

Report Prepared by:
Dr. Francisco J. Presuel–Moreno
With
Samantha Mavrak
David Anguelov

Final Report

Evaluation of Concrete Specimens Prepared with Corrosion Resistant
Reinforcement after Long Term, Greater than 15 years, Outdoor and
Laboratory Exposures

Contract Number – FDOT (BED27-977-04)
FAU (AWD003253)

Submitted to
Florida Department of Transportation
Research Center
605 Suwannee Street
Tallahassee, Florida 32399

Submitted by
Francisco Presuel–Moreno
Principal Investigator
Department of Ocean and Mechanical Engineering
Center for Marine Materials
Florida Atlantic University – Sea Tech

101 North Beach Road
Dania Beach, Florida 33004

August 2026

Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the author and not necessarily those of the State of Florida Department of Transportation.

Units Conversion Page

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Evaluation of Concrete Specimens Prepared with Corrosion Resistant Reinforcement after Long Term, Greater than 15 years, Outdoor and Laboratory Exposures				5. Report Date August 2026	
				6. Performing Organization Code FAU-OE-cmM-08-3	
7. Author(s) Francisco J. Presuel-Moreno, Samantha Mavrak, David Anguelov.				8. Performing Organization Report No. AWD003253	
9. Performing Organization Name and Address Center for Marine Materials Florida Atlantic University – Sea Tech 101 North Beach Road Dania Beach, Florida 33004				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. BED27-977-04	
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399				13. Type of Report and Period Covered Final Report March 21, 2024 – August 31, 2026	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract Samples containing corrosion resistant reinforcing bars (CRRB) were prepared between 2002 and 2007 as part of a project sponsored by the Florida Department of Transportation (FDOT) and the Federal Highway Administration (FHWA) to investigate durable long-term alternatives to conventional carbon steel reinforcement undergoing marine exposure. 75 Simulated Deck Slab (SDS) samples remain at Florida Atlantic University (FAU), additional samples continued to be monitored at the FDOT State Materials Office (FDOT-SMO), and columns with CRRB were deployed at the Crescent Beach field site. After reviewing current conditions, selected samples at FAU and at FDOT-SMO were terminated. The field site was visited twice: during one of the visits cores were obtained on selected columns. Briefly, for FAU SDS samples, most rebars appear not to be corroding. Some SDS samples with 3CR12 (with simulated crack and 2 rebars forming a crevice) and clad rebar type 2 (CT2) with intentional damage or clad breaks corroded. Most terminated samples at FDOT-SMO were Tombstone geometry; all selected samples (CT2, 304, 3CR12, MMFX, 2101 and 2304) had at least one rebar that corroded. MMFX rebars showed the most corrosion extent, followed by 3CR12. Clad breaks allowed corrosion to take place on two of the CT2 rebars. Field columns with 2101, 3CR12 and MMFX rebars are corroding based on cracks observed along the rebar length and corrosion potential. Rebar segments obtained (MMFX and 2101) confirm significant cross section loss. The project also included visits to two bridges that contain CRRB in the substructure and are not corroding.					
17. Key Word Reinforced Concrete, Corrosion Resistant Reinforcing Bar, MMFX, 3CR12, 2101, 304, 316, Clad Rebar, Long Exposure Time.				18. Distribution Statement No Restrictions.	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 263	
				22. Price	

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

ACKNOWLEDGMENTS

The author is indebted to the FDOT State Materials Office (SMO) for assistance during the field visits for this study and monitoring and termination of samples at FDOT-SMO, in particular, Mr. Oliver Chung, Mr. Shannon Deese and Mr. Ronald Simmons, and several other FDOT-SMO staff (Kye Dittman, Charlotte Kasper, Elizabeth Miller). The author acknowledges and thanks Dr. Wilfrido Martínez Molina from Universidad Michoacana de San Nicolás de Hidalgo, Mexico for loaning a Gecor 8 sensor C. The author also acknowledges the assistance of several students who worked as graduate/undergraduate research assistants at the FAU–Sea Tech Marine Materials and Corrosion Lab during the duration of this project.

EXECUTIVE SUMMARY

This research project assessed the long-term corrosion performance of corrosion-resistant reinforcing bars (CRRBs) used in concrete while exposed to marine environment. Plain carbon steel is typically used in reinforced concrete structure but is prone to corrosion, especially in marine environments due to aggressive chloride ions. Rebar corrosion is detrimental in reinforced concrete. The accumulation of corrosion products on the metal surface builds internal tensile stresses within the concrete and causes it to crack, spall, or fracture, significantly reducing the service life of the structure. Generally, CRRBs like 316 stainless steel (SS) have a stronger ability than carbon steel to withstand chloride ions before corroding. In other words, CRRBs have higher chloride thresholds which may make them more suitable for structures in marine environments. The objective of this project was to evaluate various types of CRRBs in concrete as viable long-term alternatives for conventional carbon steel reinforcement in the marine environment and to determine how each alloy performs under exposure conditions relevant to Florida Department of Transportation (FDOT) structures.

Samples were prepared between 2002 and 2007 as part of a project sponsored by FDOT and the Federal Highway Administration (FHWA). The sample geometry at Florida Atlantic University (FAU) is named simulated deck slab (SDS), and these samples contain CRRBs. 10 SDS samples were prepared in 2012 as part of a more recent project, five with 2101 rebars and five with 2304 duplex SS rebars. Two SDS samples with 2304 are still available. 75 SDS samples remain at for the simulated deck slab geometry, additional samples continue to be monitored at FDOT's State Materials Office (FDOT-SMO), and columns with CRRBs were deployed at the Crescent Beach field site. After reviewing their current condition, selected samples at FAU and at FDOT-SMO were terminated. The field site was visited twice, and during one of the visits cores were obtained on selected columns. The project also included visits to two bridges that contain CRRBs in the substructure.

The field columns (FCs) with 2101, 3CR12, and MMFX reinforcement all showed cracks along the rebars. In many cases the cracks were observed on multiple faces of the columns. The columns with black bars (BB) had more pronounced and wide cracks along the rebar, and it is likely that the corrosion took place around the whole rebar, but no cores were obtained with rebar sections. The cores obtained from columns with 2101 and MMFX rebars included a rebar section. The corrosion was localized: in some parts the corroded site resulted from multiple pits coalescing into a large deep corroding site (with x-crit large enough that it likely caused the concrete to crack), and in other parts there were deep pits. The remainder of the rebar segment showed no corrosion. None of the cores from 3CR12 field columns contained rebar segments. Intermediate alloys (MMFX, 3CR12, 2101) even if they have a higher chloride threshold, did not make the substructures that are partially immersed in seawater maintenance free. These alloys appear to provide a modest extension to the structure's service life for the field column geometry. Intermediate alloys delay when corrosion initiates and it is expected to propagate at a slower rate when compared to black carbon steel rebars. It is important to note that the 2101 rebars used with these columns had mill scale (mill scale presence significantly reduces the chloride threshold). One of the columns with 316 rebars was damaged during deployment and likely is corroding, as 316 stainless steel alloy is known to pit when immersed in seawater.

The portion of the bridge with CRRBs on the two bridges that were visited do not seem to be corroding based on the chloride profiles obtained and the surface resistivity values measured. The rebar potential for 2101LDX in the Jensen Beach Bridge did show negative potential values that are typically associated with corrosion. Non-corroding stainless steel embedded in concrete has a low passive current density, which makes it easier to polarize than carbon steel. The portion of the footer that is immersed likely has water saturated concrete with low O₂ concentration. This likely caused the rebar potential to be significantly negative - for example, more negative than -500 mV_{CSE} (mV versus the copper sulfate electrode). When the rebars in the columns are coupled to the rebar in the footers, the rebar potential along elevation was observed to be more negative than what is observed in the lab on atmospherically exposed concrete.

After approximately 20 years of exposure, simulated deck slab samples with 304, 316, 2304 showed no corrosion in most cases. Clad type 1 (CT1) rebars also performed well, and most samples with Clad type 2 (CT2) did not show corrosion. A few samples with Clad type 2 rebar, the remaining samples with 3CR12 rebars, and one sample with 304 were found to be corroding. The samples selected for dissection were selected from those samples with rebar showing corrosion. Clad type 2 had some samples that were not capped at the rebar end. Samples where the clad rebar ends were within the reservoir (CREV), corrosion of the carbon steel core caused cracks in the concrete. One sample with Clad type 2 appears to have had a holiday or defect that allowed the carbon steel core to corrode, and corrosion products bled through the surface. Samples with intentionally drilled holes in the CT2 rebars had potential values and corrosion current densities that caused corrosion stains to appear at the concrete surface, and another sample had cracks on the surface. The latter corresponded to a case where black bars made up the bottom row, and the carbon steel rebars were the ones causing the cracks, which was more evident during the forensic analysis. The terminated sample with 3CR12 rebars had a large crack and a portion of the concrete that had spalled. The geometry of this sample consisted of a simulated concrete crack transverse to the rebar lengths, and it had two 3CR12 that were attached to simulate a crevice for the rebars on the top row. The two rebars in position B showed the worst cross-sectional loss. It is possible that these two rebars provided some cathodic protection to the other rebars on the top, as well as the 3CR12 rebars in the bottom row. Concrete was milled along the mill-scale, and it was found that the chloride concentration at the second row had higher chloride concentration than at the rebar trace for rebars on the top row. This was also observed in the cores obtained as part of a previous project [1]. Only one sample with 304 that had shrinkage wrap showed corrosion stains and recently a crack. This sample was of CREV type i.e., two rebars with one of the rebar ends within the reservoir. Although this sample was not terminated, it is likely that crevice corrosion took place or corrosion took place on the rebar end.

Selected Tombstone geometry samples with 304, CT2, MMFX, 3CR12, 2101LDX, and 2304 were terminated from those exposed at FDOT-SMO, one 3-Bar square and one modified G109 were also selected for dissection. The Tombstone sample with 304 rebars was a sample with two bent rebars. It is possible that the bent region and sections close to it had high stress concentration with lower chloride threshold than a 304 rebar with not bent region. Before cleaning, there were three small corroding sites. After cleaning, only small pits were observed. For the sample with 2101LDX rebar, corrosion took place only on two rebars at a location close to the concrete top surface. The corrosion site on rebar 3 had a larger corrosion site with deep cross-sectional loss that caused the concrete to crack. The Tombstone sample with 2304: rebar B

was the only rebar that corroded, and this took place at the bottom of the rebar (this is the elevated rebar). The worst corrosion was observed on MMFX rebars, followed by 3CR12. The three rebars from both terminated samples with MMFX corroded (one Tombstone geometry and one 3-Bar square geometry). The MMFX rebars showed the worst corrosion extent conditions on those from the Tombstone geometry. The three elevated MMFX rebars from the 3 square column sample showed corroded areas and localized corrosion. Two out of three 3CR12 corroded: rebar 1 close to the bottom and rebar 3 extended several inches. The extent of corrosion on 3CR12 was less than that observed on the rebars removed from the SDS sample. The Tombstone sample with CT2 had two rebars that corroded and it appears there were flaws or holidays in the clad that allowed the carbon steel to corrode. In this case, the CT2 rebar had end-caps on the side that were immersed. The macro-cell (modified G109 sample) with CT2 had drilled holes and corrosion took place at few of the holes (2/3) based on bleed outs and observations after cleaning the deeper holes.

Overall, the long-term exposure results from samples at FAU and FDOT-SMO and the 316SS embedded in Bridge #510072 in the St. Joseph's Bay area demonstrate that the higher-alloy CRRBs – specifically 316SS, 2304 duplex SS, and 304SS – are the best corrosion-resistant alternatives for carbon steel reinforcement in marine environments. Additionally, clad reinforcement (CT1 and CT2) in samples at FAU and FDOT-SMO generally performed well, though localized corrosion occurred wherever the cladding was compromised and the carbon steel core was exposed. Provided that rebar endcaps are used and mechanical damage is minimized on the rebars, the long-term results of this study indicate that the 316SS-clad reinforcement may be a durable alternative to plain carbon steel reinforcement in the marine environment, and a cost-effective alternative to solid 316SS. The long-term exposure results of this study also indicate that intermediate alloys, including 3CR12 and MMFX, are not suitable alternatives to carbon steel reinforcement in marine environments. Forensic analysis of 3CR12 rebars from samples at FAU and FDOT-SMO showed extensive localized corrosion; one 3CR12 rebar from an SDS sample was reduced to half its original diameter due to severe pitting corrosion. Similarly, forensic analysis of MMFX rebars from samples at FDOT-SMO and from field columns at the Crescent Beach corrosion showed significant localized corrosion and cross section loss. Some samples from FDOT-SMO with 2101SS reinforcement showed corrosion, and the Crescent Beach FCs with 2101SS rebars (with mill scale) showed cracks on each face and spalling on one. On the other hand, the pickled 2101SS rebars embedded in the Jensen Beach Bridge columns and footers did not show signs of corrosion. The results of this study indicate that 2101SS reinforcement shows good long-term corrosion resistance in marine environments and may be a viable replacement to plain carbon steel reinforcement, with an important caveat: the rebars must be properly pickled and all mill scale must be removed. Overall, the results of the study contribute rare, valuable long-term exposure data for CRRBs embedded in concrete. However, only 20 years of exposure data has been analyzed thus far; as the service lives of reinforced concrete structures are expected to span 75-100 or more years, continued monitoring of field specimens and bridges is advised.

NOTE: FDOT-SMO released a notice in 2009 indicating that all data referring to 2201 rebars in this report (and previous reports) should be 2101. The 2101 rebars used between 2002 and 2007 in the samples had mill scale. In most cases the report uses 2101, but not everywhere (e.g., labels in plots).

TABLE OF CONTENTS

TECHNICAL REPORT DOCUMENTATION PAGE	iv
ACKNOWLEDGMENTS	v
EXECUTIVE SUMMARY	vi
TABLE OF CONTENTS	ix
LIST OF FIGURES	xiv
LIST OF TABLES	xxvi
1 INTRODUCTION.....	1
1.1 BACKGROUND.....	1
1.2 BRIDGES WITH CRRBS	2
1.3 BACKGROUND FOR SAMPLES AT FAU	5
1.4 BACKGROUND FOR SAMPLES AT FDOT-SMO	6
1.5 BACKGROUND FOR COLUMNS AT CRESCENT BEACH.....	6
2 EXPERIMENTAL METHODOLOGY	7
2.1 SDS SAMPLES AT FAU-SEATECH.....	7
2.1.1 Background.....	7
2.1.2 Sample Geometry and Nomenclature	7
2.2 MEASUREMENTS ON SDS	10
2.2.1 Rebar Potential Measurements with Voltmeter.....	10
2.2.2 Gecor 8.....	10
2.2.3 Galvanostatic Pulse (GP) Method.....	11
2.3 SAMPLES AT FDOT-SMO	12
2.3.1 Tombstone Samples	12
2.3.2 3-Bar Square Samples.....	12
2.3.3 Macro-Cell Slab (MS) Specimens (Modified G109).....	13
2.4 POTENTIAL AND CURRENT MEASUREMENTS ON SAMPLES AT FDOT-SMO.....	14
2.5 CRESCENT BEACH FIELD COLUMN SPECIMENS	14
2.6 MEASUREMENTS PERFORMED DURING BRIDGE VISITS (INCLUDING CORES).....	17

2.6.1	Jensen Beach Bridge	17
2.6.2	St. Joseph's Bay Bridge	20
2.7	TERMINATION PROCEDURE FOR SDS SAMPLES.....	21
2.8	MILLING/SLICING OF CORES	22
2.9	MILLING ALONG THE REBAR TRACE	22
2.10	TITRATION (CHLORIDE ANALYSIS).....	22
2.11	TERMINATION OF SAMPLES AT FDOT-SMO AND REBAR CLEANING..	22
2.11.1	Dissection of Tombstone Samples	22
3	RESULTS – SDS SAMPLES	24
3.1	REBAR POTENTIALS	24
3.2	GECOR MEASUREMENTS	29
3.2.1	Corrosion Potential	32
3.2.2	Isolated Corrosion Rate.....	37
3.2.3	Solution Resistance	43
3.3	GP MEASUREMENTS	49
3.3.1	Corrosion Currents.....	51
3.3.2	Solution Resistance.....	57
3.3.3	Open Circuit Potentials from GP measurements	64
4	RESULTS – SAMPLES AT FDOT-SMO.....	66
4.1	BACKGROUND.....	66
4.2	EVALUATION OF ELECTROCHEMICAL CORROSION DATA	67
4.3	PLOTS FOR SELECTED TOMBSTONE SAMPLES.....	67
4.4	3-BAR SQUARE SAMPLES.....	74
4.5	G109 SAMPLES.....	75
4.6	TERMINATED SAMPLES.....	76
5	RESULTS – CRESCENT BEACH.....	77
5.1	SURFACE CONDITIONS OF COLUMNS.....	77
5.1.1	Columns with MMFX.....	77
5.1.2	Columns with 3CR12.....	79
5.1.3	Columns with 2101	81
5.2	POTENTIALS	83

5.2.1	Rebar Potential Over Time.....	83
5.3	REBAR POTENTIALS MEASURED DURING RECENT VISITS	88
5.3.1	MMFX	88
5.3.2	3CR12	89
5.3.3	2101.....	89
5.4	REBAR POTENTIALS VS. HEIGHT.....	90
5.4.1	Columns with 3CR12 Rebars	90
5.4.2	Columns with 2101 Rebars.....	93
5.4.3	Columns with MMFX Rebars.....	96
5.4.4	Column with 316 Rebars	98
5.4.5	Column with Carbon Steel Rebars.....	99
5.5	CORES OBTAINED FROM CRESCENT BEACH COLUMNS	100
5.5.1	Chloride Profiles for Crescent Beach Samples	101
5.5.2	Corrosion Extent on Rebar Segments After Additional Cleaning	108
5.6	SUMMARY	112
6	RESULTS – VISITS TO BRIDGES	113
6.1	VISIT TO BRIDGE #510072, SR30A BRIDGE ST. JOSEPH’S BAY AREA	113
6.1.1	Location One.....	114
6.1.2	Location Two (South Side)	114
6.1.3	Additional Observations	115
6.2	FIELD VISIT TO JENSEN BEACH BRIDGE	116
6.2.1	Prior Visits to Jensen Beach Bridge.....	116
6.2.2	Jensen Beach Bridge– Potential vs. Height	117
6.2.3	Concrete Resistivity Measured on the Columns of the Jensen Beach Bridge	121
6.2.4	Chloride Profiles for Jensen Beach Bridge Samples	124
6.3	SUMMARY	126
7	FORENSIC ANALYSIS – SDS SAMPLES	127
7.1	REBAR CONDITION UPON EXPOSURE	127
7.1.1	4-CCRV-3CR12-2	127
7.1.2	CREV-CT2-2	132
7.1.3	4-CCON-CT2-1	136

7.1.4	BCCD-CT2-1	138
7.1.5	CSDB-CT2-1	142
7.1.6	304 Rebars and 316 Rebar	146
7.2	ANALYSIS AFTER REBAR CLEANING	148
7.2.1	4-CCRV-3CR12-2	148
7.2.2	CREV-CT2-2	156
7.2.3	4-CCON-CT2-1	159
7.2.4	BCCD-CT2-1	160
7.2.5	CSDB-CT2-1	169
7.3	REBAR TRACE CHLORIDE CONCENTRATIONS	179
8	FORENSIC ANALYSIS – FDOT-SMO SAMPLES	181
8.1	VISUAL OBSERVATIONS OF SAMPLES BEFORE FORENSIC ANALYSIS	181
8.1.1	STD3-2101-B (Tombstone)	181
8.1.2	STD3-2304-B (Tombstone)	182
8.1.3	BENT-STD3-304-C (Tombstone).....	183
8.1.4	STD3-SMI-D (Tombstone).....	184
8.1.5	STD3-3CR12-E (Tombstone)	185
8.1.6	STD3-MMFX-B (Tombstone)	186
8.1.7	ELEV-MMFX-A (3-Bar Square)	187
8.1.8	UBDB-SMI-B (G109)	188
8.2	VISUAL OBSERVATIONS OF CORROSION ON BARS AFTER TERMINATION.....	189
8.2.1	STD3-2101-B (Tombstone)	189
8.2.2	STD3-2304-B (Tombstone)	192
8.2.3	BENT-STD3-304-C (Tombstone).....	194
8.2.4	STD3-SMI-D (Tombstone).....	196
8.2.5	STD3-3CR12-E (Tombstone)	197
8.2.6	STD3-MMFX-B (Tombstone).....	199
8.2.7	ELEV-MMFX-A (3-Bar Square)	201
8.2.8	UBDB-SMI-B (G109)	203

8.3 VISUAL OBSERVATIONS OF CORROSION ON BARS AFTER	
TERMINATION AND CLEANING.....	204
8.3.1 STD3-2101-B (Tombstone)	204
8.3.2 STD3-2304-B (Tombstone)	206
8.3.3 BENT-STD3-304-C (Tombstone).....	207
8.3.4 STD3-SMI-D (Tombstone).....	208
8.3.5 STD3-3CR12-E (Tombstone)	209
8.3.6 STD3-MMFX-B (Tombstone).....	210
8.3.7 ELEV-MMFX-A (3-Bar Square)	211
8.3.8 UBDB-SMI-B (G109)	213
9 CONCLUSIONS	214
9.1 SDS SAMPLES AT FAU	214
9.2 SAMPLES EXPOSED AT FDOT-SMO	214
9.3 FIELD COLUMNS	214
9.4 VISITED BRIDGES	215
10 REFERENCES.....	216
11 APPENDICES.....	218
11.1 APPENDIX A: NAMES OF SDS SAMPLES AT FAU	218
11.2 APPENDIX B: REBAR POTENTIAL MEASUREMENTS IN 2025.....	222
11.3 APPENDIX C: QUANTITATIVE MEASUREMENTS OF CORROSION	
DAMAGE TO SDS SAMPLES.....	225
11.3.1 4-CCRV-3CR12-2	225
11.3.2 CREV-CT2-2	228
11.3.3 BCCD-CT2-1	229
11.3.4 CSDB-CT2-1	232
11.4 APPENDIX D: ADDITIONAL PLOTS FROM FIELD COLUMNS	235

LIST OF FIGURES

Figure 1-1. Progreso Pier located in Yucatan, Mexico, built with 304 round bars.	4
Figure 2-1. Configurations of SDS geometry.	8
Figure 2-2. Gecor 8 Sensor C measuring Rebar A of an SDS sample (left); Gecor 8 device (right).	11
Figure 2-3. Schematic illustration of the Tombstone type 3-bar column specimen for each of the three bar configurations (all dimensions in mm).	12
Figure 2-4. Schematic illustration of the square type 3-bar column specimen for each of the three bar configurations (all dimensions in mm).	13
Figure 2-5. Geometry of the macro-cell slab type specimen with both bent and straight bars (all dimensions in mm).	13
Figure 2-6. Geometry of field columns (Presuel-Moreno, Powers, & Hartt, Corrosion Resistant Alloys for Reinforced Concrete, 2008).	14
Figure 2-7. Diagram showing the location and type of rebar for each column at Crescent Beach Field Site.	15
Figure 2-8. Picture of columns during the October 2024 visit.	15
Figure 2-9. Picture of a test box from a field column specimen (left) and diagram of the rebar that corresponds to each wire color (right).	16
Figure 2-10. Diagram of rebar orientation within the measured columns.	17
Figure 2-11. Photo of Jensen Beach Bridge Pier 12.	18
Figure 2-12. Approximate region where Jensen Beach Bridge footer potential measurements were taken.	19
Figure 2-13. Coring of the north footer of Jensen Beach Bridge Pier 11, close to the marine growth.	20
Figure 2-14. Picture of SR30A Bridge (#510072) taken from the marina. Left circle marker indicates drilling location 1; right circle marker indicates drilling location 2.	21
Figure 2-15. Location of concrete cuts made on terminated SDS samples.	21
Figure 2-16. Schematic illustration of the concrete sectioning for 3BTC specimens.	23
Figure 3-1. Potential vs. time for terminated 4-CCRV-3CR12-2 and non-terminated companion 4-CCRV-3CR12-3.	32

Figure 3-2. Potential vs. time for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.	32
Figure 3-3. Potential vs. time for terminated BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.	33
Figure 3-4. Potential vs. time for terminated CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.	33
Figure 3-5. Potential vs. time for 4-CCON-CT2-1. Rebar C was terminated.	33
Figure 3-6. Potential vs. time for 6-CREV-304-1.	34
Figure 3-7. Potential vs. time for 4-CREV-CT2-2.	34
Figure 3-8. Potential vs. time for 6-STD2-304-2.	35
Figure 3-9. Potential vs. time for 6-CCRV-304-3.	35
Figure 3-10. Potential vs. time for 1-STD1-316-2.	36
Figure 3-11. Potential vs. time for 1-STD1-CT1-1.	36
Figure 3-12. Potential vs. time for 5-STD1-2304.	37
Figure 3-13. Potential vs. time for STD3-2304-1.	37
Figure 3-14. Isolated corrosion rates for terminated 4-CCRV-3CR12-2 and non-terminated companion 4-CCRV-3CR12-3.	38
Figure 3-15. Isolated corrosion rates for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.	38
Figure 3-16. Isolated corrosion rates for terminated BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.	38
Figure 3-17. Isolated corrosion rates for terminated CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.	39
Figure 3-18. Isolated corrosion rates for 4-CCON-CT2-1. Rebar C was terminated.	39
Figure 3-19. Isolated corrosion rates for 6-CREV-304-1.	40
Figure 3-20. Isolated corrosion rates for 4-CREV-CT2-2.	40
Figure 3-21. Isolated corrosion rates for 6-STD2-304-2.	41
Figure 3-22. Isolated corrosion rates for 6-CCRV-304-3.	41
Figure 3-23. Isolated corrosion rates for 1-STD1-316-2.	42
Figure 3-24. Isolated corrosion rates for 1-STD1-CT1-1.	42
Figure 3-25. Isolated corrosion rates for 5-STD1-2304.	43

Figure 3-26. Isolated corrosion rates for STD3-2304-1.....	43
Figure 3-27. Solution resistance vs. time for terminated 4-CCRV-3CR12-2 and non-terminated companion 4-CCRV-3CR12-3.	44
Figure 3-28. Solution resistance vs. time for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.....	44
Figure 3-29. Solution resistance vs. time for terminated sample BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.	44
Figure 3-30. Solution resistance vs. time for terminated sample CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.	45
Figure 3-31. Solution resistance vs. time for 4-CCON-CT2-1. Rebar C was terminated.	45
Figure 3-32. Solution resistance vs. time for 6-CREV-304-1.....	46
Figure 3-33. Solution resistance vs. time for 4-CREV-CT2-2.....	46
Figure 3-34. Solution resistance vs. time for 6-STD2-304-2.....	47
Figure 3-35: Solution resistance vs. time for 6-CCRV-304-3.....	47
Figure 3-36. Solution resistance vs. time for 1-STD1-316-2.....	48
Figure 3-37. Solution resistance vs. time for 1-STD1-CT1-1.	48
Figure 3-38. Solution resistance vs. time for 5-STD1-2304.....	49
Figure 3-39. Solution resistance vs. time for STD3-2304-1.....	49
Figure 3-40. Corrosion current vs. time for non-terminated sample 4-CCRV-3CR12-3.....	52
Figure 3-41. Corrosion current vs. time for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.....	52
Figure 3-42. Corrosion current vs. time for terminated BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.	52
Figure 3-43. Corrosion current vs. time terminated CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.	53
Figure 3-44. Corrosion current vs. time for 4-CCON-CT2-1. Rebar C was terminated.	53
Figure 3-45. Corrosion current vs. time for non-terminated 6-CREV-304-1.	54
Figure 3-46. Corrosion current vs. time for 4-CREV-CT2-2.....	54
Figure 3-47. Corrosion current vs. time for 6-STD2-304-2.....	55
Figure 3-48. Corrosion current vs. time for 6-CCRV-304-3.....	55
Figure 3-49. Corrosion current vs. time for 1-STD1-316-2.....	56

Figure 3-50. Corrosion current vs. time for 1-STD1-CT1-1.	56
Figure 3-51. Corrosion current vs. time for 5-STD1-2304.	57
Figure 3-52. Corrosion current vs. time for STD3-2304-1.	57
Figure 3-53. Solution resistance vs. time for non-terminated 4-CCRV-3CR12-3.	58
Figure 3-54. Solution resistance vs. time for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.	58
Figure 3-55. Solution resistance vs. time for terminated BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.	59
Figure 3-56. Solution resistance vs. time for terminated CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.	59
Figure 3-57. Solution resistance vs. time for 4-CCON-CT2-1. Rebar C was terminated.	59
Figure 3-58. Solution resistance vs. time for 6-CREV-304-1.	60
Figure 3-59. Solution resistance vs. time for 4-CREV-CT2-2.	61
Figure 3-60. Solution resistance vs. time for 6-STD2-304-2.	61
Figure 3-61. Solution resistance vs. time for 6-CCRV-304-3.	62
Figure 3-62. Solution resistance vs. time for 1-STD1-316-2.	62
Figure 3-63. Solution resistance vs. time for 1-STD1-CT1-1.	63
Figure 3-64. Solution resistance vs. time for 5-STD1-2304.	63
Figure 3-65. Solution resistance vs. time for STD3-2304-1.	64
Figure 3-66. Open circuit potential vs. time for 4-CCRV-3CR12-3.	65
Figure 3-67. Open circuit potential vs. time for 6-STD2-304-2.	65
Figure 4-1. Potential and current vs. Age measured on sample STD3-3CR12-A up to Spring 2024.	68
Figure 4-2. Potential and current vs. age measured on sample STD3-3CR12-A up to Fall 2025.	68
Figure 4-3. Potential and current vs. age measured on sample STD3-3CR12-E up to Fall 2025.	69
Figure 4-4. Potential and current vs. age measured on sample STD3-MMFX-B up to Fall 2025.	70
Figure 4-5. Potential and current vs. age measured on sample BENT-304-C up to Fall 2025.	71
Figure 4-6. Potential and current vs. age measured on sample STD3-SMI-D up to July 2025.	72
Figure 4-7. Potential and current vs. Age measured on Tombstone sample STD3-2304-B.	73
Figure 4-8. Potential and current vs. Age measured on Tombstone sample STD3-2101-B.	74

Figure 4-9. Potential and current vs. Age measured on 3-Bar square sample ELEV-MMFX-A..	75
Figure 5-1. Picture showing surface conditions of east, west, north, and south faces of column MMFX-A.	77
Figure 5-2. Picture showing surface conditions of east, west, north, and south faces of column MMFX-B.	78
Figure 5-3. Picture showing surface conditions of east, west, north, and south faces of column MMFX-C.	78
Figure 5-4. Picture showing cracks on the surface of each face of column 3CR12-A.	79
Figure 5-5. Picture showing surface conditions of east, west, and south faces of column 3CR12-B. North face not pictured.	80
Figure 5-6. Picture showing surface conditions of east, west, and south faces of column 3CR12-C. North face not pictured.	80
Figure 5-7. Picture showing cracks on the surface of each face of column 2101-A.	81
Figure 5-8. Picture showing cracks on the surface of each face of column 2101-B.	82
Figure 5-9. Picture showing cracks on the surface of each face of column 2101-C.	82
Figure 5-10. Picture showing north face of 2101-C in October 2024 (left) and September 2025 (right).	83
Figure 5-11. Plot showing the potential evolution for black bars embedded in BB column A. ...	84
Figure 5-12. Plot showing the potential evolution for MMFX rebars embedded in MMFX column A.	85
Figure 5-13. Plot showing the potential evolution for 2101 rebars embedded in 2101 column A.	85
Figure 5-14. Plot showing the potential evolution for 3CR12 rebars embedded in 3CR12 column C.	86
Figure 5-15. Plot showing the potential evolution for 304 rebars embedded in 304 column A. ..	86
Figure 5-16. Plot showing the potential evolution for 316 rebars embedded in 316 column A. ..	87
Figure 5-17. Plot showing the potential evolution for 316 rebars embedded in 316 column C. ..	87
Figure 5-18. Avg. rebar potential vs height measured in column 3CR12-A.	91
Figure 5-19. Avg. rebar potential vs height measured in column 3CR12-B.	92
Figure 5-20. Avg. rebar potential vs height measured in column 3CR12-C.	93
Figure 5-21. Avg. rebar potential vs height measured in column 2101-A.	94

Figure 5-22. Avg. rebar potential vs height measured in column 2101-B.	94
Figure 5-23. Avg. rebar potential vs height measured in column 2101-C.	95
Figure 5-24. Avg. rebar potential vs height measured in column MMFX-A.	96
Figure 5-25. Avg. rebar potential vs height measured in column MMFX-B.	97
Figure 5-26. Avg. rebar potential vs height measured in column MMFX-C.	97
Figure 5-27. Avg. Rebar Potential vs height measured in column 316-C.	98
Figure 5-28. Avg. rebar potential vs height measured in column A (with carbon steel rebar).	99
Figure 5-29. Images show the core obtained from column MMFX-1. It included a rebar segment.	100
Figure 5-30. Image shows the core obtained from column 2101-A (~20 inches above WL).	100
Figure 5-31. Image shows the core obtained from column 2101-B (~6 inches below WL).	100
Figure 5-32. Image shows the cores obtained from columns with 3CR12 reinforcement.	101
Figure 5-33. Image shows the core obtained from column 3CR12-A @ WL from the center of the column.	101
Figure 5-34. MMFX-A Core Chloride Profile.	102
Figure 5-35. MMFX-A Rebar Trace Chloride Profile.	102
Figure 5-36. 2101-A Rebar Trace Chloride Profile.	103
Figure 5-37. 2101-B Core Chloride Profile.	104
Figure 5-38. 2101-B Rebar Trace Chloride Profile.	104
Figure 5-39. 3CR12-A (12" above water line) Chloride Profile.	105
Figure 5-40. 3CR12-A @ WL(both sides) Chloride Profile.	106
Figure 5-41. 3CR12-B Core 12" above WL Chloride Profile.	107
Figure 5-42. 3CR12-B Rebar Trace at WL Chloride Profile.	107
Figure 5-43. 3CR12-C Core (at water line) Chloride Profile.	108
Figure 5-44. 3CR12-C Core (6" above water line) Chloride Profile.	108
Figure 5-45. MMFX rebar section after additional immersion in cleaning solution.	109
Figure 5-46. MMFX rebar section close-up of the region with most corrosion.	109
Figure 5-47. 2101 rebar section (Column A) after additional immersion in cleaning solution. ...	110
Figure 5-48. 2101 (Column A) rebar section close-up of the region with most corrosion.	110
Figure 5-49. 2101 rebar section (Column B) after additional immersion in cleaning solution. ...	111
Figure 5-50. 2101 (Column B) rebar section close-up of the region with most corrosion.	111

Figure 6-1. Picture of SR30A Bridge (510072) taken from the marina, left dot location 1, right dot is location 2.	113
Figure 6-2. Drilled hole to access rebar at location one. A crack was visible transverse to the phone shade.	114
Figure 6-3. South side of the bridge, showing several cracks (moisture allows for observation).	115
Figure 6-4. Close-up of two of the cracks (moisture allows for observation).	115
Figure 6-5. South side of the bridge under the deck, showing several cracks (moisture allows observation).	116
Figure 6-6. Bent 11 rebar potential vs. height.	118
Figure 6-7. Bent 12 rebar potential vs. height.	118
Figure 6-8. Bent 10 rebar potential vs. height.	119
Figure 6-9. Bent 11 rebar potential vs. height.	120
Figure 6-10. Bent 12 rebar potential vs. height.	120
Figure 6-11. Bent 11 concrete resistivity vs. height.	121
Figure 6-12. Bent 12 concrete resistivity vs. height.	122
Figure 6-13. Bent 10 concrete resistivity vs. height.	123
Figure 6-14. Bent 11 concrete resistivity vs. height.	123
Figure 6-15. Bent 12 concrete resistivity vs. height.	124
Figure 6-16. Chloride profile of Jensen Beach bent 11 north footer core (25” above marine growth).	125
Figure 6-17. Chloride profile - Jensen Beach bent 11 north footer core (5” above marine growth).	125
Figure 6-18. Chloride profile of Jensen Beach bent 11 south column, south face core (12” above bottom).	126
Figure 7-1. 4-CCRV-3CR12-2 top row, top-facing rebars and concrete rebar traces.	128
Figure 7-2. 4-CCRV-3CR12-2 top row, bottom-facing rebars and concrete rebar traces.	129
Figure 7-3. 4-CCRV-3CR12-2 bottom row, top-facing rebars and concrete rebar traces.	131
Figure 7-4. 4-CCRV-3CR12-2 bottom row, bottom-facing rebars and concrete rebar traces.	132
Figure 7-5. CREV-CT2-2 top row, top-facing rebars and concrete rebar traces.	133
Figure 7-6. CREV-CT2-2 top row, bottom-facing rebars and concrete rebar traces.	134

Figure 7-7. CREV-CT2-2 bottom row, top-facing rebars and concrete rebar traces.	135
Figure 7-8. CREV-CT2-2 bottom row, bottom-facing rebars and concrete rebar traces.	136
Figure 7-9. 4-CCON-CT2-1 top-facing, top and bottom rebars and concrete rebar traces.	137
Figure 7-10. 4-CCON-CT2-1 bottom-facing, top and bottom rebars and concrete rebar traces.	138
Figure 7-11. BCCD-CT2-1 top-facing, top rebars and concrete rebar traces.	139
Figure 7-12. BCCD-CT2-1 bottom-facing, top rebars and concrete rebar traces.	140
Figure 7-13. BCCD-CT2-1 top-facing, bottom rebars and concrete rebar traces.	141
Figure 7-14. BCCD-CT2-1 bottom-facing, bottom rebars and concrete rebar traces.	142
Figure 7-15. CSDB-CT2-1 top-facing, top rebars and concrete rebar traces.	143
Figure 7-16. CSDB-CT2-1 bottom-facing, top rebars (excluding rebar A) and concrete rebar traces.	144
Figure 7-17. CSDB-CT2-1 top-facing, bottom rebars and concrete rebar traces.	145
Figure 7-18. CSDB-CT2-1 bottom-facing, bottom rebars and concrete rebar traces.	146
Figure 7-19. Images of one 316 SS rebar and two 304 SS rebars before cleaning.	147
Figure 7-20. Bottom-facing side of 304SS rebar before cleaning, showing some corrosion.	147
Figure 7-21. Closeups of pitting corrosion on 316SS rebar.	147
Figure 7-22. Closeups of pitting corrosion on 304SS rebars.	148
Figure 7-23. 4-CCRV-3CR12-2 top row, top-facing rebars after cleaning.	149
Figure 7-24. 4-CCRV-3CR12-2 top row, bottom-facing rebars after cleaning.	150
Figure 7-25. 4-CCRV-3CR12-2 bottom row, top-facing rebars after cleaning.	151
Figure 7-26. 4-CCRV-3CR12-2 bottom row, bottom-facing rebars after cleaning.	151
Figure 7-27. Rebars A1 and A2 closeups (top and bottom).	152
Figure 7-28. Rebar B1 closeups (top and bottom or side image).	153
Figure 7-29. Rebar B2 closeups (top and bottom).	154
Figure 7-30. Rebars C1 and C2 closeups.	155
Figure 7-31. Notable closeups of 3CR12 bottom row rebars.	156
Figure 7-32. Concrete fracture caused by corrosion from rebar B1.	157
Figure 7-33. Concrete crack near rebar A2, likely caused by corrosion from rebar B1.	157
Figure 7-34. Concrete crack caused by corrosion from rebar C1.	158
Figure 7-35. Corrosion of unclad, embedded rebar end of rebar B1 after cleaning.	158
Figure 7-36. Corrosion of unclad, embedded rebar end of rebar C1 after cleaning.	159

Figure 7-37. Both sides of 4-CCON-CT2-1 rebar C.....	159
Figure 7-38. Closeup of pits on cladding, top face of 4-CCON-CT2-1 rebar C.....	160
Figure 7-39. Top side of rebar A and select segments of sample BCCD-CT2-1.	160
Figure 7-40. Hole 1 on top side of rebar A of sample BCCD-CT2-1.	161
Figure 7-41. Hole 9 on top side of rebar A of sample BCCD-CT2-1.	161
Figure 7-42. Top side of rebar B and select segments of sample BCCD-CT2-1.....	162
Figure 7-43. Hole 9 on top side of rebar B of sample BCCD-CT2-1.....	162
Figure 7-44. Bump with crack in hole 10 on top side of rebar B of sample BCCD-CT2-1.	163
Figure 7-45. Top side of rebar C and select segments of sample BCCD-CT2-1.....	164
Figure 7-46. Hole 2 on top side of rebar C of sample BCCD-CT2-1.....	164
Figure 7-47. Bump with crack in hole 3 on top side of rebar C of sample BCCD-CT2-1.	165
Figure 7-48. Bottom side of rebar A and select segments of sample BCCD-CT2-1.	165
Figure 7-49. Hole 5 on bottom side of rebar A of sample BCCD-CT2-1.....	166
Figure 7-50. Bottom side of rebar B and select segments of sample BCCD-CT2-1.....	166
Figure 7-51. Hole 3 on bottom side of rebar B of sample BCCD-CT2-1.....	167
Figure 7-52. Bottom side of rebar C and select segments of sample BCCD-CT2-1.....	168
Figure 7-53. Hole 4 on bottom side of rebar C of sample BCCD-CT2-1.....	168
Figure 7-54. Hole 6 on bottom side of rebar C of sample BCCD-CT2-1.....	169
Figure 7-55. Top side of rebar A and select segments of sample CSDB-CT2-1.....	170
Figure 7-56. Hole 1 on top side of rebar A of sample CSDB-CT2-1.....	170
Figure 7-57. Top side of rebar B and select segments of sample CSDB-CT2-1.	171
Figure 7-58. Hole 2 on the top side of rebar B of sample CSDB-CT2-1.	171
Figure 7-59. Top side of rebar C and select segments of sample CSDB-CT2-1.	172
Figure 7-60. Hole 8 on top side of rebar C of sample CSDB-CT2-1.	173
Figure 7-61. Bottom side of rebar A and select segments of sample CSDB-CT2-1.....	174
Figure 7-62. Hole 1 on bottom side of rebar A of sample CSDB-CT2-1.	174
Figure 7-63. Hole 7 on bottom side of rebar A of sample CSDB-CT2-1.	174
Figure 7-64. Bottom side of rebar B and select segments of sample CSDB-CT2-1.	175
Figure 7-65. Hole 1 on bottom side of rebar B of sample CSDB-CT2-1.....	175
Figure 7-66. Hole 5 on bottom side of rebar B of sample CSDB-CT2-1.....	176

