, shallow pitting was present after 8-weeks of exposure (longest tested duration) in ducts with wet conditions but with no correlated loss of mechanical properties. Corrosion development in this investigation showed similar morphology to that found previously. Likewise, strands within the most aggressive environments in the same exposure schedule as in the previous work did not show any dramatic degradation in performance as tested.

C.2.2 Visual Evaluation of Unstressed Strand

Figure C6 Typical As Received Condition of Strands Prior to Exposure

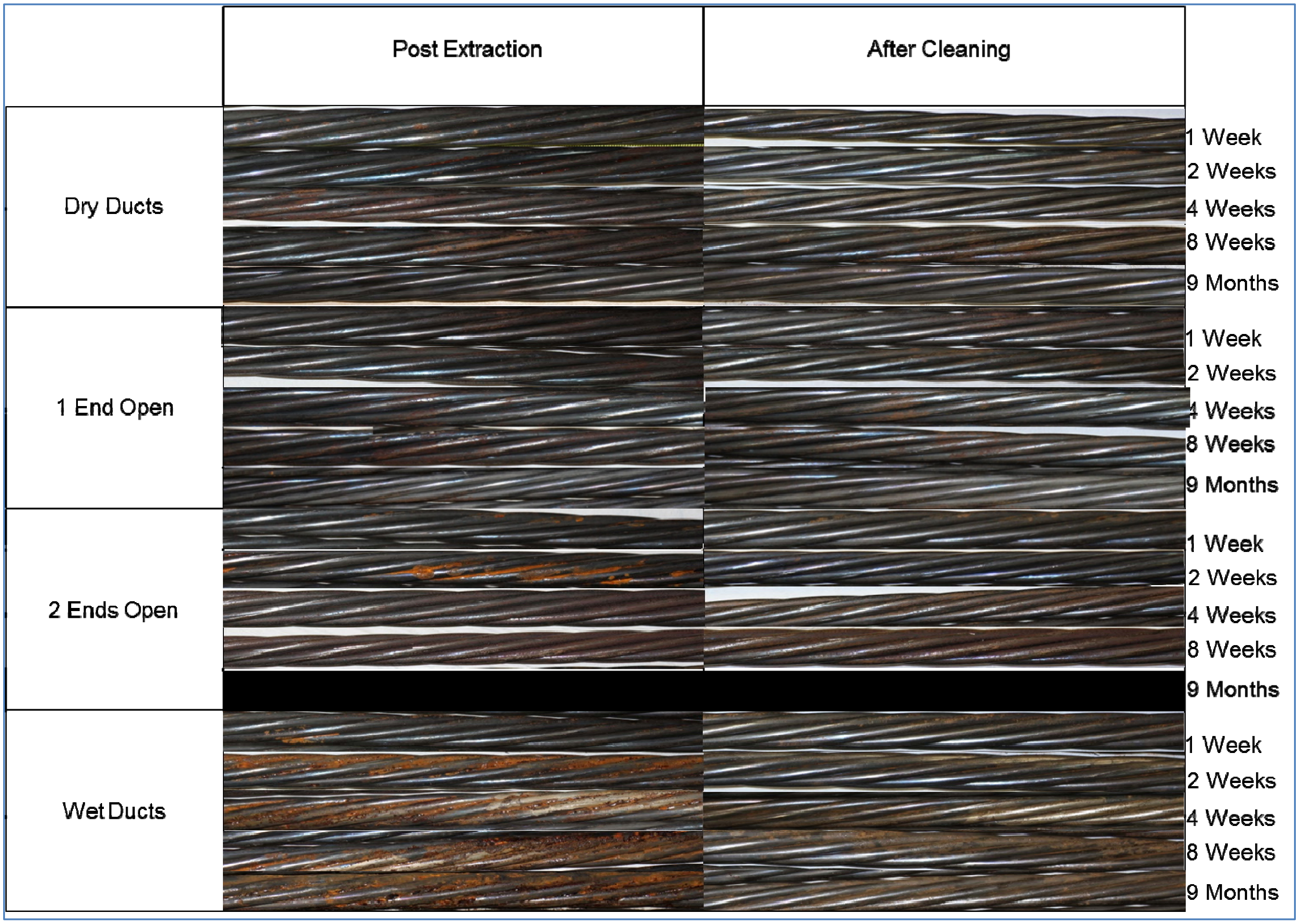


Figure C7 Duct Condition Comparison of Exposed SSK Strands

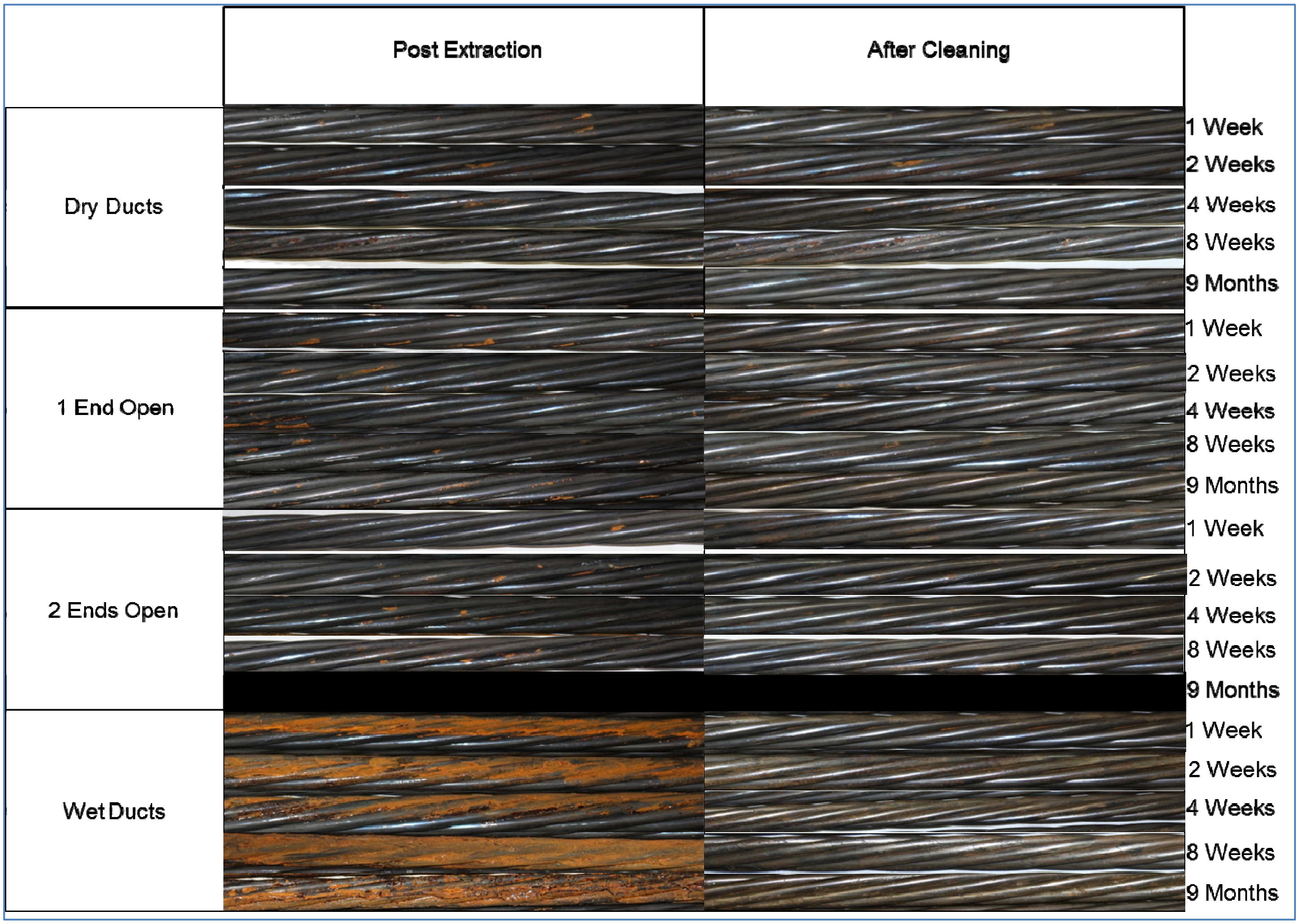


Figure C8 Duct Condition Comparison of Exposed USF Strands

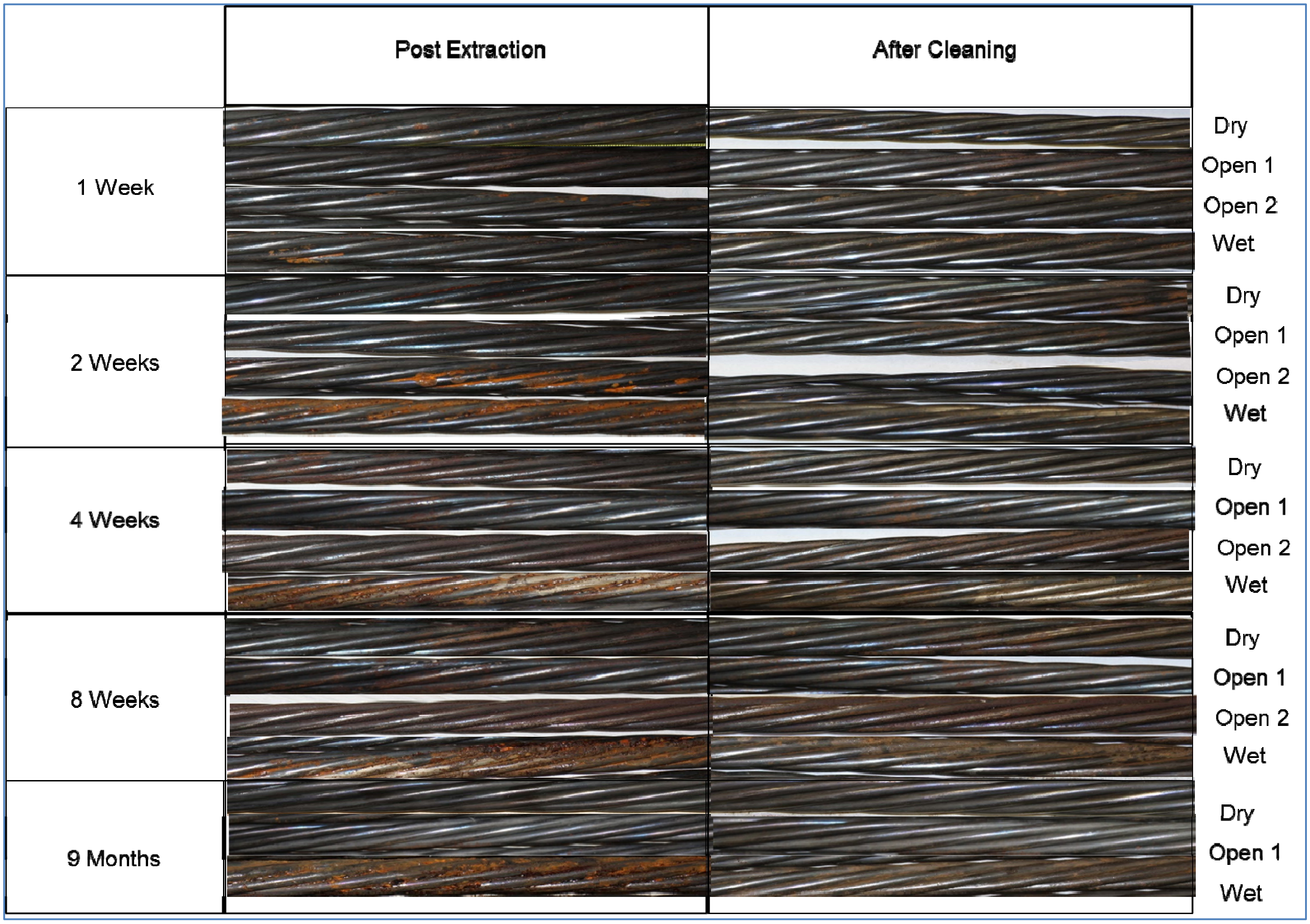


Figure C9 Exposure Length Comparison of Exposed SSK Strands

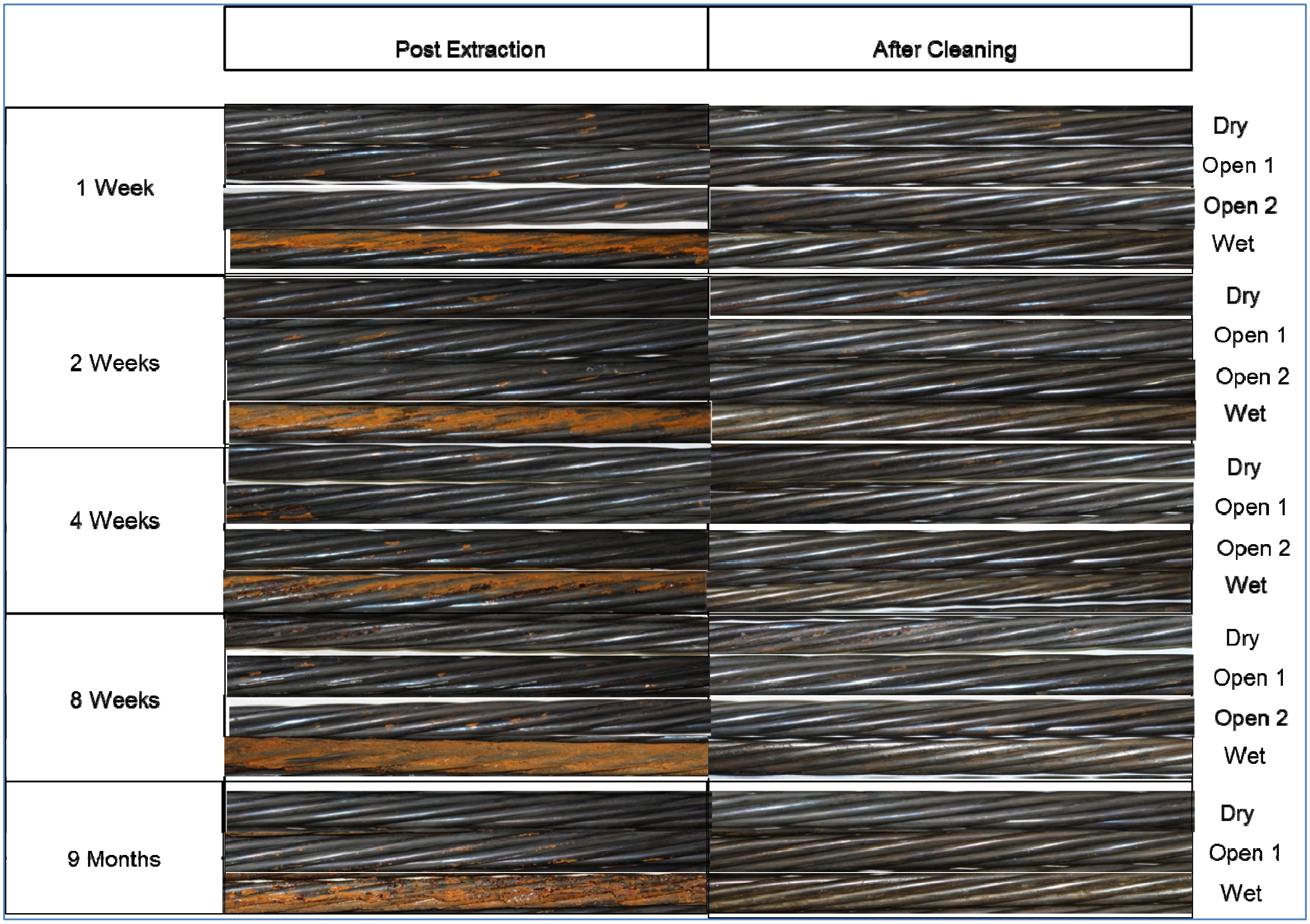


Figure C10 Exposure Length Comparison of Exposed USF Strands

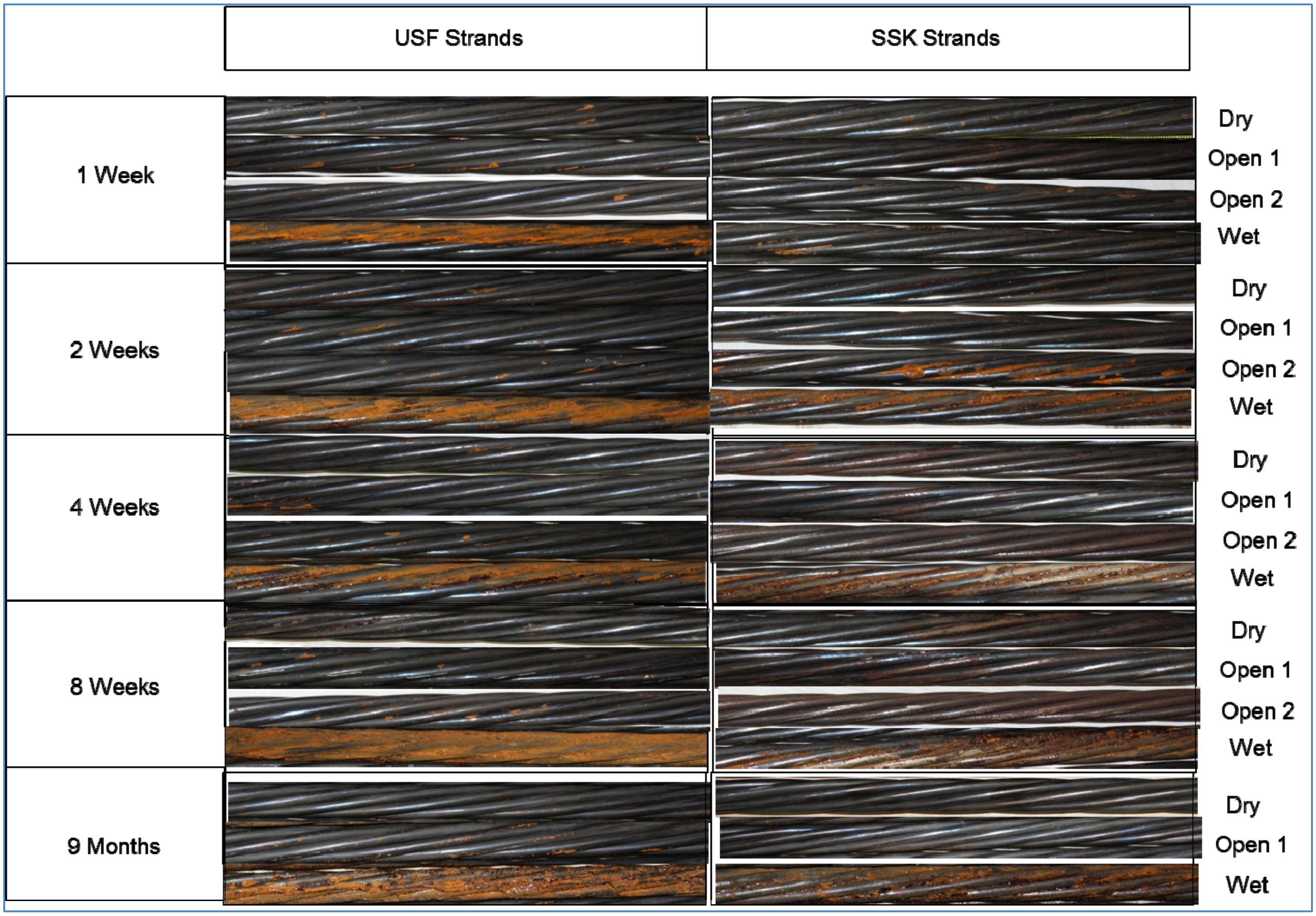


Figure C11 Environment Comparison of Exposed Strand - As Extracted

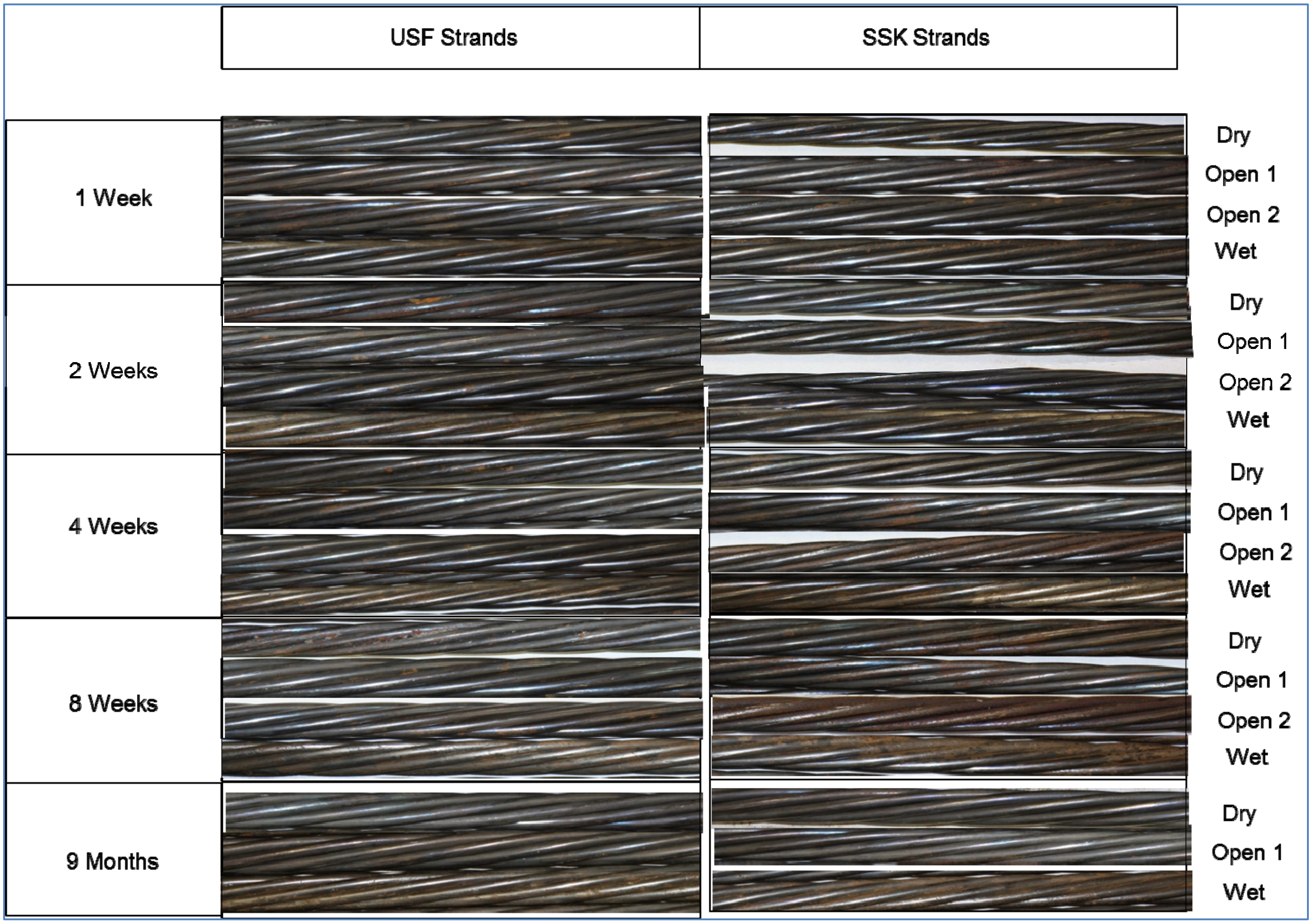


Figure C12 Environment Comparison of Exposed Strand – Cleaned

C.3 Tensile Testing

Three performance descriptors were evaluated from the results of the tensile pull test: total load at failure, total elongation, and load at 1% elongation. These values were then compared to the mechanical performance criteria as specified by ASTM A416 (ASTM International, 2006). The graphs in Figure C15 through Figure C26 show the cumulative fractions of each respective category. The vertical red lines indicate the ASTM specified requirement for satisfactory performance. Major slippage occurred when testing some strands. The cause was loss of gripping due to either improper application of the silicon carbide (SiC) at the ends, or failure to suitably clean the jack grips before each sample was tested. Samples which displayed obvious grip slippage are not represented in the following data. Figure C13 shows the samples ready for testing with SiC coated ends. Figure C14 shows a sample break and the fully engaged grips used for testing.