Figure 7-67. Bump with crack next to Hole 6 on bottom side of rebar B of sample CSDB-CT2-1.	176
Figure 7-68. Hole 3 on bottom side of rebar C of sample CSDB-CT2-1.	177
Figure 7-69. Hole 3 on bottom side of rebar C of sample CSDB-CT2-1.	177
Figure 7-70. Hole 8 on bottom side of rebar C of sample CSDB-CT2-1.	178
Figure 7-71. Hole 9 on bottom side of rebar C of sample CSDB-CT2-1.	179
Figure 8-1. Front and back side of sample STD3-2101-B before termination.	181
Figure 8-2. Right side crack of sample STD3-2101-B before termination.....	182
Figure 8-3. Front and back side of sample STD3-2304-B before termination.	182
Figure 8-4. Back side of sample STD3-SMI-D before termination.....	183
Figure 8-5. Front side of sample BENT-STD3-304-C before termination.	183
Figure 8-6. Back side of sample STD3-SMI-D before termination.....	184
Figure 8-7. Front side of sample STD3-SMI-D before termination.	185
Figure 8-8. Front and back side of sample STD3-3CR12-E before termination.	185
Figure 8-9. Back side crack of sample STD3-3CR12-E before termination.	186
Figure 8-10. Front and back side of sample STD3-MMFX-B before termination.	186
Figure 8-11. Crack observed on the front side of sample STD3-MMFX-B before termination.	187
Figure 8-12. Front side of sample ELEV-MMFX-A before termination.	187
Figure 8-13. Back side of sample ELEV-MMFX-A before termination.	188
Figure 8-14. Top (left) and bottom (right) trace of sample UBDB-SMI-B (G109).	189
Figure 8-15. Top trace and close-up of sample UBDB-SMI-B (G109).	189
Figure 8-16. All rebars of sample STD3-2101-B.....	190
Figure 8-17. Close up of corrosion spot on rebar 2 of sample STD3-2101-B at multiple angles.	191
Figure 8-18. Close up of corrosion spot on rebar 3 of sample STD3-2101-B at multiple angles.	192
Figure 8-19. All rebars of sample STD-2304-B.....	193
Figure 8-20. Close up corrosion spot on rebar 2 of sample STD-2304-B.	193
Figure 8-21. All rebars of sample BENT-STD3-304-C.	194
Figure 8-22. Close up corrosion spots on rebar 1 of sample BENT-STD3-304-C.	195
Figure 8-23. Close up corrosion spot on end of rebar 2 of sample BENT-STD3-304-C.....	195

Figure 8-24. Close up corrosion spots on rebar 3 of sample BENT-STD3-304-C.	196
Figure 8-25. All rebars and close up image of corrosion spot on rebar 3 of sample STD3-SMI-D.	197
Figure 8-26. All rebars of sample STD3-3CR12-E.	198
Figure 8-27. Corrosion spots on rebar 1 (right 2 images) and 2 (left) of sample STD3-3CR12-E.	198
Figure 8-28. Corrosion spots on rebar 3 of sample STD3-3CR12-E.....	199
Figure 8-29. All rebars of sample STD3-MMFX-B.	199
Figure 8-30. Corrosion spots observed on rebar 1 of sample STD3-MMFX-B.	200
Figure 8-31. Corrosion spots observed on rebar 2 of sample STD3-MMFX-B.	200
Figure 8-32. Corrosion spots observed on rebar 3 of sample STD3-MMFX-B.	201
Figure 8-33. All rebars of sample ELEV-MMFX-A.....	201
Figure 8-34. Corrosion spots on rebar 1 of sample ELEV-MMFX-A.	202
Figure 8-35. Corrosion spots on rebar 2 of sample ELEV-MMFX-A.	202
Figure 8-36. Corrosion spots on rebar 3 of sample ELEV-MMFX-A.	203
Figure 8-37. Corrosion spots on top side of sample UBDB-SMI-B (G109).	203
Figure 8-38. Corrosion spots on bottom side of sample UBDB-SMI-B (G109).....	204
Figure 8-39. All rebars of sample STD3-2101-B after cleaning.....	205
Figure 8-40. Corrosion spot observed on rebar 2 of STD3-2101-B.	205
Figure 8-41. Full length of rebar 3 and notable areas of corrosion damage of sample STD3-2101-B.....	206
Figure 8-42. Corrosion spot observed on rebar 2 of sample STD3-2304-B.	206
Figure 8-43. Sample STD3-2304-B - full length of rebar 3 and corrosion sites.	207
Figure 8-44. STD3-304-C (BENT) - full length of rebar 1 and corroding locations.....	207
Figure 8-45. STD3-304-C (BENT) rebar 3 corroding site after cleaning.....	208
Figure 8-46. STD3-SMI-D - full length of rebar 1 and notable corroding site after cleaning....	208
Figure 8-47. STD3-SMI-D - full length of rebar 3 and notable areas of corrosion damage.	209
Figure 8-48. STD3-3CR12-E - full length of rebar 1 and notable areas of corrosion damage...	209
Figure 8-49. STD3-3CR12-E - full length of rebar 3 and notable areas of corrosion damage...	210
Figure 8-50. STD3-MMFX-B - full length of rebar 1 and notable areas of corrosion damage..	210
Figure 8-51. STD3-MMFX-B - full length of rebar 2 and notable areas of corrosion damage...	211

Figure 8-52. STD3-MMFX-B - full length of rebar 3 and notable areas of corrosion damage...	211
Figure 8-53. ELEV-MMFX-A - full length of rebar 1 and notable areas of corrosion damage.	212
Figure 8-54. ELEV-MMFX-A - full length of rebar 2 and notable areas of corrosion damage.	212
Figure 8-55. ELEV-MMFX-A - full length of rebar 3 and notable areas of corrosion damage.	213
Figure 8-56. Rebar removed from UBDB-SMI-B sample: left top side full U rebar view and two close-up of the drilled holes.....	213
Figure 11-1. Rebar potential vs. height measured in column 3CR12-A. Two column faces per wire were measured and plotted.	235
Figure 11-2. Rebar potential vs. height measured in column 3CR12-C. Two column faces per wire were measured and plotted.	236

LIST OF TABLES

Table 1-1. List of bridges containing CRRB evaluated as part of Dr. Hartt's project (Hartt, Powers, Lysogorski, Paredes, & Virmani, 2006).	2
Table 2-1. Compositions of SDS concrete mix types.	8
Table 2-2. SDS specimen nomenclature and conditions.....	9
Table 3-1. Potential measurements in mV vs. CSE for indoor samples, January 2025.....	24
Table 3-2. Potential measurements vs CSE for indoor samples, February 2025.....	25
Table 3-3. Potential measurements vs CSE for indoor samples, June 2025.	25
Table 3-4. Potential measurements vs. CSE for selected outdoor samples, January 2025.	26
Table 3-5. Potential measurements vs. CSE for selected outdoor samples, February 2025.	26
Table 3-6. Potential measurements vs. CSE for selected outdoor samples, May 2025.	27
Table 3-7. Potential measurements vs CSE for a larger selection of outdoor samples, December 2025.....	28
Table 3-8. Samples with rebars that had isolated corrosion rates greater than $1 \mu\text{A}/\text{cm}^2$	30
Table 3-9. Samples with rebars that had average isolated corrosion rates greater than $0.4 \mu\text{A}/\text{cm}^2$ and less than $1 \mu\text{A}/\text{cm}^2$	30
Table 3-10. Samples with rebars that had average corrosion currents greater than $20 \mu\text{A}$	50
Table 3-11. Samples with rebars that had average corrosion currents greater than $12 \mu\text{A}$ and less than $20 \mu\text{A}$	51
Table 4-1. FDOT-SMO samples selected for termination.	76
Table 5-1. Rebar potential measurements vs. CSE for each MMFX column, taken October 2024.	88
Table 5-2. Rebar potential measurements vs. CSE for each MMFX column, taken September 2025.....	88
Table 5-3. Rebar potential measurements vs. CSE for each 3CR12 column, taken October 2024.	89
Table 5-4. Rebar potential measurements vs. CSE for each 3CR12 column, taken September 2025. No contact available for yellow wire.	89
Table 5-5. Rebar potential measurements vs. CSE for each 2101 column, taken October 2024.	89
Table 5-6. Rebar potential measurements vs. CSE for each 2101 column, taken September 2025.	90

Table 6-1. Jensen Beach bent 11, D_{app} from cores obtained.	126
Table 7-1. Average chloride concentrations of terminated SDS samples' rebar traces.....	180
Table 11-1. List of all monitored SDS samples at FAU.....	218
Table 11-2. Comprehensive list of electrically disconnected rebar potential measurements from January, February, and May 2025.	222
Table 11-3. Rebar A1 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion. ..	225
Table 11-4. Rebar A2 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion. ..	225
Table 11-5. Rebar B1 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion. ..	225
Table 11-6. Rebar B2 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion. ..	225
Table 11-7. Rebar C1 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion. ..	227
Table 11-8. Rebar C2 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion. ..	227
Table 11-9. Rebar D of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.	227
Table 11-10. Rebar E of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion. ..	227
Table 11-11. Rebar F of sample 4-CCRV-3CR12-2 diameter loss due to pitting corrosion.	228
Table 11-12. CREV-CT2-2 corrosion penetration depths at unclad rebar ends.....	228
Table 11-13. Hole depths of sample BCCD-CT2-1 rebar A.	229
Table 11-14. Hole depths of sample BCCD-CT2-1 rebar B.	229
Table 11-15. Hole depths of sample BCCD-CT2-1 rebar C.	230
Table 11-16. Rebar A of sample BCCD-CT2-1: spaces between holes and hole orientation.	230
Table 11-17. Rebar B of sample BCCD-CT2-1: spaces between holes and hole orientation.....	231
Table 11-18. Rebar C of sample BCCD-CT2-1: spaces between holes and hole orientation.....	231
Table 11-19. Hole depths of sample CSDB-CT2-1 rebar A.....	232
Table 11-20. Hole depths of sample CSDB-CT2-1 rebar B.....	232
Table 11-21. Hole depths of sample CSDB-CT2-1 rebar C.....	233
Table 11-22. Rebar A of sample CSDB-CT2-1: spaces between holes and hole orientation.	233
Table 11-23. Rebar B of sample CSDB-CT2-1: spaces between holes and hole orientation.	234
Table 11-24. Rebar C of sample CSDB-CT2-1: spaces between holes and hole orientation.	234

1 INTRODUCTION

1.1 BACKGROUND

This research project assessed the long-term corrosion performance of corrosion-resistant reinforcing bars (CRRBs) used in concrete exposed to marine and atmospheric conditions. Plain carbon steel is typically used in reinforced concrete structure but is prone to corrosion especially in marine environments due to aggressive chloride ions. Rebar corrosion is detrimental in reinforced concrete. The accumulation of corrosion products on the metal surface builds internal tensile stresses within the concrete and causes it to crack, spall, or fracture, significantly reducing the service life of the structure. CRRBs like stainless steel (SS) have higher Pitting Resistance Equivalence Numbers (PREN), i.e. more alloying components like chromium that yield better corrosion resistance. Additionally, CRRBs generally have higher chloride thresholds, or a higher resistance to chloride-induced corrosion, than carbon steel. Chloride threshold is dependent upon a wide range of variables. Angst et al. suggested that the most influential factors dictating chloride threshold include material properties, such as the presence of corrosion products on the steel or cracks in the concrete; concrete composition, exposure conditions, such as moisture and temperature; potential; and size [2]. The objective of this project was to evaluate various types of CRRBs in concrete as viable long-term alternatives for conventional carbon steel reinforcement in the marine environment and to determine how each alloy performs under exposure conditions relevant to Florida Department of Transportation (FDOT) structures.

This report describes the current state of samples prepared between 2002 and 2007. These samples were prepared with CRRBs, made of various steel alloys. Samples were also prepared with black bar (BB), i.e., regular carbon steel reinforcement. The methodology chapter (Chapter 2) lists the different types of CRRB investigated. The study included intermediate alloy CRRBs, i.e., with a higher chloride threshold than BB, but still subject to corrosion initiating and propagating. The intermediate alloys studied are MMFX, 3CR12 and 2101 (with mill scale, which lowers the chloride threshold). Two clad rebars (316 SS), a duplex stainless steel (2304), 304SS and two types of 316SS. In this report, “CRRB” (Corrosion Resistant Reinforcement Bars) and “CRA” (Corrosion Resistant Alloys) are used interchangeably.

The simulated deck slab (SDS) samples were prepared at the FDOT State Materials Office (FDOT-SMO) and transported to Florida Atlantic University (FAU) [3]. Most SDS samples were prepared between 2002 and 2004, with one batch in 2005 and the last group in 2006. The initial project’s principal investigator (PI) was Dr. William Hartt. Field column (FC) samples were prepared that were then deployed at the Crescent Beach field site. These columns have four rebars and a titanium mixed metal oxide (Ti-MMO) reference electrode; connections were made to a junction box so that rebars could be monitored overtime. The columns were prepared between September 2005 and March 2007. Three different types of samples were prepared that remained at FDOT-SMO: Tombstone geometry (with 3 rebars), 3-Bar Square and Macro-cell slab (modified G109). These samples were prepared between January 2004 and February 2007. Additional Tombstone samples were prepared in 2014 with 2101 and 2304 rebars.

Additional SDS Samples with duplex rebars (2101LDX and 2304) were cast at FDOT-SMO in May 2012 and transported to FAU in July 2012. These samples were prepared as part of a later project [1]. The rebars were provided by a different manufacturer than the 2304 rebars used in

2005. The samples were prepared with 10% Type F Fly Ash as cement replacement. Chapter 5 in [1] provides details of the preconditioning and electromigration used to drive additional chlorides into the concrete. The ionic current (during the electromigration) polarized the duplex rebars to more positive rebar potential values and corrosion initiated. Two SDS with 2304 rebars remain and were included in this project.

As part of a task in the current experimental campaign, bridges in Florida with CRRBs were to be identified and visited if accessible without disturbing traffic. Four bridges with CRRBs were identified: two are near St. Joseph's Bay (along SR30A), one is in Jensen Beach Bridge and a fourth in the Florida Keys. The Jensen Beach Bridge was visited twice in 2025. One of the two bridges in the St. Joseph's Bay area was visited during May 2025.

1.2 BRIDGES WITH CRRBS

As part of Dr. Hartt's project, a task consisted of documenting bridges that used CRRBs. In some cases, the specified reinforcement was substituted. The bridges, their locations, and CRRB type are listed in Table 1-1. The details of the findings can be found in [4]. A bridge crossing Medicine Creek and an adjoining field runoff stream on SR 6 (NBI Bridge number 6059 or A6059) near Galt, MO contains 316LN SS rebars on the bridge deck. This bridge is one of the bridges that is part of the TEA-21 Innovative bridge construction program. Another example of a bridge built with CRRB as part of TEA-21 is Bridge crossing the Middle Fork of the Flathead River on U.S. 2 near Essex, Flathead County, MT. The CRRBs used were 316LN and 2205.

Table 1-1. List of bridges containing CRRB evaluated as part of Dr. Hartt's project [4].

FHWA Project No.	Road	Location	CRRB Type
DE-00-01	SR 82	DE	MMFX-II
FL-00-01	SR 679	FL	Solid 2205SS
FL-01-01	Jensen Beach Causeway	FL	MMFX-II
			Solid 2101SS
ID-02-01	Westmond Bridge, U.S. 95	ID	MMFX-II
ID-02-02	SH21	ID	MMFX-II
IA-01-01	Highway 520	IA	MMFX-II
KY-01-02	CR1218 Galloway Road	KY	MMFX-II
MI-01-02	EBD I-496	MI	Solid SS

FHWA Project No.	Road	Location	CRRB Type
MO-00-01	Route 6	MO	Solid 316LN SS
MT-01-01	U.S. 2	MT	Solid 316LN SS
NC-02-02	SR1178 over I-95	NC	MMFX-II
ND-00-1	I-94	ND	316SS Clad
NH-02-01	I-93	NH	MMFX-II
OK-01-01	I-35	OK	MMFX-II
PR-02	PR-102	PR	MMFX-II
SC-00-01	Route SC73	SC	316SS Clad, 2205SS, MMFX-II
SD-01-01	U.S. 281	SD	2205SS
SD-02-01	Russell Avenue	SD	2205SS
SD-02-01	Maple Avenue	SD	2205SS
VA-98-01	WBL Route 460	VA	316SS Clad Type 1
VA-01-01	Route 123 bridge over Occoquan	VA	MMFX-II
VT-02-01	VT 105	VT	MMFX-II

The oldest structure that is known to contain CRRBs is the Progreso Pier in Yucatan, Mexico. The Progreso Pier was built with 220 tons of 304 round smooth bars between 1937 and 1941 [5]. Figure 1-1 shows an image of the Progreso Pier.



Figure 1-1. Progreso Pier located in Yucatan, Mexico, built with 304 round bars.

Stainless steel reinforcing bars are part of several specifications and standards: AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications, EN 1992-1-1, and CSA S6-19 as it refers to structures with exposure classes XS (chloride) and XC (carbonation). ISO 15630 refers to testing procedures and ASTM A955 defines mechanical properties and bar identification for solid stainless rebar. The Virginia Department of Transportation (VDOT) and Virginia Transportation Research Council (VTRC) published a report on recommended practices to identify different CRRBs [6].

At least two state departments of transportation (DOTs) have changed their specifications to include CRRBs when the bridge will be subjected to an aggressive chloride environment. The VDOT now requires the use of CRRBs for new bridges; the initial memorandum was published in 2009, with revisions published in 2023 and 2026 [7].

Examples of bridges with CRRB with higher PREN include I-74 Mississippi River Bridge which used 2507 super duplex rebars (2017-2021); the bridge deck was cast with AISI 2507 including the barriers. St. Croix Crossing Bridge, Stillwater, Minnesota (2014 to 2017), used about 6000 tons of 2304 rebars [8].

Canada has several bridges that have been built with stainless steel rebars. For example, Kenaston Overpass in Winnipeg used 400,000 lbs of 2304 [9]. Another example is the Samuel De Champlain Bridge in Montreal (replacement), which also used 2304 rebars in critical areas (15000T). The Hurdman Bridge in Ontario employed 2205 [8].

Since the early 2000s, several state transportation departments have used MMFX steel in bridges exposed to aggressive chloride environments [10]. Often, MMFX has been employed in concrete bridge decks. For example, decks in eight out of 16 total bridge spans in Bridge No. 890146 in Jensen Beach, Florida were constructed with MMFX and have been in service since 2007 [11]. Additionally, MMFX has been used as shear reinforcement in bridge girders by the Oklahoma

DOT [10]. As listed in Dr. Hartt's project [4], over half of the 23 job sites that used CRRBs specifically employed MMFX. These include bridges in Delaware, Florida, Idaho, Iowa, Kentucky, New Hampshire, North Carolina, Oklahoma, Puerto Rico, South Carolina, Virginia, and Vermont. This section presented examples of bridges with CRRBs and is in no way a complete list of bridges with CRRBs. There are other bridges with CRRBs in North America and around the world.

1.3 BACKGROUND FOR SAMPLES AT FAU

As indicated above, SDS samples were prepared between 2002 to 2006 in six batches at FDOT-SMO; the samples were cast with corrosion resistant alloy rebars. Most of the remaining SDS samples have rebars made of 304SS, 316SS, SS Clad (316) two types or 2304. At the beginning of this project there were two SDS samples with 3CR12 rebars that showed cracks, and one of these two samples was terminated to examine the corrosion extent on the rebars. The remaining SDS samples, approximately 75 samples, have been exposed outdoors. Once exposed at FAU SeaTech after transport from FDOT-SMO and placement of the reservoirs, the SDS samples were exposed to one week wet and one week dry cycles with 15% NaCl solution for at least 12 years. After that period of time, the solution was added less frequently and the solution reservoirs in many of them degraded due to weathering and aging of the plastic reservoir. In some instances, once the reservoirs started leaking, a new layer of marine adhesive was applied or the reservoir removed and re-glued. The samples continued to be exposed outdoors and as the samples aged, most samples lost the reservoir cover. Since then, the samples were exposed to chloride deposition from ocean spray, rain and outdoor weather, with periodic additions of NaCl chloride solution. The reservoir in several samples was replaced in 2022 with a subset of these samples brought indoors (five samples permanently, and others intermittently), the galvanostatic pulse measurements and Gecor device were used to assess electrochemical activity [12] [13]. Five SDS samples with 2304 rebars were prepared in 2012 as part of a different project in [1] and subjected to accelerated corrosion; two of the samples remain and are part of the current study (these samples have been exposed indoors all the time). At the beginning of this project corrosion potential measurements were made on SDS samples exposed outdoors to identify the samples that had the more active rebars.

The condition of the reservoirs was assessed visually at the beginning of the project. The rebar potential was measured vs. a saturated calomel electrode. The samples with active potential were identified. The reservoir was replaced on many of the SDS placed outdoors, and in some cases the old reservoir was re-attached using marine adhesive. Electrochemical characterization over time took place using either using the galvanostatic pulse method with a potentiostat or using a Gecor8 with the immersion probe (probe C). Chapter 3 describes the results obtained on selected samples. Methodology details are given in Chapter 2. A few samples were selected for forensic analysis from those that had a higher corrosion rate and more negative potential. On some cases, the concrete above and below the rebar on the top row were milled (rib markings) to estimate the chloride concentration. In some cases, the milling of the rebar trace was not possible due to the corrosion products.

1.4 BACKGROUND FOR SAMPLES AT FDOT-SMO

Three other sample geometries were prepared at FDOT-SMO between 2002 and 2005. Similar to what occurred on the samples at FAU, most samples with lower grade alloys were terminated as they started corroding. A few Tombstone specimens remain with the intermediate alloy type, most of the remaining samples were cast with CT2 clad, 316, 304, 2101 and 2304 rebars. FDOT shared the files with the measurements in 2024. FAU obtained average values for rebar potential (or total potential) and samples with negative rebar potential or that had suffered a significant potential drop were chosen for additional monitoring (Deliverable 2). An updated file was sent by FDOT in 2025 and, after reviewing the data, no significant changes were observed (Deliverable 5). A list of samples was provided to FDOT-SMO for visual inspection. FDOT-SMO performed a visual inspection on candidate samples, and in some cases, other samples prepared with the same reinforcement. A sub-set of samples were selected for termination. FDOT personnel terminated the samples, removed the rebars and documented the state upon removing the rebar. The FDOT field team met with the PI at the main FAU campus and provided rebars for removal of corrosion products and to assess corrosion extent.

1.5 BACKGROUND FOR COLUMNS AT CRESCENT BEACH

Installation of concrete columns containing CRBBs began at the Crescent Beach field site in 2005. Two visits to this site took place in addition to the semi-annual visits that FDOT-SMO performs. The first visit was scheduled to coincide with the visit that FDOT-SMO did during Fall 2024. It was identified that all columns with black steel rebar, 2101, 3CR12 and MMFX rebars had extensive cracks. The worst condition was observed on the columns with carbon steel. The rebar potential of each rebar for the columns with MMFX, 2101 and 3CR12 was measured during the initial visit. Cores were obtained from the sections with cracks along the rebar length. The initial two cores obtained from columns with 3CR12 rebars did not include the rebar. One core with rebar was obtained from a column with MMFX and two cores with rebars were obtained from the columns with 2101. A month later FDOT-SMO returned to the site and cored one column with 3CR12. The core penetrated the whole column width and in between the rebars. The short cores and long cores were milled or sliced and the concrete powder used for chloride analysis. The chloride profiles were obtained and are reported on the field columns chapter. The second visit took place during September 2025, during this visit corrosion potential along the rebar length were obtained on columns with 3CR12, MMFX and 2101 rebars, and along two rebars for one of the columns with 316 rebars and one of the columns with black carbon steel bars.

2 EXPERIMENTAL METHODOLOGY

2.1 SDS SAMPLES AT FAU-SEATECH

2.1.1 Background

SDS samples were fabricated between 2002 and 2006 at FDOT-SMO and delivered to FAU in six batches. Most SDS samples were prepared between 2002 and 2004, with one batch in 2005 and the last group in 2006. All SDS samples are of the same shape and size. Specimen dimensions are 30x30x15 cm with 1 inch (2.53 cm) concrete cover above the top three rebars. To facilitate NaCl ponding, plastic reservoirs of the same size were fitted on the top surface of each sample. Samples have 6 embedded rebars: three on the top row and three on the bottom. The top row of each sample is composed of corrosion resistant rebars. For most samples, the bottom row of rebars is the same kind as the top; however, some samples have black bars in the bottom row.

For the first 12 years, the reservoirs were periodically filled with 15% weight percent (wt%) NaCl solution on a one week on, one week off cycle [3]. After the end of the previous studies, the samples remained outside and the reservoirs degraded. Because the reservoir cover was lost on many samples, they endured exposure to chloride deposition from ocean spray, rain, and ambient weather. In a study that concluded in 2023, reservoirs were replaced on selected samples and filled with 3% wt% NaCl solution [13]. By 2025, many reservoirs had degraded again and were replaced. To install a new reservoir, the old reservoir is first removed. The bottom of a Sterilite container with an adequate footprint is cut off using a Dremel and then glued with marine epoxy to the concrete surface. As of 2025, the reservoirs were periodically filled with 5% wt% NaCl solution.

2.1.2 Sample Geometry and Nomenclature

Rebars are aligned in the samples in one of two configurations in Figure 2-1. Some samples were initially prepared with intentional damage, like rebar crevices or concrete cracks, to simulate real-world damage. Only specimens with crevice geometry have six rebars in the top row. Initially, rebars were electrically connected with stainless steel wire and rigged such that they could be disconnected for measurements. However, the top row rebars remained disconnected in most samples for the duration of this experimental campaign.

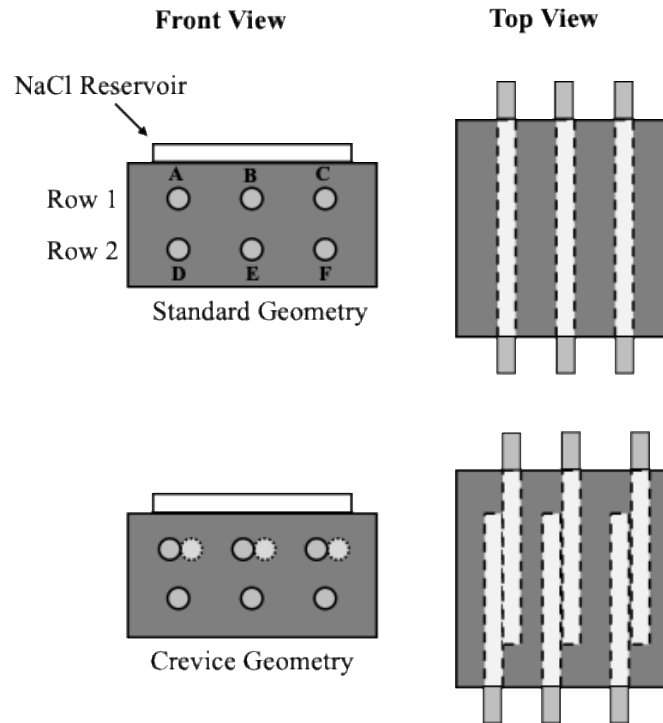


Figure 2-1. Configurations of SDS geometry.

Three types of concrete mixes were employed, designated STD1, STD2, and STD3. STD1 mix had the highest water to cement ratio of the three and contained greater amounts of fine aggregates, silica sand. STD3 mix contained 10% fly ash F as cementitious replacement [3]. Concrete mixture components are itemized in Table 2-1.

Table 2-1. Compositions of SDS concrete mix types.

Concrete Material per yd ³ (0.8 m ³)	STD1	STD2	STD3
Cement (Bags)	5	7	7
Cement, kg	213	300	269
Water, kg	107	122	124
Water/Cement Ratio	0.50	0.41	0.46
Fine Aggregate (silica sand), kg	652	540	551
Coarse Aggregate (limestone), kg	753	753	727
Fly Ash F, kg	0	0	30

Specimen names are in the format of: “[Lot #] - [Concrete Mix Type or Geometry] - [Reinforcement Type] - [Specimen #]”. Lot # refers to one of the six batches in which the samples were delivered to FAU. Concrete Mix Type refers to the composition of the concrete mix, while Geometry refers to the condition of the rebars, such as if intentional cracks or crevices were included during preparation. Table 2-2 lists the concrete conditions and rebar steel types of each SDS sample monitored in the most recent study.

Table 2-2. SDS specimen nomenclature and conditions.

Condition Code	Description
STD1	STD1 concrete mix.
STD2	STD2 concrete mix.
STD3	STD3 concrete mix.
CCON	STD1 concrete mix, simulated concrete crack.
USDB	STD1 concrete mix, 3 mm diameter clad holes 25 mm apart on top bars.
CREV	STD1 concrete mix, top bar crevice.
CCRV	STD1 concrete mix, simulated concrete crack, top bar crevice.
BCCD	STD1 concrete mix, 3 mm diameter clad holes 25 mm apart on top bars, bottom bars black steel.
CSDB	STD1 concrete mix, simulated concrete crack, 3 mm diameter clad holes 25 mm apart.
WB	STD1 concrete mix, top bars wire brushed.
PICK (ACID)	STD1 concrete mix, top bars lab pickled, cathode as received.

The names and statuses of each SDS specimen monitored in the most recent study are listed in Table 11-1 in APPENDIX A: NAMES OF SDS SAMPLES AT FAU. Many original specimen labels are no longer available, as outdoor exposure weathered them away. Additionally, several samples were relocated several years ago within the same area. Thus, new sample IDs were assigned. A best-effort attempt was made to correlate the new IDs with the original IDs based on observable rebar characteristics and sample geometry. Two kinds of 316SS alloys were used, but it is not known which one is used in a given sample. Two clad rebar types use 316SS with a carbon steel core. Clad Type 1 is labeled CT1 and uses Stelax rebars, while Clad Type 2 is labeled CT2 and uses SMI (now CMC) rebars.

Seven samples were brought inside in 2022 and kept in the lab for the duration of the current study: 6-CCRV-304-3, 1-STD1-316-2, 1-STD1-CT1-1, 5-STD1-2304, 6-STD1-304-1, STD3-2304-1, and STD3-2304-5. The 2304SS used in the samples labeled STD3-2304 was produced by a different manufacturer than that used in the 5-STD1-2304 sample, but the nominal chemical composition is listed as being the same, so it is only given once here. The samples kept inside the lab were stored in raised, covered containers in a tub with water at the bottom to maintain a consistent level of humidity.

2.2 MEASUREMENTS ON SDS

2.2.1 Rebar Potential Measurements with Voltmeter

Half-cell potential measurements were taken of each rebar in each SDS sample using a high-impedance voltmeter and a reference electrode. The reference electrode utilized was either the saturated copper sulfate electrode (abbreviated CSE or CCS) or the saturated calomel electrode (SCE). The CSE measures approximately 73 mV more positive than the SCE. The rebar was connected to the positive terminal of the voltmeter with an alligator clip, while the reference electrode was connected to the common (COM/negative) terminal. Before measurements were taken, each reservoir was filled with 5wt% NaCl solution. Global rebar potential measurements were then conducted by placing the reference electrode in the reservoir along the length of the rebar to be measured. Governed by ASTM standard C876, the likelihood of rebar corrosion is deduced based on the negativity of the measured potential values with respect to the copper sulfate electrode. Potential measurements with the voltmeter were taken only three times, several months apart, since January 2025. Any measurements taken using the saturated calomel electrode were converted to CSE values.

2.2.2 Gecor 8

The Gecor 8 commercial device measures each rebar's open circuit potential, corrosion rate (confined and non-confined, in units of current density), electrical concrete resistance, and concrete resistivity values for the measured rebar. Some of these parameters are direct measurements, and others are internal calculations based on measurements and given values. To establish electrical contact, a wire connected to the device is attached to the rebar to be measured with an alligator clip. The probe used, designated Sensor C, is also wired to the device. The probe has four embedded copper sulfate reference electrodes, with one of these electrodes surrounded by a stainless-steel guard ring. This guard ring confines the polarizing current to a given area under the electrode, allowing for more accurate readings of the corrosion area in the case of localized corrosion under the confined electrode.

To ensure good contact, a sponge is placed between the probe and the concrete during measurements. The concrete electrical resistance and resistivity are measured using the area of concrete between the probe and the surface of the rebar. To start measuring, the "Measurement in submerged or very wet structures" option must be chosen on the machine, and the length and diameter of the rebar must be entered into the machine for the calculation of the corrosion current density. The values are 230 mm for the length and either 13 or 16 mm for the diameter based on the rebar type.

The concrete cover quality also must be manually entered: complete cover or spalled. Measurements were conducted at least every month when possible. The device began having performance issues in July 2025 that made measurements sporadic and ultimately impossible after October 2025. As of January 2026, the device's functionality was mostly restored, and data collection restarted. Figure 2-2 shows the Gecor 8 probe measuring an indoor SDS specimen (left) and the machine itself (right).



Figure 2-2. Gecor 8 Sensor C measuring Rebar A of an SDS sample (left); Gecor 8 device (right).

2.2.3 Galvanostatic Pulse (GP) Method

Galvanostatic pulse measurements were conducted using a Gamry Potentiostat device set to perform the galvanostatic pulse test. In this test, a titanium mixed metal oxide (TiMMO) mesh serves as the counter electrode and is placed in the reservoir. Additionally, a saturated calomel reference electrode is placed in the reservoir. The working electrode probe of the galvanostatic device is connected to the selected rebar and the counter electrode probe is connected to the TiMMO mesh. An appropriate current pulse is chosen based on previously used values for that rebar. The selected current should ensure that the potential difference between the initial potential and the final potential is greater than 4 mV but less than 20 mV. The test begins by measuring the open circuit potential of the selected rebar. Then, the selected current is applied for 150 seconds, and the resulting change in potential is plotted on a graph depicting potential versus time. After 200 milliseconds of applying the current pulse, the initial on-potential of the rebar is recorded. Similarly, the final potential of the system is recorded when the current pulse application concludes after 150 seconds. Based on the potential values and the magnitude of the applied current, several values are calculated: corrosion current, solution resistance, and polarization resistance. If the corroding area of the rebar were known, corrosion current density (i.e. corrosion rate) would be calculable. However, this is not possible due to the rebars' embedment in the concrete. Measurements were made on indoor samples at least once a month, while measurements on outdoor samples were less frequent and mostly limited to those suspected to be active.

2.3 SAMPLES AT FDOT-SMO

The samples described below were reinforced with various alloy rebars: 316, 304, STD1, STD2, MMFX, 3CR12 and Black Bars. The results section presents results on selected samples for those samples that continue to be monitored. The report by Dr. Hartt [3] provides additional details of the sample preparation, curing, and monitoring. Below, a brief description of the different sample geometries is included.

2.3.1 Tombstone Samples

FDOT designed the Tombstone specimens to simulate a marine bridge substructure element. Three bar configurations, normal (STD), bent (BENT), and elevated (ELEV), were prepared, as illustrated schematically in Figure 2-3. The results section describes the monitoring on these samples.

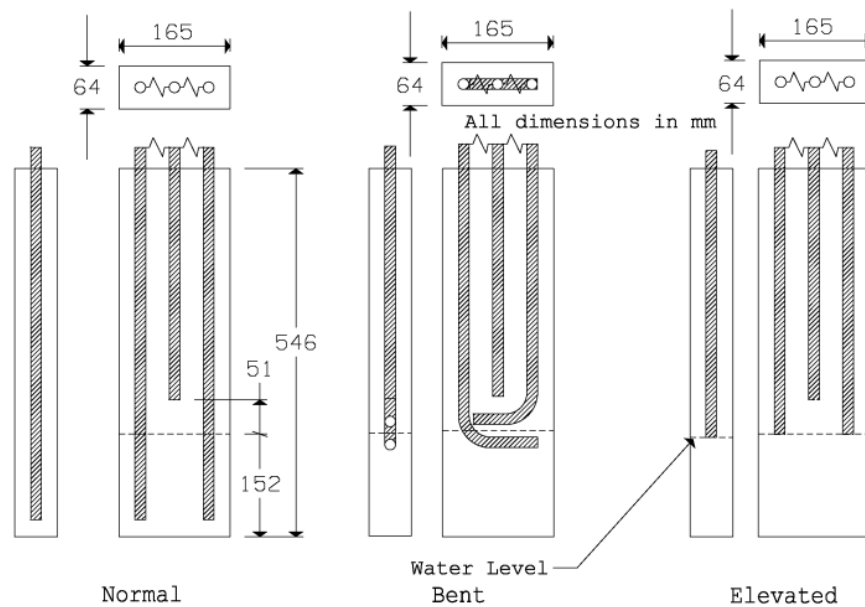


Figure 2-3. Schematic illustration of the Tombstone type 3-bar column specimen for each of the three bar configurations (all dimensions in mm).

2.3.2 3-Bar Square Samples

3-Bar Square Samples with a square cross section were also prepared. Three bar configurations, normal (STD), bent (BENT), and elevated (ELEV), were prepared, as illustrated schematically in Figure 2-4. The results section describes the monitoring of one of these samples.

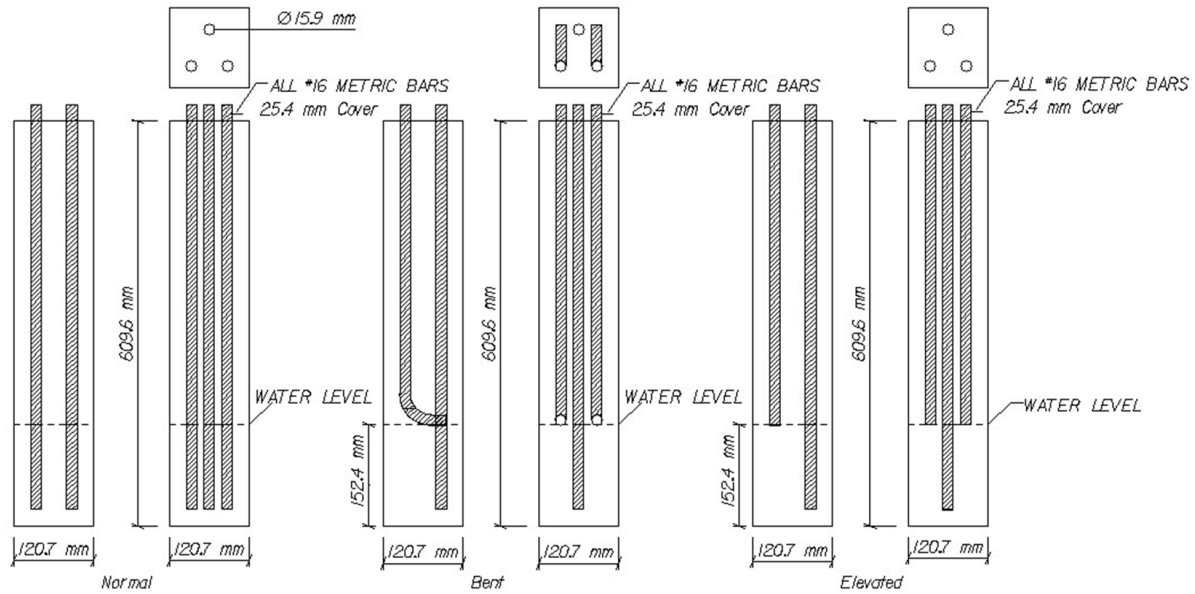


Figure 2-4. Schematic illustration of the square type 3-bar column specimen for each of the three bar configurations (all dimensions in mm).

2.3.3 Macro-Cell Slab (MS) Specimens (Modified G109)

The design for these specimens is a modification of the standard G109 geometry and consisted of either a single straight or U-bent top bar and four straight bottom bars, the latter being positioned at two elevations beneath the top bar. This geometry is illustrated by Figure 2-5. The standard condition was with the reinforcement wire brushed (ARWB), but one set was prepared with bars as-received. In this study only an SMI with U-bent and drilled holes was selected for forensic analysis.

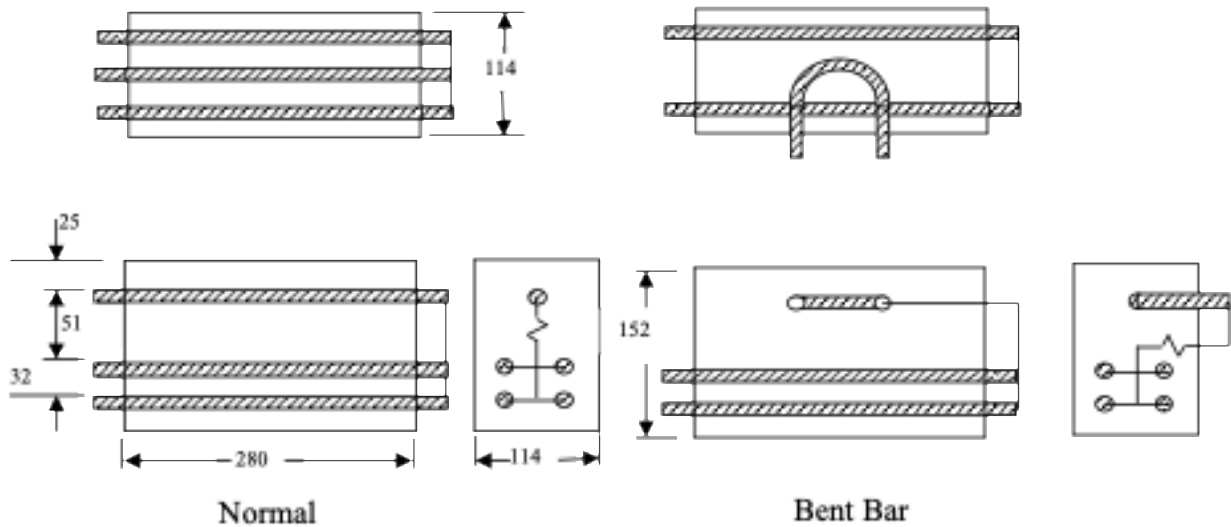


Figure 2-5. Geometry of the macro-cell slab type specimen with both bent and straight bars (all dimensions in mm).

2.4 POTENTIAL AND CURRENT MEASUREMENTS ON SAMPLES AT FDOT-SMO

Once exposure was initiated, potential of all three bars coupled (total potential) and voltage drop across the two resistors was measured daily for each specimen utilizing a pair of Agilent 34970A data acquisition systems. The potential drop was converted to current before preparing the plots. In addition, each rebar potential was measured by hand vs. CSE for several years, but it is not currently being measured. Section 3.1 in Chapter 3 presents plots for selected samples.

2.5 CRESCENT BEACH FIELD COLUMN SPECIMENS

All field column specimens are comprised of the STD1 concrete mix design with four bars in each column. Each reinforcement type has three columns, denoted as A, B, and C. The schematic in Figure 2-6 illustrates the field column geometry. Reinforcement types include black bar (BB), 3Cr12, MMFX-2, 2101, 316.16SS, 304SS, and CT2 with end caps. Each bar has been electrically disconnected from the others throughout their exposure and during potential measurements.

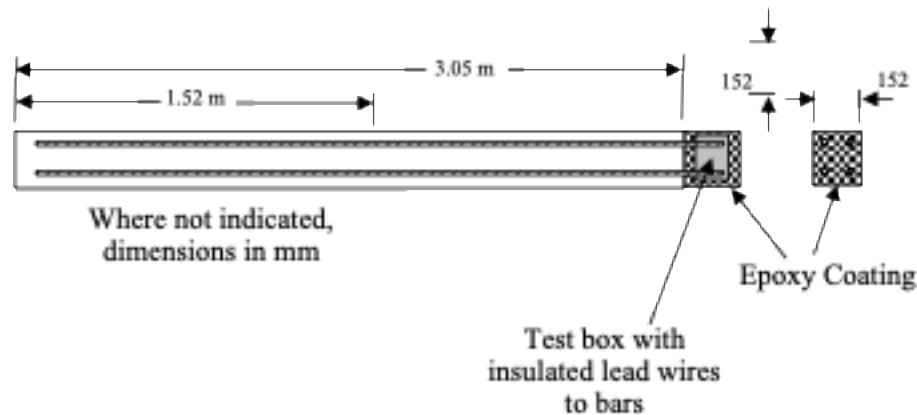


Figure 2-6. Geometry of field columns [3].

The columns are installed in the intracoastal waterway at Crescent Beach, Florida. The lower 1.2 m of each specimen was embedded in the sand, resulting in a mean high water approximately 1.8 m above the specimen base. Figure 2-7 includes a diagram of each column, rebar type, and their location at the site. The finished side of each column faces east. Figure 2-8 is a picture of the columns at the site in October 2024.

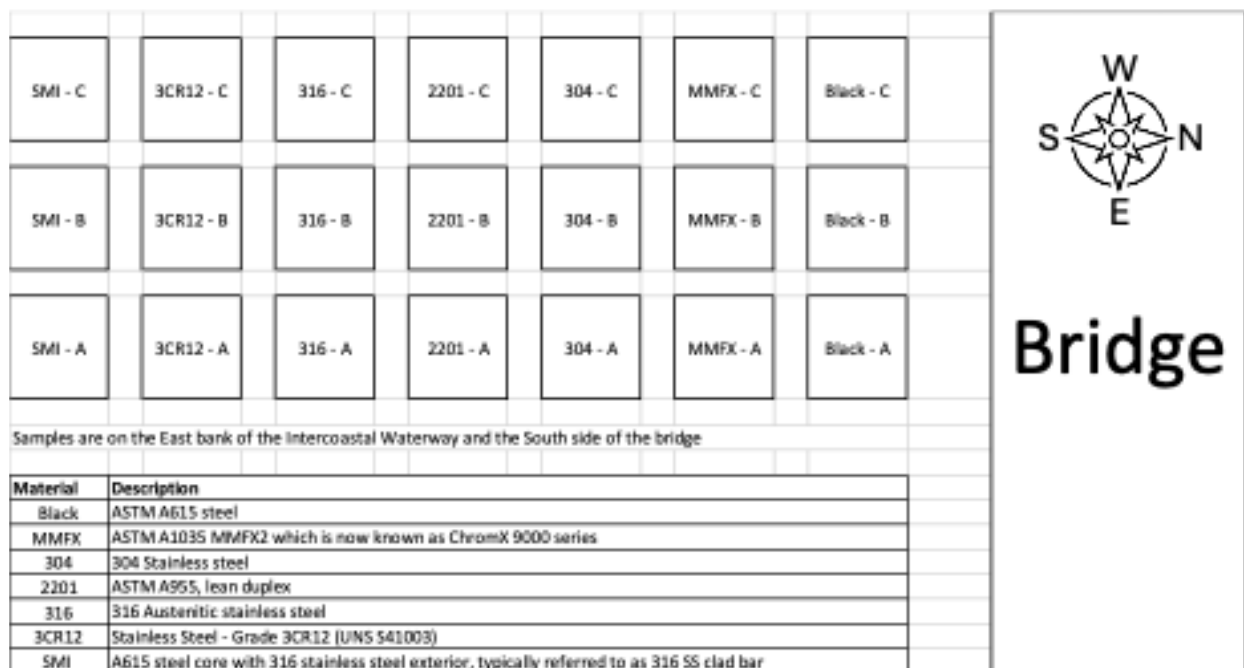


Figure 2-7. Diagram showing the location and type of rebar for each column at Crescent Beach Field Site.

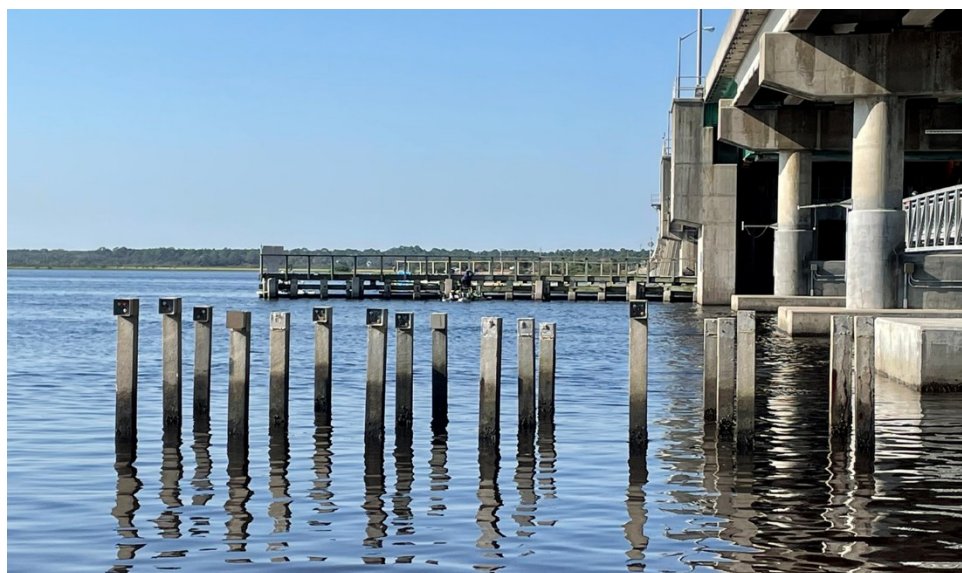


Figure 2-8. Picture of columns during the October 2024 visit.

The columns with corrosion resistant reinforcement have been monitored semiannually by FDOT-SMO since 2007. For each of the four bars, the overall rebar potential is measured by placing a copper-copper sulfate electrode either in the water or in the moist sand near the base of the column, depending on the tide. The test boxes at the top of each column contain insulated wires that allow electrical connection to each rebar. When the rebar potential values of a column exhibit a significantly negative shift, the column is declared active, the test box is removed,

concrete cores are obtained, and rebar monitoring by FDOT-SMO ceases. A photograph of a test box and a diagram of the rebar that corresponds to each wire color for all columns, except those containing 304 and CT2, is shown in Figure 2-9.

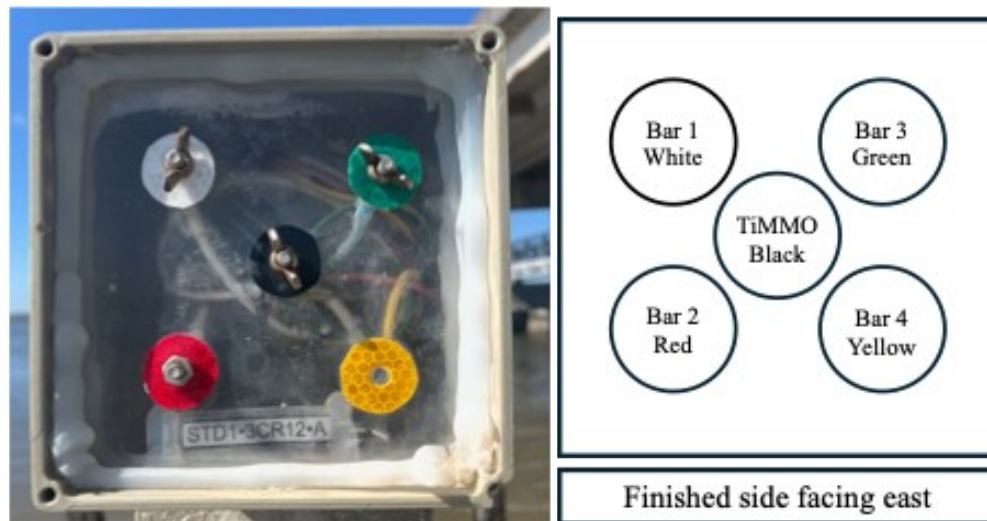


Figure 2-9. Picture of a test box from a field column specimen (left) and diagram of the rebar that corresponds to each wire color (right).

In October 2024, FAU and FDOT-SMO conducted a field visit to the Crescent Beach site and inspected the MMFX, 3CR12, and 2101 columns. Columns with 304, 316 and CT2 rebar were excluded as previous measurements indicated no signs of corrosion. Although most of the columns were active, the wires were still visible, and the wire cover was peeled to facilitate good electrical contact with each rebar. A single potential measurement was taken for each of the 12 columns, and the surfaces of each column were evaluated for evidence of cracks and corrosion. Core samples were extracted from selected columns and given to FAU for chloride analysis. Of the core samples, three reached the rebar: one with MMFX rebar and two with 2101 rebar. Two of the cores, extracted from 3CR12 columns, did not reach the rebar. As of October 2024, only one of the 12 columns was still being monitored by FDOT-SMO. The column contained 3CR12 rebar and was declared active after the October 2024 visit as visible cracks had appeared on the column surface. FDOT-SMO obtained two additional cores from this column in November 2024 and delivered them to FAU for analysis the following spring.

In September 2025, FAU conducted a field visit and inspected each MMFX, 3CR12, and 2101 column. Additionally, one 316 and one black bar column were inspected. The column with 316 rebar was of interest as it was damaged upon installation and showed signs of corrosion initiation in previous measurements. In addition to overall rebar potential measurements, the potential was measured as a function of elevation on each column. The reference electrode was placed at 2-inch (5-cm) increments along each column, starting as close to the top of the column as possible and ending at the water line. To determine the correct surface on which to place the reference electrode, the diagram in Figure 2-10 was used.

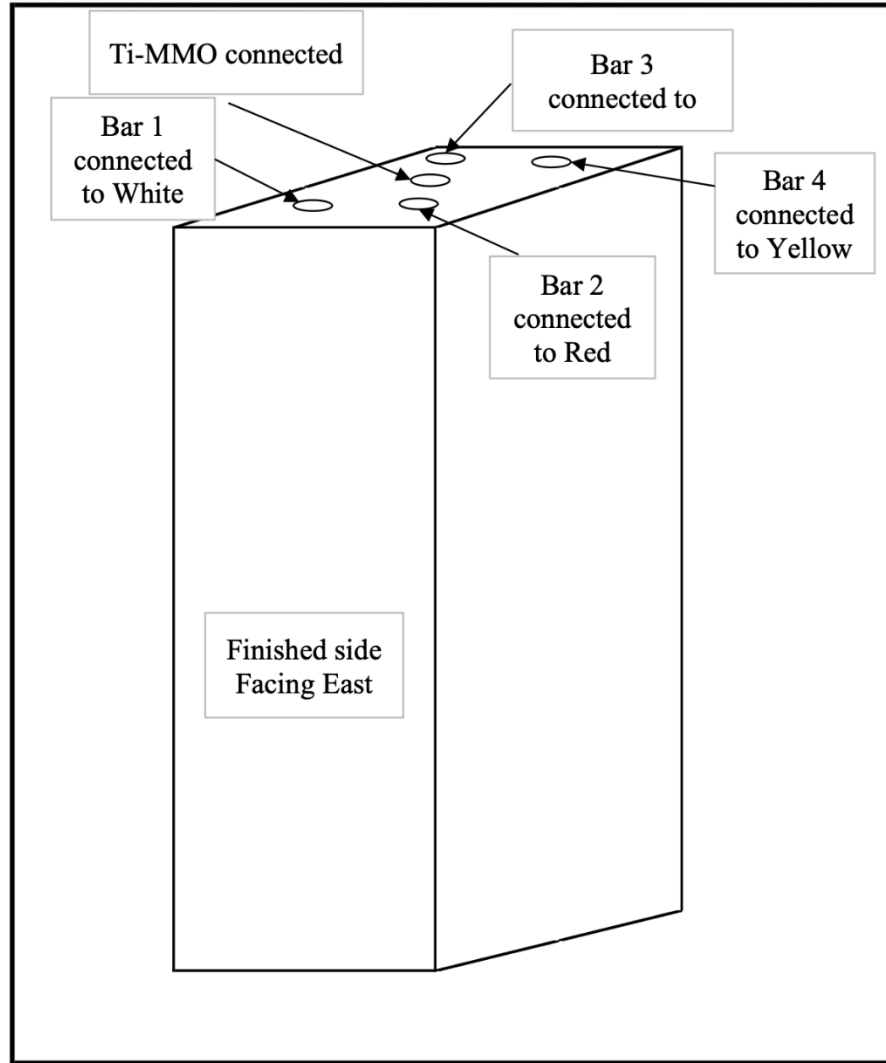


Figure 2-10. Diagram of rebar orientation within the measured columns.

2.6 MEASUREMENTS PERFORMED DURING BRIDGE VISITS (INCLUDING CORES)

During the most recent monitoring period, two bridges with corrosion resistant reinforcement that had been in service for over 10 years were visited. These bridges included the Jensen Beach Bridge (#890145) and one of the St. Joseph's Bay area bridges (SR30A Bridge, #510072). The Jensen Beach Bridge was visited twice: once in March 2025 and once in July 2025. The St. Joseph's Bay bridge was visited once in May 2025.

2.6.1 Jensen Beach Bridge

The Jensen Beach Bridge (#890145) is instrumented for electrical connection in Piers 10, 11, and 12. The instrumented elements allowed for measuring corrosion potentials to determine the presence of any corrosion activity, and for measuring the electrical resistivity of the concrete to

indirectly assess concrete quality and chloride penetration. The piers consist of two octagonal columns each. The two columns comprising Pier 12 are pictured in Figure 2-11.



Figure 2-11. Photo of Jensen Beach Bridge Pier 12.

The corrosion resistant reinforcement in Piers 11 and 12 is 2101LDX SS, while Pier 10 was constructed with black bars for comparison. As part of a prior study from 2020, concrete core samples were obtained to directly observe the condition of the reinforcement and to determine the chloride content at various depth in the concrete. Findings for the 2101LDX SS were compared to similar data obtained for standard ASTM A615 black bars that were used on other similar components of the bridges and under the same environmental conditions. Monitoring started in 2003, with annual visits occurring for the first 10 years. Additional visits were made once in 2016 and once more in 2019. The 2020 report indicated that no observable difference in corrosion resistance was found between 2101LDX SS and black bars in the column and footings. As of 2025, the corrosion resistant reinforcement in Jensen Beach Bridge had undergone exposure for 22 years.

Because Pier 10 is only accessible via boat, only Piers 11 and 12 were inspected during the March 2025 visit. Using a voltmeter and a copper sulfate electrode, potential measurements were made on the north and south faces of both the north and south columns of each pier. Potential was measured every 12 inches, starting at the bottom of the column and ending approximately 72 inches above. Resistivity measurements were made in the same manner. Potential measurements were also made on the north and south footers of both piers, near the top of the footers, as illustrated in Figure 2-12. Furthermore, global rebar potential measurements were made for both columns of each pier by immersing the reference electrode in the seawater. Additionally, each

column face was inspected visually for cracks and photographed. Where possible, cracks were measured with a tape measure.



Figure 2-12. Approximate region where Jensen Beach Bridge footer potential measurements were taken.

For the July 2025 visit, FDOT brought a boat to access Pier 10. The same techniques for potential and resistivity measurements from the previous visit were employed in July 2025 for Piers 10, 11, and 12. Cracks in each column were again examined and photographed, with crack lengths measured where possible. Concrete cores were also obtained during the July 2025 visit from the north footer and the south face of the south column of Pier 11. One core was obtained from the south column, approximately 12 inches above the column base. Two cores were obtained from the north footer: one was located approximately 5 inches above the marine growth (see Figure 2-13), and one was located approximately 20 inches above the marine growth. The cores were taken back to FAU to mill and analyze the chloride content.



Figure 2-13. Coring of the north footer of Jensen Beach Bridge Pier 11, close to the marine growth.

2.6.2 St. Joseph's Bay Bridge

The SR30A Bridge (#510072) was not instrumented and required drilling to the rebar depth to make electrical contact to the reinforcement. The corrosion resistant rebars examined in the SR30A bridge were 316SS. A portable ground-penetrating radar (GPR) device was used to locate the rebar prior to drilling. Figure 2-14 shows the bridge and bulkhead on both sides. The approximate drilling locations are demarcated by red circles. After exposing the rebar, an electrical connection was made to measure rebar potential at several locations using a voltmeter and a copper sulfate reference electrode. Overall rebar potential was also measured by placing the reference electrode in the water. Surface resistivity measurements also were taken at several locations near the drilling locations. Additionally, surfaces of the bridge were inspected for cracks and photographed.



Figure 2-14. Picture of SR30A Bridge (#510072) taken from the marina. Left circle marker indicates drilling location 1; right circle marker indicates drilling location 2.

2.7 TERMINATION PROCEDURE FOR SDS SAMPLES

Selected SDS specimens that showed signs of extensive corrosion, including negative potentials, concrete cracks, and rust stains, were terminated and flagged to be dissected for forensic analysis. After retiring all tests and exposure, the ponding bath was dismantled. Subsequently, two cuts were made with a wet saw. The cuts were made parallel to the reinforcement layout and centered between the middle bar and the two outer bars of each layer. Additional cuts were made for each of the three resulting specimen parts perpendicular to the rebar center, avoiding touching the rebar. A schematic of the cuts is demonstrated in Figure 2-15. For select samples, these cuts were also made at the level of the bottom layer. To split open each specimen section, a chisel was placed in one of the saw cuts and tapped gently with a hammer until a fracture formed. This fracture created a split that exposed both the rebar and its trace, which were then analyzed for corrosion and photographed.

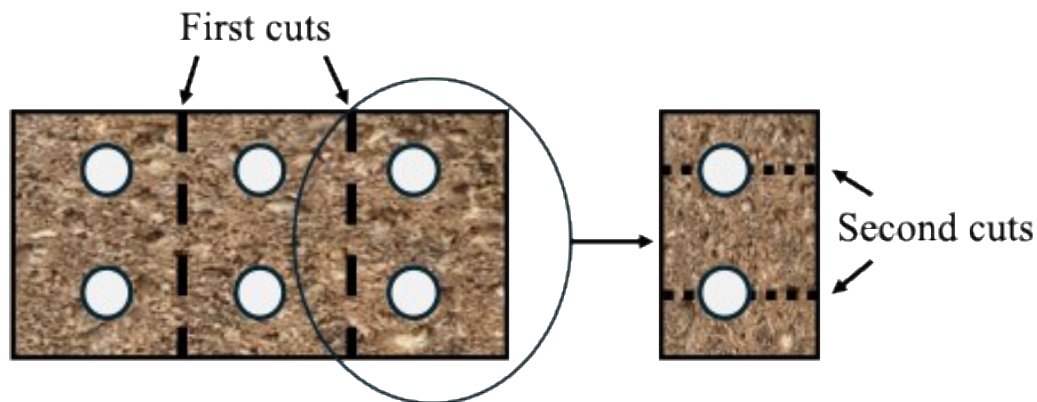


Figure 2-15. Location of concrete cuts made on terminated SDS samples.

2.8 MILLING/SLICING OF CORES

Concrete cores obtained from the concrete surfaces of field sites (Crescent Beach and Jensen Beach) were taken back to FAU for chloride analysis. Concrete powder was generated from the cores using two methods. The first method involved individually mounting the concrete cores, surface side up, on a mill. For the topmost layers, cuts were milled with a 50-mm-diameter diamond hole core bit at depths of approximately 1-4 mm to generate at least 4 grams of powder. If the core was initially too long to fit in the mill mount, it was cut with a wet saw to fit. The second method involved slicing and crushing the concrete slices. If the core was too cracked or irregularly shaped to stably mill, it was sliced with the wet saw, parallel to the top surface at 3-6 mm intervals. Each slice was then ground to powder using a mortar and pestle.

2.9 MILLING ALONG THE REBAR TRACE

To determine the chloride concentration at the rebar depth for both SDS and field specimens, powder was generated from concrete cores or sections containing rebar traces with a mill. Using a 10-mm-diameter square end cutter (end-mill), a shallow cut was milled along the section of each individual rebar trace that was free of corrosion products.

2.10 TITRATION (CHLORIDE ANALYSIS)

To analyze the chloride concentration of the concrete powder obtained from cores and rebar traces, a modified version of the FDOT wet chemistry method [14] was used. The standard method calls for the preparation of 4 grams of concrete powder per sample in triplicate. In the current study, less concrete powder was used per sample, and duplicates were made instead of triplicates. For cores, each sample to be titrated was composed of 2 grams, if enough concrete powder was available. For rebar traces, significantly less powder was obtained, and many had less than 1 gram per sample. However, some of the rebar trace samples were prepared in triplicate to account for the smaller mass of powder.

2.11 TERMINATION OF SAMPLES AT FDOT-SMO AND REBAR CLEANING

The samples at FDOT-SMO that were selected for termination were first removed from the tanks and photograph to assess the surface condition (identify cracks or corrosion products bleeds). The rebars were then removed as per FDOT's standard operating procedures. Images of the rebars after the samples were removed were taken to document rebar surface condition.

2.11.1 Dissection of Tombstone Samples

Dissection of these specimens was performed by making a saw cut to steel depth on the front and back faces along both longer bars starting at the bottom of the specimen and extending up about 0.25 m or more if visual cracking was apparent beyond this. A cut to the steel depth was then made on the front and back faces perpendicular to the reinforcement bars at the 0.25 m elevation across the width of the specimen or just above the highest reaching crack. Once all the cuts were made, a hammer and chisel were used to split off the cut portion of concrete and expose the reinforcement. Figure 2-16 provides a schematic illustration of these cuts on a specimen.

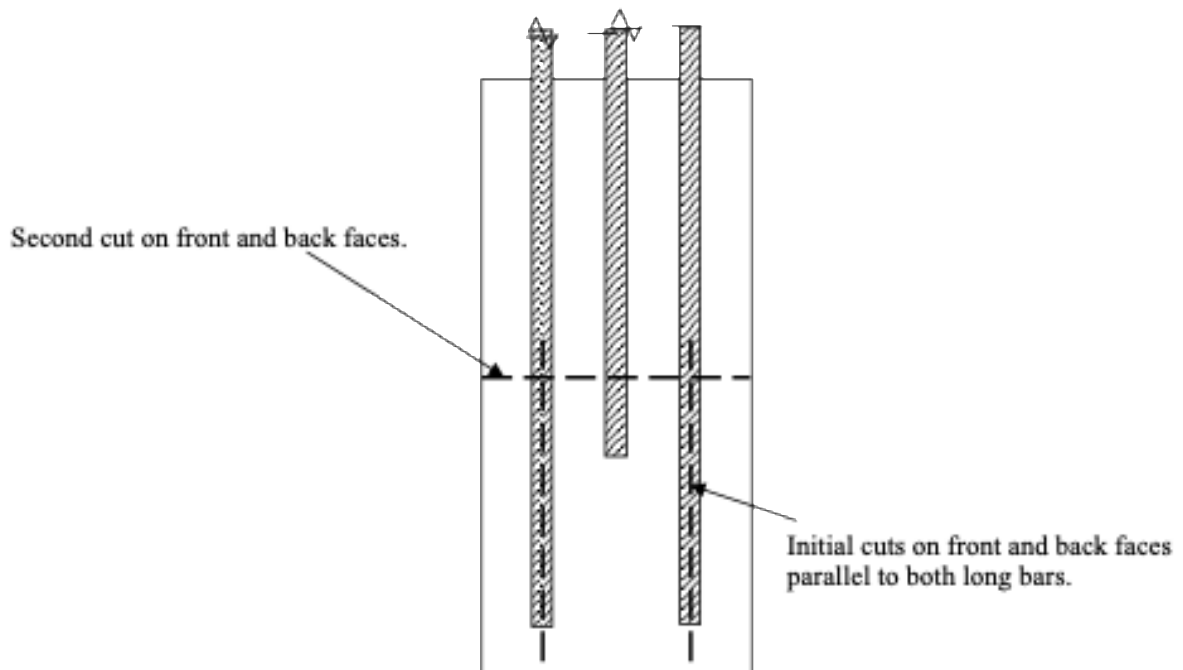


Figure 2-16. Schematic illustration of the concrete sectioning for 3BTC specimens.

Each of the rebars were placed in concentrated cleaning vinegar for at least one day. MMFX rebars were immersed a second day after changing the cleaning vinegar solution. Upon removal from the vinegar solution, each rebar was brushed with metal bristle brush and then a regular plastic bristle brush to remove any debris. Each rebar was then rinsed and then dried with compressed air. Each of the full rebars were then photographed, as well as areas of concern, which were taken with a microscope.

3 RESULTS – SDS SAMPLES

Section 3.1 refers to rebar potential measurements performed to identify samples that might be active. In some cases, the concrete was quite dry, and the values might have been influenced by the moisture condition of the concrete. Section 3.2 presents plots for corrosion potential (E_{corr}), isolated corrosion rate (i_{corr}) and solution resistance (R_s) values measured on selected samples, including: those later selected for termination and companion samples, i.e., the samples that show the most activity; a second group of samples with intermediate i_{corr} values; and finally, a third group with lower i_{corr} . Section 3.3 presents GP results after converting the polarization resistant (R_c) values to corrosion current (I_{corr} ; not area-corrected). Similar grouping but less GP measurements were performed on the samples exposed outdoors.

3.1 REBAR POTENTIALS

Several sets of rebar potential measurements were conducted throughout the present study. The samples were grouped based on whether they were inside the lab or outdoors. Both groups were measured at least three times: once in January 2025, once in February 2025, and once in May or June 2025. For the measurements taken in January and February 2025, the voltmeter and a saturated calomel electrode was used. The measurements taken in May and June were pulled from Gecor 8 readings. All values are reported in millivolts with respect to the copper sulfate electrode. The potentials for the indoor samples for January, February, and June 2025 are reported in Table 3-1, Table 3-2, and Table 3-3, respectively. The potential values for most of the indoor samples remained more positive than -250 mV_{CSE} throughout the three sets of measurements, reflecting the lack of corrosion activity during this period. One exception was rebar A of 1-STD1-316-2 in June 2025, which had a potential of -271.37 mV . This value is within the “uncertain” range of ASTM standard C876, but active corrosion is unlikely for this sample based on results from other methods.

Table 3-1. Potential measurements in mV vs. CSE for indoor samples, January 2025.

Sample	Alternate ID	Rebar A (mV_{CSE})	Rebar B (mV_{CSE})	Rebar C (mV_{CSE})
224	6-CCRV-304-3	-175.1	-176.3	-166.8
308	1-STD1-316-2	-186.4	-169.1	-129.1
310	1-STD1-CT1-1	-190.9	-178.3	-178.9
334	5-STD1-2304	-208.2	-173.5	-176.2
335	6-STD1-304-1	-119.4	-121.7	-117.9
CRA-2	STD3-2304-1	-193.0	-195.8	-172.2
CRA-2-5	STD3-2304-5	-126.5	-133.4	-128.2

Table 3-2. Potential measurements vs CSE for indoor samples, February 2025.

Sample	Alternate ID	Rebar A (mV_{CSE})	Rebar B (mV_{CSE})	Rebar C (mV_{CSE})
224	6-CCRV-304-3	-176.1	-185.3	-170.19
308	1-STD1-316-2	-96.41	-170.33	-134.37
310	1-STD1-CT1-1	-202.3	-163.26	-175.2
334	5-STD1-2304	-199.6	-170.9	-174.8
335	6-STD1-304-1	-122.86	-124.86	-120.38
CRA-2	STD3-2304-1	-193.7	-178.2	-206.3
CRA-2-5	STD3-2304-5	-172.04	-157.25	-146.57

Table 3-3. Potential measurements vs CSE for indoor samples, June 2025.

Sample	Alternate ID	Rebar A (mV_{CSE})	Rebar B (mV_{CSE})	Rebar C (mV_{CSE})
224	6-CCRV-304-3	-184.7	-121.78	-213.6
308	1-STD1-316-2	-271.4	-222.45	-248.22
310	1-STD1-CT1-1	-119.1	-174.22	-101.93
334	5-STD1-2304	-136.6	-186.39	-186.22
335	6-STD1-304-1	-67.8	-70.34	-66.45
CRA-2	STD3-2304-1	-133.4	-155.16	-200.88
CRA-2-5	STD3-2304-5	-134.4	-144.1	-97.45

Potential measurements for selected outdoor samples in January 2025, February 2025, and May 2025 are listed in Table 3-4, Table 3-5, and Table 3-6, respectively. For an expanded list of potential measurements for outdoor samples, see Table 11-2 in APPENDIX B: REBAR POTENTIAL MEASUREMENTS IN 2025. Samples: 4-CCRV-3CR12-3, CREV-CT2-1, and the later terminated samples 4-CCRV-3CR12-2 and CREV-CT2-2 mostly reported very negative potentials in each set of measurements, illustrating a high likelihood of active corrosion. Exceptions include rebars A and B of CREV-CT2-1 and rebar C of CREV-CT2-2, which

reported slightly more positive potential values. However, corrosion activity for CREV-CT2-1 remains likely based on results from other methods. Corrosion activity for CREV-CT2-2 was confirmed after its termination, detailed in a later chapter. Samples showing no active corrosion throughout the three sets of measurements include those with 316, undamaged CT1, and 304 rebars. The potential values for these samples all remained more positive than $-215 \text{ mV}_{\text{CSE}}$ for each dataset, demonstrating a near-zero probability of activity.

Table 3-4. Potential measurements vs. CSE for selected outdoor samples, January 2025.

Sample	Alternate ID	Rebar A (mV_{CSE})	Rebar B (mV_{CSE})	Rebar C (mV_{CSE})
218	4-CCRV-3CR12-2	-456	-403	-440
219	4-CCRV-3CR12-3	-460	-470	-458
227	CREV-CT2-1	-258.2	-345	-393
228	CREV-CT2-2	-428	-426	-280
301	1-STD2-316-1	-70.8	-76.4	-69.7
305	1-STD2-CT1-2	-100	-111.1	-79.8
336	6-STD1-304-2	-97.1	-103.3	-99

Table 3-5. Potential measurements vs. CSE for selected outdoor samples, February 2025.

Sample	Alternate ID	Rebar A (mV_{CSE})	Rebar B (mV_{CSE})	Rebar C (mV_{CSE})
218	4-CCRV-3CR12-2	-513	-459	-476
219	4-CCRV-3CR12-3	-432	-497	-472
227	CREV-CT2-1	-261.5	-401	-454
228	CREV-CT2-2	-409	-403	-273
301	1-STD2-316-1	-3.6	-8.6	-1.4
305	1-STD2-CT1-2	-45.1	-58.6	-56
336	6-STD1-304-2	-39.5	-36.3	-39.3

Table 3-6. Potential measurements vs. CSE for selected outdoor samples, May 2025.

Sample	Alternate ID	Rebar A (mV_{CSE})	Rebar B (mV_{CSE})	Rebar C (mV_{CSE})
218	4-CCRV-3CR12-2	-433.29	-386.95	-409.42
219	4-CCRV-3CR12-3	-436.85	-496.58	-513.26
227	CREV-CT2-1	-294.42	-307.1	-455.03
228	CREV-CT2-2	-326.15	-348.9	-212.54
301	1-STD2-316-1	-1.65	-74.24	-62.29
305	1-STD2-CT1-2	-111.4	-101.15	-154.72
336	6-STD1-304-2	-212.16	-205.73	-201.09

Table 3-7. Potential measurements vs CSE for a larger selection of outdoor samples, December 2025.

Sample	Alternate ID	Rebar A Potential	Rebar B Potential	Rebar C Potential
103	6-CREV-304-1	-	-375	-
208	4-CCON-CT2-2	-62.5	-287	-307
209	4-CCON-CT2-3	-221	17.6	-249
213	4-CCRV-CT2-1	-49.5	-	-
215	USDB-CT2-1	-172.6	-60.3	-72.3
216	USDB-CT2-2	-167.8	-253	-174.8
217	USDB-CT2-3	-117.7	-32	-4.2
219	4-CCRV-3CR12-3	-476	-495	-470
220	6-CCRV-304-1	-380	-	-
221	6-CCRV-304-2	-318	-	-
222	6-CCON-304-1	-	-	-105.1
225	6-WB-304-1	-375	-204	-229
227	CREV-CT2-1	-449	-500	-615
304	1-STD2-CT1-1	-69.8	-	-71.1
306	1-STD2-CT1-3	-28.2	-	-
311	1-STD1-CT1-2	-141.6	-152.6	-282
312	1-STD1-CT1-3	-90.4	-	-
315	BCCD-CT2-1	-490	-330	-209
316	BCCD-CT2-2	-323	-416	-365
327	CCON-316-?	-67.5	-44.5	-64.7

Sample	Alternate ID	Rebar A Potential	Rebar B Potential	Rebar C Potential
328	CCON-316-?	-	-105.2	-
337	6-STD1-304-3	-116.9	-143.5	-92.8
339	6-STD2-304-2	-149	-218	-240
341	CSDB-CT2-2	-	-	-309
342	CSDB-CT2-1	-382	-364	-261
345	6-CCON-304-3	-126.4	-	-
346	6-WB-304-2	-167.4	-223	-349

Several outdoor samples were remeasured a fourth time in December 2025 because the Gecor 8 was out of service at the time. Not all rebars were measured for each sample; only rebars that were possibly active based on previous recorded values were measured. Measurements from this period were taken with the voltmeter and a copper sulfate electrode and are reported in Table 3-7. Most samples showed little to no corrosion activity based on their positive potential values, but several exceptions were noted. Samples with potentials indicating a high likelihood of active corrosion included: rebar B of 6-CREV-304-1; all rebars of 4-CCRV-3CR12-3; rebar A of 6-CCRV-304-1; rebar A of 6-WB-304-1; all rebars of CREV-CT2-1; rebar A of BCCD-CT2-1; rebars B and C of BCCD-CT2-2; and rebars B and C of CSDB-CT2-1. Except for 6-WB-304-1, the common characteristic among all suspected active samples was the inclusion of intentional damage during fabrication: concrete cracks, rebar crevices, drilled holes in the rebars, or some combination of these.

3.2 GECOR MEASUREMENTS

The Gecor 8TM was used to measure corrosion potential, isolated corrosion rate, and solution resistance of each sample. All results reported are for electrically isolated rebars. Samples are grouped according to their corrosion activity, as indicated by their isolated corrosion rates. Samples that demonstrated high active corrosion, i.e. isolated corrosion rates higher than 1 $\mu\text{A}/\text{cm}^2$, are listed in Table 3-8. The results from these samples are discussed first. Table 3-9 lists samples that experienced moderate active corrosion, i.e. isolated corrosion rates above 0.4 and below 1 $\mu\text{A}/\text{cm}^2$. Selected results from this group of samples are analyzed next. Finally, samples that showed little to no corrosion activity, with average isolated corrosion rates less than 0.4 $\mu\text{A}/\text{cm}^2$, are discussed. Each sample in the group with the lowest corrosion activity was kept indoors for the duration of the monitoring period, while the rest were exposed outdoors. Data collection start dates vary for the samples and are displayed on each plot.

Table 3-8. Samples with rebars that had isolated corrosion rates greater than 1 $\mu\text{A}/\text{cm}^2$.

Sample	Rebar
4-CCRV-3CR12-2	A, B, C
4-CCRV-3CR12-3	A, B, C
CREV-CT2-1	B, C
CREV-CT2-2	A, B, C
BCCD-CT2-1	C
CSDB-CT2-1	B, C
CSDB-CT2-2	C

Table 3-9. Samples with rebars that had average isolated corrosion rates greater than 0.4 $\mu\text{A}/\text{cm}^2$ and less than 1 $\mu\text{A}/\text{cm}^2$.

Sample	Rebar
6-CREV-304-1	B
4-CCON-CT2-1	C
4-CREV-CT2-2	A, B, C
4-CREV-CT2-3	B, C
4-CCRV-CT2-2	A
USDB-CT2-3	B
6-CCRV-304-2	A
6-CCON-304-1	A, B, C
6-WB-304-1	B, C
6-CREV-304-3	A, C

Sample	Rebar
CREV-CT2-1	A
1-STD2-CT1-1	B
1-STD2-CT1-2	A, B
1-STD1-CT1-2	A
BCCD-CT2-1	A, B
BCCD-CT2-2	A, B, C
6-STD1-304-1	B
6-STD1-304-2	B, C
6-STD1-304-3	B, C
6-STD2-304-1	A, B, C
6-STD2-304-2	A, B, C
CSDB-CT2-2	A, B
CSDB-CT2-1	A
6-STD2-304-3	A, B, C
6-CCON-304-2	A, B
6-CCON-304-3	A, B, C
6-WB-304-2	A, B, C

3.2.1 Corrosion Potential

For samples with high corrosion activity, plots showing the corrosion potentials measured with the Gecor 8 are shown in Figure 3-1 through Figure 3-5. Plots of samples that were terminated are presented next to their non-terminated counterpart. Corroding samples generally showed potentials more negative than $-350 \text{ mV}_{\text{CSE}}$, though some samples showed a wide range of variability between individual rebars. For example, rebar C of terminated BCCD-CT2-1 (Figure 3-3) measured potentials in the range that would suggest no active corrosion, while rebar A of the same sample measured significantly more negative potentials.

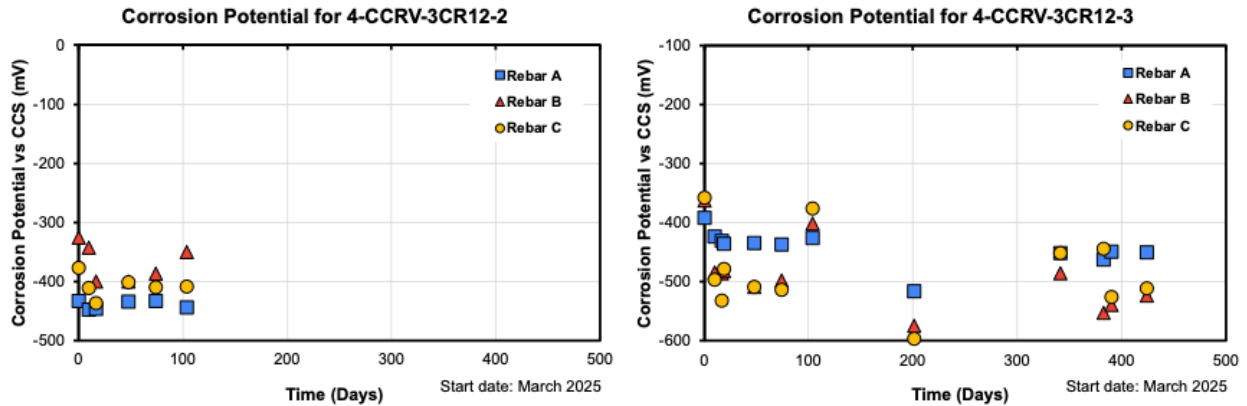


Figure 3-1. Potential vs. time for terminated 4-CCRV-3CR12-2 and non-terminated companion 4-CCRV-3CR12-3.

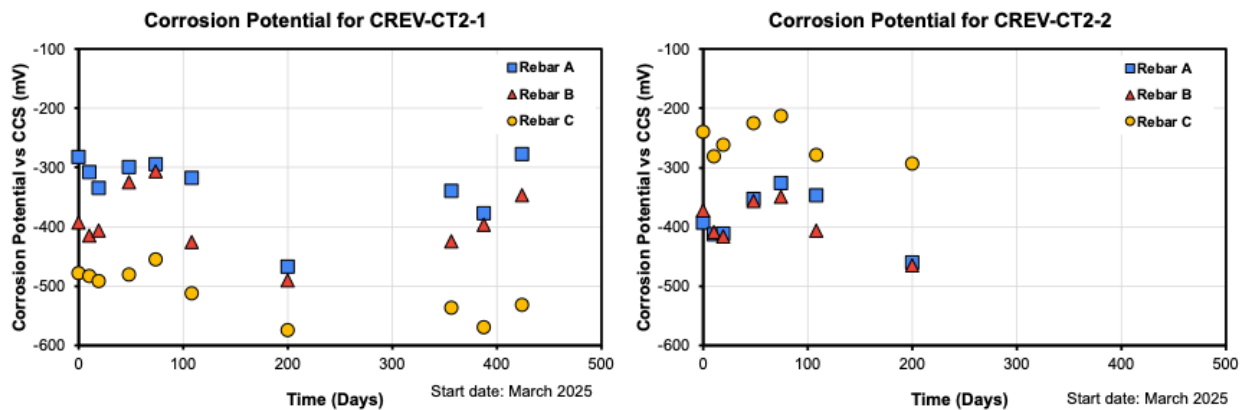


Figure 3-2. Potential vs. time for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.