Figure C13 Sample Strands' Ends Coated in Grit Material Awaiting Tensile Testing

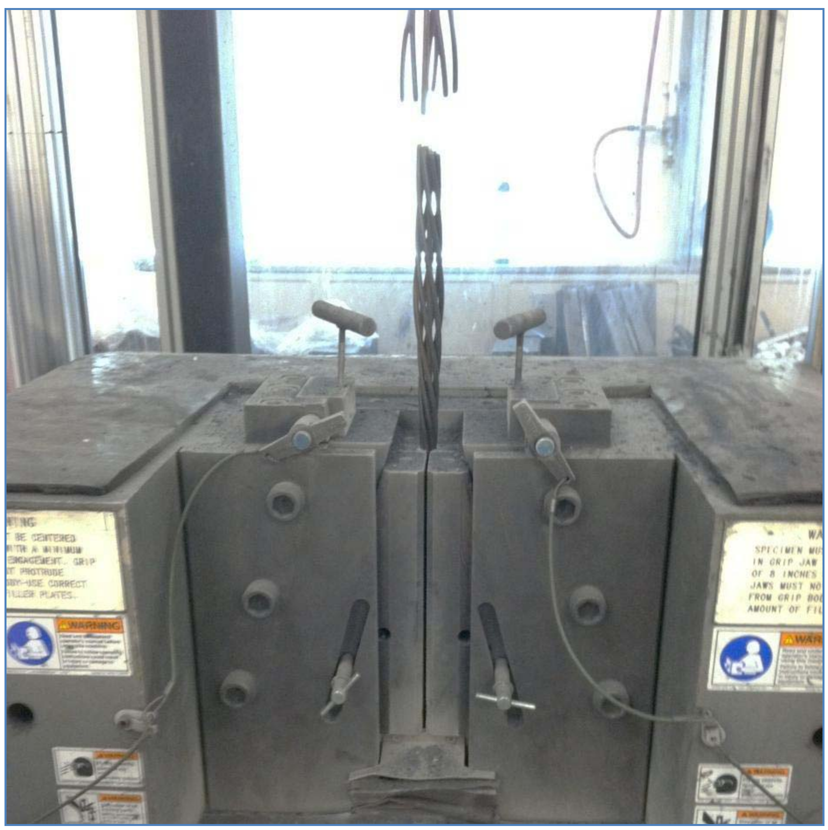


Figure C14 Sample Strand Break and Fully Engaged Grip

One strand, SW2D2, showed a satisfactory load to failure, however, it did not satisfy the 3.5% total elongation requirement. The cause is most likely a reported problem with the extensometer used during testing. Normal practice condoned by ASTM 416 is to test two (2) additional specimens from the same batch, should either of the other two (2) fail, the batch is to then be rejected, otherwise the failure may be ascribed to a testing irregularity (ASTM International, 2006). As multiple strands from the same exposure duration, environment, and duct condition did not show any trend towards this reduction in elongation it may be assumed that this specimen's failure to meet standards was due to a testing irregularity.

As can be appreciated for the global summary of data in Figure C15, the most striking feature of the tensile test results is that all samples properly tested (that is, without grip slipping) met or exceeded the specified strength requirement (red line). The lowest force datum in that figure corresponds to a 2-week, One-End Open exposure at SSK, but as indicated in the Results section this is likely the result of an undetected testing irregularity. The strength requirement was exceeded even by the visibly corroded supplemental, 9-month wet exposure samples. It is noted however that 4 out of the 16 tensile test samples in that group were distinctly differentiated as the next lowest strength data, clearly identified in Figure C18 that compares the effect of exposure length.

Figures C16 to C18 show that other than the result from the exceedingly long exposure of the supplemental samples, only test location appeared to be a differentiating factor in terms of strength loss. However, as shown in Figure C16, the difference between median load at failure at the inland and seashore facility samples was only about 1%, and both strength values still amply exceeded the ASTM requirement. As it will be shown below, a comparable small difference was apparent in