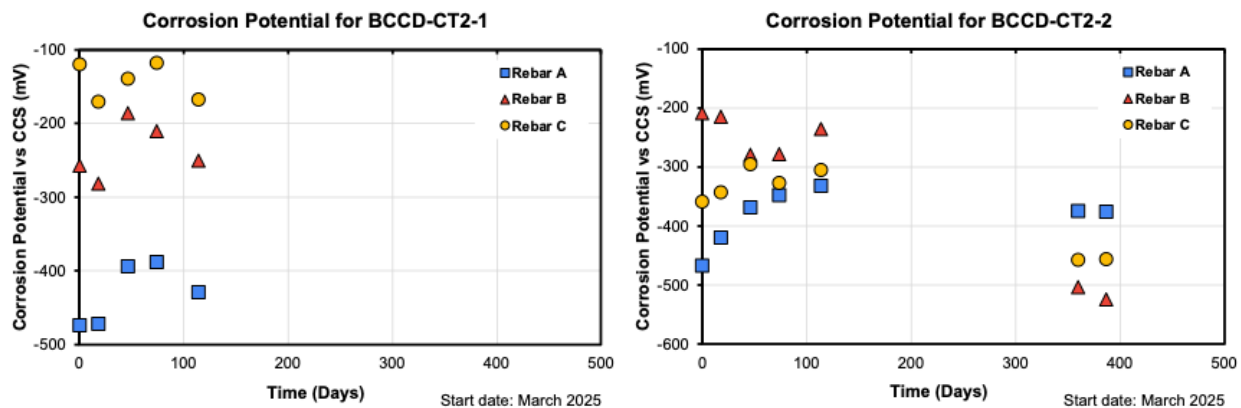


Figure 3-3. Potential vs. time for terminated BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.

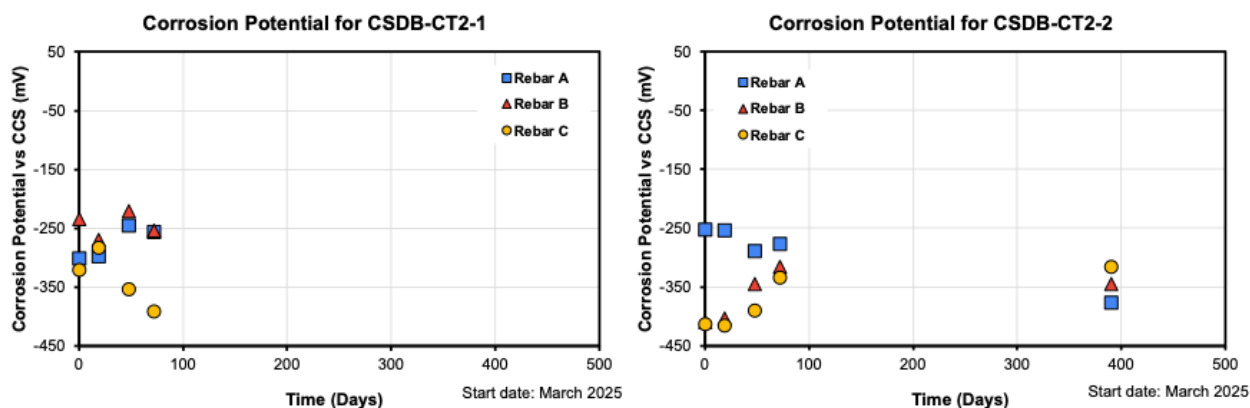


Figure 3-4. Potential vs. time for terminated CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.

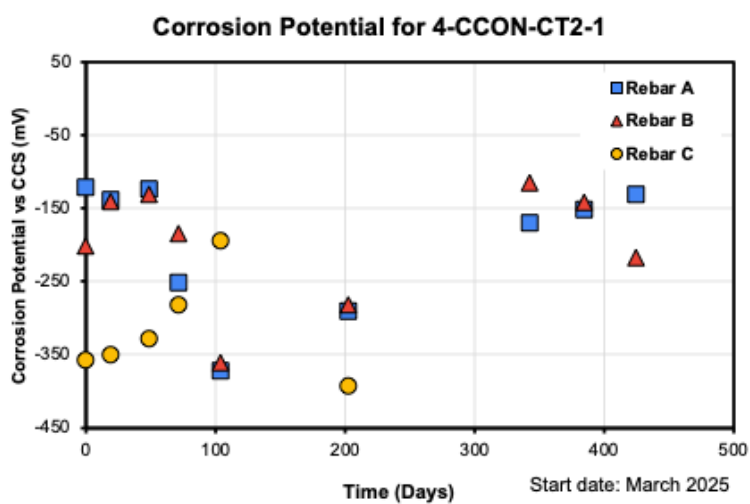


Figure 3-5. Potential vs. time for 4-CCON-CT2-1. Rebar C was terminated.

Plots of corrosion potential over time for selected samples with all rebars showing moderate corrosion activity are shown in Figure 3-6 through Figure 3-8. With the exception of rebar B of sample 6-CREV-304-1 (Figure 3-6), potentials for each rebar from the selected samples measured more positive than $-250 \text{ mV}_{\text{CSE}}$ on average. Rebar B of 6-CREV-304-1 had an average potential of approximately $-410 \text{ mV}_{\text{CSE}}$ over the monitoring period, indicating a high likelihood of active corrosion. Upon visual examination of this sample, a concrete crack in the reservoir directly above rebar B was observed.

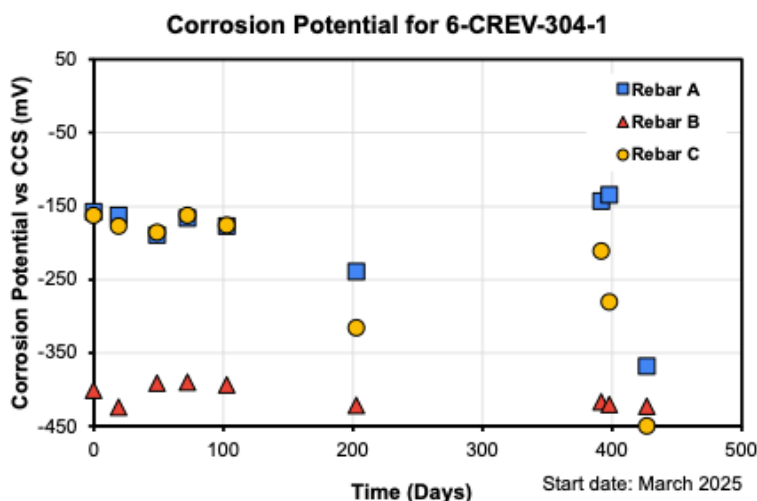


Figure 3-6. Potential vs. time for 6-CREV-304-1.

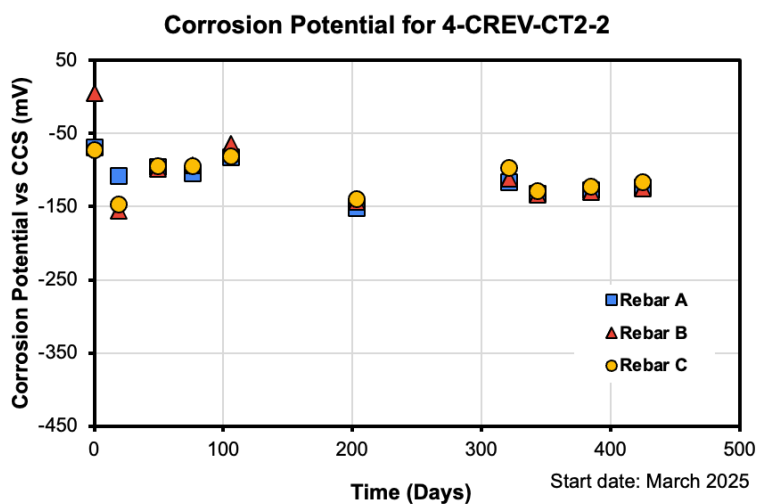


Figure 3-7. Potential vs. time for 4-CREV-CT2-2.

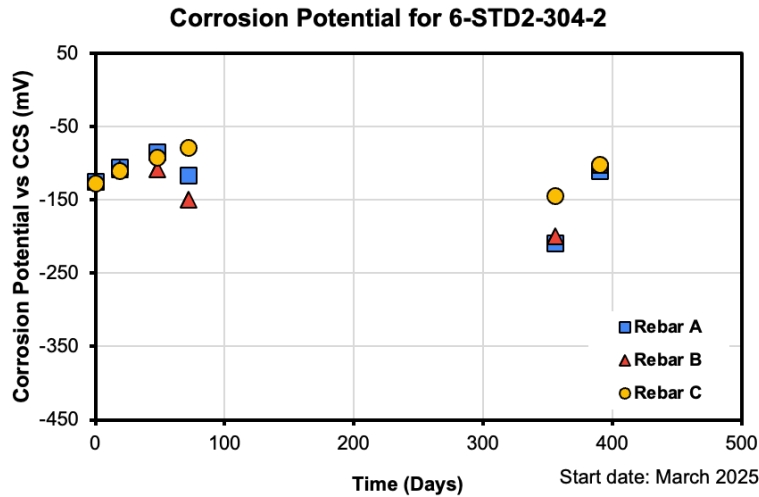


Figure 3-8. Potential vs. time for 6-STD2-304-2.

Plots of corrosion potential over time for indoor samples with little to no corrosion activity are shown in Figure 3-9 through Figure 3-13. Potentials for the samples measured more positive than $-250 \text{ mV}_{\text{CSE}}$, with some excursions to more negative values. Sample 6-CCRV-304 (Figure 3-9) had a significant negative potential shift towards the end of the monitoring period; however, isolated corrosion rates suggest the sample did not become active. The CT1 sample with undamaged cladding (Figure 3-11) measured potentials in the same range as the sample with solid 316 rebar (Figure 3-10). The samples with 2304 rebars (Figure 3-12 and Figure 3-13) presented similar potential measurements, generally oscillating between $-150 \text{ mV}_{\text{CSE}}$ and $-250 \text{ mV}_{\text{CSE}}$, despite their differing concrete mix types.

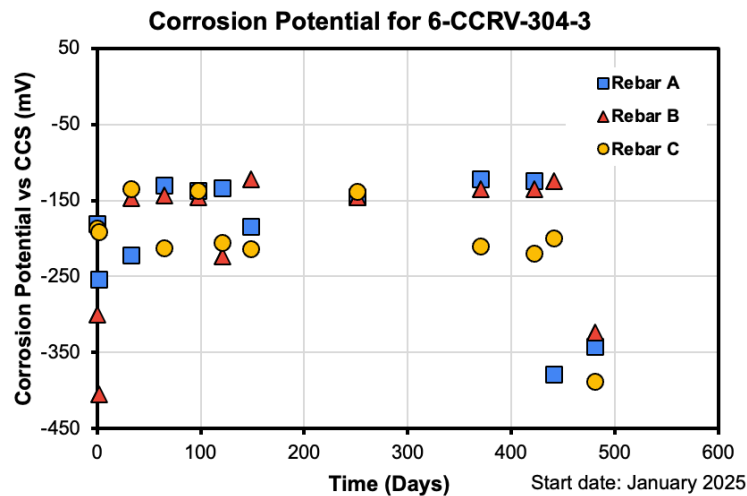


Figure 3-9. Potential vs. time for 6-CCRV-304-3.

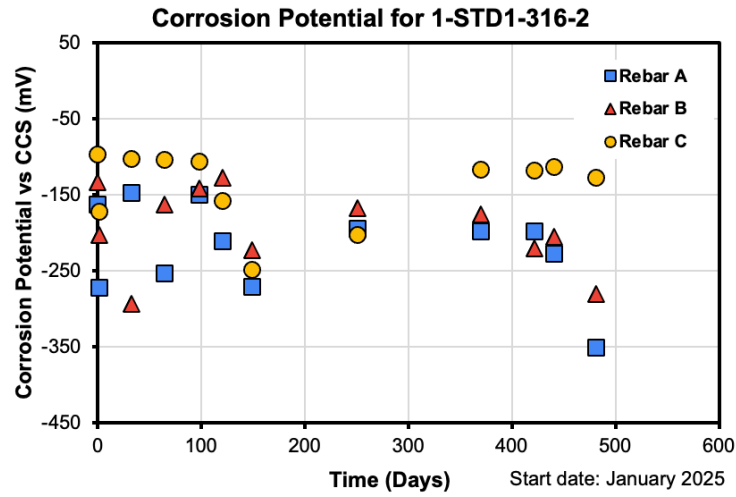


Figure 3-10. Potential vs. time for 1-STD1-316-2.

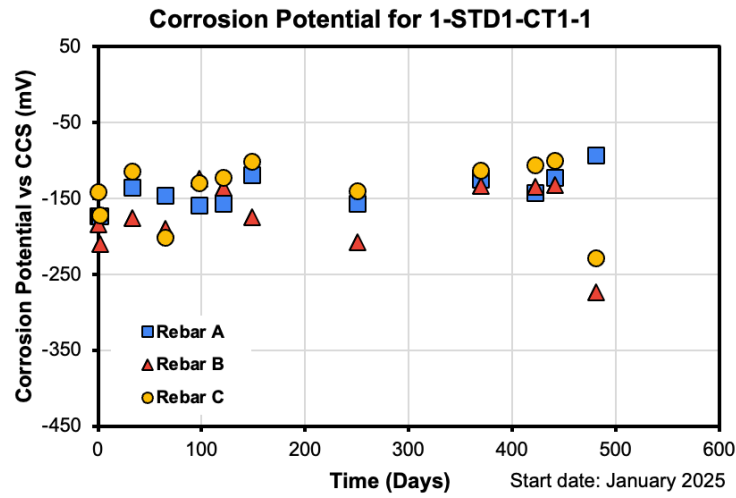


Figure 3-11. Potential vs. time for 1-STD1-CT1-1.

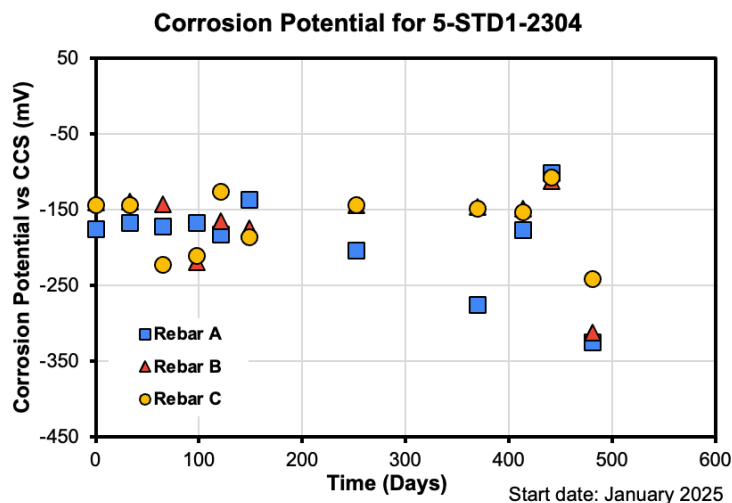


Figure 3-12. Potential vs. time for 5-STD1-2304.

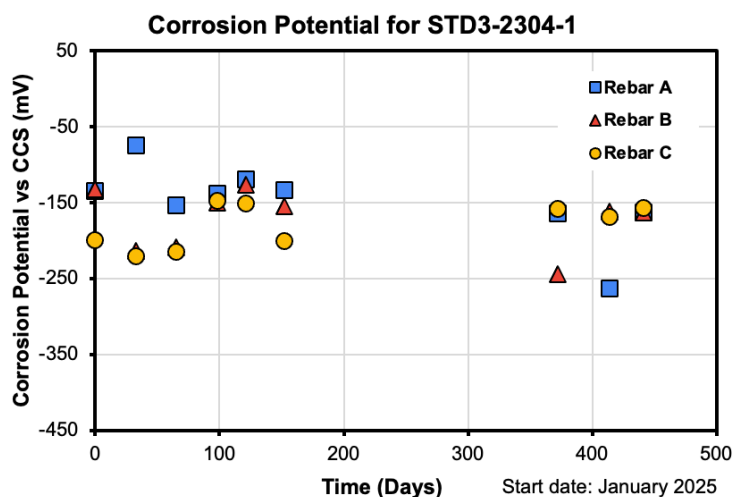


Figure 3-13. Potential vs. time for STD3-2304-1.

3.2.2 Isolated Corrosion Rate

For samples with high corrosion activity, plots showing isolated corrosion rates measured with the Gecor 8 are shown in Figure 3-14 through Figure 3-18. Plots of samples that were terminated are presented next to their non-terminated counterpart. Corroding samples generally showed isolated corrosion rates higher than $1 \mu\text{A}/\text{cm}^2$, with some samples exceeding $15\text{--}30 \mu\text{A}/\text{cm}^2$, evidencing accelerated active corrosion. Some specimens have rates that hovered around $0.5 \mu\text{A}/\text{cm}^2$, indicating moderate active corrosion. Rebar C of 4-CCRV-3CR12-3 in Figure 3-14 often showed low corrosion rates throughout the monitoring period because the corrosion products on the rebar end prevented good electrical contact. After sanding the rebar end, good contact was established and the corrosion rate measured thereafter was higher than $6 \mu\text{A}/\text{cm}^2$.

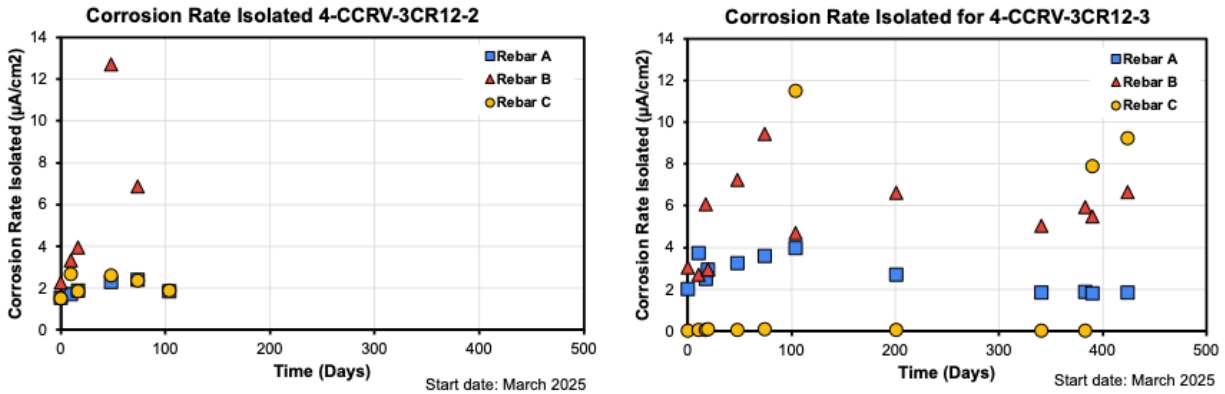


Figure 3-14. Isolated corrosion rates for terminated 4-CCRV-3CR12-2 and non-terminated companion 4-CCRV-3CR12-3.

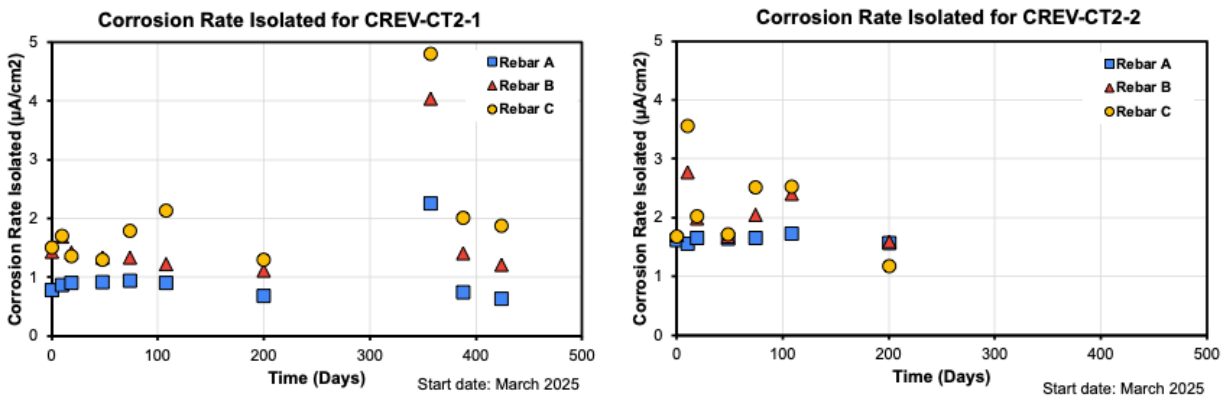


Figure 3-15. Isolated corrosion rates for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.

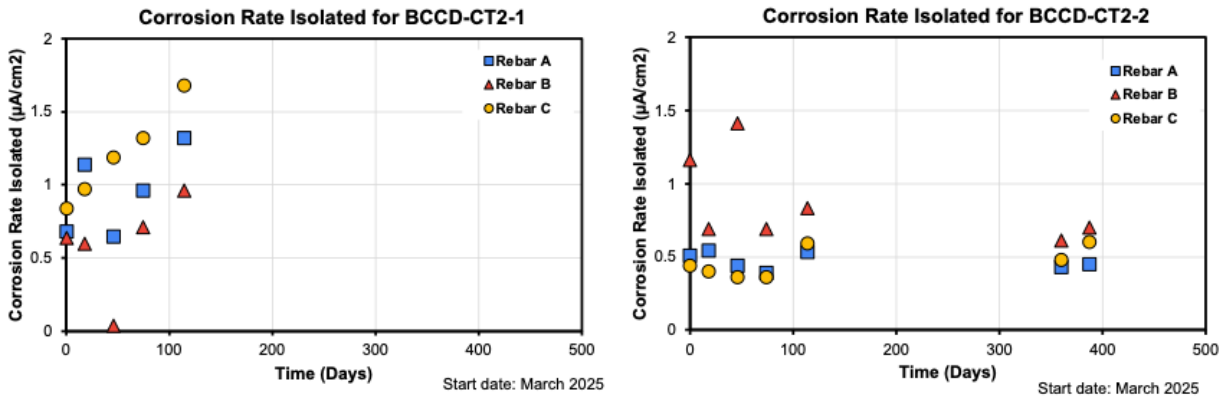


Figure 3-16. Isolated corrosion rates for terminated BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.

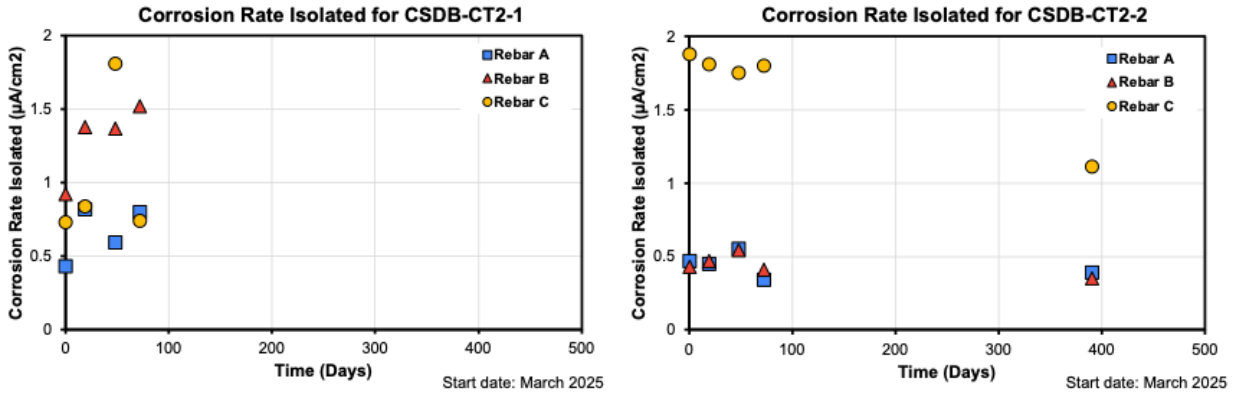


Figure 3-17. Isolated corrosion rates for terminated CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.

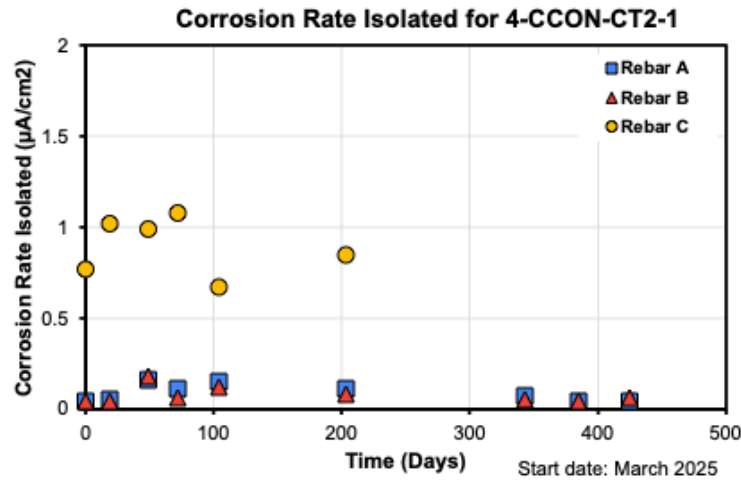


Figure 3-18. Isolated corrosion rates for 4-CCON-CT2-1. Rebar C was terminated.

Plots of isolated corrosion rates over time for selected samples showing moderate corrosion activity in each rebar are shown in Figure 3-19 through Figure 3-21. The average isolated corrosion rates for each rebar in the selected samples ranged between $0.4 \mu\text{A}/\text{cm}^2$ and $1 \mu\text{A}/\text{cm}^2$ except for rebars A and C of 6-CREV-304-1 (Figure 3-19), which had average rates below $0.4 \mu\text{A}/\text{cm}^2$.

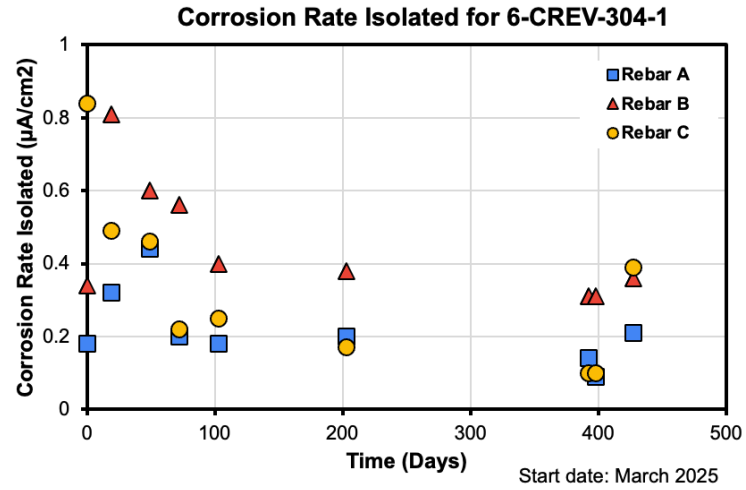


Figure 3-19. Isolated corrosion rates for 6-CREV-304-1.

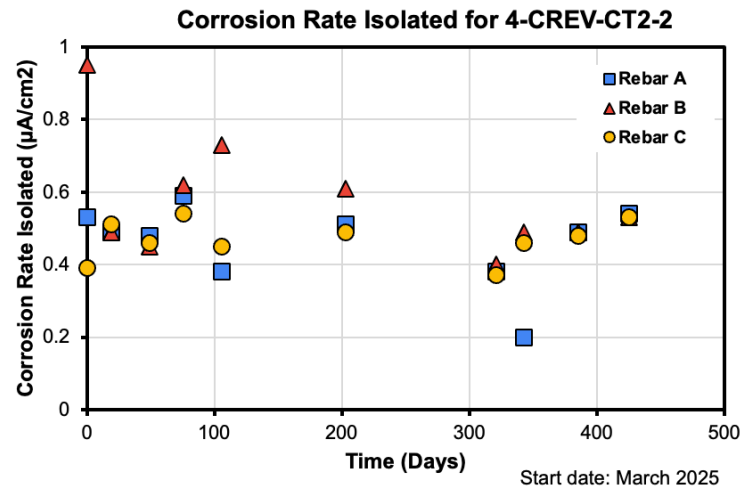


Figure 3-20. Isolated corrosion rates for 4-CREV-CT2-2.

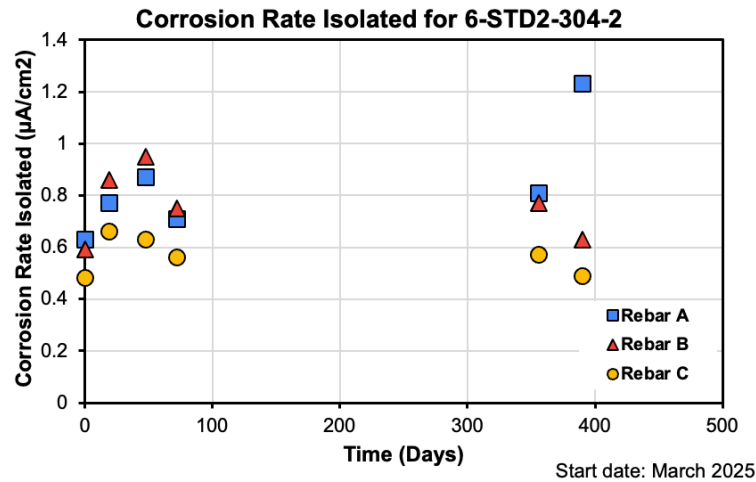


Figure 3-21. Isolated corrosion rates for 6-STD2-304-2.

Plots of corrosion isolated corrosion rates for indoor samples with little to no corrosion activity are shown in Figure 3-22 through Figure 3-26. Corrosion rates for these samples generally measured less than $0.2 \mu\text{A}/\text{cm}^2$ throughout the study, with some notable exceptions. In the beginning of the monitoring period, sample 6-CCRV-304 (Figure 3-22) measured above $0.4 \mu\text{A}/\text{cm}^2$ several times, eventually shifting back down below $0.2 \mu\text{A}/\text{cm}^2$. Rebar A of sample 1-STD1-CT1-2 (Figure 3-24) consistently measured corrosion rates above $0.2 \mu\text{A}/\text{cm}^2$ for most of the monitoring period. Whether this is active corrosion or another electrochemical reaction is unclear. Overall, the low isolated corrosion rates indicate little corrosion activity.

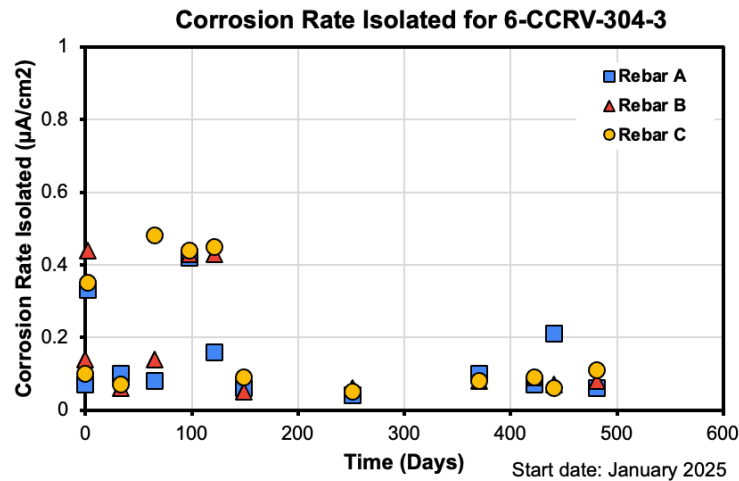


Figure 3-22. Isolated corrosion rates for 6-CCRV-304-3.

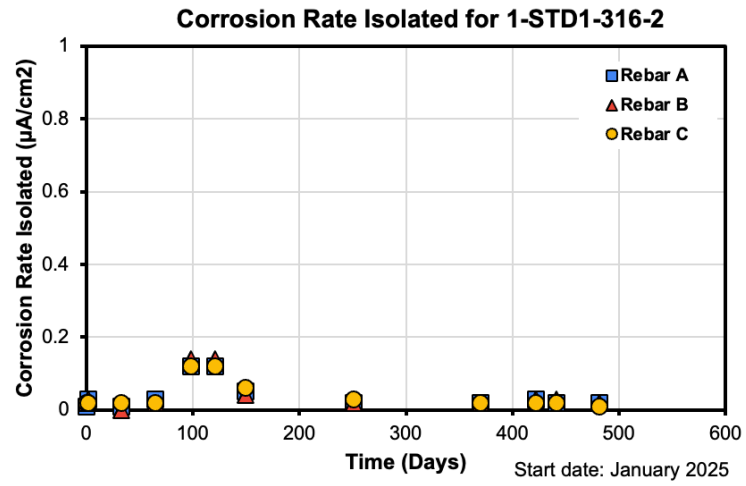


Figure 3-23. Isolated corrosion rates for 1-STD1-316-2.

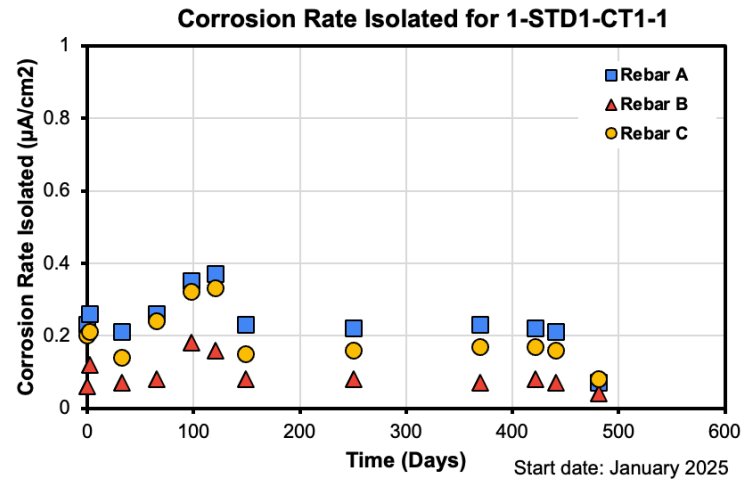


Figure 3-24. Isolated corrosion rates for 1-STD1-CT1-1.

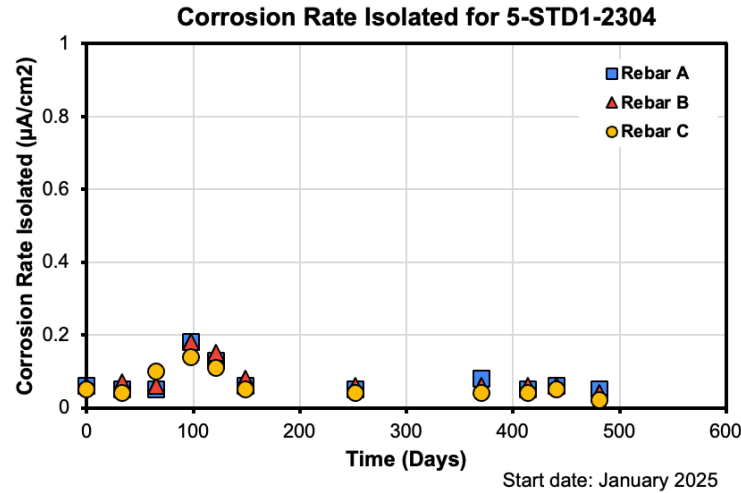


Figure 3-25. Isolated corrosion rates for 5-STD1-2304.

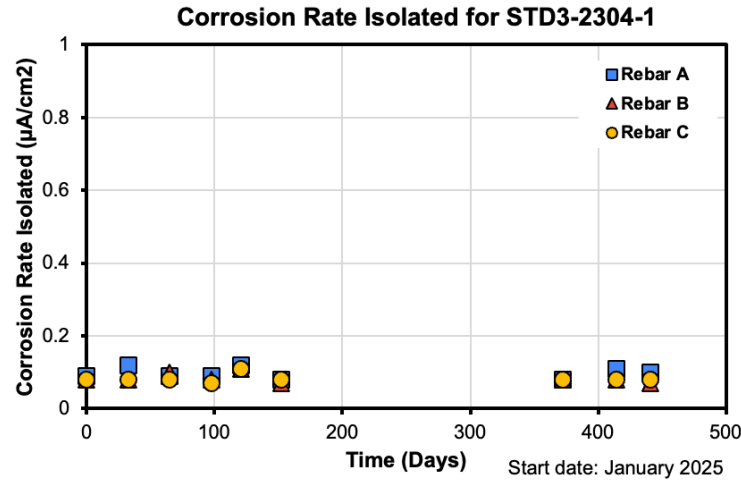


Figure 3-26. Isolated corrosion rates for STD3-2304-1.

3.2.3 Solution Resistance

Solution resistance refers to the resistance of the concrete between the probe and the embedded rebar, providing insight into the quality of the concrete cover. For corroding samples, plots showing solution resistance measured with the Gecor 8 are shown in Figure 3-27, Figure 3-28, Figure 3-29, Figure 3-30, and Figure 3-31. Plots of samples that were terminated are presented next to their non-terminated counterpart. Corroding samples generally had low solution resistance, indicating that chlorides penetrated the concrete and compromised the quality of the concrete cover above the rebars. The plots demonstrate that solution resistance for most corroding samples was lower than 0.3 kΩ. Due to the bad electrical contact on rebar C of 4-CCRV-3CR12-3, solution resistance measured higher on this rebar compared to A and B until the rebar was sanded. After good contact was made, the solution resistance measured lower values which were comparable to the other rebars in the specimen.

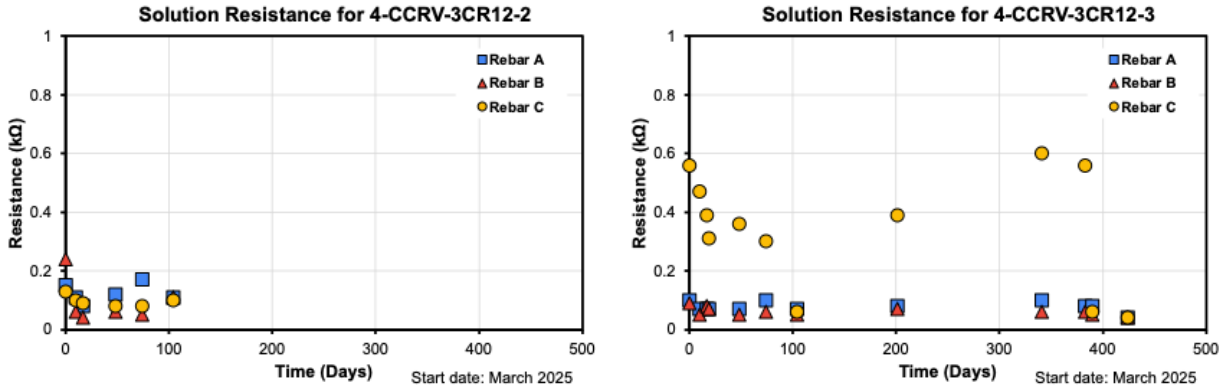


Figure 3-27. Solution resistance vs. time for terminated 4-CCRV-3CR12-2 and non-terminated companion 4-CCRV-3CR12-3.

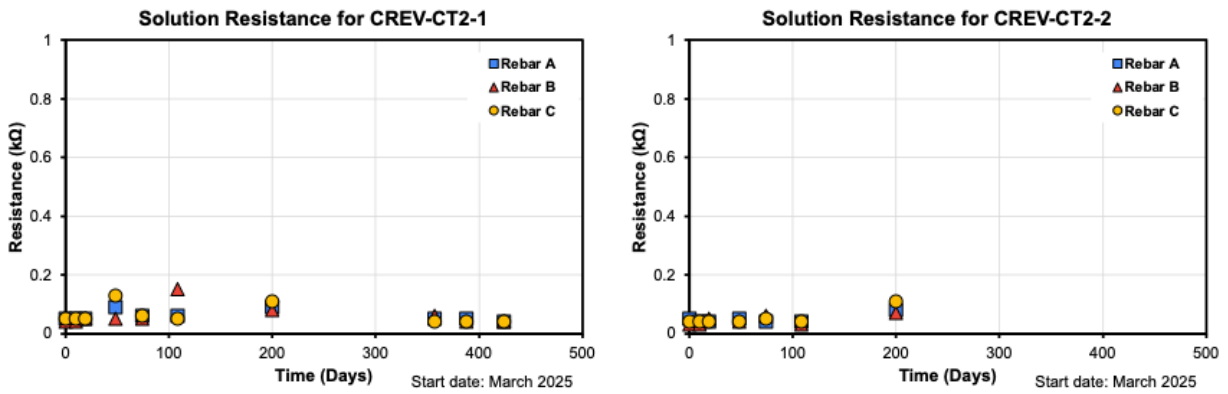


Figure 3-28. Solution resistance vs. time for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.

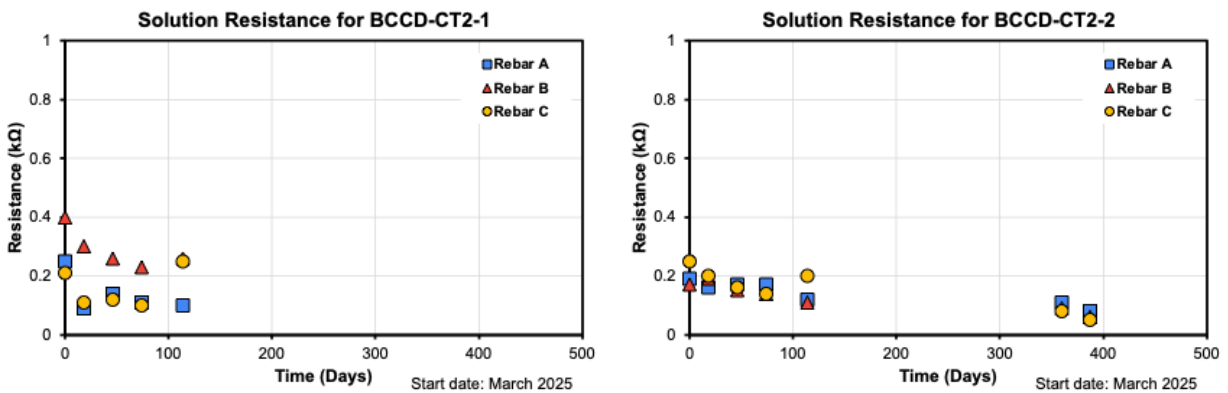


Figure 3-29. Solution resistance vs. time for terminated sample BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.