the load at 1% extension data (Figure C24), but notably not present in the elongation at failure results (Figure C20). The possible difference may tentatively be ascribed to salt spray from the nearby bay acting on the open-duct exposed strands, as well as briefly on all the other strands during the placement/extraction procedures. The deposited salt could promote the formation of small regions of electrolyte on the surface and initiating pitting or other forms of localized corrosion. The previously noted indications of somewhat greater visual appearance of surface distress in the SSK specimens (Visual Inspection section) are supportive of this interpretation. The associated enhanced pitting and local cross section loss would then be a possible explanation for the apparent differentiation. The subsequent pile tests with stressed strand, addressed in the main body of this report, explored this potential mechanism further by including intentionally salted-surface specimens. As it will be shown there, while the pre-salted specimens showed more surface rusting, there was no strong differentiation from the rest in tensile test behavior.

Total elongation at failure of all the strands tested (with one exception, for the same sample with the lowest tensile mentioned earlier) met or exceeded the minimum requirement (3.5%). The median value (7%) greatly exceeded the requirement.

Elongation values showed no clear differentiation with respect to duct condition or internal environment. Duration of exposure of tests also did not appear to have an effect on ductility values, with the exception of the supplemental 9-month exposure samples which showed as a group a marginal reduction (~1%) in median total elongation, and several values at the extreme low end of the elongation distribution. This comparative loss of ductility is likely associated with the loss of cross section and stress concentration effects from the greater incidence of pitting present in these very long exposure specimens.

The values of load at 1% extension (Figures C23 to C26) followed trends consistent with those noted above and likely associated with the same factors.

It is noted that compliance with the mechanical specifications as evaluated by the tensile test is only one aspect of the many issues that may concern durability of a PT tendon, so the present results should be considered only in that light (Reis, 2007).

The availability of the supplemental, very long exposure 9-month samples in this work showed that in that case there was some indication of reduction in mechanical performance associated with pitting, although standardized strength test requirements were still largely met even for those samples. It is noted, however, that strands in this group that showed visible pitting would be liable to rejection based on visual appearance alone (Sason, 1992). Mechanical testing results are shown in Section C.3. In general, 8 week exposures rated a value of 5 on the Sason scale, while the strands left in the ducts for 9 months before the summer month start of the present unstressed study rated a value of 4. The one, two, and four week unstressed exposures ranged from a rating of 1 to 3, respectively.

In summary, the principal conclusions of both studies concur with one another even though the exposure conditions in the present work (warmer season) were nominally somewhat more aggressive than in the former.

C.3.1 Load at Failure

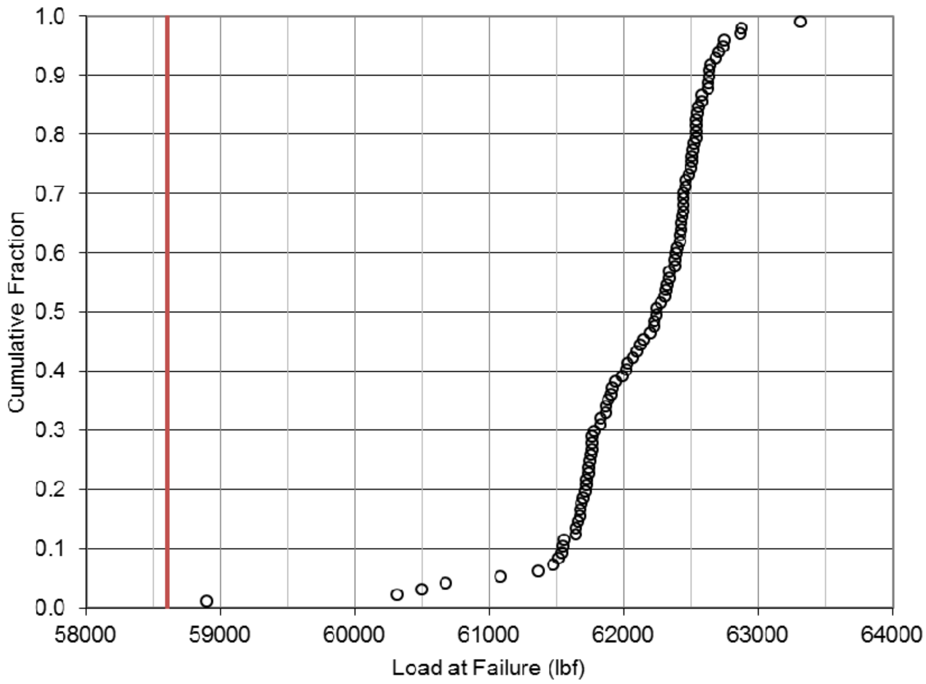


Figure C15 Total Cumulative Fraction of Load at Failure

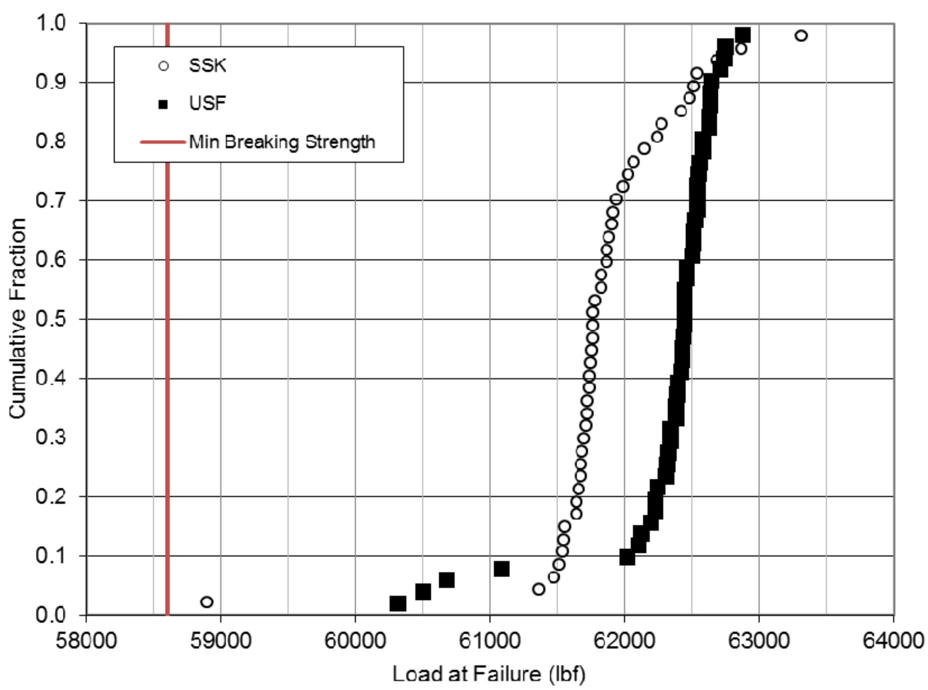


Figure C16 Cumulative Fraction of Load at Failure - Environment Comparison

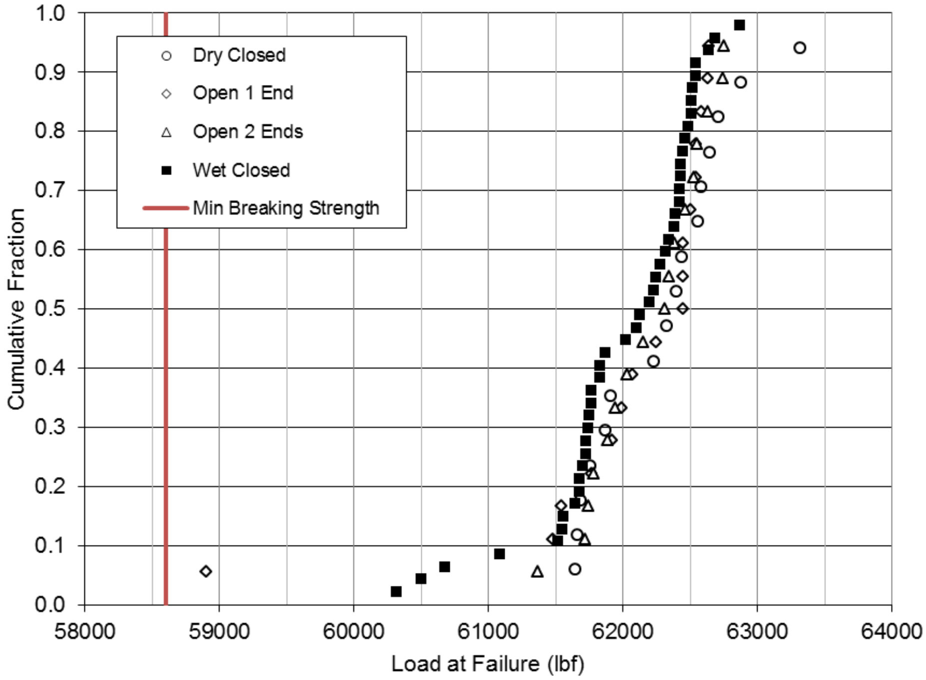


Figure C17 Cumulative Fraction of Load at Failure - Duct Condition Comparison

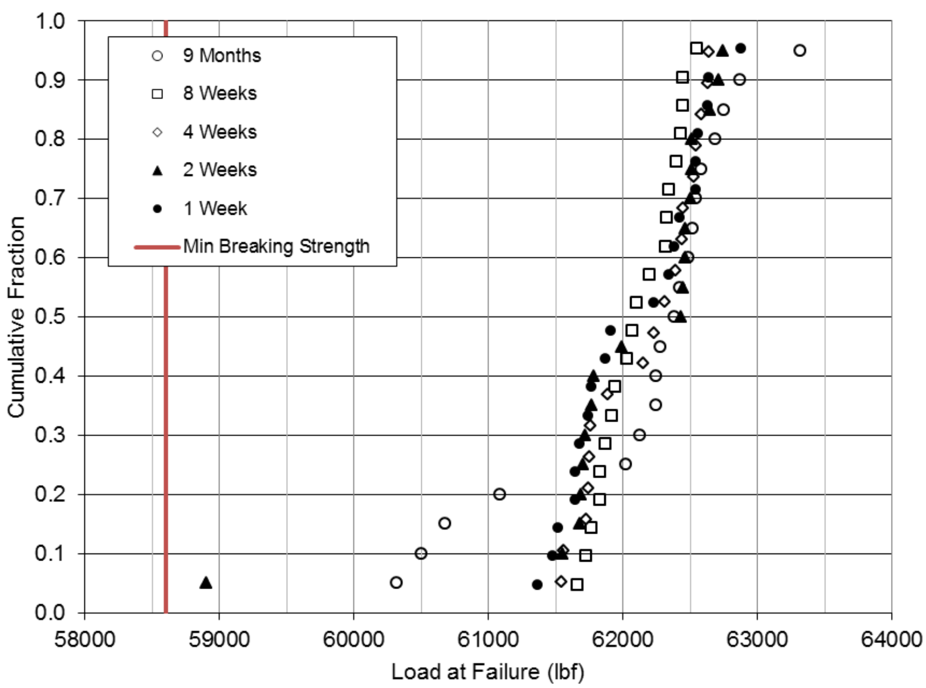


Figure C18 Cumulative Fraction of Load at Failure - Exposure Length Comparison

C.3.2 Total Elongation

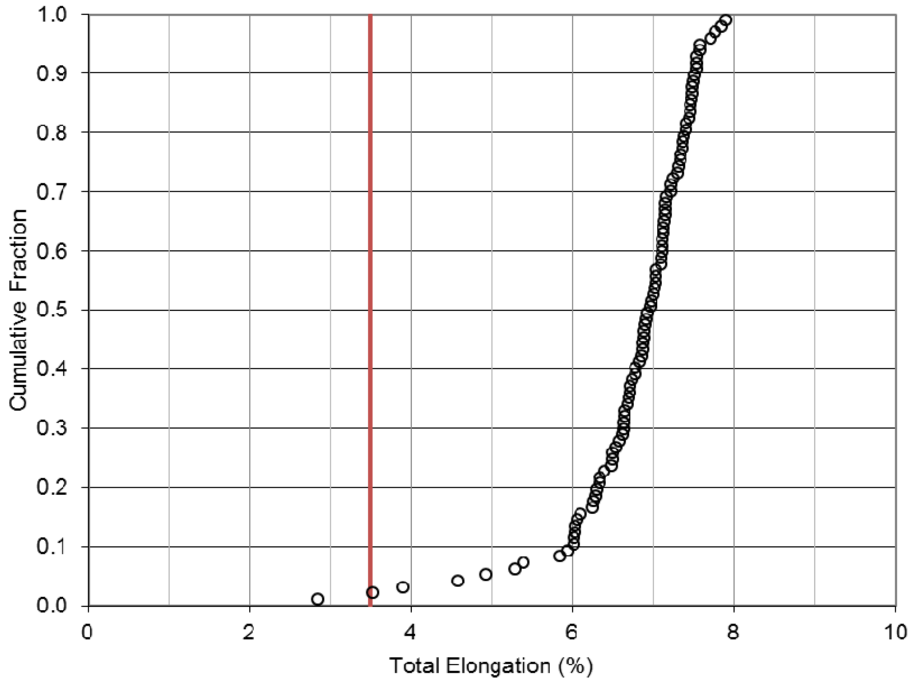


Figure C19 Total Cumulative Fraction of Total Elongation at Failure

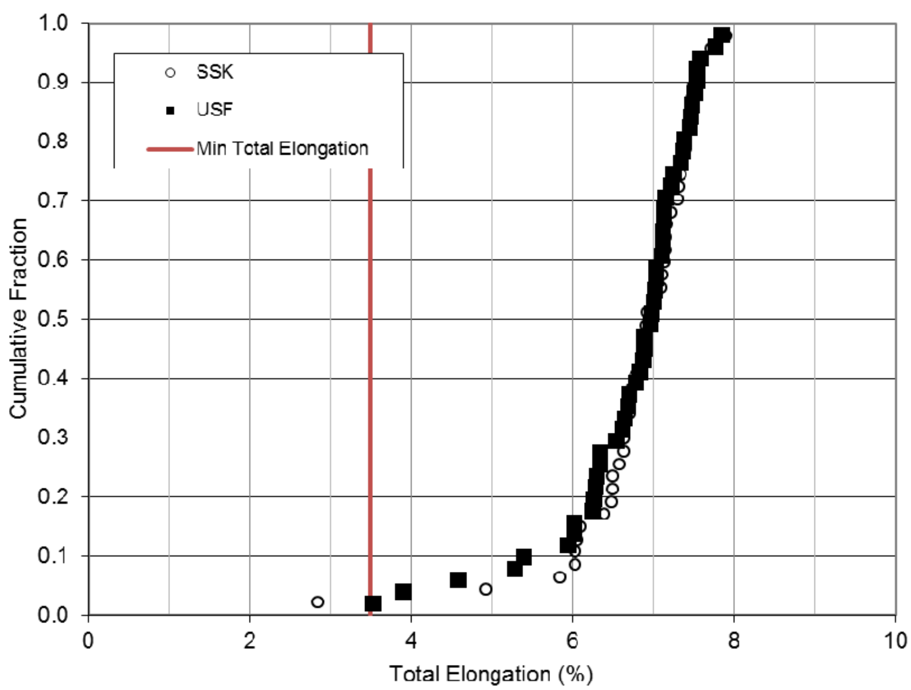


Figure C20 Cumulative Fraction of Total Elongation at Failure - Environment Comparison

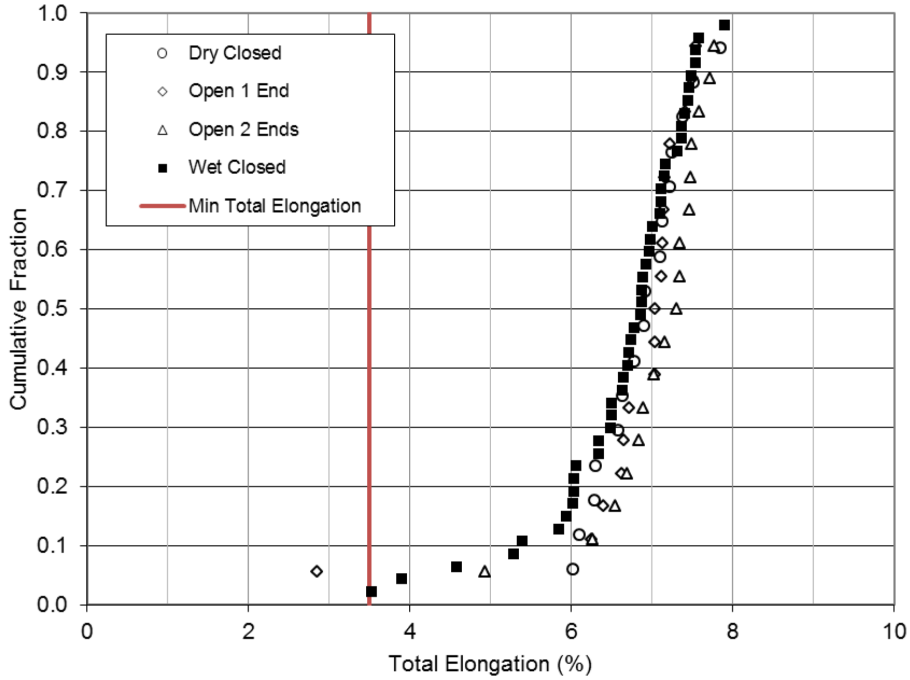


Figure C21 Cumulative Fraction of Total Elongation at Failure - Duct Condition Comparison

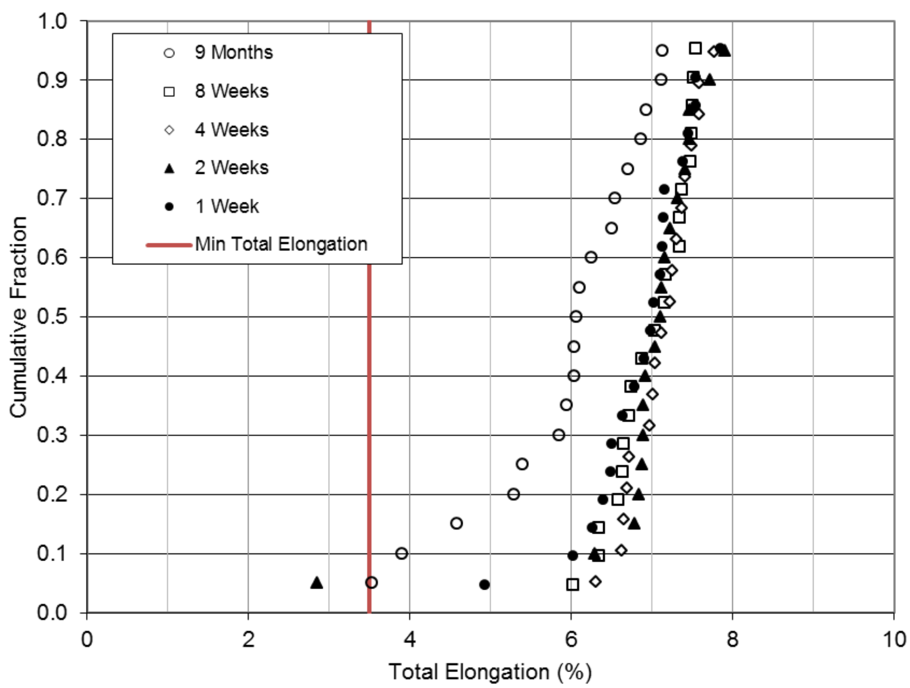


Figure 5 Cumulative Fraction of Total Elongation at Failure - Exposure Length Comparison