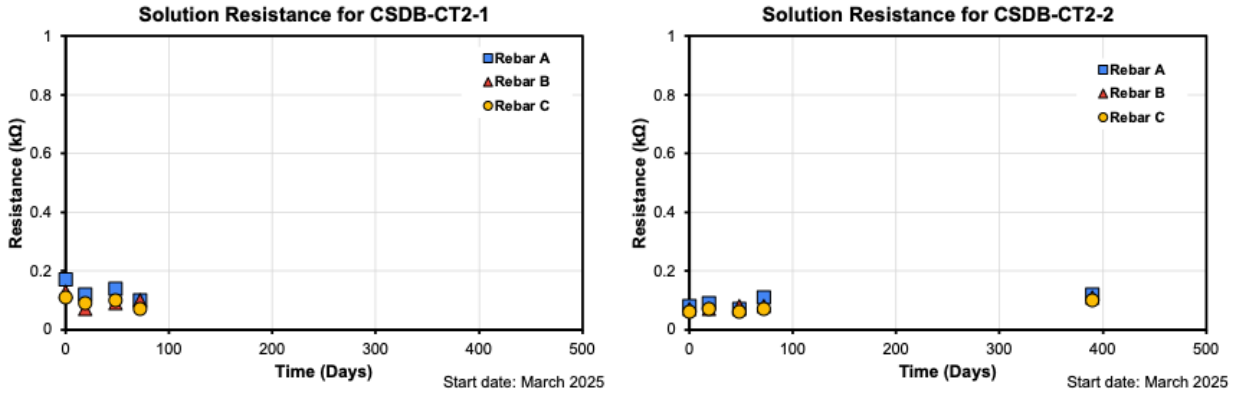


Figure 3-30. Solution resistance vs. time for terminated sample CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.

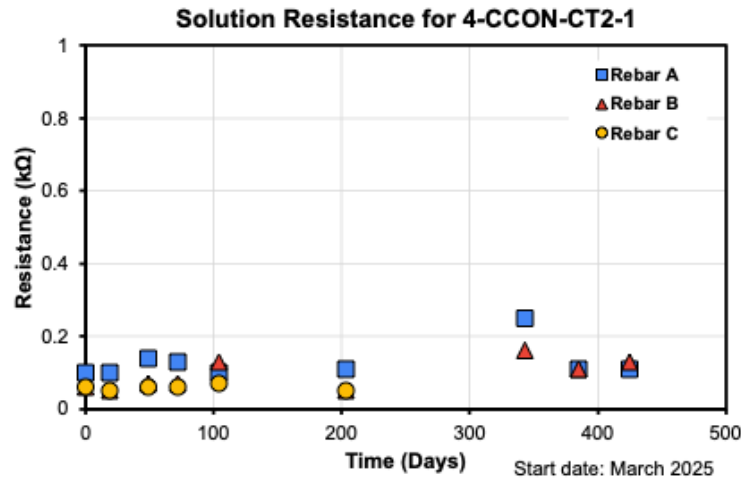


Figure 3-31. Solution resistance vs. time for 4-CCON-CT2-1. Rebar C was terminated.

Plots of solution resistance over time for selected samples showing moderate corrosion activity in each rebar are shown in Figure 3-32 through Figure 3-34. Sample 6-CREV-304-1 (Figure 3-32) had low solution resistance values that averaged below 0.2 kΩ. The concrete crack in the reservoir above rebar B of this sample likely facilitated an easier path for chlorides to penetrate. Samples 4-CREV-CT2-2 (Figure 3-33) and 6-STD2-304-2 (Figure 3-34) had solution resistances that averaged above 0.2 kΩ and less than 0.6 kΩ, which may be evidence of slightly less chloride penetration than in samples with lower solution resistances and higher corrosion activity. Although STD2 concrete has a lower w/c ratio and is of a higher quality than STD1 (as in 4-CREV-CT2-2), solution resistances between the two types are comparable after corrosion has initiated.

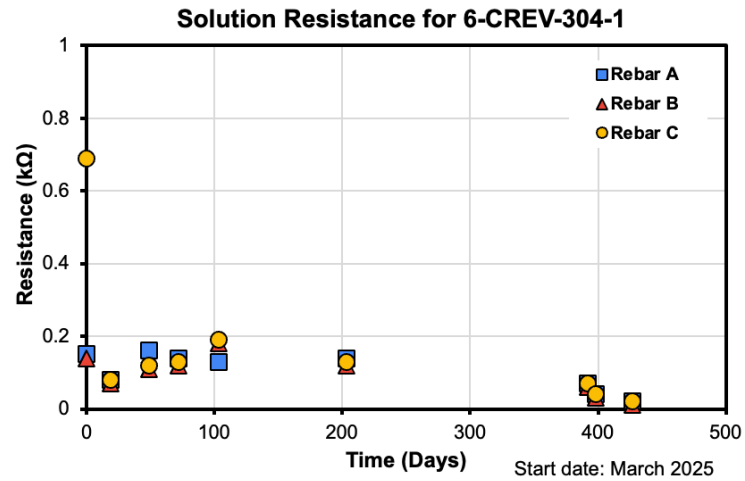


Figure 3-32. Solution resistance vs. time for 6-CREV-304-1.

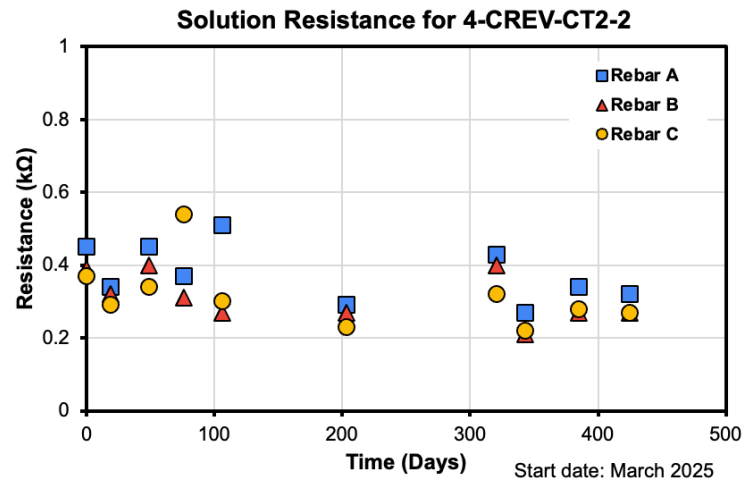


Figure 3-33. Solution resistance vs. time for 4-CREV-CT2-2.

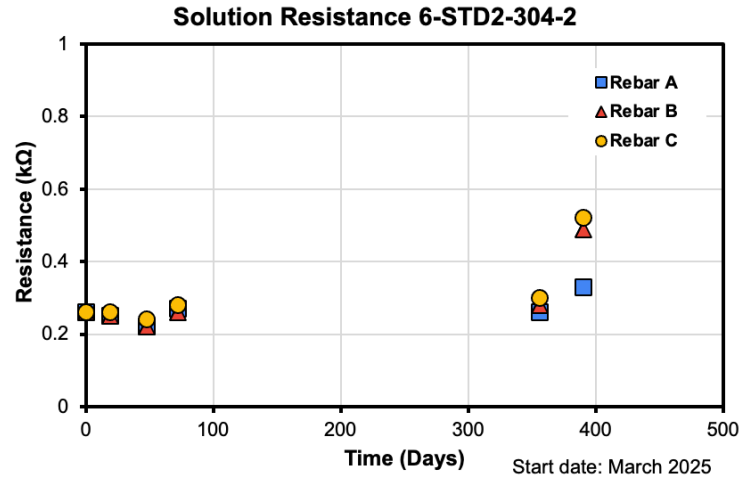


Figure 3-34. Solution resistance vs. time for 6-STD2-304-2.

Plots of solution resistance over time for indoor samples with little to no corrosion activity are shown in Figure 3-35 through Figure 3-39. Except for STD3-2304-1, each sample measured relatively low solution resistances. Samples 6-CCRV-304-3 (Figure 3-35), 1-STD1-316-2 (Figure 3-36), and 1-STD1-CT1-1 (Figure 3-37) generally measured solution resistances below 0.2 kΩ, as they were stored in the same closed tank which maintained a high relative humidity throughout the duration of the monitoring period. It was often necessary to leave the tank open for a couple days and allow the samples to partially dry and prevent sensor errors while measuring.

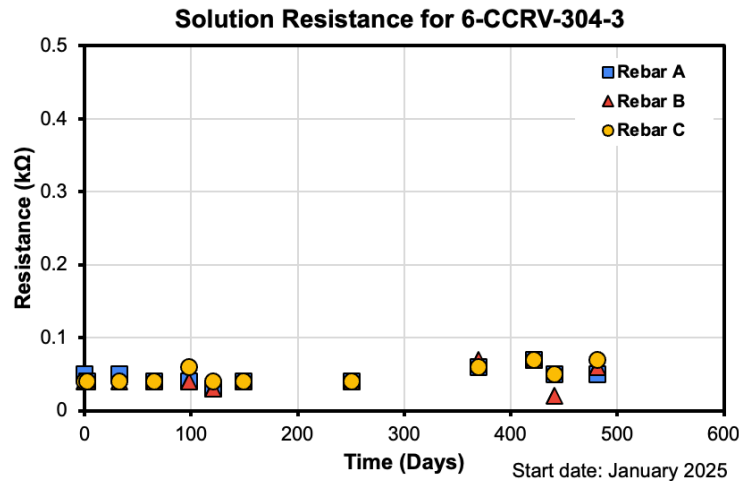


Figure 3-35: Solution resistance vs. time for 6-CCRV-304-3.

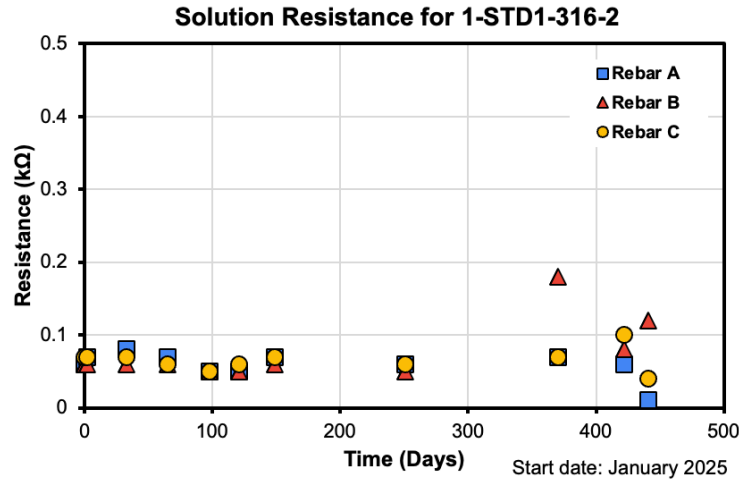


Figure 3-36. Solution resistance vs. time for 1-STD1-316-2.

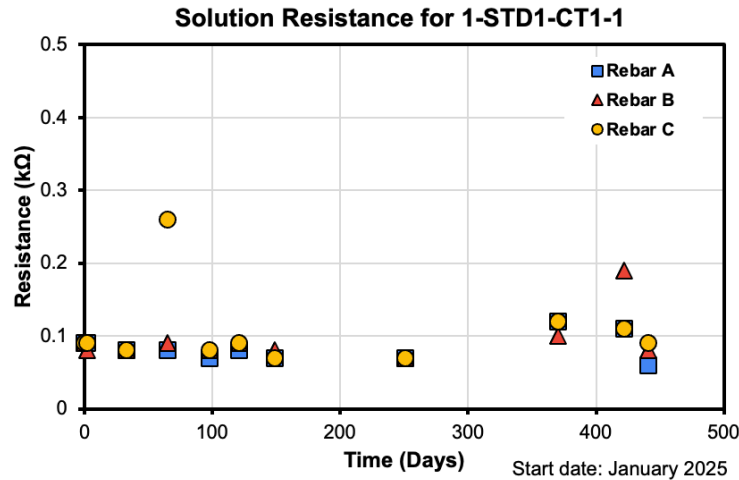


Figure 3-37. Solution resistance vs. time for 1-STD1-CT1-1.

Sample 5-STD1-2304 (Figure 3-38) measured somewhat higher solution resistances, ranging between 0.2 kΩ and 0.4 kΩ. The tank in which this sample was stored was not as airtight, and therefore the relative humidity to which it was exposed was lower. Sample STD3-2304-1 (Figure 3-39) measured significantly higher solution resistances, ranging between 1 kΩ and 2 kΩ. Recall that the STD3 concrete mix included 10% fly ash F; the higher solution resistances presented by this sample resulted from the higher quality concrete mix.

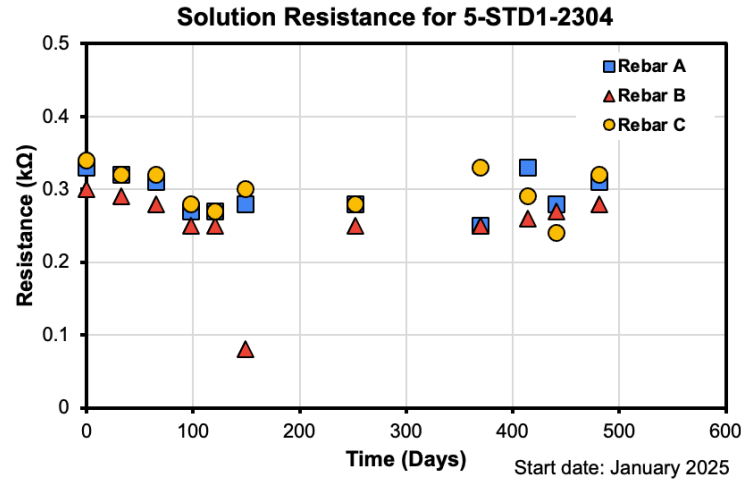


Figure 3-38. Solution resistance vs. time for 5-STD1-2304.

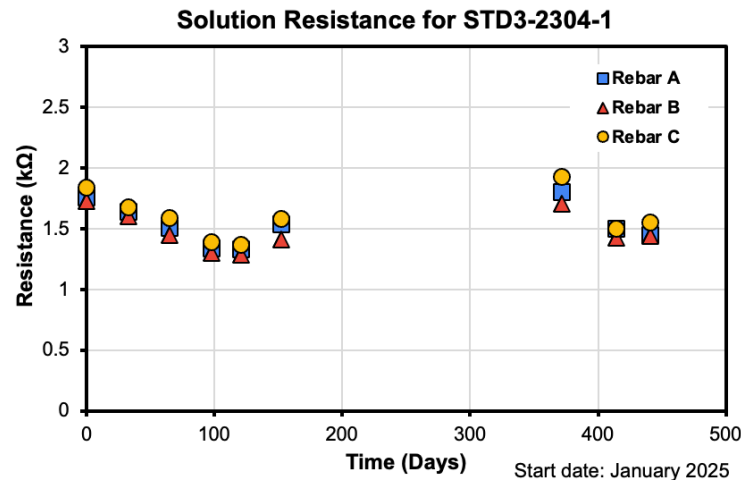


Figure 3-39. Solution resistance vs. time for STD3-2304-1.

3.3 GP MEASUREMENTS

Galvanostatic pulse (GP) measurements were used to calculate corrosion current (I_{corr}) and solution resistance (R_s) of each electrically disconnected sample and results are presented in this section. Additionally, open circuit potential (OCP), with respect to the saturated calomel reference electrode, was measured directly for each sample. Some examples of OCP vs. time plots are presented. All results reported are for electrically isolated rebars. Samples are grouped according to ranges of average corrosion currents: greater than $20 \mu\text{A}$, presented first; between $12 \mu\text{A}$ and $20 \mu\text{A}$, presented second; and less than $12 \mu\text{A}$, presented last. When accounting for the surface area of the embedded portion of each rebar, these values roughly translate to the same ranges of isolated corrosion current densities used to group samples in the Gecor results section: greater than $1 \mu\text{A}/\text{cm}^2$, between 0.4 and $1 \mu\text{A}/\text{cm}^2$, and less than $0.4 \mu\text{A}/\text{cm}^2$. However, the corrosion resistant rebars in each sample that to corrode locally rather than uniformly. Thus, the

conversion between corrosion current and corrosion current density is not 1:1, as it is impossible to know what localized surface area of each rebar is corroding while it remains embedded in the concrete.

Table 3-10. Samples with rebars that had average corrosion currents greater than 20 μA .

Sample	Rebar
6-CREV-304-1	B
4-CCON-CT2-2	B
4-CCON-CT2-3	A
USDB-CT2-1	B
4-CCRV-3CR12-3	A, B, C
6-WB-304-1	A
CREV-CT2-1	A, B, C
BCCD-CT2-2	A, B, C
CSDB-CT2-2	A, B, C

Data collection start dates vary for the samples and are displayed on each plot. Table 3-10 lists non-terminated samples with I_{corr} greater than 20 μA . Plots for a subset of these samples and their terminated counterparts, if available, are presented. Table 3-11 lists samples non-terminated samples with I_{corr} greater than 12 μA and less than 20 μA . Each sample in the group with the lowest corrosion currents was kept indoors for the duration of the monitoring period, while the rest were exposed outdoors.

Table 3-11. Samples with rebars that had average corrosion currents greater than 12 μA and less than 20 μA .

Sample	Rebar
4-CREV-CT2-2	A, C
4-CREV-CT2-3	B
4-CCRV-CT2-1	A
USDB-CT2-1	A, C
USDB-CT2-3	B
1-STD2-CT1-1	B, C
1-STD2-CT1-3	C
1-STD1-CT1-2	A
6-STD2-304-2	A, B, C

3.3.1 Corrosion Currents

For samples with high corrosion activity ($I_{\text{corr}} > 20 \mu\text{A}$), plots showing the corrosion currents are shown in Figure 3-40 through Figure 3-45. Plots of samples that were not terminated are presented next to their terminated counterpart where available. The companion of sample 4-CCRV-3CR12-3 was terminated before GP measurements commenced on outdoor samples. Corroding samples generally showed corrosion currents higher than 50 μA , though some samples showed a wide range of variability between individual rebars. For example, rebars B and C of 4-CCRV-3CR12-3 (Figure 3-40) had corrosion currents that reached above 1000 μA , while rebar A stayed well below 500 μA . The terminated rebar C of 4-CCON-CT2-1 (Figure 3-44) had corrosion currents consistently measuring above 50 μA while non-terminated rebars A and B of the same sample showed lower corrosion currents, ranging below 20 μA . Not pictured are the non-terminated companion samples of 4-CCON-CT2-1, which yielded more moderate I_{corr} values but still showed signs of corrosion. Rebar B of 6-CREV-304-1 (Figure 3-45) displayed corrosion currents between 20 μA and 40 μA , while the corrosion currents of rebars A and B of the same sample remained below 10 μA . The concrete crack above rebar B of 6-CREV-304-1 likely allowed more chlorides to reach this rebar, increasing corrosion and leading to higher corrosion current values.

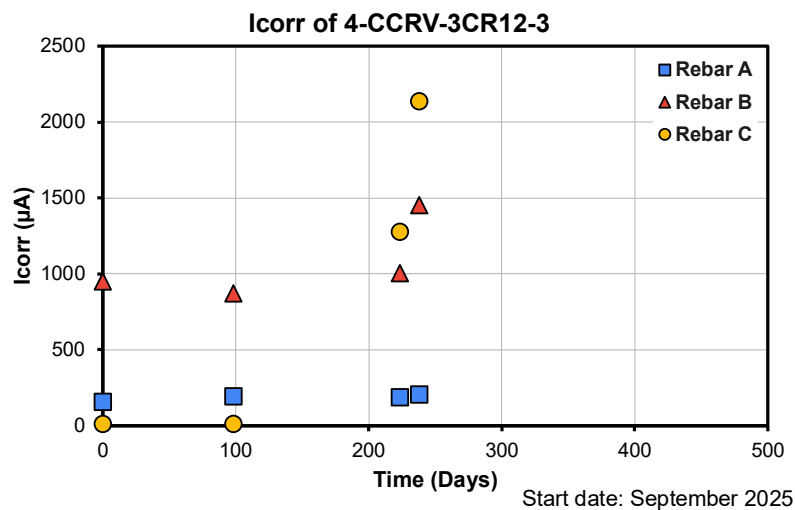


Figure 3-40. Corrosion current vs. time for non-terminated sample 4-CCRV-3CR12-3.

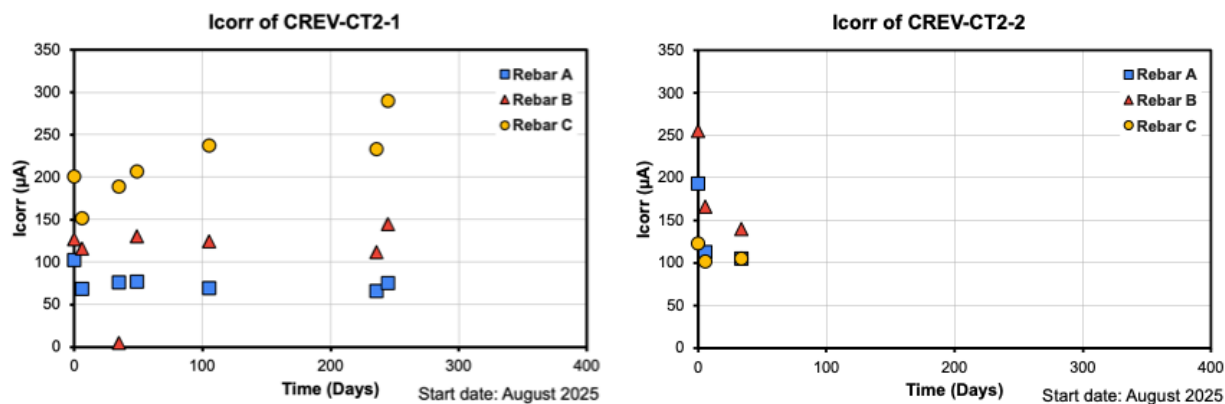


Figure 3-41. Corrosion current vs. time for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.

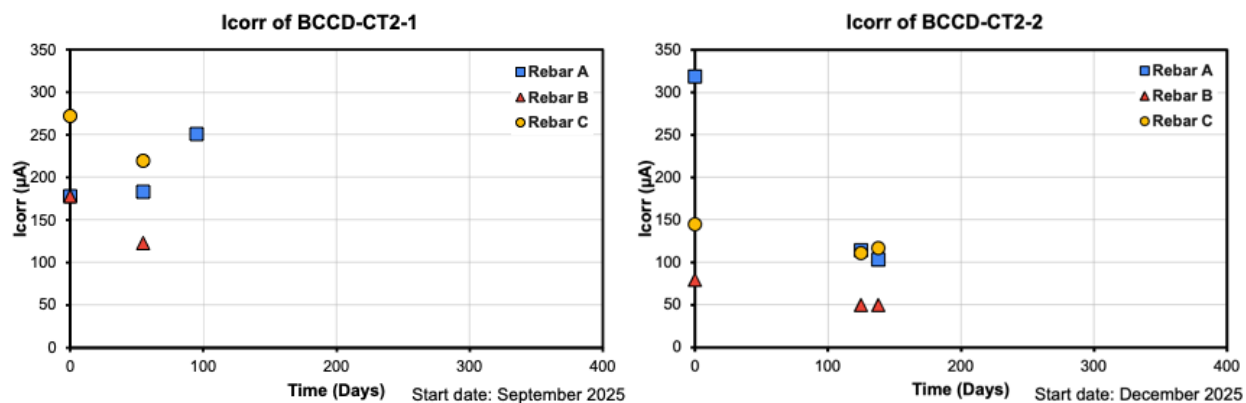


Figure 3-42. Corrosion current vs. time for terminated BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.

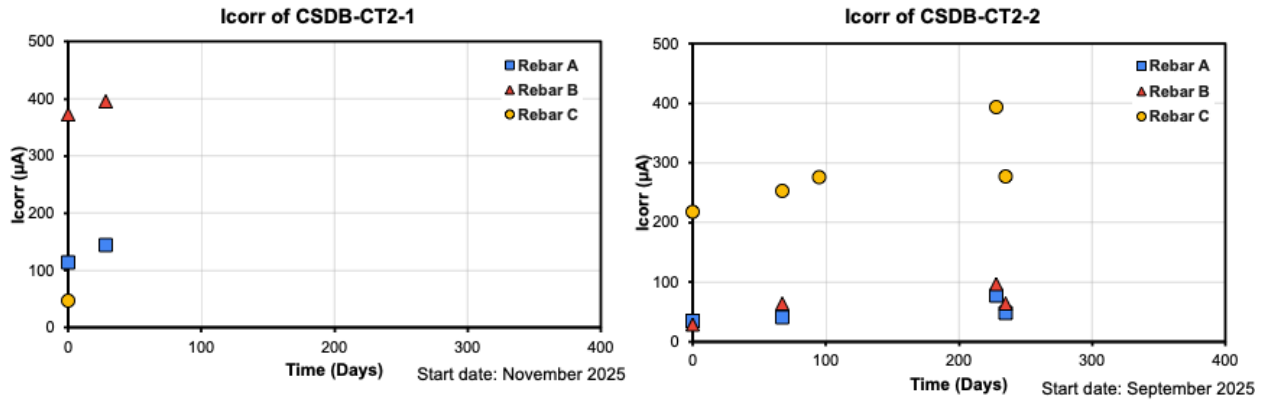


Figure 3-43. Corrosion current vs. time terminated CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.

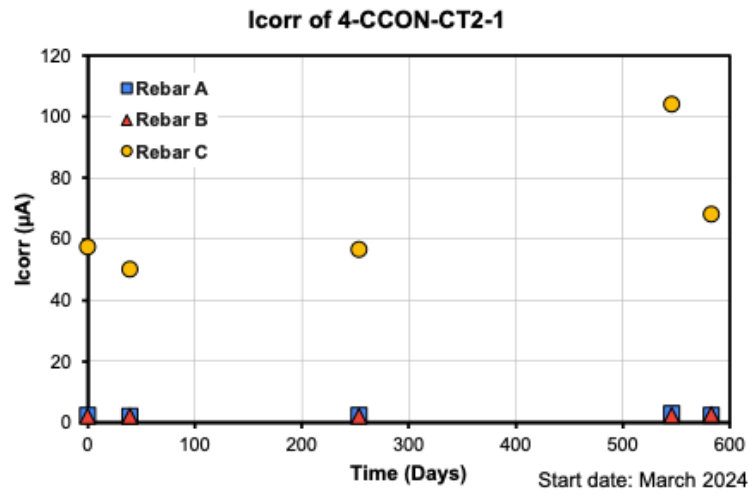


Figure 3-44. Corrosion current vs. time for 4-CCON-CT2-1. Rebar C was terminated.

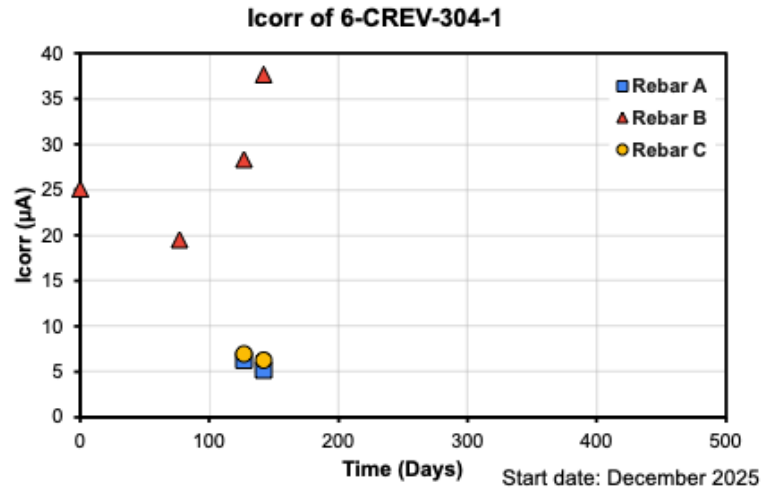


Figure 3-45. Corrosion current vs. time for non-terminated 6-CREV-304-1.

For samples with moderate corrosion activity ($12 \mu\text{A} < I_{\text{corr}} < 20 \mu\text{A}$), plots showing the corrosion currents are shown in Figure 3-46 and Figure 3-47. Corrosion currents of rebars A and C of 4-CREV-CT2-2 (Figure 3-46) each averaged between $13 \mu\text{A}$ and $14 \mu\text{A}$. Corrosion currents of 6-STD2-304-2 (Figure 3-47) averaged between $14 \mu\text{A}$ and $17 \mu\text{A}$.

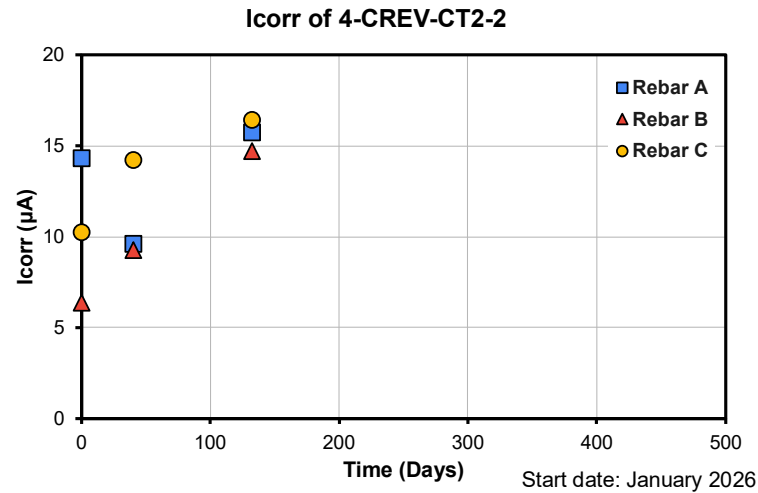


Figure 3-46. Corrosion current vs. time for 4-CREV-CT2-2.

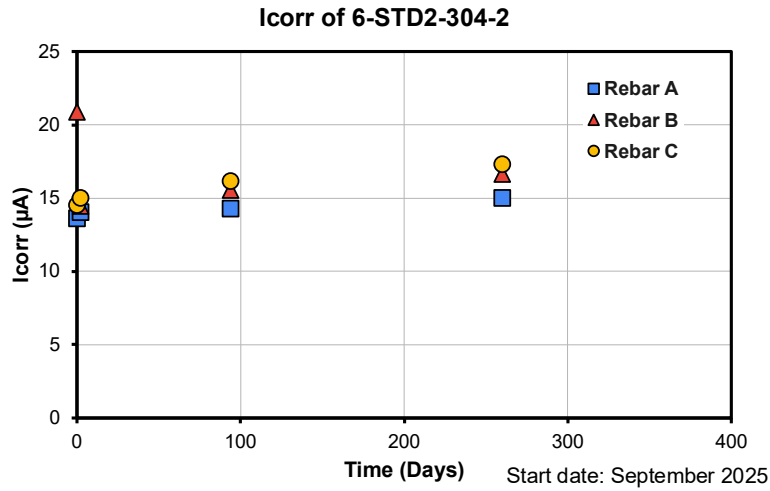


Figure 3-47. Corrosion current vs. time for 6-STD2-304-2.

Plots of corrosion current vs. time for indoor samples with little to no corrosion activity are shown in Figure 3-48 through Figure 3-52. Corrosion currents for these samples generally remained stable, measuring less than 10 μA throughout the study. Out of this group, the highest corrosion currents were experienced by the sample with clad rebars, 1-STD1-CT1-1 (Figure 3-50). The samples with the most corrosion resistant alloys and no intentional damage displayed the lowest corrosion currents, i.e. below 3 μA for each rebar. These included 1-STD1-316-2, 5-STD1-2304, and STD3-2304-1 (Figure 3-49, Figure 3-51, and Figure 3-52, respectively).

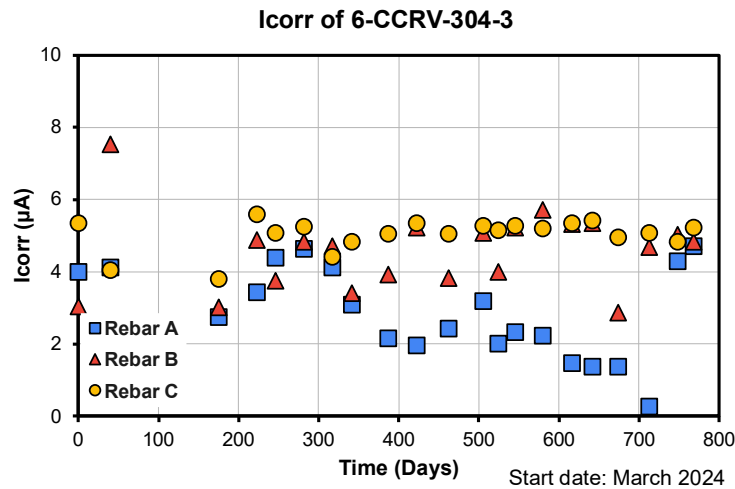


Figure 3-48. Corrosion current vs. time for 6-CCRV-304-3.

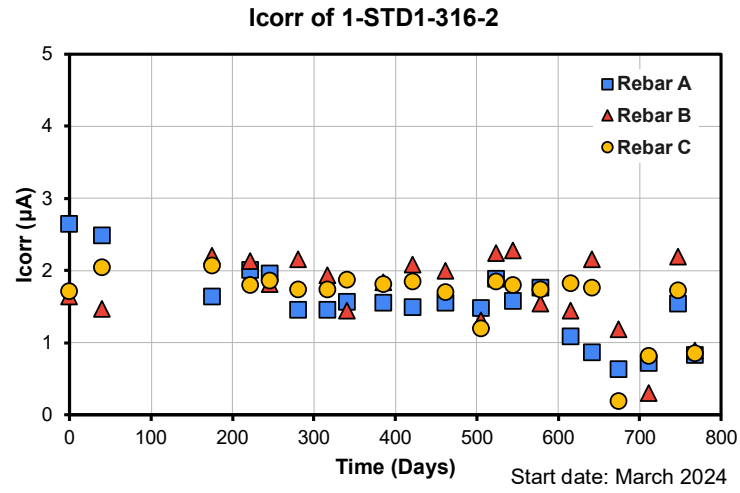


Figure 3-49. Corrosion current vs. time for 1-STD1-316-2.

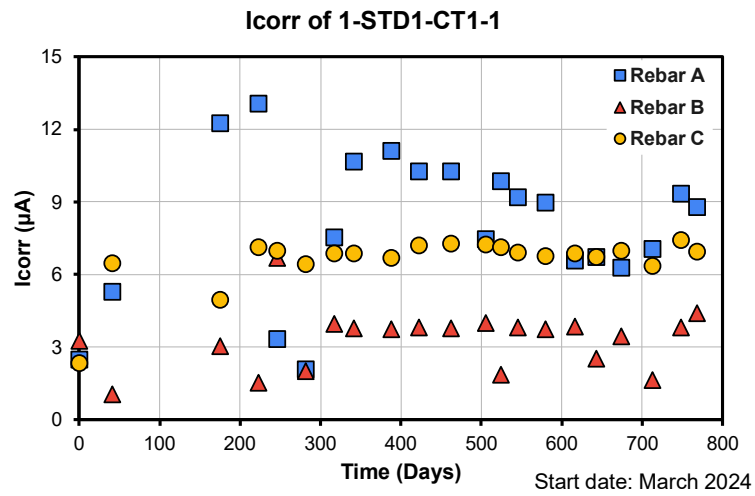


Figure 3-50. Corrosion current vs. time for 1-STD1-CT1-1.

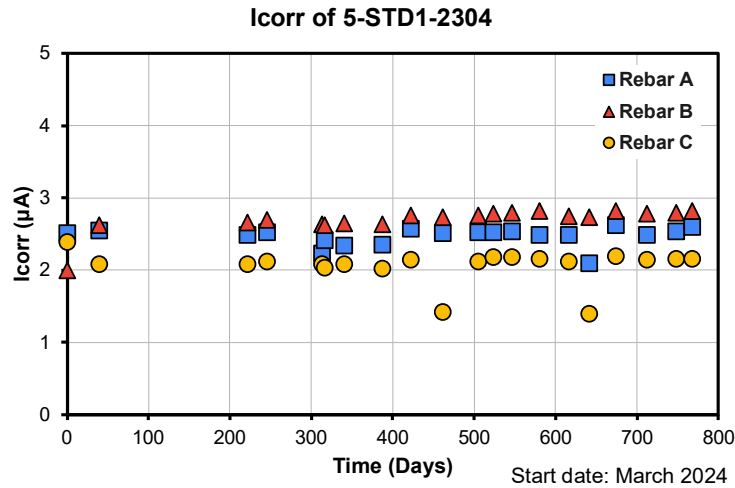


Figure 3-51. Corrosion current vs. time for 5-STD1-2304.

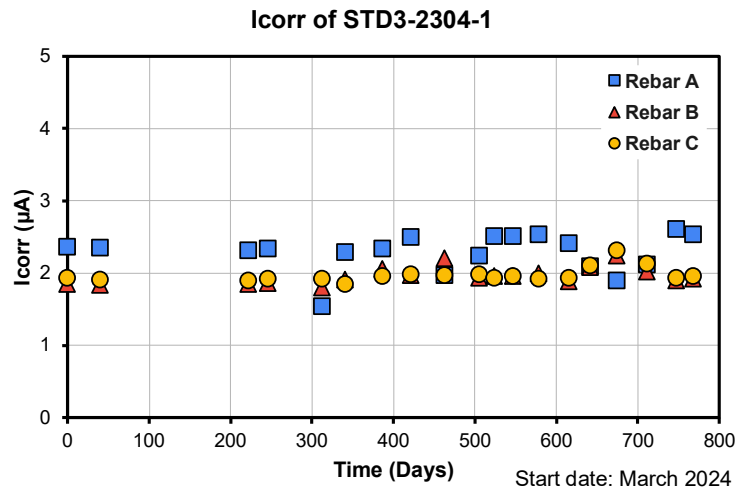


Figure 3-52. Corrosion current vs. time for STD3-2304-1.

3.3.2 Solution Resistance

For samples with the highest corrosion currents, plots showing solution resistance calculated from the galvanostatic pulse method are shown in Figure 3-53 through Figure 3-58. Where possible, plots of samples that were not terminated are presented next to their terminated counterpart. Corroding samples generally had low solution resistance, indicating that chlorides penetrated the concrete and compromised the quality of the concrete cover above the rebars. Solution resistance values are comparable to those measured with the Gecor 8. The plots demonstrate that solution resistance for most corroding samples was lower than 0.3 kΩ.

Due to bad electrical contact on rebar C of 4-CCRV-3CR12-3 (Figure 3-53), solution resistance was higher on this rebar compared to A and B until the rebar was sanded. After good contact was made, solution resistance values lowered and were comparable to the other rebars in the

specimen. The terminated rebar C of 4-CCON-CT2-1 (Figure 3-57) consistently showed solution resistances lower than the non-terminated rebars A and B, possibly evidencing more localized chloride penetration over rebar C.

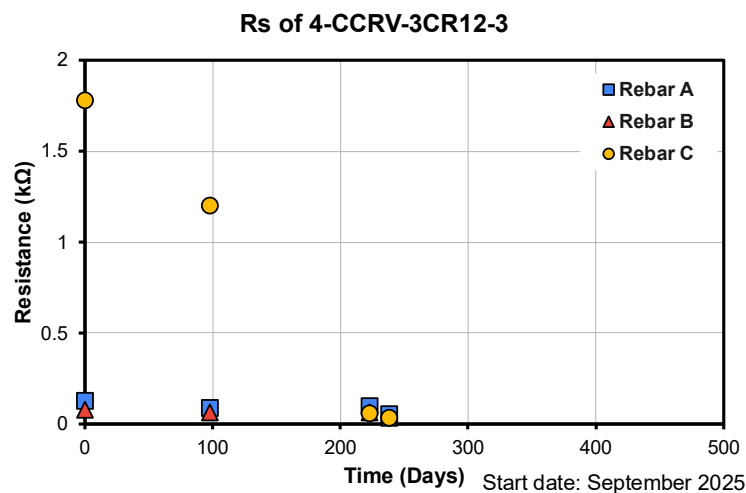


Figure 3-53. Solution resistance vs. time for non-terminated 4-CCRV-3CR12-3.

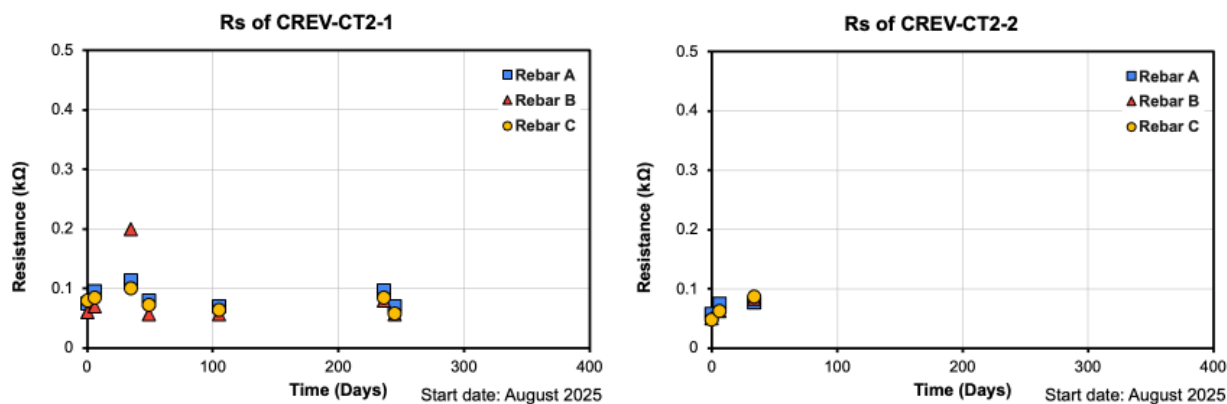


Figure 3-54. Solution resistance vs. time for terminated CREV-CT2-2 and non-terminated companion CREV-CT2-1.

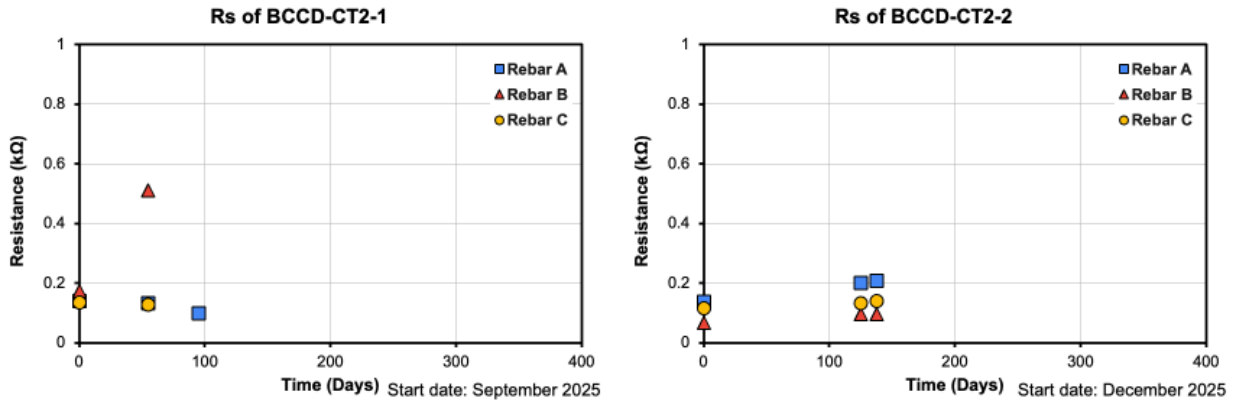


Figure 3-55. Solution resistance vs. time for terminated BCCD-CT2-1 and non-terminated companion BCCD-CT2-2.

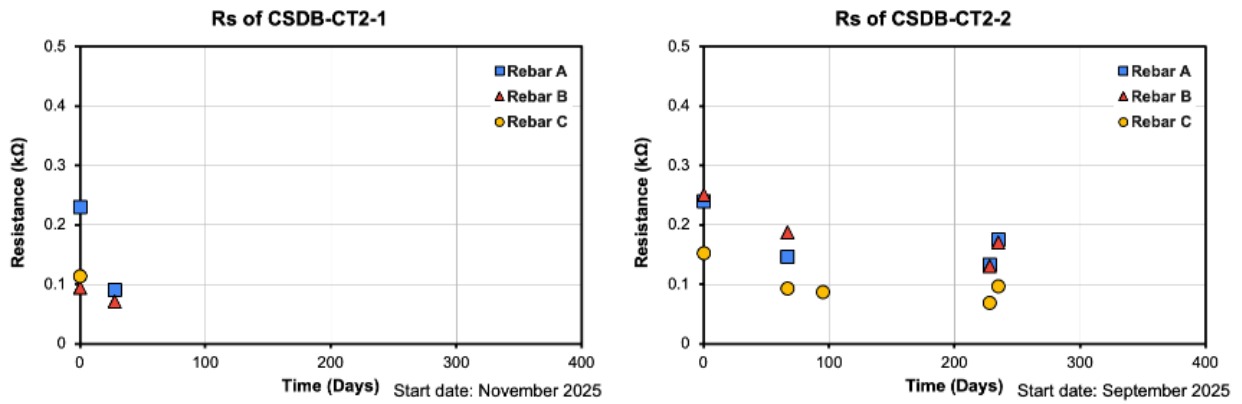


Figure 3-56. Solution resistance vs. time for terminated CSDB-CT2-1 and non-terminated companion CSDB-CT2-2.

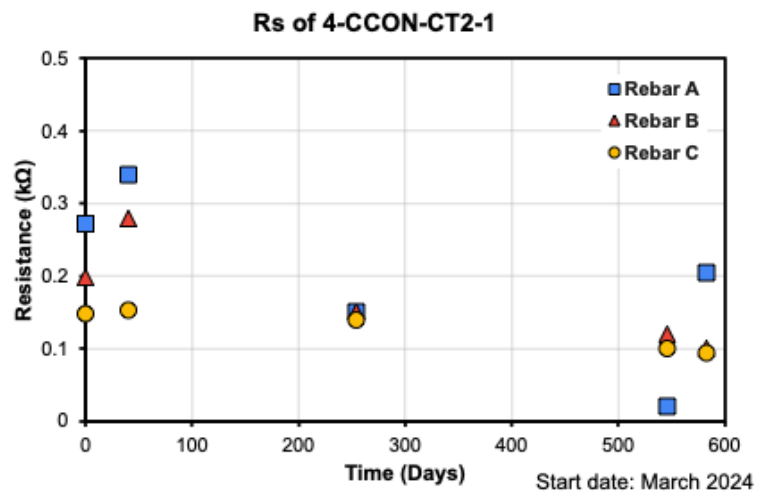


Figure 3-57. Solution resistance vs. time for 4-CCON-CT2-1. Rebar C was terminated.

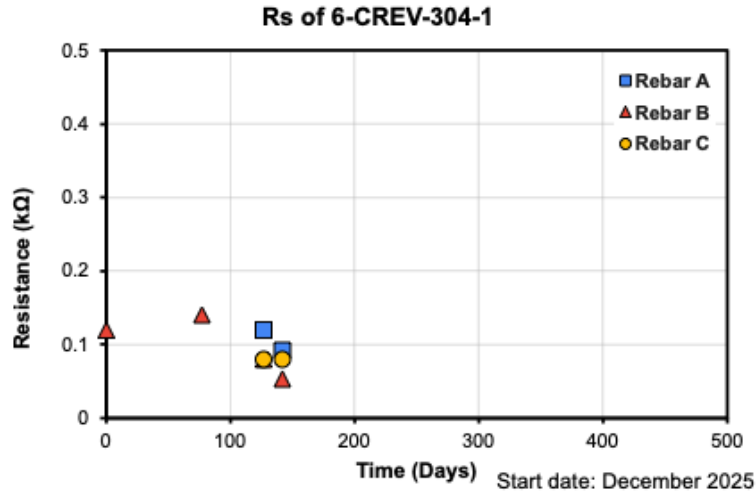


Figure 3-58. Solution resistance vs. time for 6-CREV-304-1.

Plots of solution resistance over time for selected samples showing moderate I_{corr} values are shown Figure 3-59 and Figure 3-60. Samples 4-CREV-CT2-2 (Figure 3-59) and 6-STD2-304-2 (Figure 3-60) had solution resistances that averaged between 0.1 kΩ and 0.6 kΩ, which is comparable to the values measured with the Gecor 8. Although the concrete quality of 6-STD2-304-2 was higher than that of 4-CREV-CT2-2 (which was composed of STD1 concrete), solution resistances calculated for the STD2 sample were slightly lower on average than those calculated for 4-CREV-CT2-2.

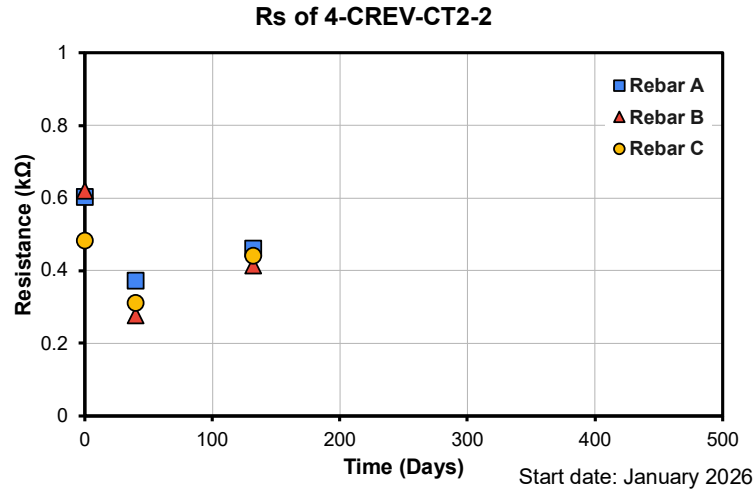


Figure 3-59. Solution resistance vs. time for 4-CREV-CT2-2.

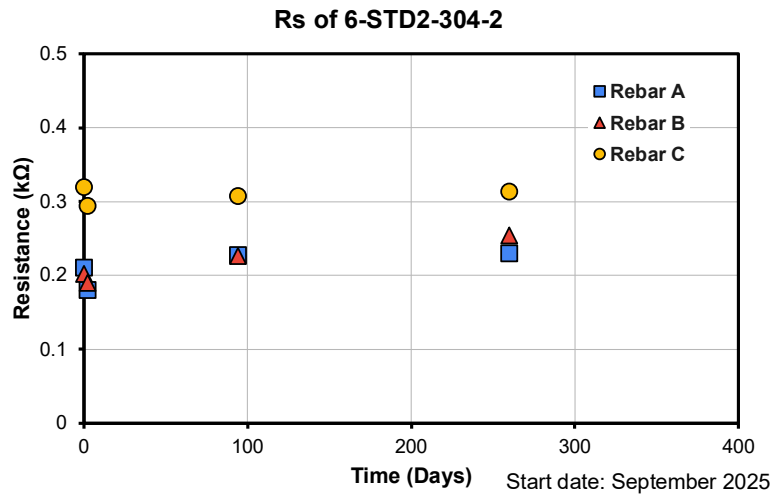


Figure 3-60. Solution resistance vs. time for 6-STD2-304-2.

Plots of solution resistance over time for indoor samples with little to no corrosion activity are shown in Figure 3-61 through Figure 3-65. Except for STD3-2304-1 and a few excursions from other samples, each sample demonstrated low, stable solution resistances. On average, the lowest solution resistances were reported by samples 6-CCRV-304-3 (Figure 3-61), 1-STD1-316-2 (Figure 3-62), and 1-STD1-CT1-1 (Figure 3-63), as these samples were stored in the tank experienced the highest constant relative humidity. Values for these samples averaged below 0.25 kΩ. Sample 5-STD1-2304 (Figure 3-64) averaged solution resistances slightly higher, oscillating around 0.34 kΩ for all rebars, as the tank in which this sample was stored experienced lower humidity levels. Solution resistances for STD3-2304-1 (Figure 3-65) averaged around 1.76 kΩ over all rebars due to its higher quality concrete, made possible by a lower w/c ratio and supplemental fly ash F.

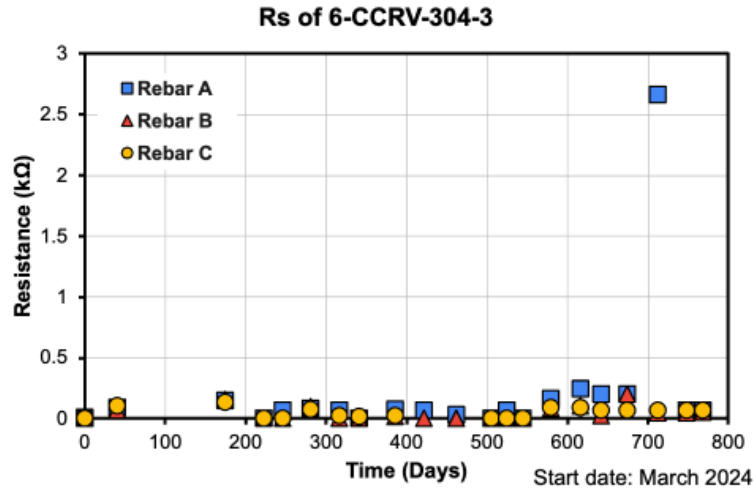


Figure 3-61. Solution resistance vs. time for 6-CCRV-304-3.

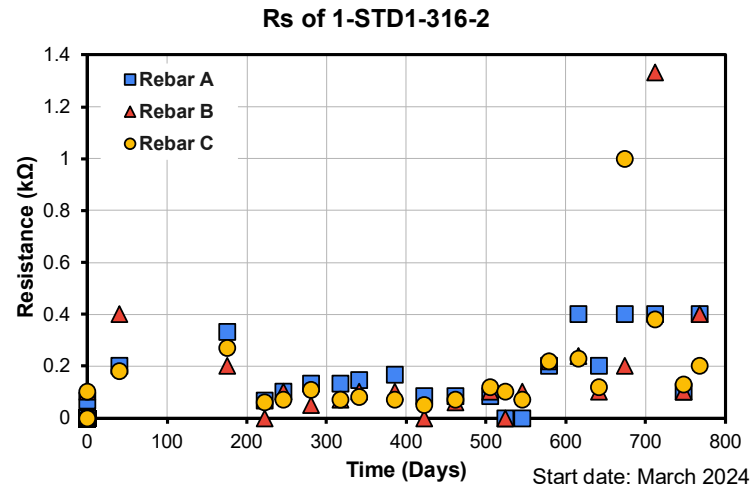


Figure 3-62. Solution resistance vs. time for 1-STD1-316-2.

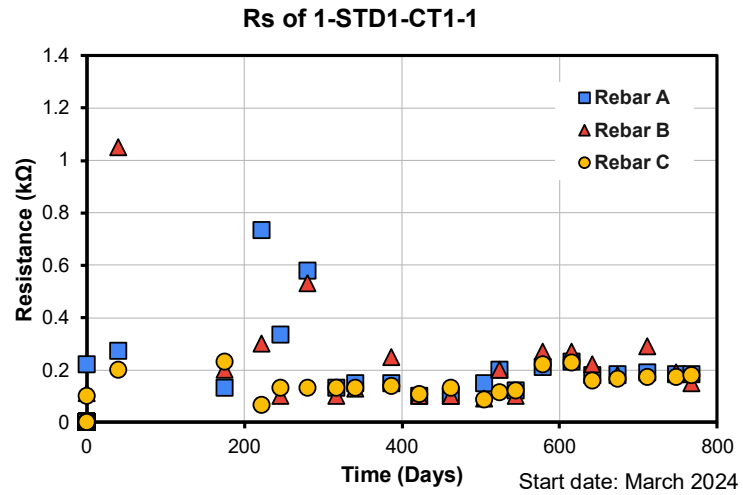


Figure 3-63. Solution resistance vs. time for 1-STD1-CT1-1.

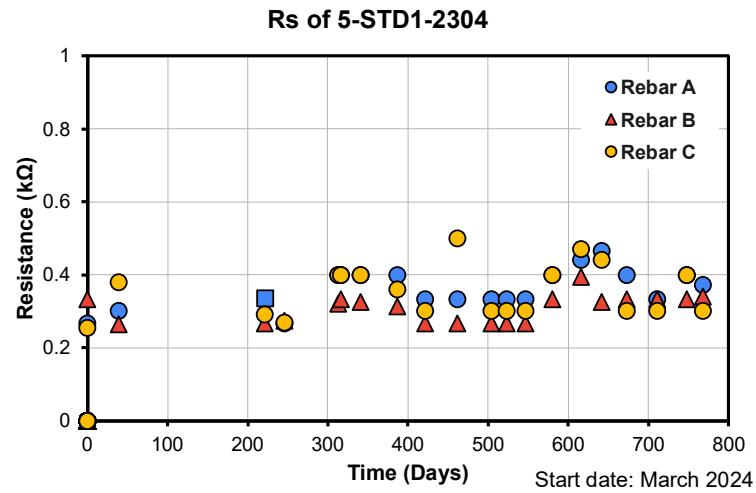


Figure 3-64. Solution resistance vs. time for 5-STD1-2304.

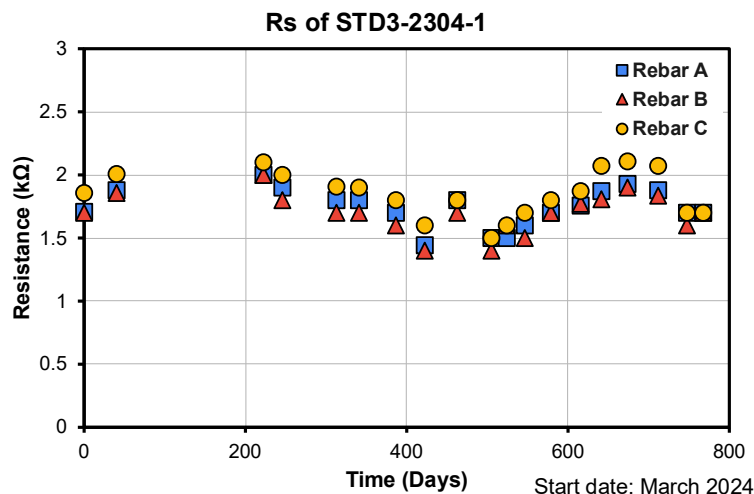


Figure 3-65. Solution resistance vs. time for STD3-2304-1.

3.3.3 Open Circuit Potentials from GP measurements

Two examples of open circuit potentials (i.e. corrosion potentials) vs. time as measured by the GP method are shown in Figure 3-66 and Figure 3-67. Sample 4-CCRV-3CR12-3 is presented first, demonstrating active corrosion with open circuit potentials averaging more negative than $-380 \text{ mV}_{\text{SCE}}$ ($-453 \text{ mV}_{\text{CSE}}$). Sample 6-STD2-304-2 is presented next, with open circuit potentials ranging between about $-120 \text{ mV}_{\text{SCE}}$ ($-193 \text{ mV}_{\text{CSE}}$) and $-10 \text{ mV}_{\text{SCE}}$ ($-83 \text{ mV}_{\text{CSE}}$). The open circuit potentials of most samples as measured with the GP method are comparable to their corrosion potentials as measured with the Gecor 8, after converting SCE to CSE.

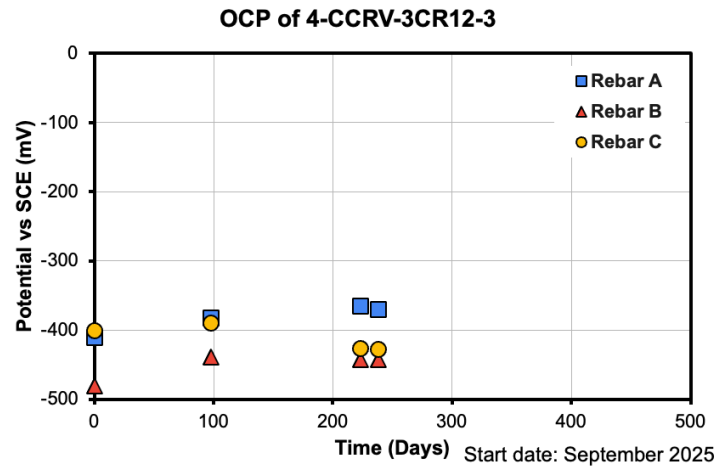


Figure 3-66. Open circuit potential vs. time for 4-CCRV-3CR12-3.

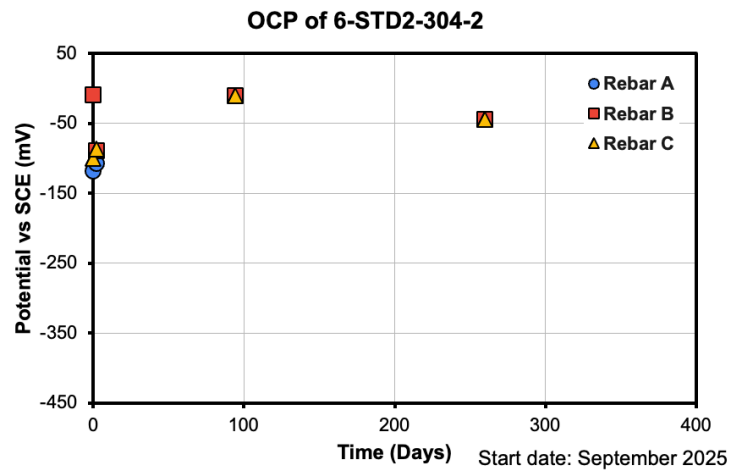


Figure 3-67. Open circuit potential vs. time for 6-STD2-304-2.

4 RESULTS – SAMPLES AT FDOT-SMO

4.1 BACKGROUND

G-109, Tombstone and 3-Bar Square samples were prepared at the same time as the 6-Bar simulated deck slab (SDS) samples that have been exposed at FAU [1]. The monitoring of the SDS samples is described in chapter 3. The G-109, Tombstone and 3-Bar square samples were kept at FDOT-SMO. The samples at FDOT-SMO that continue to be monitored, have been, in some cases, monitored for close to 7400 days. Most of the samples that continue to be monitored at FDOT-SMO contain the more resistant rebar alloys: 304, 316, 2304, and stainless clad rebars. A new set of Tombstone samples were prepared about >11 years ago; these Tombstone samples were reinforced with duplex LDX2101 and duplex 2304 rebars. At the start of this project, all Tombstones with duplex rebars continued to be monitored, as well as most of the Tombstone's samples with 304, 316 and clad rebars. A few samples remain for samples prepared with MMFX rebars and 3CR12 rebars that were cast between 2004 and 2006. FDOT-SMO considers the rebars in a sample to be active when a shift greater than 100 mV takes place and the macro-cell is greater than 5 μ A. Tombstone samples are not terminated unless a crack is observed and/or rust bleeds reach the sample surface.

To assess the condition of the samples at FDOT-SMO, FDOT-SMO provided FAU with several excel files. Three of these files contain sample and/or mix details. One file contained the details of the mixes (one of the tabs in that file described each mix composition) including mix names, the date the samples were cast and what type of samples were prepared for each mix and the type of rebar. Another file lists the different sample geometries names; in some cases, the names listed were re-named for the SDS samples at FAU. The third file lists the samples that were kept at FDOT-SMO and were not terminated (i.e., these are the samples that continue to be monitored). This excel file also lists the columns exposed at the field site (Crescent Beach). The table lists which samples remain for a given group and the current age with respect to when exposure initiated.

Additionally, FDOT-SMO provided the files that contain the data measured over time. Depending on the sample type, the file lists for each sample the rebar potentials and macro-cell currents that were measured. Some of the measurements stopped being made, for example, manual potential measurements (isolating each rebar), the total rebar (i.e., the interconnected rebars vs. a reference electrode in the solution) continue to be monitored on square columns and Tombstone samples. Selected plots were updated and are included in this chapter. An updated version of the measured data was provided to FAU during early Fall 2025. After inspecting the initial set of files (Fall 2024), a list of candidate samples was provided to FDOT-SMO for further inspection. FDOT-SMO conducted the inspection and, in some cases, a different sample from the same group was recommended for termination. The forensic analysis is presented in a different chapter.

4.2 EVALUATION OF ELECTROCHEMICAL CORROSION DATA

Three summary Excel files were prepared (one per type of sample) as part of Deliverable 2. The tables included both the samples that continue to be monitored and information about those terminated (and when). For those samples that continue to be monitored, the average total rebar potential over the most recent 100 to 200 days were tabulated potential (total rebar potential or interconnected rebar potential, this is the potential value that continues to be measured). For samples that have macro-cell current measurements, the table included the average macro-cell current over the 100 to 200 days selected. For samples terminated, the last total rebar potential value measured is included as well as the average total potential value over the last 200 days before stopping the measurements. The data files provided by FDOT-SMO were accessed to create the summary files. The summary files were included as part of deliverable 2 and no additional discussion of them will be included in this chapter.

Selected plots were updated for samples that continue to be monitored. This was done to visualize transitions that have taken place over the exposure period. By looking at the plots and gathered values, a list of samples that have not been terminated but appear to be corroding actively were identified. A visual inspection was requested and then carried out by FDOT-SMO on these samples. One of the goals was to identify if cracks were visible. For some of the Tombstone samples that appear to have active rebars, the potential value that continues to be measured (total/interconnected rebars with reference electrode in the solution) is indicative of active corrosion, but there was no way to know if there were cracks or corrosion products bleeding to the sample surface. The macro-cell currents continued to be measured, and the values typically appeared to be less than 30 μA on samples with active rebars. This is an indirect indication that corrosion is likely proceeding at a slow rate, when compared to the currents measured on samples that were terminated.

4.3 PLOTS FOR SELECTED TOMBSTONE SAMPLES

Four STD3-3CR12 Tombstone samples remained out of six. The total (interconnected) rebar potential was more negative than $-390 \text{ mV}_{\text{SCE}}$ on all four samples, but the average macro-cell current measured (over the 200 days range selected Fall 2024) - between rebar 1 and rebar 2&3 or between rebars 2&3 and rebar 3 - was less than 30 μA . Figure 4-1 shows a plot on how the rebar potential and interconnected rebar potential evolved on sample STD3-3CR12-A, as well as the macro-cell current values measured. The last total rebar potential in the plot is around $-400 \text{ mV}_{\text{SCE}}$, whereas the macro-cell current for rebar 3 to rebars 1&2 is around +20 μA and the current measured between Rebar 2 and rebars 2&3 is around -30 μA . Figure 4-2 shows an updated plot for the data shown in Figure 1 that includes additional measurements. Upon inspection it was found that STD3-3CR12-E was the Tombstone sample to terminate. Figure 4-3 shows the plot for sample STD3-3CR12-E, a similar trend as the one described for Figure 4-1 which can be observed. The total potential in sample STD3-3CR12-E was more negative and had more potential transients than sample A. There are companion current transients for the currents measured between rebar 3 and rebar 1&2.

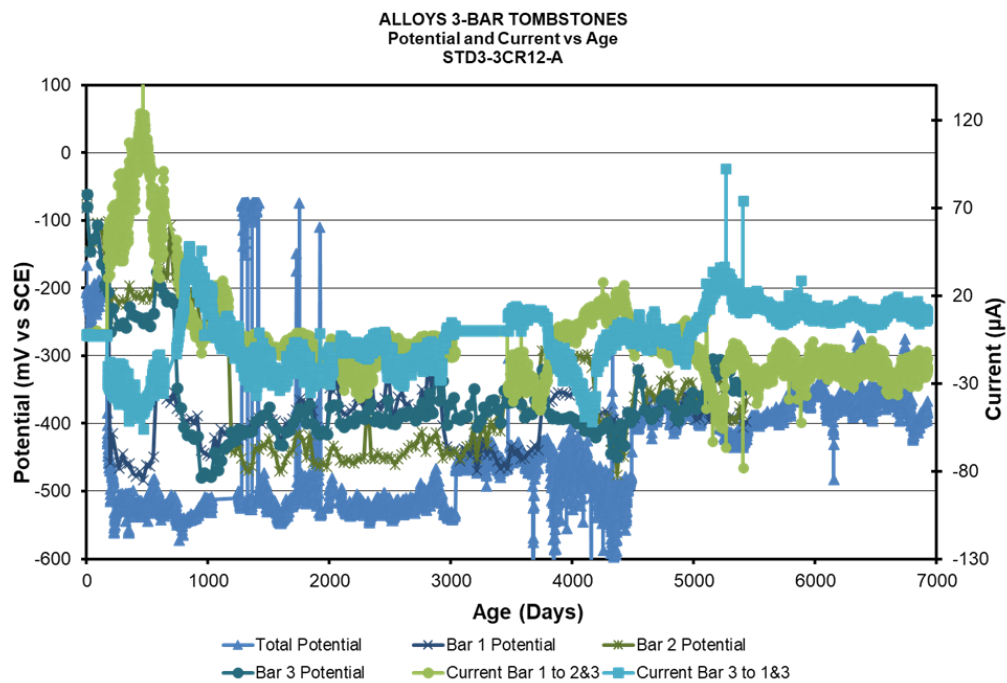


Figure 4-1. Potential and current vs. Age measured on sample STD3-3CR12-A up to Spring 2024.

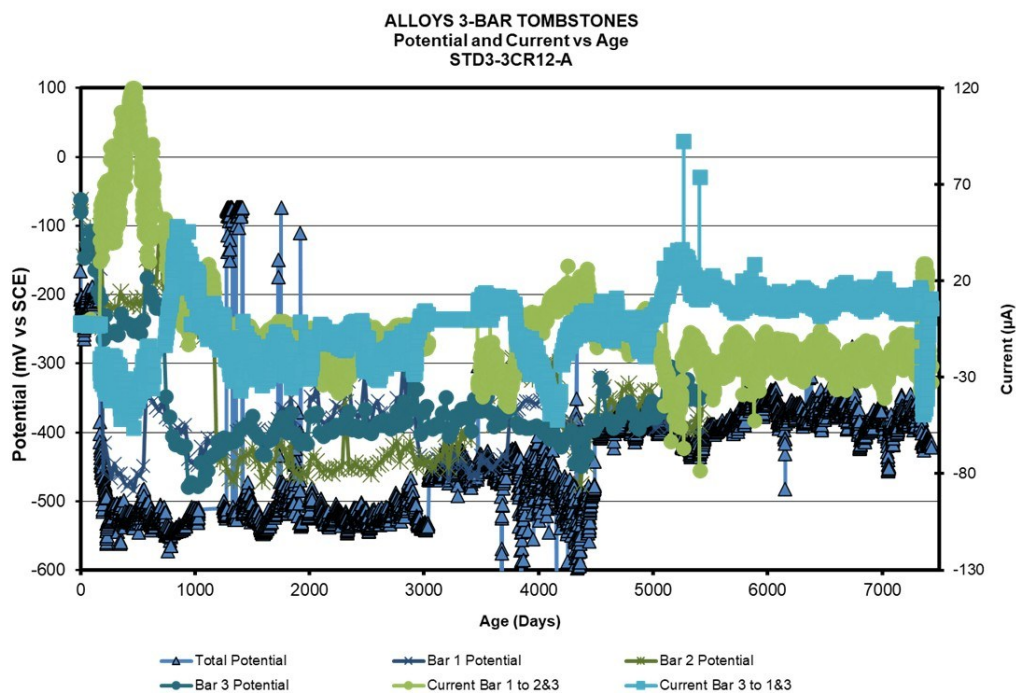
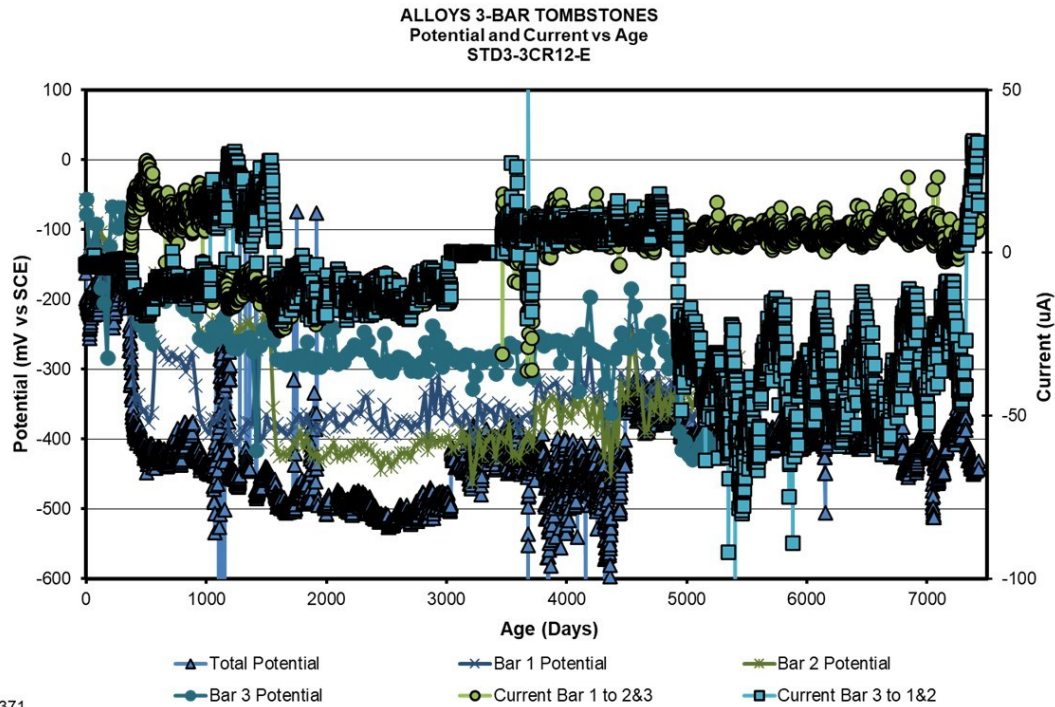


Figure 4-2. Potential and current vs. age measured on sample STD3-3CR12-A up to Fall 2025.



371

Figure 4-3. Potential and current vs. age measured on sample STD3-3CR12-E up to Fall 2025.

One Tombstone STD3-MMFX sample continued to be monitored (the other five had been terminated), the average rebar potential of this Tombstone sample is $-411 \text{ mV}_{\text{SCE}}$, with macro-cell current around $-10 \mu\text{A}$ for rebar 3 to rebar 1&2. There were several excursions to values as negative as $-50 \mu\text{A}$. Figure 4-4 shows the total potential and currents measured on STD3-MMFX-B. STD3-MMF-B was chosen to be terminated.

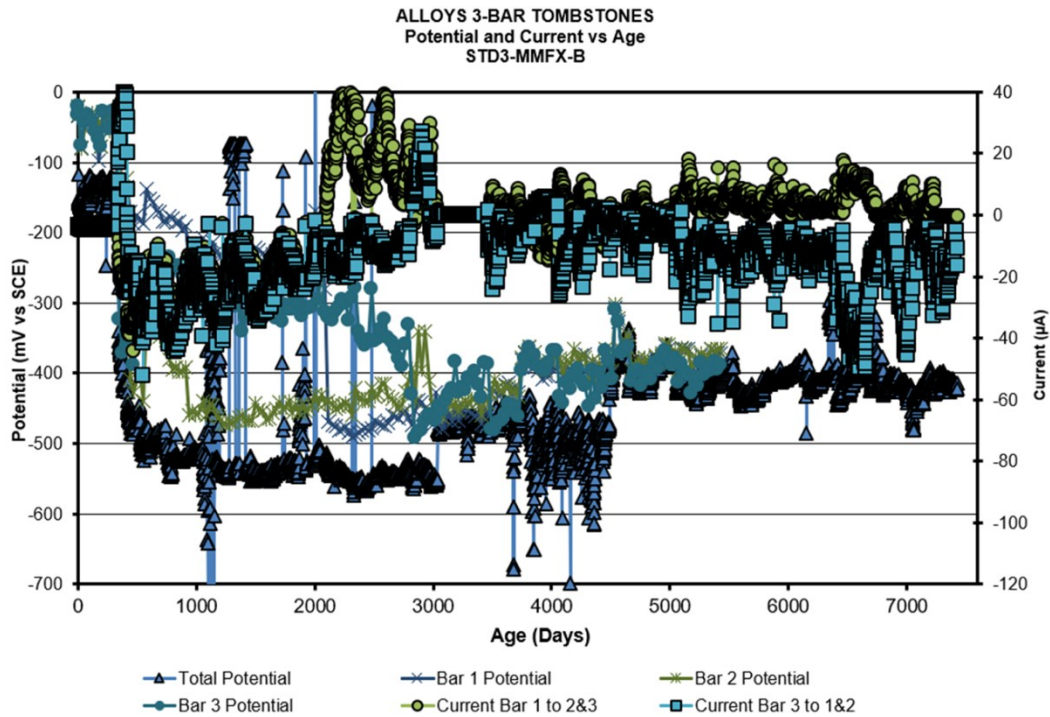


Figure 4-4. Potential and current vs. age measured on sample STD3-MMFX-B up to Fall 2025.

For Tombstone samples with 304 rebars, at least one rebar per sample appears to have experienced a transient to more active rebar potential values. In many cases this was rebar 2. No Tombstone sample with 304 rebar had been terminated. Sample BENT-304-C Tombstone was chosen for termination as part of this project. Figure 4-5 shows the potential vs. time and current vs. time for this sample. The total potential seems to indicate that there were more potential transients than what each individual rebar (manually measured) experienced. The manually measured rebar values stopped being measured at around day 4800 of monitoring. The total potential transients observed might be indicative of repassivation taking place when the total potential reached noble values (more positive than $-100 \text{ mV}_{\text{SCE}}$), but the transients in the opposite direction indicate that a new corroding or that a dormant site became active. The macro-cell current magnitude seems to indicate low activity. The positive macro-cell current reached $5 \text{ } \mu\text{A}$, whereas the negative macro-cell current reached values as negative as $-10 \text{ } \mu\text{A}$, but many readings were close to zero μA .

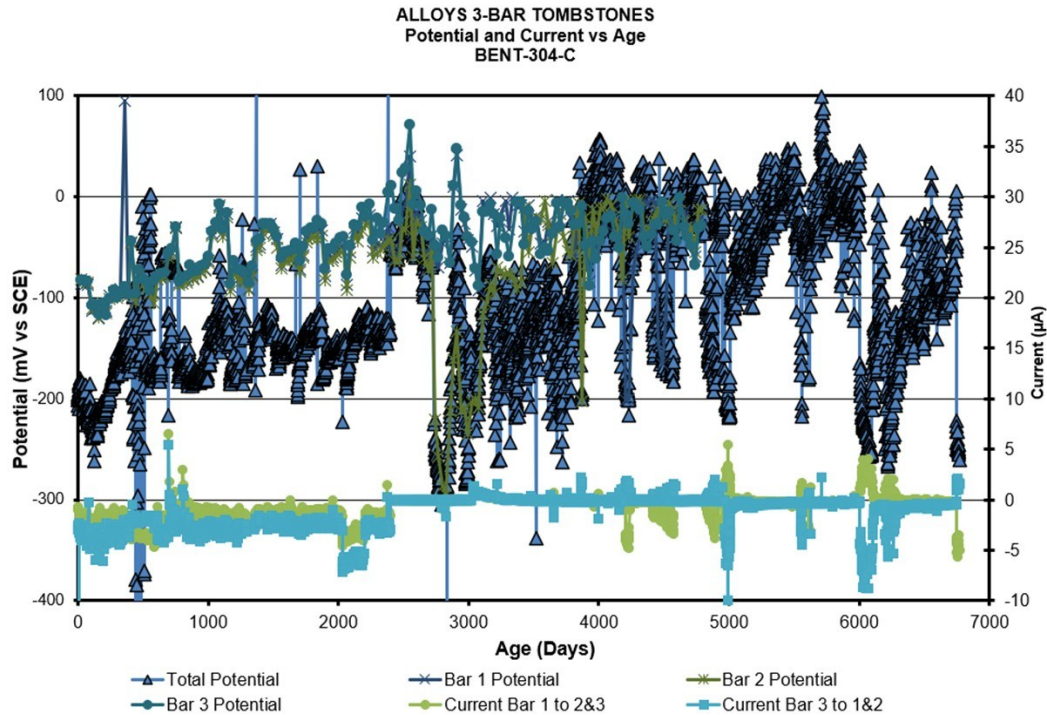


Figure 4-5. Potential and current vs. age measured on sample BENT-304-C up to Fall 2025.

All six STD3-SMI Tombstone samples have average rebar potentials more negative than $-190 \text{ mV}_{\text{SCE}}$ (with two of these samples having average total rebar potential values more negative than $-300 \text{ mV}_{\text{SCE}}$), the macro-cell current on these samples was less than $20 \text{ } \mu\text{A}$ (with most measured value less than $8 \text{ } \mu\text{A}$). Bar 1 became active first on samples C and B, Bar 2 became active first on samples A, E and F, whereas Bar 3 became active first on sample D. Sample STD3-SMI-D was chosen for termination. Figure 4-6 shows the rebar and current vs. age. Two ELEV-SMI Tombstone samples and one BENT-SMI samples similarly have average rebar potential slightly more negative than $-190 \text{ mV}_{\text{SCE}}$. All ELEV-SMI and BENT SMI had at least one rebar that became active. No rebar of the three STD2-SMI samples became active.

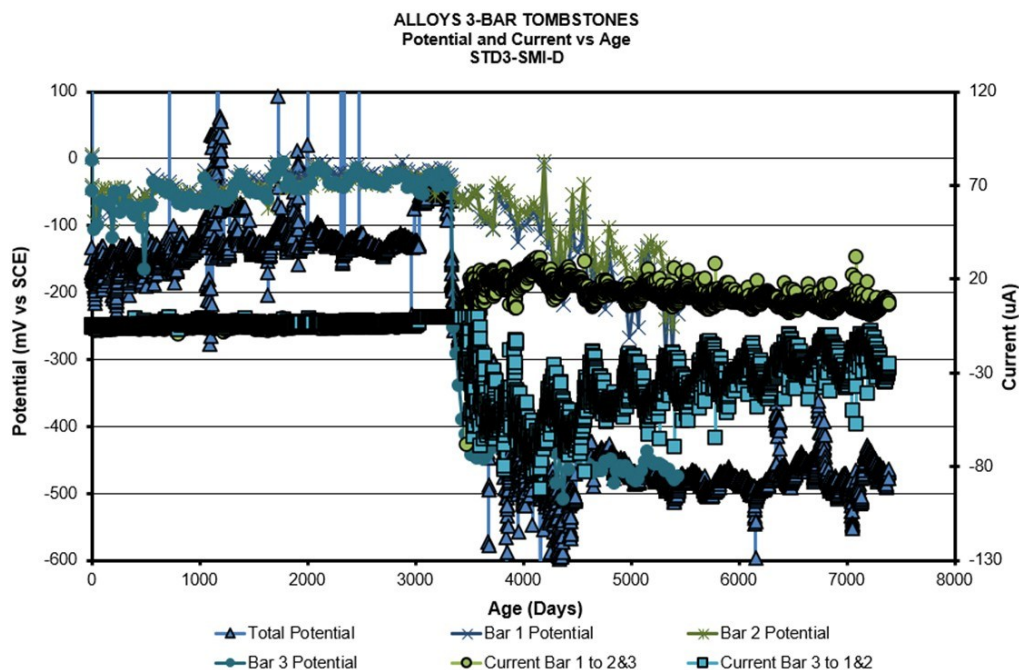


Figure 4-6. Potential and current vs. age measured on sample STD3-SMI-D up to July 2025.

For the more recently prepared Tombstone samples with duplex stainless steel rebars. Figure 4-7 shows the total rebar potential and current vs. time for sample STD3-2304-B. Tombstone sample STD3-2304-B with 2304 rebar has an average total rebar potential of $-325 \text{ mV}_{\text{SCE}}$, and modest macro-cell current values. The transition to more negative total rebar potential values on this sample took place after 2000 days of exposure. The other four Tombstone samples with 2304 rebars do not seem to be corroding based on the total rebar potential.

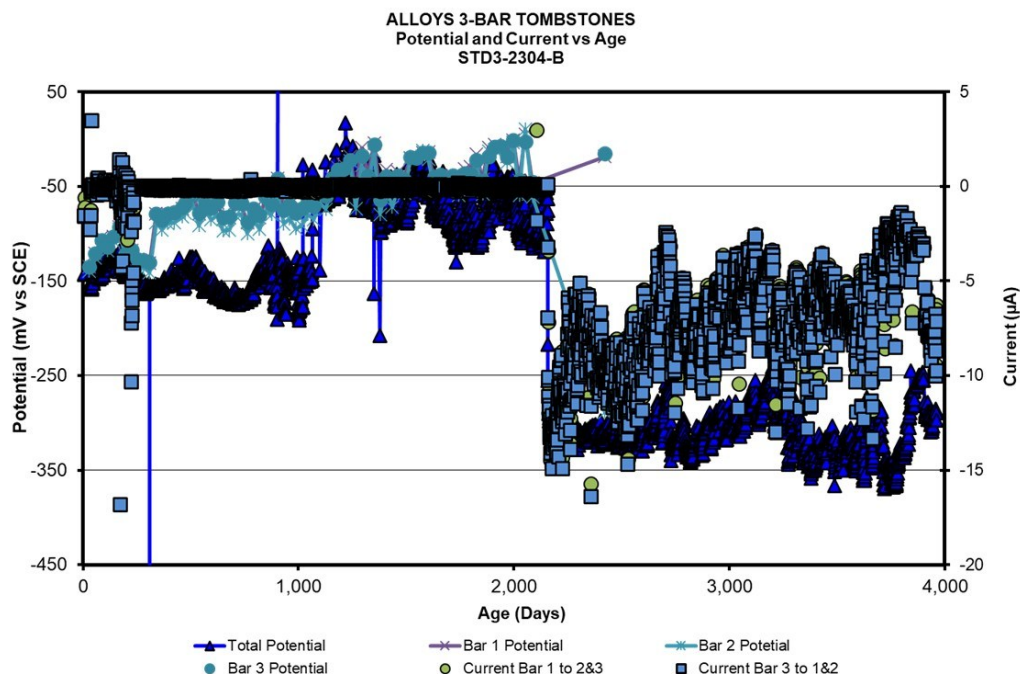


Figure 4-7. Potential and current vs. Age measured on Tombstone sample STD3-2304-B.