C.3.3 Load at 1% Extension

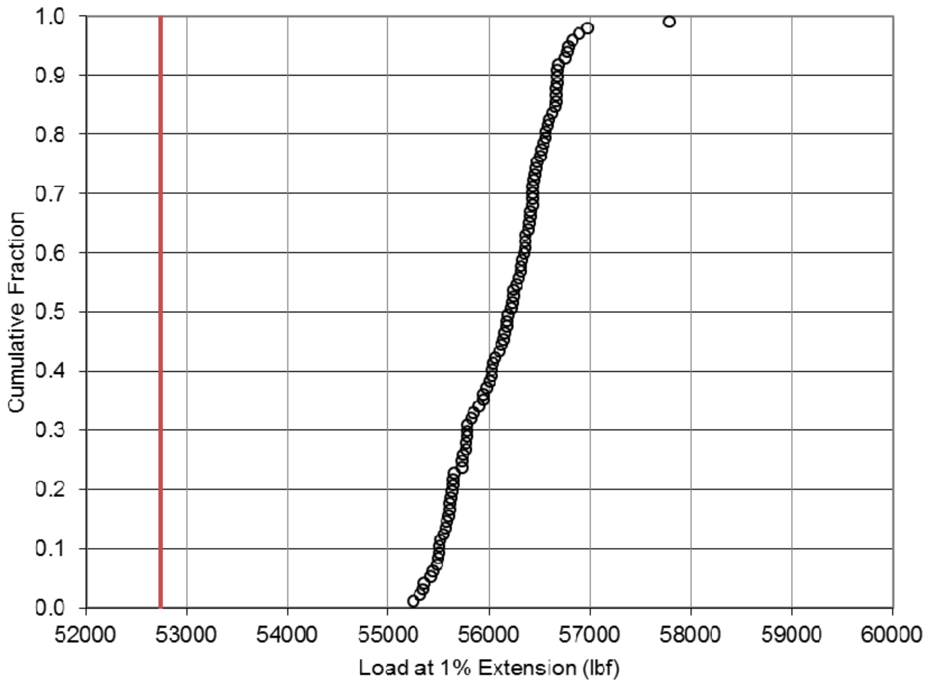


Figure C23 Total Cumulative Fraction of Load at 1% Extension

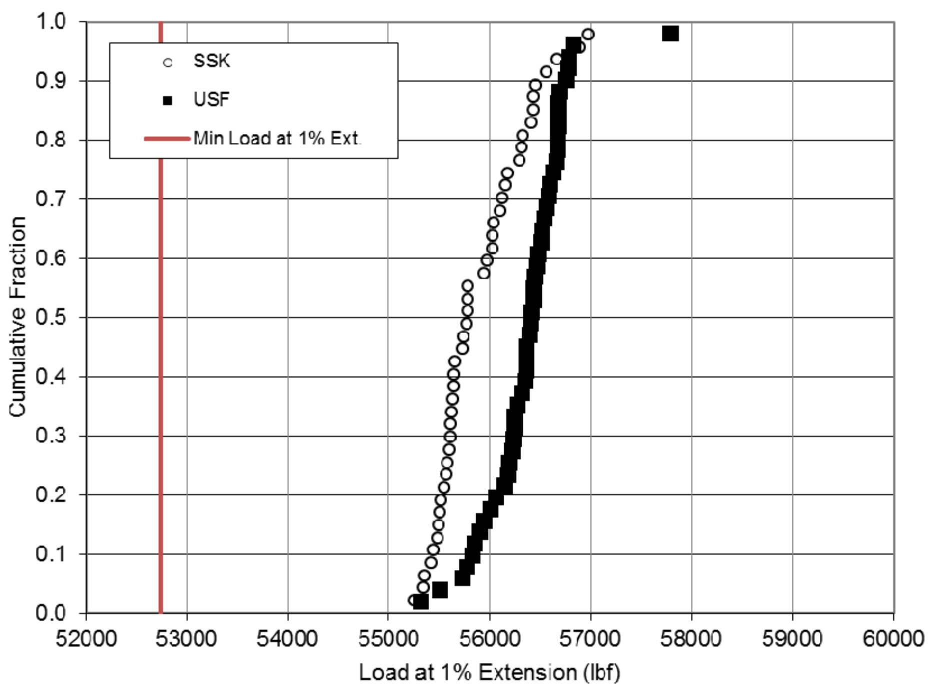


Figure C24 Cumulative Fraction of Load at 1% Extension - Environment Comparison

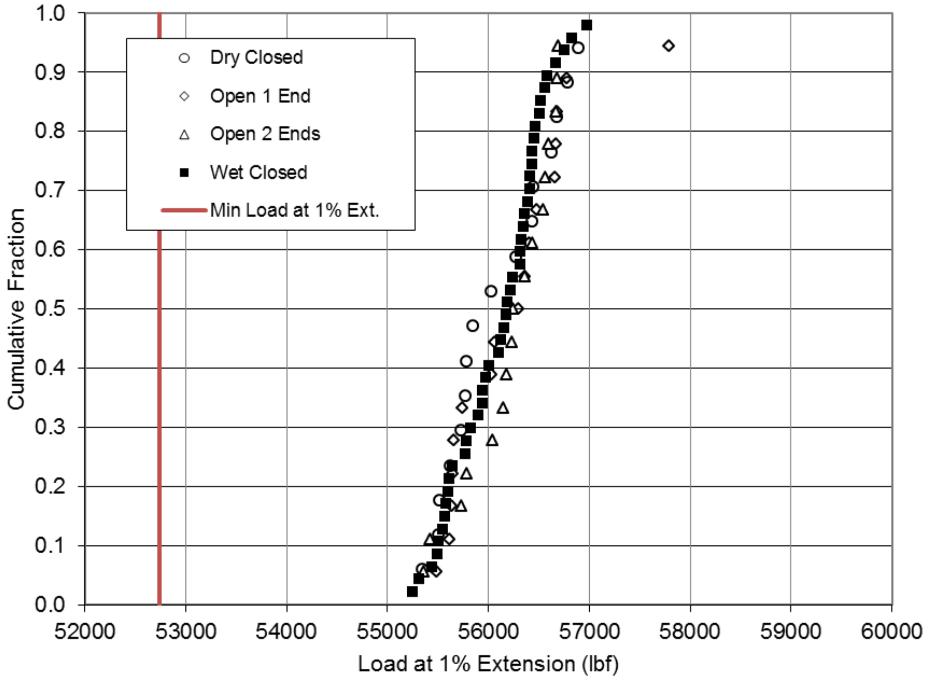


Figure C25 Cumulative Fraction of Load at 1% Extension - Duct Condition Comparison

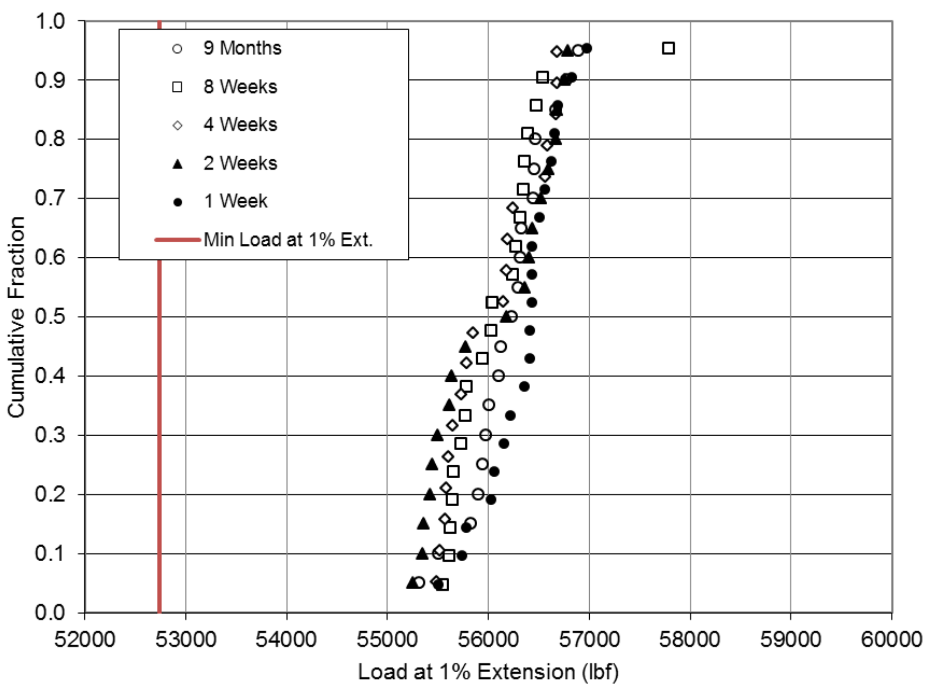


Figure C26 Cumulative Fraction of Load at 1% Extension - Exposure Length Comparison

C.3.4 Statistics

Table C2 Standard Deviation Values for Each Experiment Variable

Experiment Variable	*Load at Failure (lbf)*	*Elongation to Failure (%)*	*Load at 1% Ext. (lbf)*
Total	600	0.86	470
USF	525	0.89	393
SSK	588	0.82	424
Dry	480	0.51	492
1-Open	867	1.04	578
2-Open	394	0.67	414
Wet	558	0.91	427
1-Week	458	0.64	365
2-Week	838	1.02	555
4-Week	384	0.39	436
8-Week	275	0.45	503
9-Month	815	0.99	393

Table C3 Mean Values for Each Experiment Variable

Experiment Variable	*Load at Failure (lbf)*	*Elongation to Failure (%)*	*Load at 1% Ext. (lbf)*
Total	61956	6.87	56437
USF	62493	7.03	56437
SSK	61956	6.87	55924
Dry	62196	6.92	55997
1-Open	62288	7.04	56289
2-Open	62189	7.06	56272
Wet	62038	6.35	56191
1-Week	62148	6.89	56406
2-Week	62212	7.15	56102
4-Week	62223	7.14	56106
8-Week	62147	7.02	56158
9-Month	62013	5.86	56142

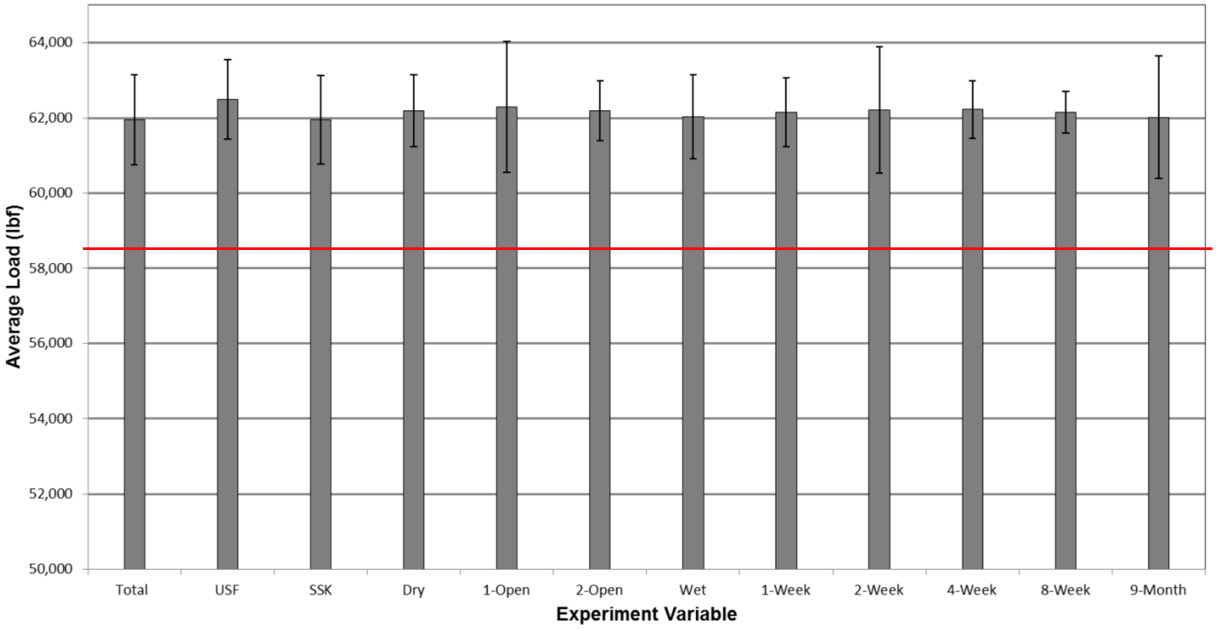


Figure C27 Average Load at Failure by Experiment Variable - Error Bars are 2 Standard Deviations Tall (Red Line Indicates ASTM A416 Minimum Requirement)

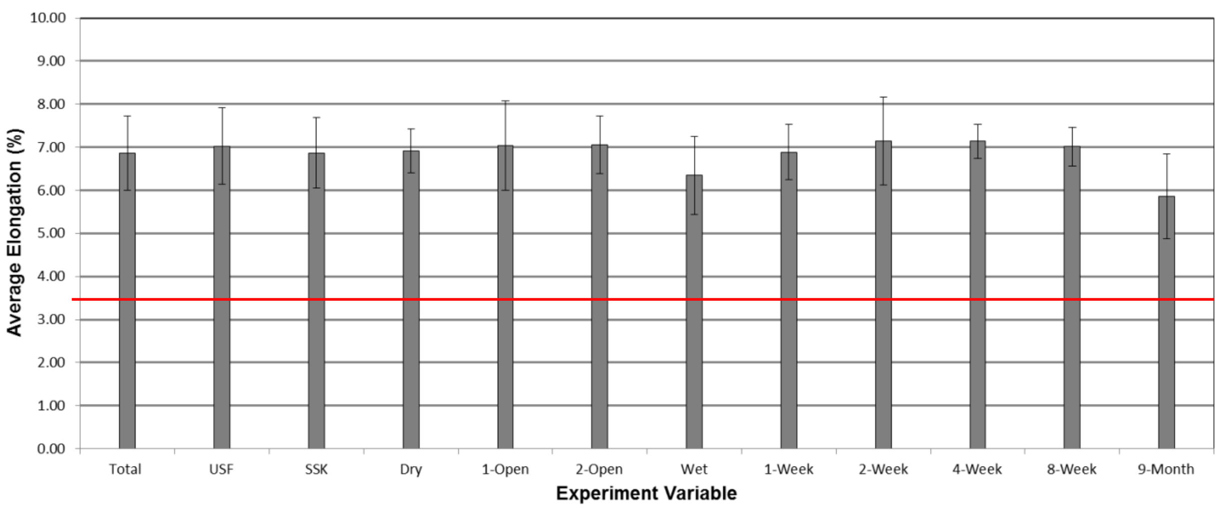


Figure C28 Average Elongation to Failure by Experiment Variable - Error Bars are 2 Standard Deviations Tall (Red Line Indicates ASTM A416 Minimum Requirement)

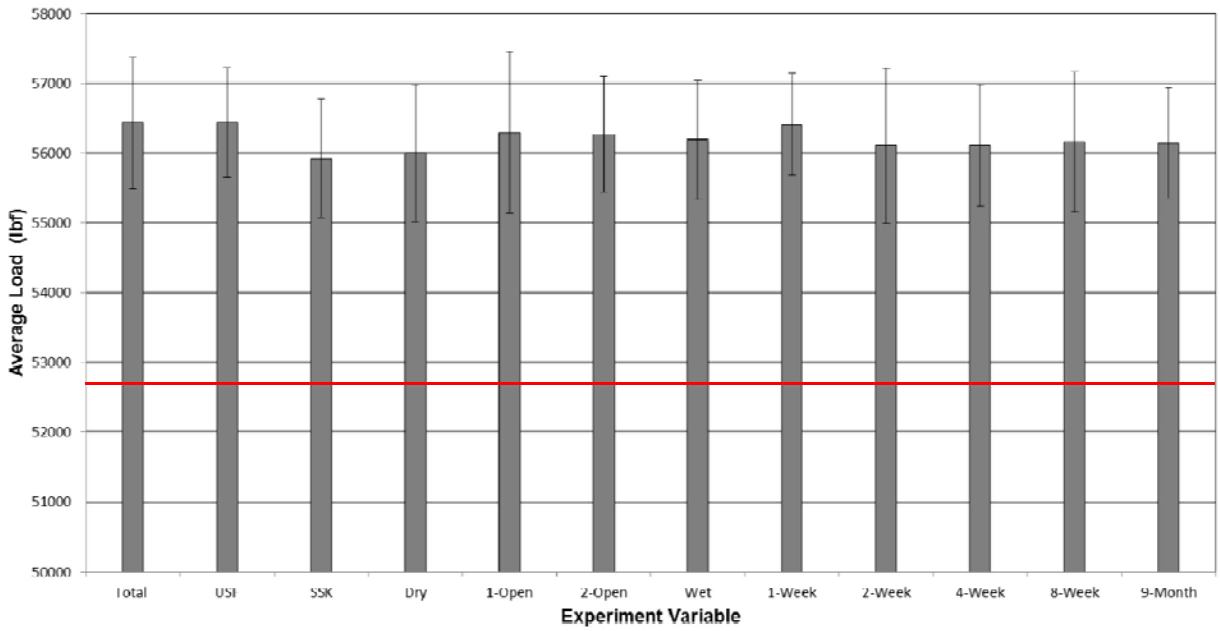


Figure C29 Average Load at 1% Extension by Experiment Variable - Error Bars are 2 Standard Deviations Tall (Red Line Indicates ASTM A416 Minimum Requirement)

C.4 Conclusions of the Extension of Project BDK84-977-04 Experiments to Warm Season Conditions

1. Tension testing of exposed unstressed strands in all conditions examined resulted in strength values from valid tests that always met or exceeded the ASTM A416 specification. Ductility as measured by elongation to failure met or exceeded the ASTM A416 specification in all cases except one which may be ascribed to a test irregularity.

2. Corrosion damage on unstressed strands during ungrouted periods of durations in the order of those otherwise currently prescribed did not appear to seriously degrade mechanical performance as measured by standardized tests.

3. The results of this study generally concur with those from Project BDK84-977-04 experiments performed in the same facility, even though the present tests were conducted in a warmer season.

Appendix D: Complete Mechanical Testing Results for all 216 Pile Exposure Cases. Blank Cells for Load to 1% Extension and Total Elongation Correspond to Tests with Grip Slippage. Cases 1-54 and 109-162 are for Inland while the Rest are for Seashore Location Exposures

Case Number	Closed?	Open?	Wet?	Salted?	Weeks Exposed	Load to Failure (lbf)	Load to 1% Extension (lbf)	Total Elongation (%)
1	N	N	Y	N	1	44640	40380	7.42
2	N	N	Y	N	1	43990	39580	5.83
3	N	N	Y	N	1	44510	40080	6.79
4	N	Y	N	N	1	43050	40070	6.9
5	N	Y	N	N	1	44110	39720	6.29
6	N	Y	N	N	1	44620	40060	7.31
7	Y	N	N	N	1	44440	40040	6.73
8	Y	N	N	N	1	42160	39720	5.28
9	Y	N	N	N	1	43010	40110	4.1
10	N	N	Y	N	1	44350	40070	7.23
11	N	N	Y	N	1	44370	39970	7.9
12	N	N	Y	N	1	44520	40180	7.3
13	N	Y	N	N	1	44470	40290	7.42
14	N	Y	N	N	1	44240	39850	6.76
15	N	Y	N	N	1	44470	39920	6.79
16	Y	N	N	N	1	44410	40140	7.3
17	Y	N	N	N	1	39390		
18	Y	N	N	N	1	44440	40240	6.41
19	N	N	Y	N	2	43570	40300	5.29
20	N	N	Y	N	2	44510	40330	7.49
21	N	N	Y	N	2	44100	39780	6.43
22	N	Y	N	N	2	44430	40120	6.89
23	N	Y	N	N	2	44490	40440	7.29
24	N	Y	N	N	2	44230	39800	6.75
25	Y	N	N	N	2	44430	40120	5.98
26	Y	N	N	N	2	44400	40120	6.22
27	Y	N	N	N	2	44300	40140	6.58
28	N	N	Y	N	2	44320	40140	7.01
29	N	N	Y	N	2	44500	40210	6.01
30	N	N	Y	N	2	44410	40040	7.02
31	N	Y	N	N	2	44450	40050	7.66
32	N	Y	N	N	2	44630	40480	7.06
33	N	Y	N	N	2	44470	40120	7.65

Case Number	Closed?	Open?	Wet?	Salted?	Weeks Exposed	Load to Failure (lbf)	Load to 1% Extension (lbf)	Total Elongation (%)
34	Y	N	N	N	2	44470	40580	7.04
35	Y	N	N	N	2	44480	40160	6.74
36	Y	N	N	N	2	44360	39590	7.39
37	N	N	Y	N	4	39460		
38	N	N	Y	N	4	44160	39810	6.78
39	N	N	Y	N	4	44400	40580	7
40	N	Y	N	N	4	44510	40250	7.63
41	N	Y	N	N	4	44200	40300	6.48
42	N	Y	N	N	4	44340	40000	7.46
43	Y	N	N	N	4	44280	40090	7.14
44	Y	N	N	N	4	44380	40130	7.24
45	Y	N	N	N	4	44460	40230	6.1
46	N	N	Y	N	4	44530	40160	6.87
47	N	N	Y	N	4	44180	40090	6.22
48	N	N	Y	N	4	44390	40360	7.26
49	N	Y	N	N	4	37840		
50	N	Y	N	N	4	44400	40160	6.88
51	N	Y	N	N	4	44350	40010	7.04
52	Y	N	N	N	4	44420	40180	6.29
53	Y	N	N	N	4	44310	40080	6.25
54	Y	N	N	N	4	44230	40070	6.76
55	Y	N	N	N	1	44280	39940	6.76
56	Y	N	N	N	1	44300	39870	7.24
57	Y	N	N	N	1	44350	40080	8.23
58	N	Y	N	N	1	44440	40040	7.55
59	N	Y	N	N	1	41770	39800	1.42
60	N	Y	N	N	1	44490	39700	7.84
61	N	N	Y	N	1	44480	40140	7.1
62	N	N	Y	N	1	44390	39880	7.23
63	N	N	Y	N	1	44400	40330	7.33
64	Y	N	N	Y	1	44390	40150	6.83
65	Y	N	N	Y	1	44400	40000	7.2
66	Y	N	N	Y	1	44480	39870	7.55
67	N	Y	N	Y	1	44510	40140	6.14
68	N	Y	N	Y	1	44490	40120	6.78
69	N	Y	N	Y	1	44490	39970	7.32
70	N	N	Y	Y	1	44740	40310	7.37
71	N	N	Y	Y	1	44540	40210	7.41
72	N	N	Y	Y	1	44260	39830	6.98