All new set Tombstone samples with 2101LDX rebar have total average rebar potential more negative than $-350 \text{ mV}_{\text{SCE}}$. For the new set of Tombstone samples with 2101LDX rebars, the total potential transitioned to $-300 \text{ mV}_{\text{SCE}}$ (total/interconnected) or more negative between 1000 and 1400 days for samples A, B and E. The rebars in sample 2101-C transitioned to $\sim -300 \text{ mV}_{\text{SCE}}$ after 3000 days and rebars in sample D transitioned to active values at around 200 days. All samples have reached total rebar potential of around $-400 \text{ mV}_{\text{SCE}}$. The measured macro-cell current values are less than $50 \text{ } \mu\text{A}$ for most rebars (except sample E rebar 3 to 1&2 with a value of $-70 \text{ } \mu\text{A}$). Figure 4-8 shows the total rebar potential and current measured on sample STD3-2101-B. In this sample, Bar 3 is the rebar that seems to drive the total potential value after Bar 3 transitioned to more negative rebar potential values. Before all rebars contributed to the total potential value (i.e., all rebars had similar noble potential), Rebar 3 activated first for samples A and B, Rebar 2 activated first for samples C and D and Rebar 1 for sample E (but Rebar 2 became active soon after). Sample STD3-2101-B was the sample selected for termination.

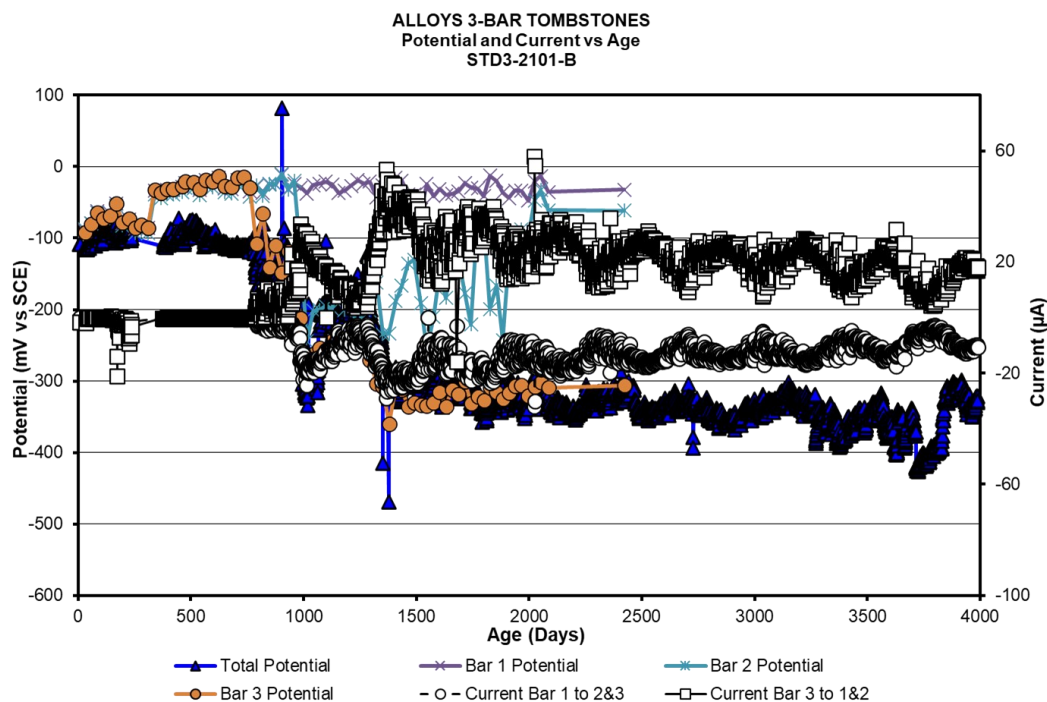


Figure 4-8. Potential and current vs. Age measured on Tombstone sample STD3-2101-B.

The other samples that continue (from the other groups) to be monitored that were not mentioned in here (i.e., samples with 316 rebars) have total potential values nobler than $-100 \text{ mV}_{\text{SCE}}$ and small measured currents (less than $1 \text{ } \mu\text{A}$). No rebar on the Tombstone samples prepared with 316 rebars appear to be active, i.e., no transient in measured potential has taken place.

4.4 3-BAR SQUARE SAMPLES

There are several 3-Bar square samples with 304(316) and 316 rebars from several sets (i.e., of several rebar geometries and compositions), none of the rebars in these 3-Bar square samples with these rebar types seem to be corroding based on total potential (as per the average potential over the last 100 days available) or macro-cell current (less than $1 \text{ } \mu\text{A}$ over the last 200 days with values available). One sample remains with MMFX rebars for group ELEV-MMFX. Figure 4-9 shows how the potential and current evolved over the monitored period for 3-Bar square sample ELEV-MMFX-A. The plot shows that the total rebar potential is more negative than $-400 \text{ mV}_{\text{SCE}}$ and with macro-cell current of approximately $10 \text{ } \mu\text{A}$. The last sample with 3CR12 rebar was terminated after 5000 days, corresponding to sample STD1-3CR12-F with an average total potential of $-400 \text{ mV}_{\text{SCE}}$ and macro-cell current of $\sim 30 \text{ } \mu\text{A}$. No sample with 2101 rebars remains, and no 3-Bar square sample was prepared with 2101LDX or 2304 rebars.

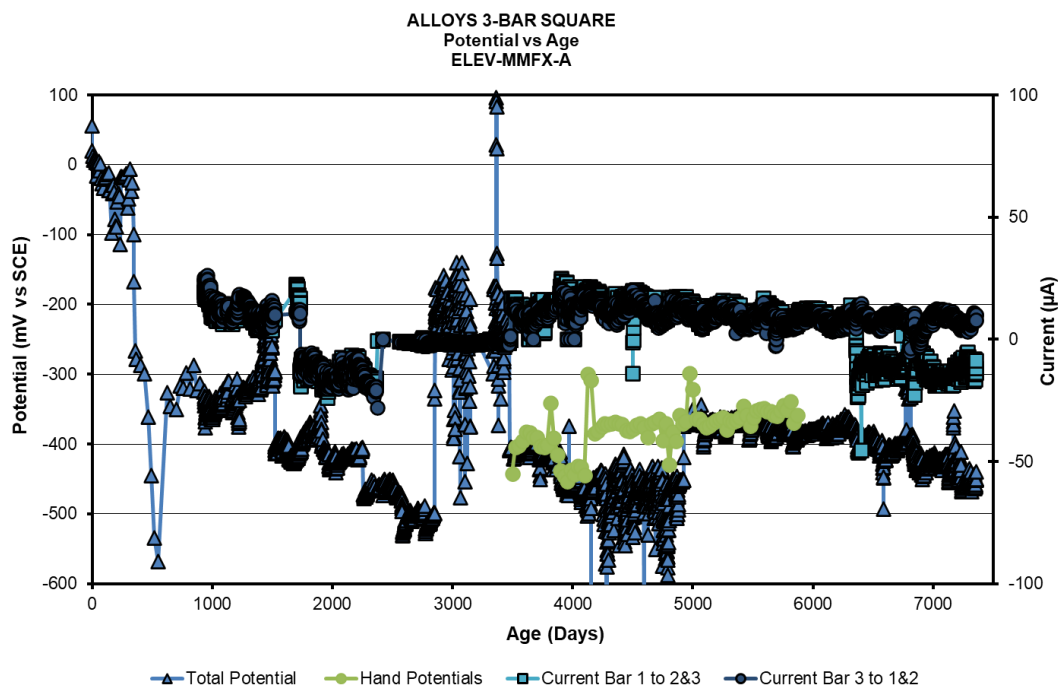


Figure 4-9. Potential and current vs. Age measured on 3-Bar square sample ELEV-MMFX-A.

4.5 G109 SAMPLES

Most of the samples that continue to be monitored contain either clad rebar, 304(316), 316 or 304 rebars for a variety of conditions and compositions prepared. A few of the samples with clad rebars appear to be active. Rebar potential drifted to more negative values on a few samples with 316 rebars, for example ARWB-316-C has average rebar potential ~ -213 mV_{SCE}, but very small current is being measured across the shunt resistor. After inspection and review of the recent measurements sample UBDB-SMI-B was chosen for termination.

4.6 TERMINATED SAMPLES

Upon inspection at FDOT-SMO and discussion with FAU the following samples, listed in Table 4-1, were selected for termination. A different chapter includes the forensic results on the terminated samples that were exposed at FDOT-SMO.

Table 4-1. FDOT-SMO samples selected for termination.

Tombstone	3-Bar Square	G109
STD3-2101-B	ELEV-MMFX-A	UBDB-SMI-B
STD3-2304-B		
BENT-304-C		
STD3-3CR12-E		
STD3-SMI-D		
STD3-MMFX-B		

5 RESULTS – CRESCENT BEACH

5.1 SURFACE CONDITIONS OF COLUMNS

During the October 2024 and the September 2025 visits to the Crescent Beach Field Site, the surfaces of each column were assessed for cracks and corrosion. The focus was on the columns with intermediate CRAs, i.e. MMFX, 3CR12, and 2101. Each alloy has three columns, denoted as A, B, and C. Figures Figure 5-1 through Figure 5-9 depict most of the column surfaces for MMFX, 3CR12, and 2101 in October 2024. For most of the columns, diagrams of crack length and location were prepared and were included in Deliverable 3. Figure 5-10 shows a comparison of a portion of 2101 column C in October 2024 versus September 2025.

5.1.1 Columns with MMFX

Three surfaces showed cracks for Column A with MMFX rebars, shown in Figure 5-1. In October 2024, a core was obtained that included a rebar segment on the west face. The southern face showed no cracks. Similarly, three surfaces showed cracks for Column B with MMFX rebars (Figure 5-2). The east face had no visible cracks. For MMFX Column C, three surfaces showed cracks (Figure 5-3). Like Column B, the east face had no visible cracks.

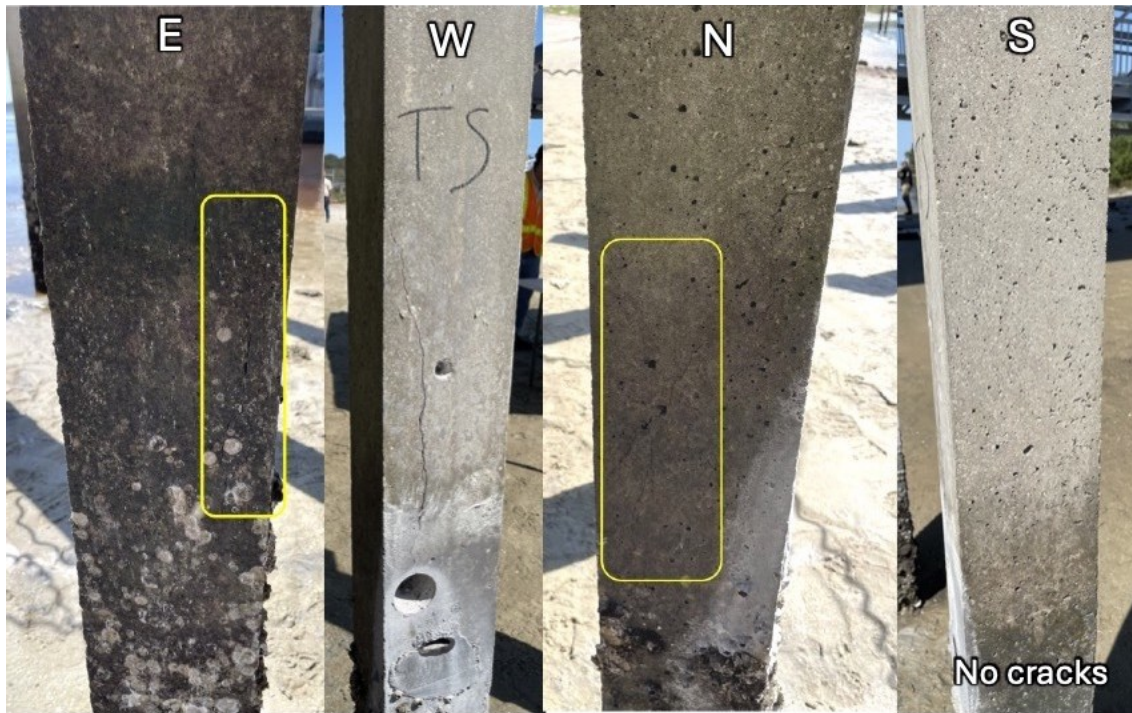


Figure 5-1. Picture showing surface conditions of east, west, north, and south faces of column MMFX-A.

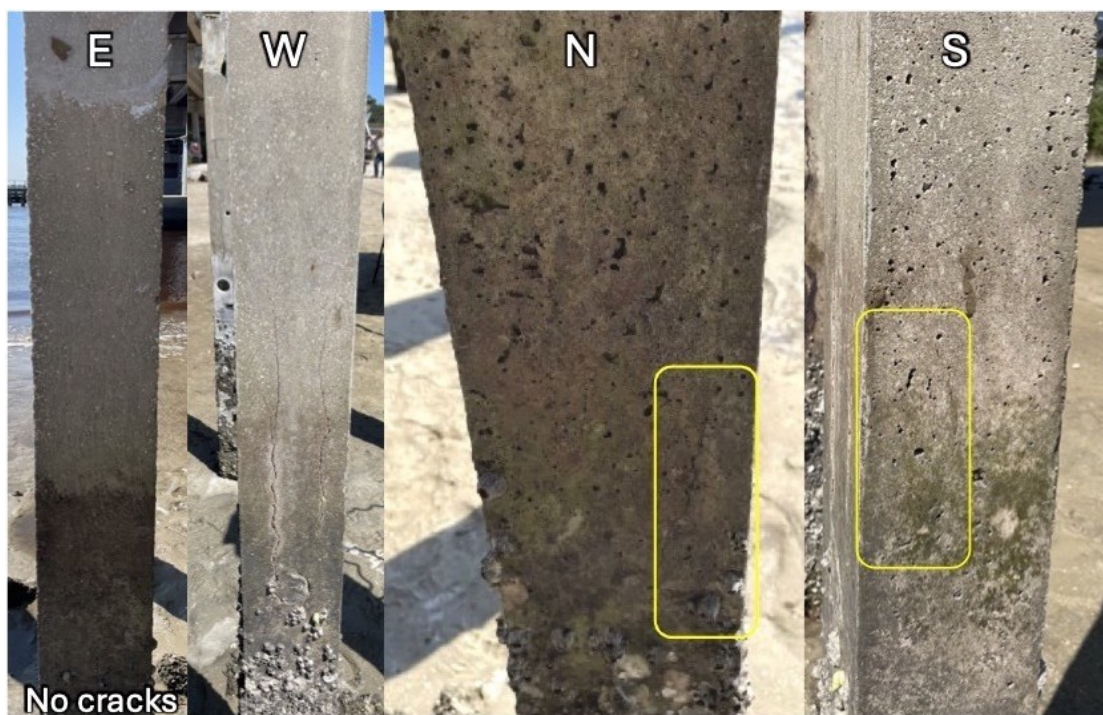


Figure 5-2. Picture showing surface conditions of east, west, north, and south faces of column MMFX-B.

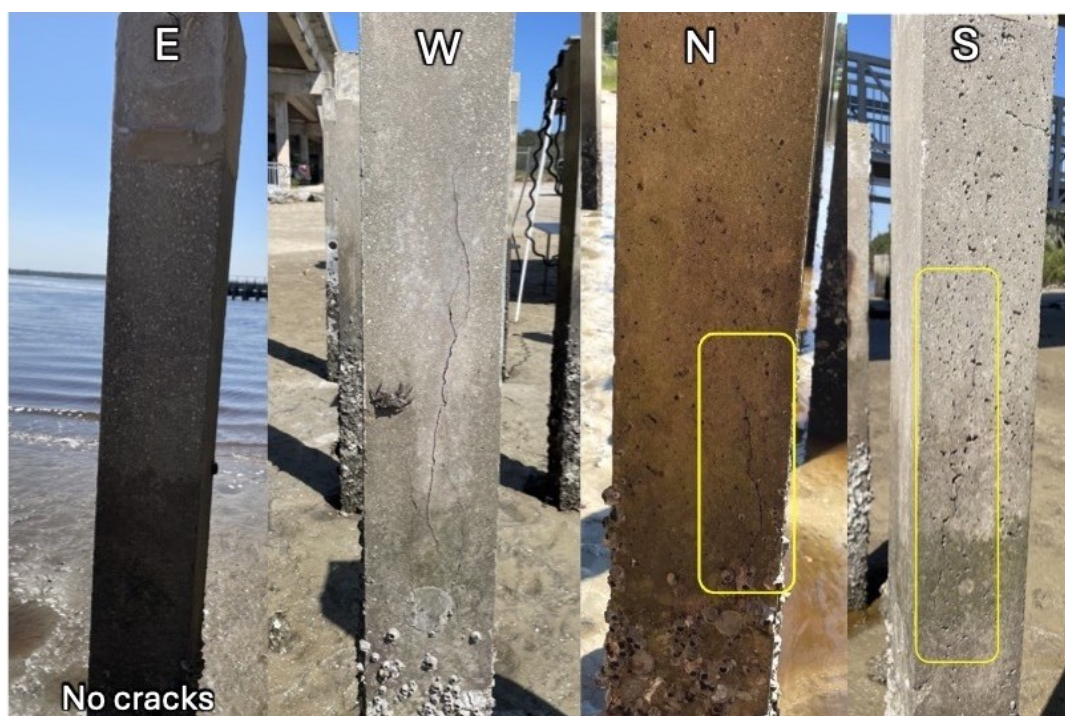


Figure 5-3. Picture showing surface conditions of east, west, north, and south faces of column MMFX-C.

5.1.2 Columns with 3CR12

Most 3CR12 column surfaces showed cracks. All four surfaces in Column A had cracks (Figure 5-4). Cores were obtained by FDOT-SMO from Column A on a different date or after FAU had left the site. No rebars were included in the cores obtained.

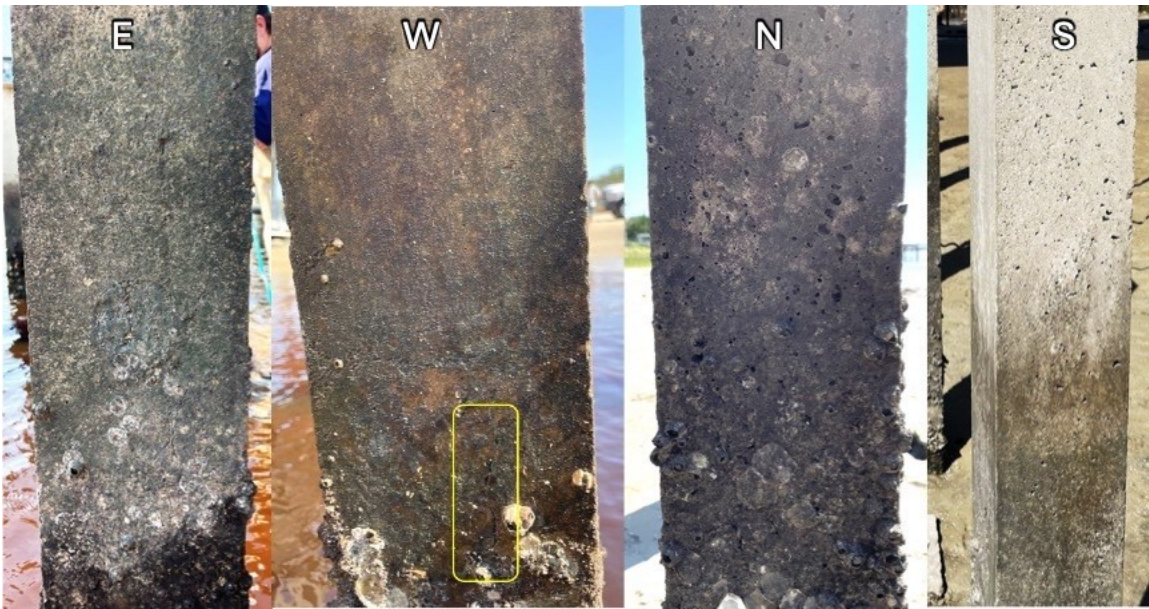


Figure 5-4. Picture showing cracks on the surface of each face of column 3CR12-A.

Only two column surfaces in Column B (Figure 5-5) showed signs of cracks: the west face and the south face. Two cores were obtained from Column B, but no rebar was removed. One of the cores reached the rebar. Only a small section of the rebar trace was observed in the core, and no corrosion markings were transferred to the concrete. Three surfaces in Column C showed cracks along the rebar length (Figure 5-6). Two cores were obtained from Column C: one 6" above water line and one at the water line. One of the two cores reached the rebar; no corrosion markings were transferred to the rebar trace.

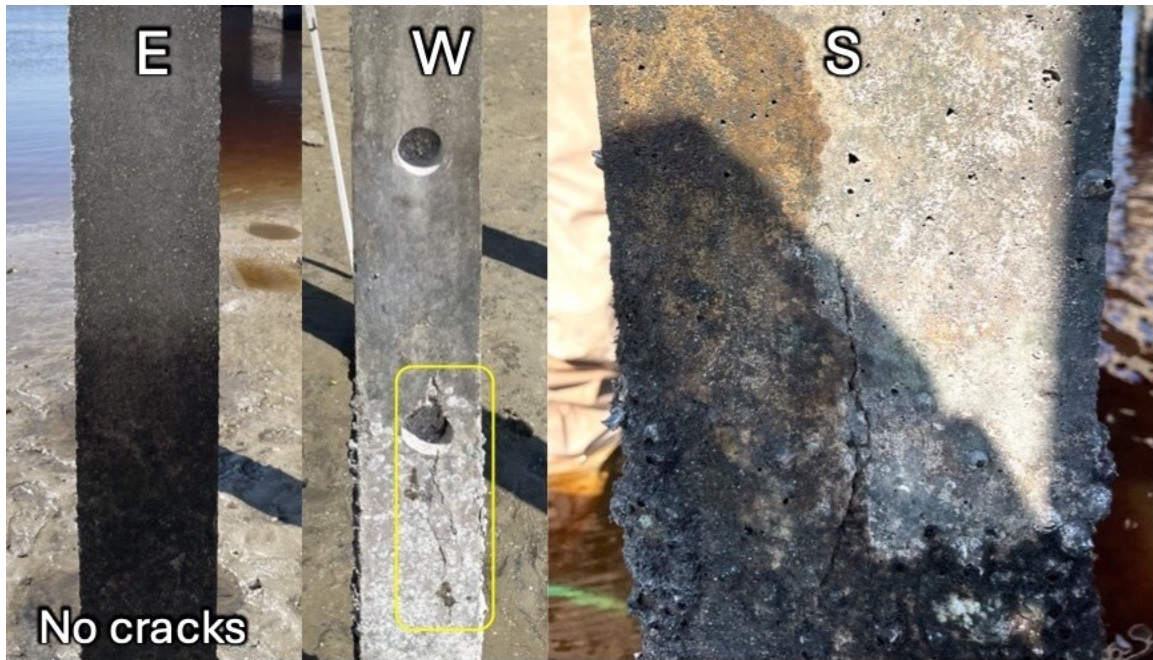


Figure 5-5. Picture showing surface conditions of east, west, and south faces of column 3CR12-B. North face not pictured.

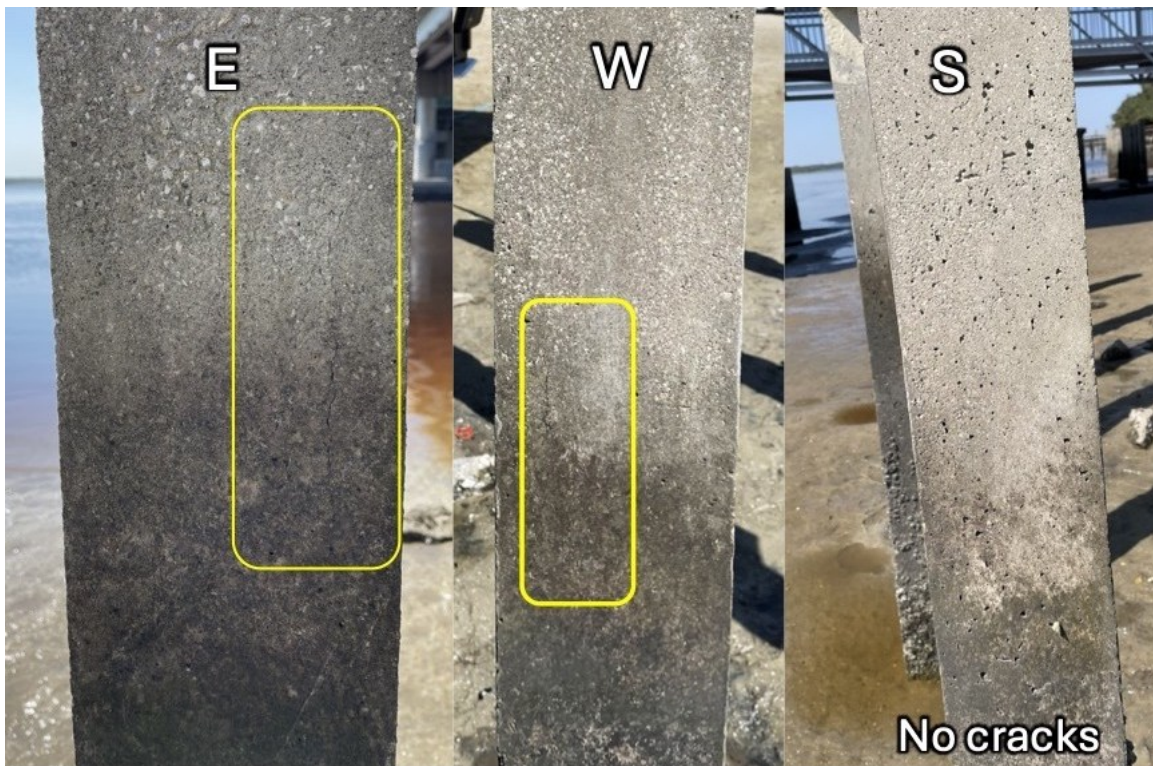


Figure 5-6. Picture showing surface conditions of east, west, and south faces of column 3CR12-C. North face not pictured.

5.1.3 Columns with 2101

Each surface of every column with 2101 reinforcement showed cracks. In some cases, cracks extended along two rebar lengths on the same surface. Cores were obtained by FDOT-SMO from columns A and B along a crack. In both cases, a rebar segment was removed.

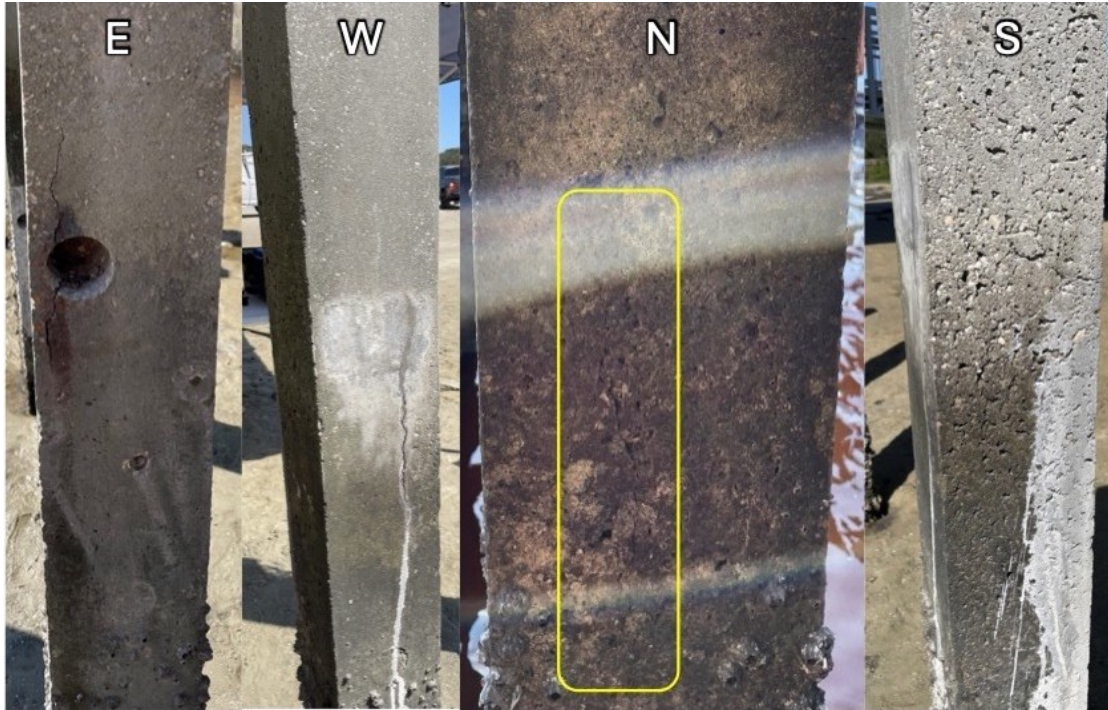


Figure 5-7. Picture showing cracks on the surface of each face of column 2101-A.

Figure 5-7 shows the surface condition for column 2101-A, three surfaces (E, W, N) showed cracks. Several surfaces on columns 2101-B and 2101-C had at least two visible cracks along the lengths of two rebars. The west and north faces of 2101-B, shown in Figure 5-8, exemplifies this. The east and west faces of 2101-C in Figure 5-9 also exhibit several cracks along rebar lengths.

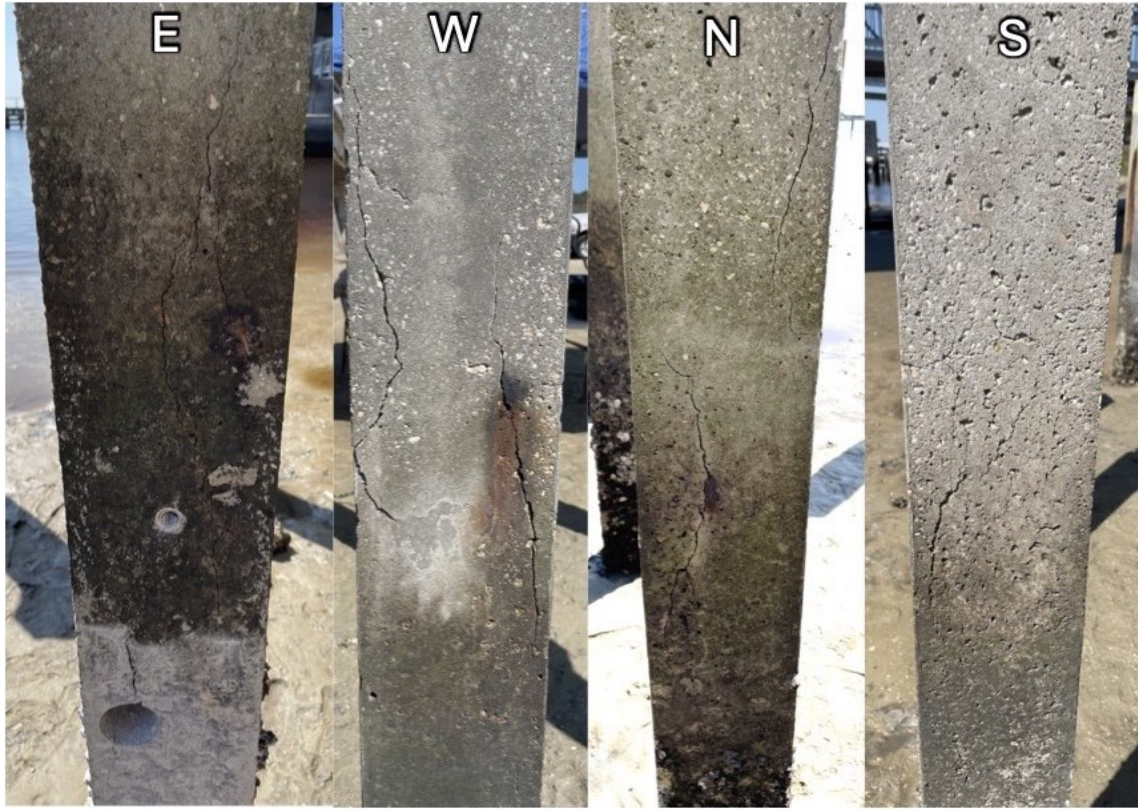


Figure 5-8. Picture showing cracks on the surface of each face of column 2101-B.



Figure 5-9. Picture showing cracks on the surface of each face of column 2101-C.

Column 2101-C north face experienced spalling due to corrosion of the reinforcement between the October 2024 and September 2025 visits. A large crack was visible in October 2024, as shown in Figure 5-10 on the left. By September 2025, the concrete had spalled in the same location, exposing corrosion products from the embedded rebar, as seen in Figure 5-10 on the right.



Figure 5-10. Picture showing north face of 2101-C in October 2024 (left) and September 2025 (right).

5.2 POTENTIALS

5.2.1 Rebar Potential Over Time

This section presents rebar potential vs. time for selected columns. The plots were prepared from the data provided by FDOT-SMO. Figure 5-11 shows column BB-A, with conventional black rebar. All rebars show potential values more negative than $-400 \text{ mV}_{\text{CSE}}$, this in part could be due to the low oxygen availability for the section on the ground that likely is wet most of the time. Figure 5-12 shows the rebar potential evolution for column MMFX-Column A. Similar transition to values more negative than $-400 \text{ mV}_{\text{CSE}}$ are also observed. Figure 5-13 shows how the 2101 rebar potential evolved, in this case the transition to values more negative than $-400 \text{ mV}_{\text{CSE}}$ were observed after 500 days. Figure 5-14 shows how the 3CR12 rebars embedded in column C evolved with time. The rebar potential reach values as negative as $-500 \text{ mV}_{\text{CSE}}$ within a short period of time. LPR measurements not included in here indicated that the corrosion rate was moderate during the period shown. Figure 5-15 shows column A with 304 rebars, the rebar potential in this column ranged between $-200 \text{ mV}_{\text{CSE}}$ and $-100 \text{ mV}_{\text{CSE}}$. Figure 5-16 (Column A)

and Figure 5-17 (Column C) show plots on how the rebar potential evolved for columns with 316 rebars. In column A the rebar potential ranged between $-300 \text{ mV}_{\text{CSE}}$ and $-150 \text{ mV}_{\text{CSE}}$, whereas the rebar potential values in column C transition to values that ranged between $-300 \text{ mV}_{\text{CSE}}$ and $-500 \text{ mV}_{\text{CSE}}$. Column C with 316 was damaged during placement at the site and the measured values are likely due to the rebars becoming in contact with seawater shortly after deployment. It is known that 316 suffers pitting corrosion when immersed in seawater.

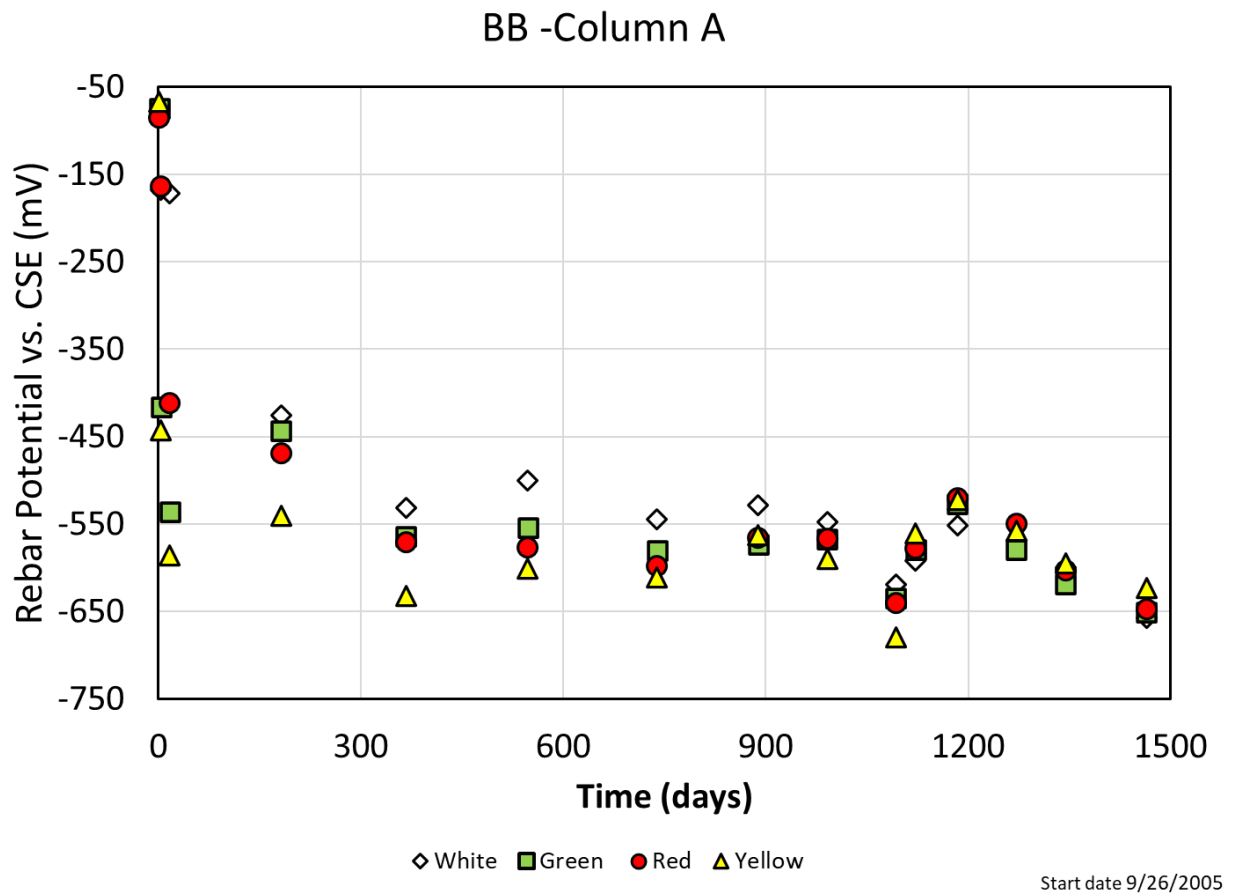


Figure 5-11. Plot showing the potential evolution for black bars embedded in BB column A.

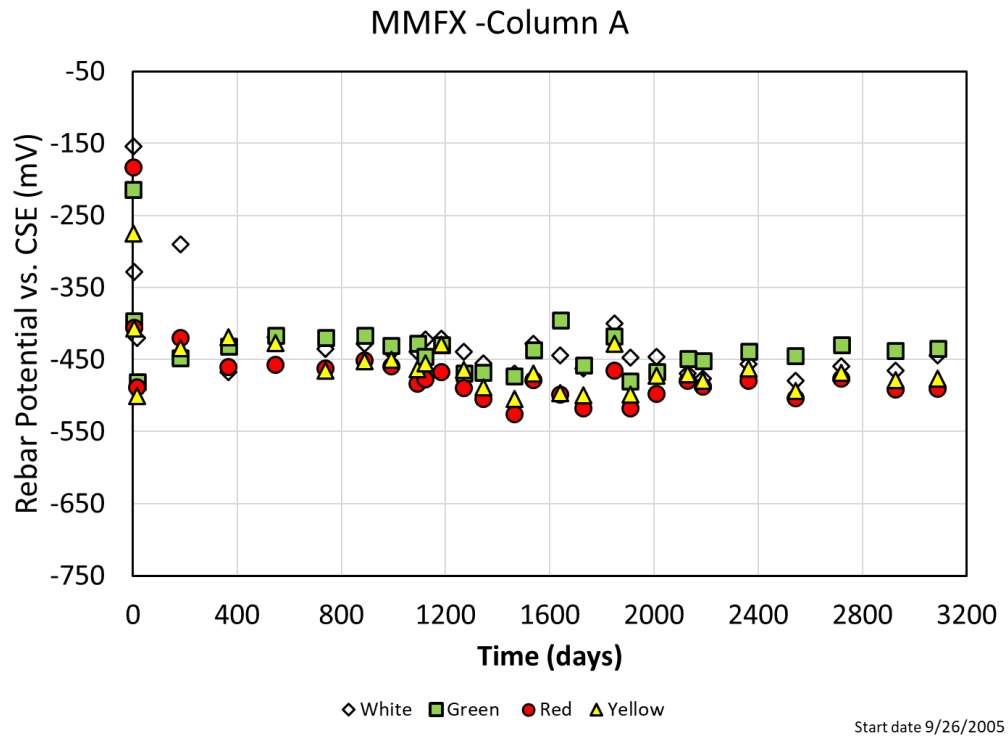


Figure 5-12. Plot showing the potential evolution for MMFX rebars embedded in MMFX column A.

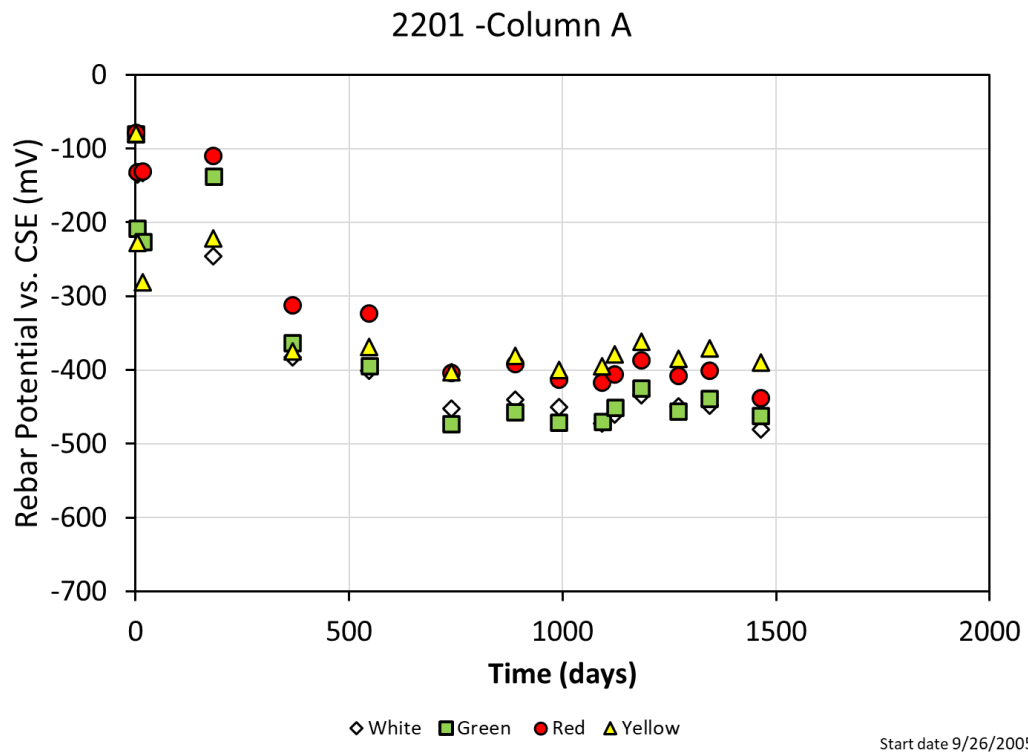


Figure 5-13. Plot showing the potential evolution for 2101 rebars embedded in 2101 column A.