Case Number	Closed?	Open?	Wet?	Salted?	Weeks Exposed	Load to Failure (lbf)	Load to 1% Extension (lbf)	Total Elongation (%)
73	Y	N	N	N	2	44420	40190	6.4
74	Y	N	N	N	2	44370	39840	7.16
75	Y	N	N	N	2	44200	39770	6.72
76	N	Y	N	N	2	43730	40160	7.3
77	N	Y	N	N	2	44400	40240	7.36
78	N	Y	N	N	2	44420	40060	7.12
79	N	N	Y	N	2	44440	40240	7.25
80	N	N	Y	N	2	44320	44320	5.96
81	N	N	Y	N	2	44350	40030	6.04
82	Y	N	N	Y	2	44530	40280	6.73
83	Y	N	N	Y	2	44110	40260	5.45
84	Y	N	N	Y	2	40190	40150	0.86
85	N	Y	N	Y	2	44570	40300	7.64
86	N	Y	N	Y	2	44010	39800	6.96
87	N	Y	N	Y	2	32910		
88	N	N	Y	Y	2	44430	40110	7.21
89	N	N	Y	Y	2	44450	40210	6.73
90	N	N	Y	Y	2	44460	40090	5.77
91	Y	N	N	N	4	44040	40140	7.15
92	Y	N	N	N	4	44400	40160	6.73
93	Y	N	N	N	4	41750	40310	3.55
94	N	Y	N	N	4	42750	40130	5.31
95	N	Y	N	N	4	44340	40020	6.84
96	N	Y	N	N	4	44200	40110	6.97
97	N	N	Y	N	4	44440	40450	6.44
98	N	N	Y	N	4	44470	40610	6.66
99	N	N	Y	N	4	44430	40170	6.11
100	Y	N	N	Y	4	44620	40320	7.37
101	Y	N	N	Y	4	44460	40230	6.95
102	Y	N	N	Y	4	18930		
103	N	Y	N	Y	4	44510	40310	5.26
104	N	Y	N	Y	4	44530	40190	7.18
105	N	Y	N	Y	4	44440	40070	6.61
106	N	N	Y	Y	4	44460	40260	6.15
107	N	N	Y	Y	4	44470	40200	6.77
108	N	N	Y	Y	4	44470	40020	6.98
109	Y	N	N	Y	1	44380	39660	7.57
110	Y	N	N	Y	1	44410	39970	7.33
111	Y	N	N	Y	1	42960	39950	3.21

Case Number	Closed?	Open?	Wet?	Salted?	Weeks Exposed	Load to Failure (lbf)	Load to 1% Extension (lbf)	Total Elongation (%)
112	Y	N	N	Y	1	44290	40070	6.4
113	Y	N	N	Y	1	44480	40010	7.55
114	Y	N	N	Y	1	44410	40050	6.39
115	Y	N	N	N	1	44410	39920	7.53
116	Y	N	N	N	1	44320	39890	6.32
117	Y	N	N	N	1	44460	39920	6.24
118	Y	N	N	Y	1	44500	40190	7.91
119	Y	N	N	Y	1	44240	39890	7.48
120	Y	N	N	Y	1	44460	38950	7.97
121	Y	N	N	Y	1	44420	40030	7.55
122	Y	N	N	Y	1	44410	40040	7.42
123	Y	N	N	Y	1	39630	37500	0.88
124	Y	N	N	N	1	44410	40200	6.17
125	Y	N	N	N	1	44490	40230	5.94
126	Y	N	N	N	1	44360	40020	6.57
127	Y	N	N	Y	2	44290	40000	7.16
128	Y	N	N	Y	2	44440	40030	7.67
129	Y	N	N	Y	2	44260	39860	7.75
130	Y	N	N	Y	2	44410	39970	7.32
131	Y	N	N	Y	2	44410	40100	5.87
132	Y	N	N	Y	2	41570	39450	6.76
133	Y	N	N	N	2	42240	39950	5.12
134	Y	N	N	N	2	44420	40040	7.94
135	Y	N	N	N	2	44390	40030	6.3
136	Y	N	N	Y	2	44280	39880	6.07
137	Y	N	N	Y	2	44300	40100	6.8
138	Y	N	N	Y	2	44450	40090	6.52
139	Y	N	N	Y	2	44290	40010	6.08
140	Y	N	N	Y	2	44430	40070	7.04
141	Y	N	N	Y	2	44510	40160	7.14
142	Y	N	N	N	2	44280	39930	7.02
143	Y	N	N	N	2	44270	42010	5.08
144	Y	N	N	N	2	44410	39940	6.6
145	Y	N	N	Y	4	44240	39850	7.09
146	Y	N	N	Y	4	44350	39930	7.35
147	Y	N	N	Y	4	43980	39600	6.45
148	Y	N	N	Y	4	44270	39930	7.22
149	Y	N	N	Y	4	44160	39740	7.3
150	Y	N	N	Y	4	44230	39840	7.45

Case Number	Closed?	Open?	Wet?	Salted?	Weeks Exposed	Load to Failure (lbf)	Load to 1% Extension (lbf)	Total Elongation (%)
151	Y	N	N	N	4	44210	40180	7.57
152	Y	N	N	N	4	44370	40290	7.26
153	Y	N	N	N	4	44210	39780	6.88
154	Y	N	N	Y	4	44240	40210	7.18
155	Y	N	N	Y	4	44370	40150	7.59
156	Y	N	N	Y	4	44210	39800	7.91
157	Y	N	N	Y	4	44120	40260	7.33
158	Y	N	N	Y	4	44260	40120	7.14
159	Y	N	N	Y	4	44190	39780	7.11
160	Y	N	N	N	4	44200	39980	7.33
161	Y	N	N	N	4	44240	40350	7.18
162	Y	N	N	N	4	44300	39220	6.91
163	Y	N	N	N	1	44400	40150	7.37
164	Y	N	N	N	1	44090		
165	Y	N	N	N	1	44290	40090	7.6
166	N	Y	N	N	1	44270		
167	N	Y	N	N	1	44320	41450	6.75
168	N	Y	N	N	1	44160	40160	6.88
169	N	N	Y	N	1	44310	40410	6.89
170	N	N	Y	N	1	44180	40320	6.92
171	N	N	Y	N	1	44200	41500	6.54
172	Y	N	N	Y	1	44360	40270	7.22
173	Y	N	N	Y	1	44290	39920	7.07
174	Y	N	N	Y	1	44320	39960	7.16
175	N	Y	N	Y	1	44340	40070	7.17
176	N	Y	N	Y	1	44230	40120	7.28
177	N	Y	N	Y	1	44170	39780	6.61
178	N	N	Y	Y	1	44240	40130	7.37
179	N	N	Y	Y	1	44200	40140	7.31
180	N	N	Y	Y	1	44340	39970	7.37
181	Y	N	N	N	2	44350	39920	7.09
182	Y	N	N	N	2	44330	39990	6.87
183	Y	N	N	N	2	44230	39750	6.48
184	N	Y	N	N	2	44340	40040	7.3
185	N	Y	N	N	2	44350	40010	7.01
186	N	Y	N	N	2	44280	39850	6.25
187	N	N	Y	N	2	44320	39890	7.01
188	N	N	Y	N	2	44220	39830	6.8
189	N	N	Y	N	2	44390	39850	7.36

Case Number	Closed?	Open?	Wet?	Salted?	Weeks Exposed	Load to Failure (lbf)	Load to 1% Extension (lbf)	Total Elongation (%)
190	Y	N	N	Y	2	44320	39870	6.96
191	Y	N	N	Y	2	44010	40940	5.78
192	Y	N	N	Y	2	44460	40040	7.47
193	N	Y	N	Y	2	44350	39830	7.54
194	N	Y	N	Y	2	44080	39610	6.67
195	N	Y	N	Y	2	44130	39650	6.34
196	N	N	Y	Y	2	44190	39900	7.34
197	N	N	Y	Y	2	44140	39710	7.11
198	N	N	Y	Y	2	44240	39680	7.41
199	Y	N	N	N	4	44460	40350	6.87
200	Y	N	N	N	4	44570	40240	8.03
201	Y	N	N	N	4	44230	39750	8.09
202	N	Y	N	N	4	44300	40150	6.76
203	N	Y	N	N	4	44450	40310	7.65
204	N	Y	N	N	4	44360	39880	7.25
205	N	N	Y	N	4	44280	40040	7.32
206	N	N	Y	N	4	44320	40150	7.27
207	N	N	Y	N	4	44280	39990	6.88
208	Y	N	N	Y	4	42560	39990	3.52
209	Y	N	N	Y	4	44170	39750	6.86
210	Y	N	N	Y	4	44200	39750	7.08
211	N	Y	N	Y	4	44430	40230	7.05
212	N	Y	N	Y	4	44420	40090	6.6
213	N	Y	N	Y	4	44220	39850	6.34
214	N	N	Y	Y	4	44300	39750	7.9
215	N	N	Y	Y	4	44280	40030	7.43
216	N	N	Y	Y	4	44170	39750	6.49