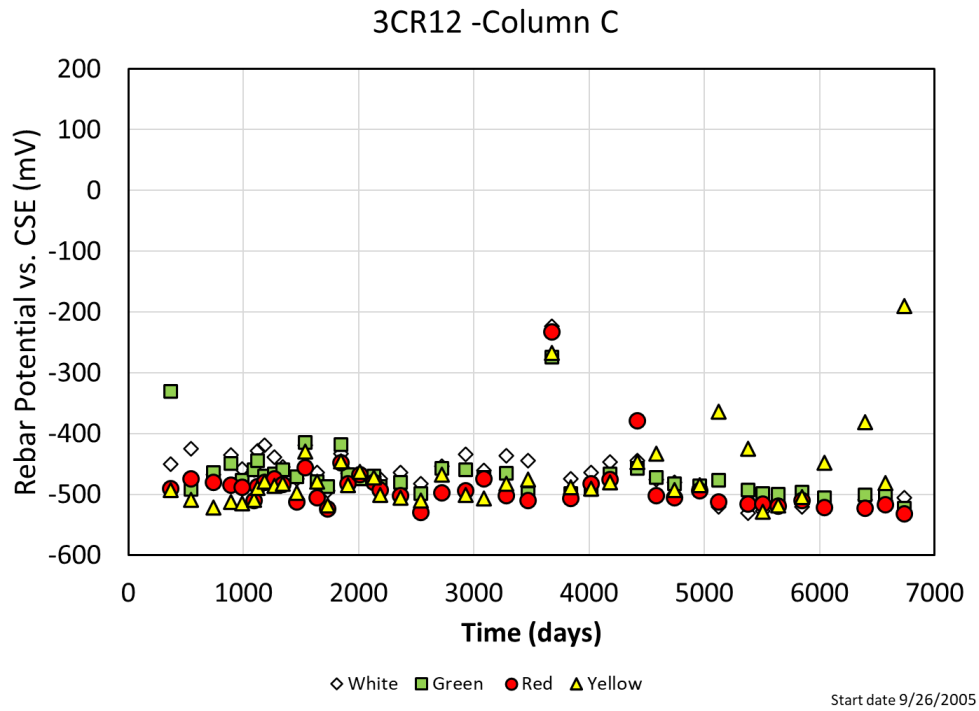


Figure 5-14. Plot showing the potential evolution for 3CR12 rebars embedded in 3CR12 column C.

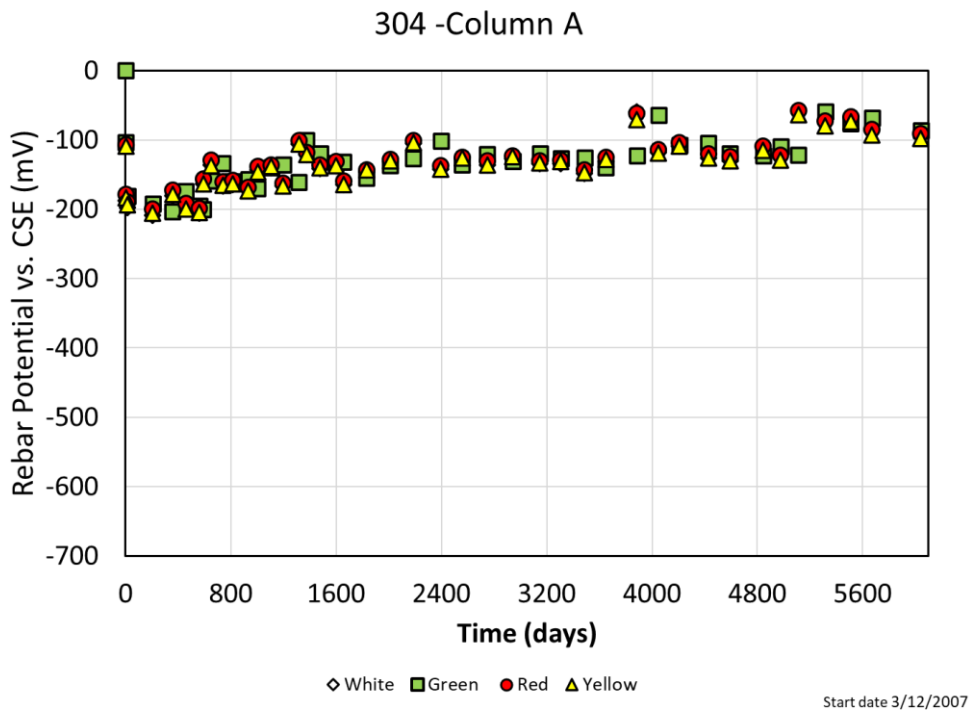


Figure 5-15. Plot showing the potential evolution for 304 rebars embedded in 304 column A.

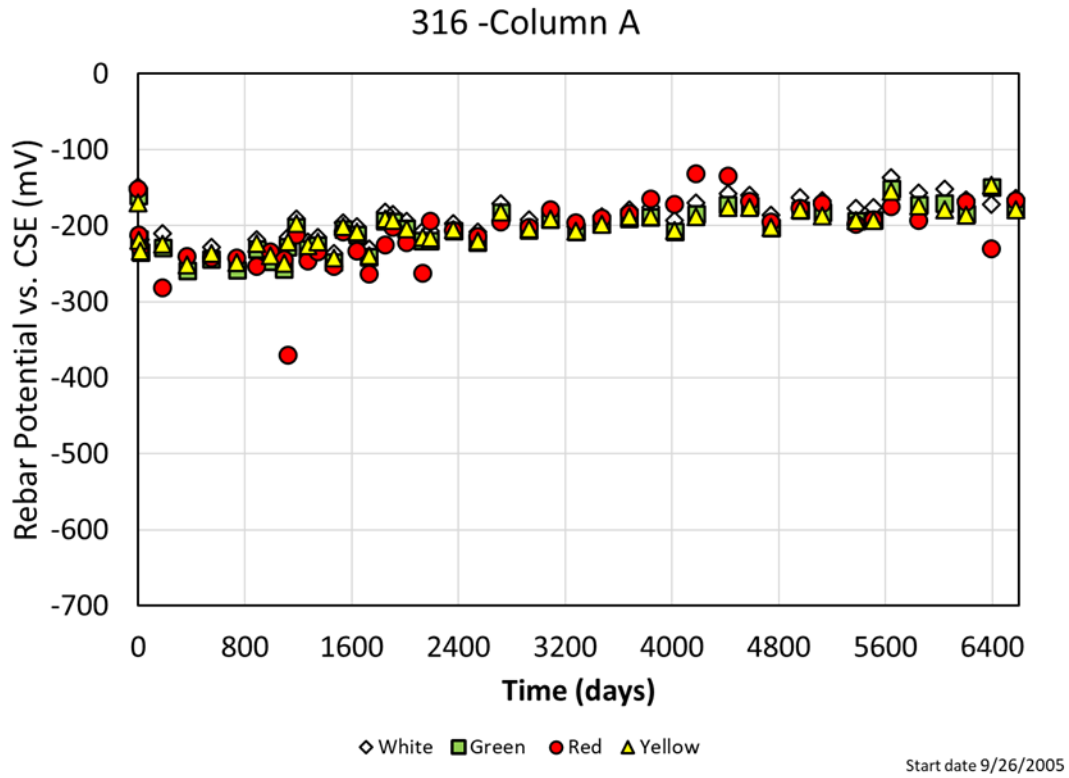


Figure 5-16. Plot showing the potential evolution for 316 rebar embedded in 316 column A.

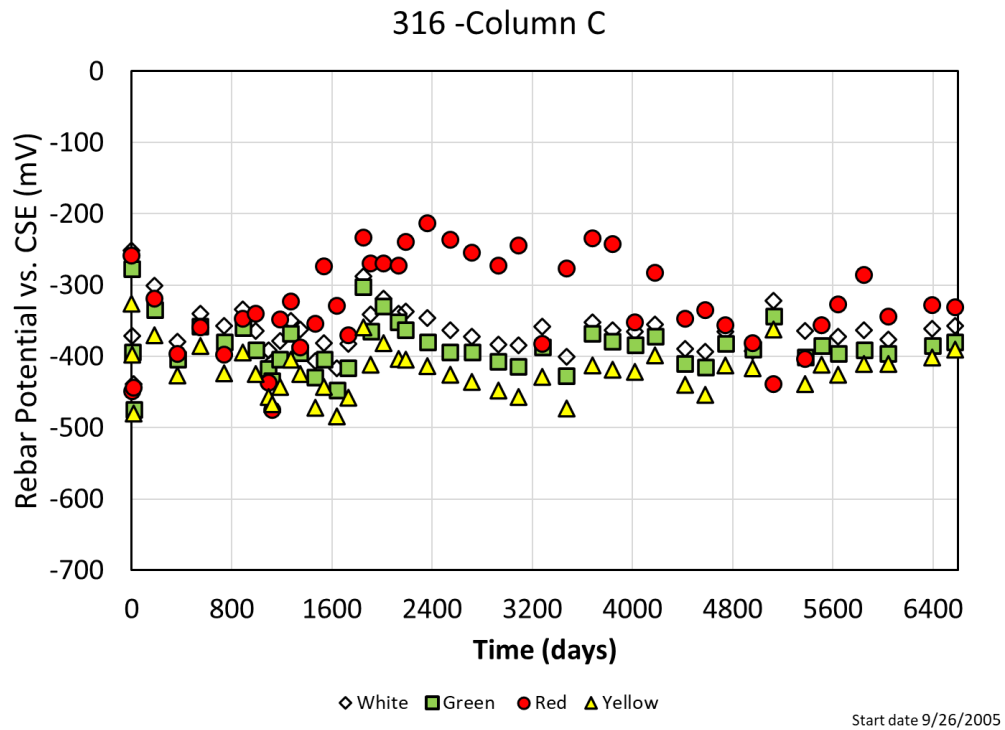


Figure 5-17. Plot showing the potential evolution for 316 rebar embedded in 316 column C.

5.3 REBAR POTENTIALS MEASURED DURING RECENT VISITS

The rebar potential values measured during the two visits are reported in the next section for columns with MMFX, 3CR12 and 2101 CRRBs. For all values reported, the reference electrode was placed in the water.

5.3.1 MMFX

Table 5-1 and Table 5-2 show the MMFX rebar potential values measured during the October 2024 visit and the September 2025 visit, respectively.

Table 5-1. Rebar potential measurements vs. CSE for each MMFX column, taken October 2024.

Column	Yellow Wire	White Wire	Green Wire	Red Wire
A	-479 mV _{CSE}	-483 mV _{CSE}	-496 mV _{CSE}	-494 mV _{CSE}
B	-527 mV _{CSE}	-539 mV _{CSE}	-534 mV _{CSE}	-478 mV _{CSE}
C	-544 mV _{CSE}	-533 mV _{CSE}	-533 mV _{CSE}	-533 mV _{CSE}

Table 5-2. Rebar potential measurements vs. CSE for each MMFX column, taken September 2025.

Column	Yellow Wire	White Wire	Green Wire	Red Wire
A	-466 mV _{CSE}	-469 mV _{CSE}	-493 mV _{CSE}	-475 mV _{CSE}
B	-571 mV _{CSE}	-252 mV _{CSE}	-588 mV _{CSE}	-459 mV _{CSE}
C	-505 mV _{CSE}	-562 mV _{CSE}	-538 mV _{CSE}	-536 mV _{CSE}

5.3.2 3CR12

Table 5-3 and Table 5-4 show the 3CR12 rebar potential values measured during the October 2024 visit and the September 2025 visit, respectively.

Table 5-3. Rebar potential measurements vs. CSE for each 3CR12 column, taken October 2024.

Column	Yellow Wire (mV_{CSE})	White Wire (mV_{CSE})	Green Wire (mV_{CSE})	Red Wire (mV_{CSE})
A	-478	-450	-486	-515
B	-531	-411	-500	-516
C	-484	-501	-523	-533

Table 5-4. Rebar potential measurements vs. CSE for each 3CR12 column, taken September 2025. No contact available for yellow wire.

Column	Yellow Wire (mV_{CSE})	White Wire (mV_{CSE})	Green Wire (mV_{CSE})	Red Wire (mV_{CSE})
A	Unavailable	-447 mV _{CSE}	-481	-290
B	-559	-372	-567	-538
C	-254	-466	-497	-458

5.3.3 2101

Table 5-5 and Table 5-6 show the 2101 rebar potential values measured during the October 2024 visit and the September 2025 visit, respectively.

Table 5-5. Rebar potential measurements vs. CSE for each 2101 column, taken October 2024.

Column	Yellow Wire (mV_{CSE})	White Wire (mV_{CSE})	Green Wire (mV_{CSE})	Red Wire (mV_{CSE})
A	-406	-474	-404	-421
B	-388	-447	-386	-417
C	-388	-393	-410	-391

Table 5-6. Rebar potential measurements vs. CSE for each 2101 column, taken September 2025.

Column	Yellow Wire (mV_{CSE})	White Wire (mV_{CSE})	Green Wire (mV_{CSE})	Red Wire (mV_{CSE})
A	-406	-455	-449	-413
B	-402	-379	-388	-372
C	-393	-400	-337	-367

5.4 REBAR POTENTIALS VS. HEIGHT

During the September 2025 visit, the rebar potential values along the rebar length were measured for all columns with 3CR12, MMFX, and 2101. Additionally, the rebar potential values were measured along two rebars for a column with 316 and along two rebars for a column with carbon steel rebars. The measurements started from the top of the column. In some cases, the two column sides for a given rebar were measured, but due to the tide moving relatively fast, it was decided to measure one side only (since values were quite similar). APPENDIX D: ADDITIONAL PLOTS FROM FIELD COLUMNS contains the detail for the few columns where two sides were measured. The rebar potential values measured in water or on saturated sand (if tide had receded) are shown at a height of about 28 inches. All rebar potential values shown here are vs. CSE (copper sulfate electrode). The symbols have color similar to the wire to which the measurements were made.

5.4.1 Columns with 3CR12 Rebars

Figure 5-18 shows the rebar potential measured in Column 3CR12-A. In column 3CR12-A, the rebar connected to the red wire had the more positive rebar potential values (when compared to the other rebars in this column), with a ~24 inches section of the rebar at a potential around -300 mV_{CSE}. Rebar potential measurements for the rebar connected to the yellow wire were not made due to lack of good contact. The rebar potential in the other rebars reached values as negative as -500 mV_{CSE}. Figure 5-19 shows that two rebars in column 3CR12-B reached values more negative than -550 mV_{CSE}. For column 3CR12-B, the rebar connected to the white wire displayed a more positive values when compared to the other rebars. A portion of the rebar connected to the white wire showed values close to -420 mV_{CSE}, but the rebar section closest to the ground and on the water had a rebar potential of -400 mV_{CSE}. This suggests a section of the rebar being more active above the ground.

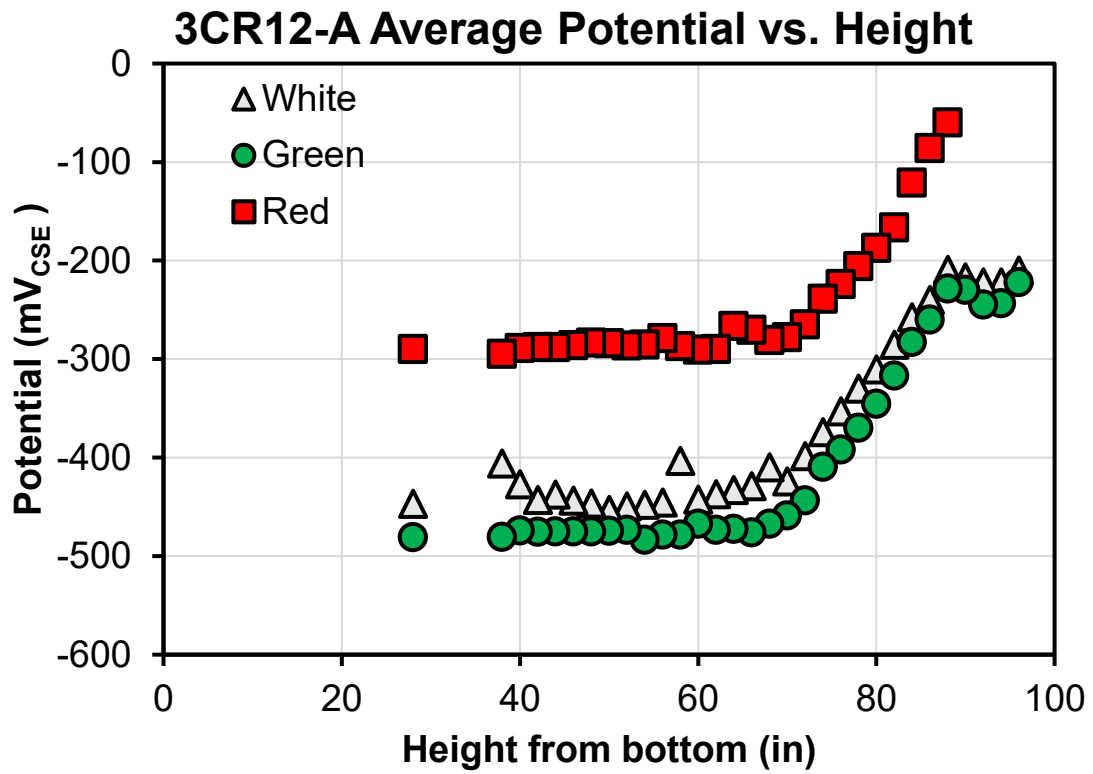


Figure 5-18. Avg. rebar potential vs height measured in column 3CR12-A.

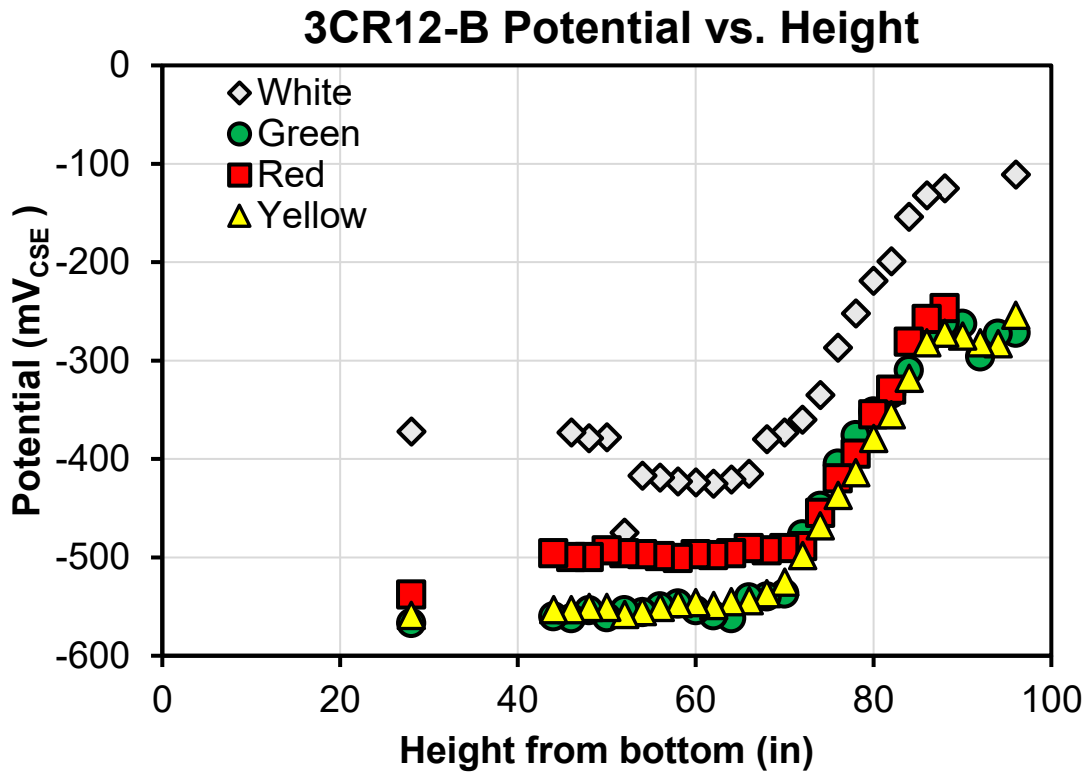


Figure 5-19. Avg. rebar potential vs height measured in column 3CR12-B.

Figure 5-20 shows rebar values vs. height for the four rebars embedded in column 3CR12-C. In this column, the rebar connected to the yellow wire had more positive rebar potential values compared to the other three rebars. The rebar connected to the green lead had the most negative rebar potential values. All rebars show a section that has more negative potential values. All columns showed sections with cracks during the October 2024 visit.

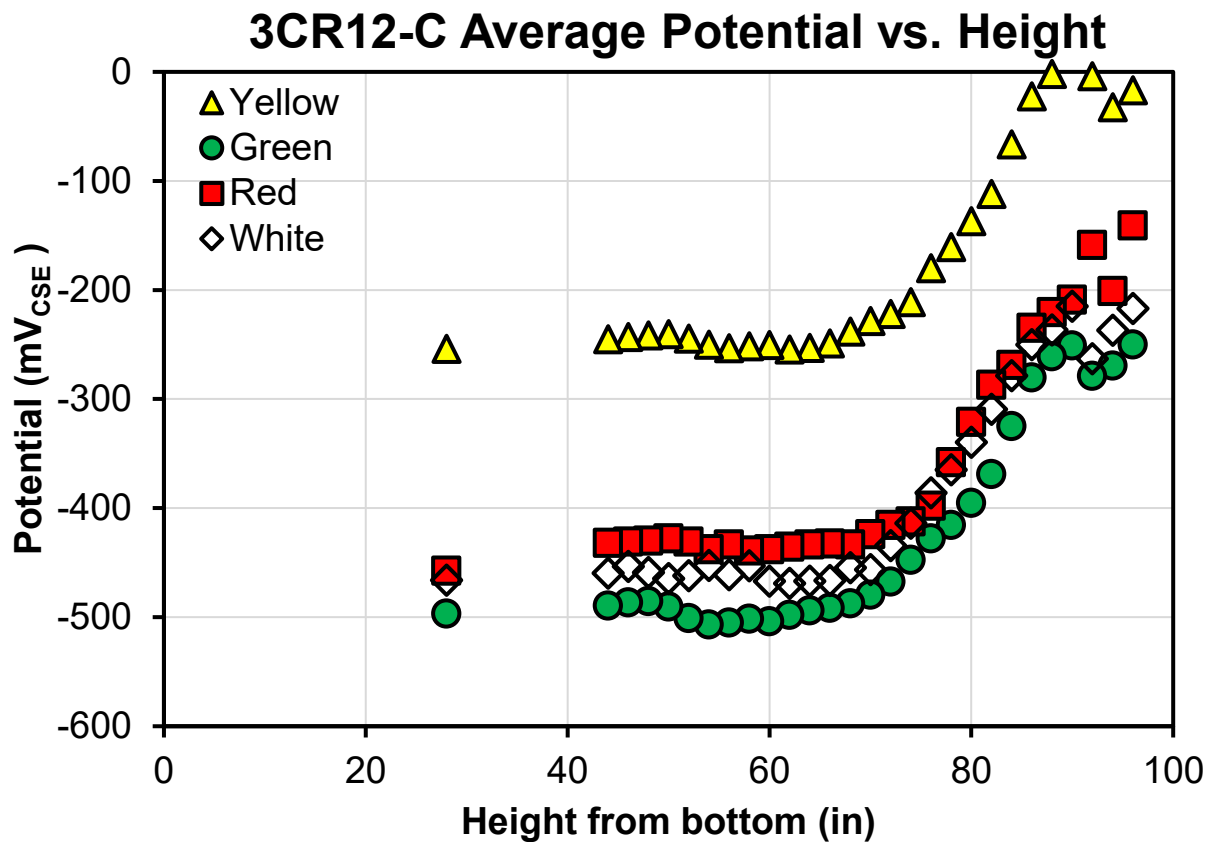


Figure 5-20. Avg. rebar potential vs height measured in column 3CR12-C.

5.4.2 Columns with 2101 Rebars

This section shows the plots for rebar potential vs. height measured on the columns with 2101 rebars. These rebars are believed to have mill-scale upon casting. The mill-scale presence likely lowered the chloride threshold. In column 2101-A all rebars showed similar rebar potential vs. height, this can be observed in Figure 5-21. The rebar in contact with the white wire appears to have a section between 60 and 75 inches that is more negative than the rest. In all rebars, the section above 80 had rebar potential that increased steeply toward more positive values. For example, rebar connected to the yellow wire had values as high as -100 mV_{CSE}. Similar trends were observed on columns 2101-B and 2101-C. Figure 5-22 shows the potential vs. height measured on the rebars in column 2101-B and Figure 5-23 shows the potential vs. height plots obtained on rebars embedded in Column 2101-C. All rebars in these three columns show a section that is indicative of active corrosion.

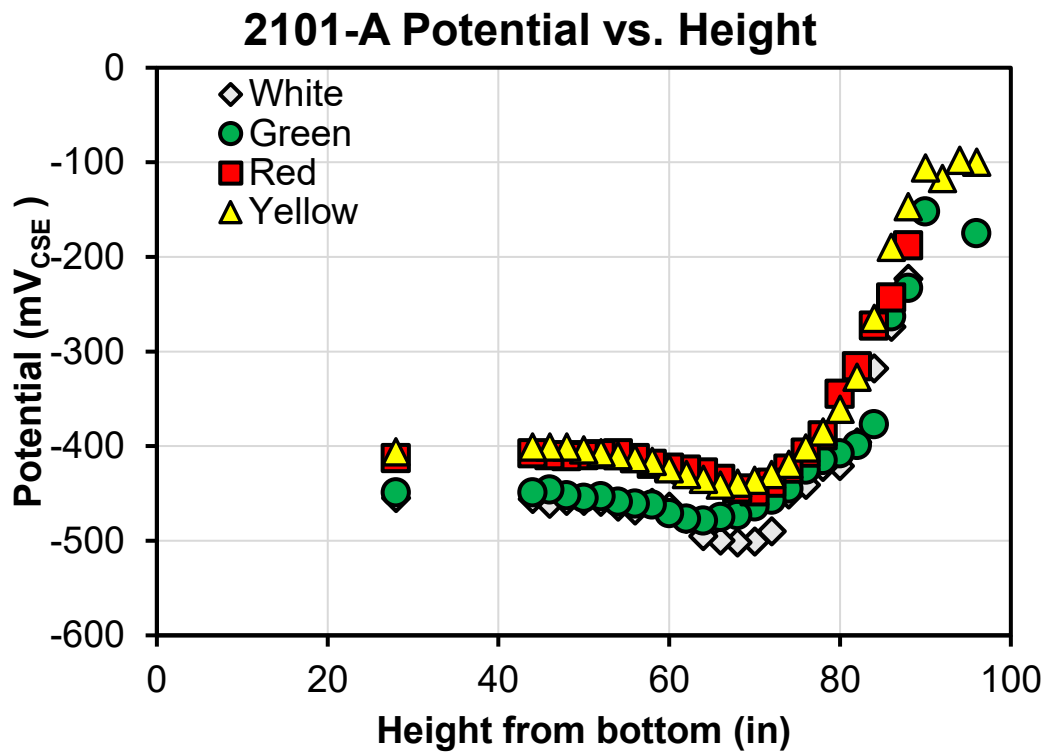


Figure 5-21. Avg. rebar potential vs height measured in column 2101-A.

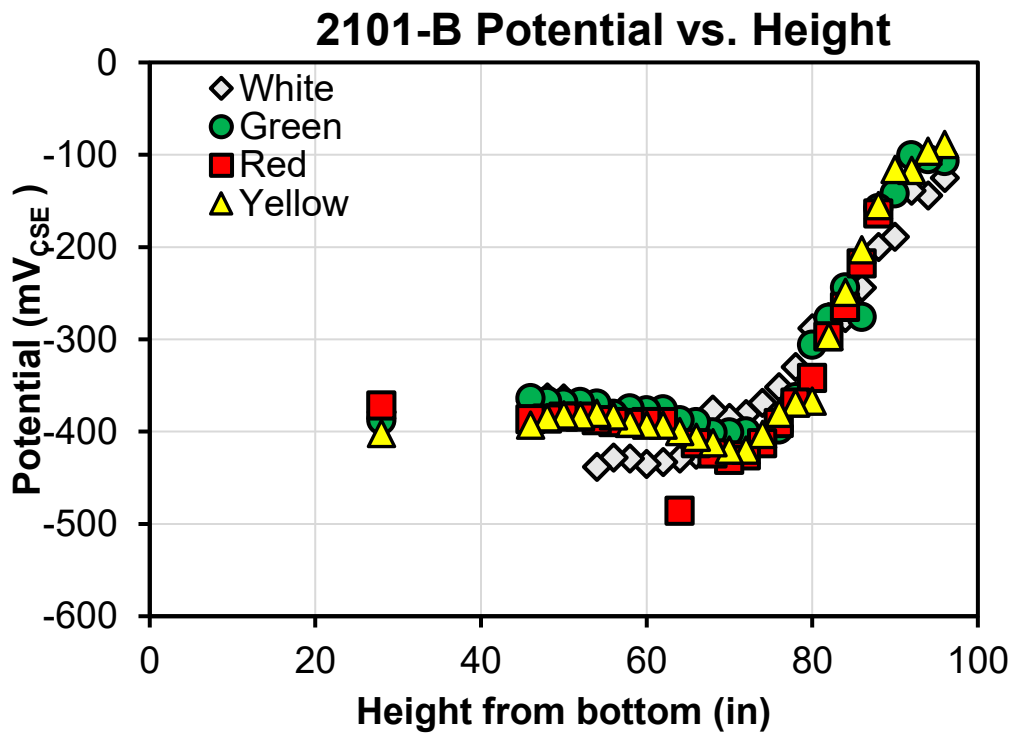


Figure 5-22. Avg. rebar potential vs height measured in column 2101-B.

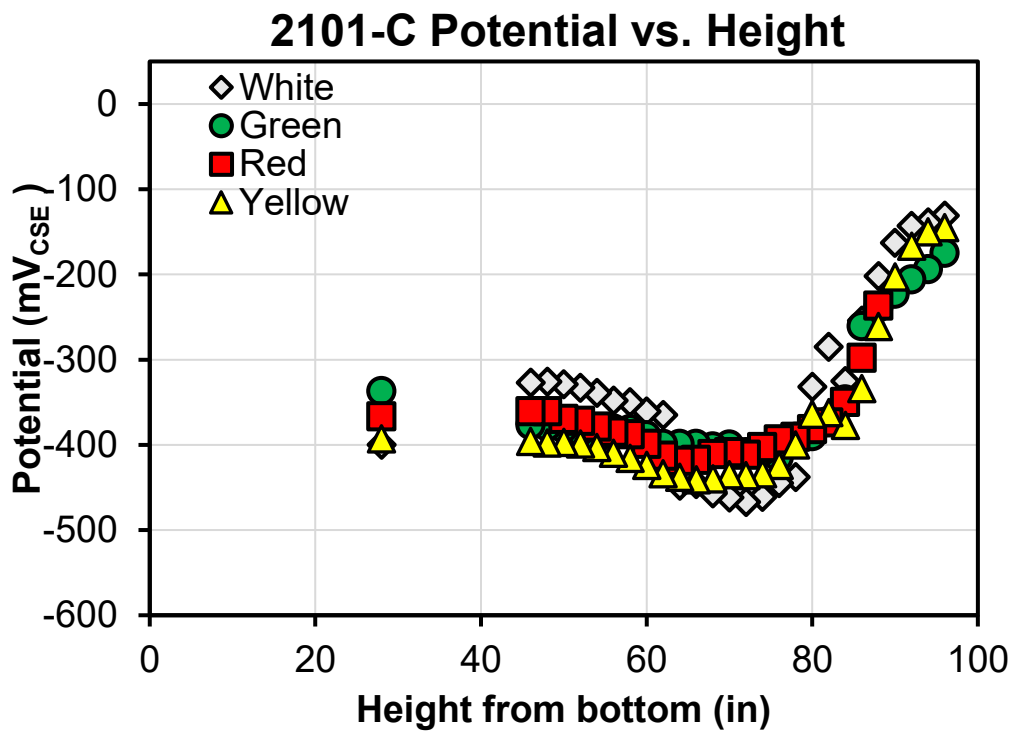


Figure 5-23. Avg. rebar potential vs height measured in column 2101-C.

5.4.3 Columns with MMFX Rebars

Figure 5-24, Figure 5-25 and Figure 5-26 show the potential vs. height measured on the rebars for Columns MMFX-A, MMFX-B and MMFX-C, respectively. Two columns MMFX-A and MMFX-C showed rebars that reach potential values more negative than $-520 \text{ mV}_{\text{CSE}}$, with column MMFX-C having the rebar with the more negative potentials. Two of the rebars in column MMFX-B (Figure 5-25) also showed rebar values close to $-600 \text{ mV}_{\text{CSE}}$. The rebar connected to the white wire in Column MMFX-B showed the most positive values from all 12 MMFX rebars.

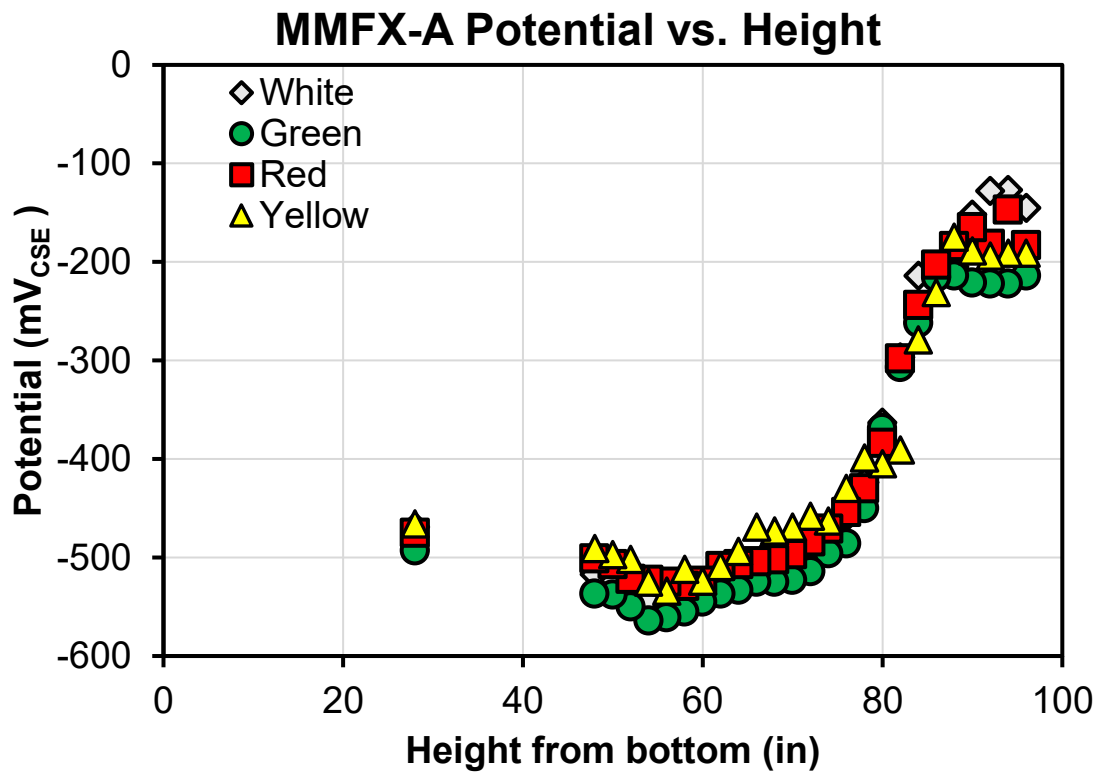


Figure 5-24. Avg. rebar potential vs height measured in column MMFX-A.

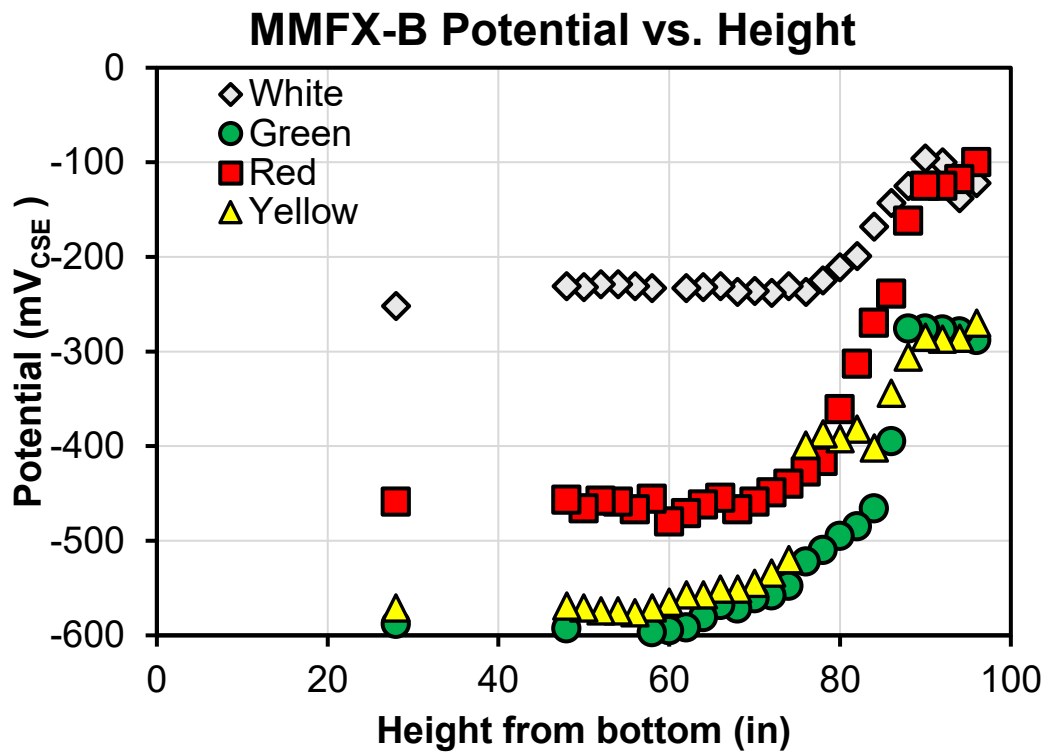


Figure 5-25. Avg. rebar potential vs height measured in column MMFX-B.

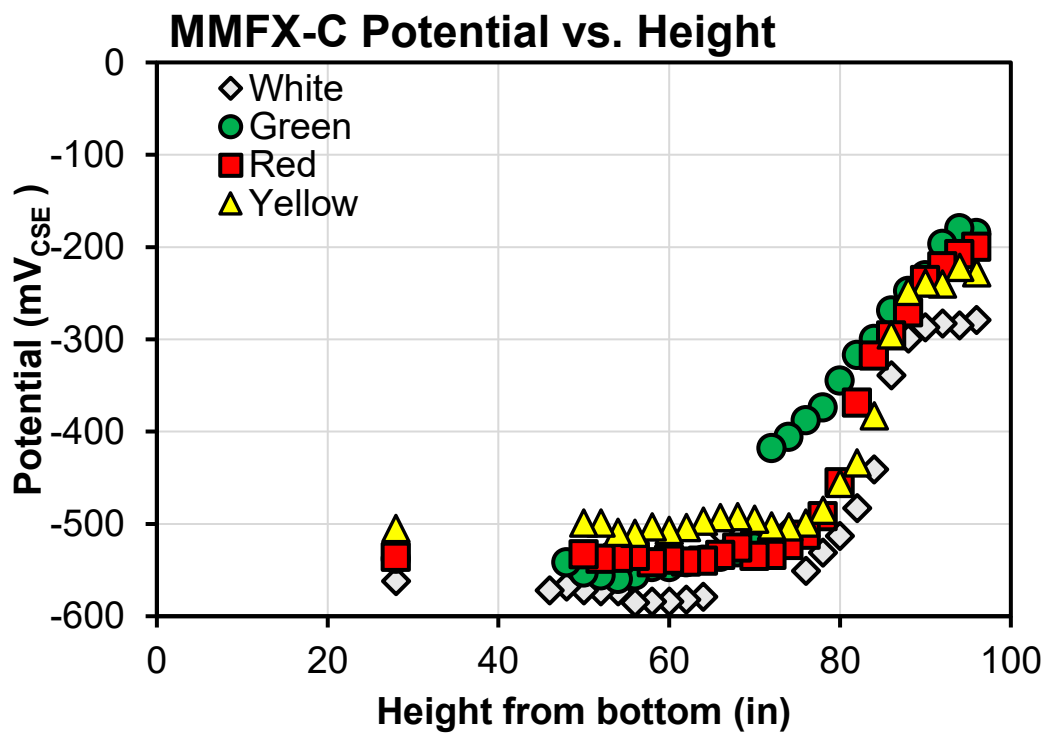


Figure 5-26. Avg. rebar potential vs height measured in column MMFX-C.

5.4.4 Column with 316 Rebars

Column 316-C was damaged while driving them into place. It is likely that the rebar corrosion is taking place on section below the column region that was damaged. The two rebars measured seem to indicate that there is active corrosion taking place. Figure 5-27 shows the two wires' rebar potential vs. height measurements from Column 316-C. The rebar potential ranged between $-420 \text{ mV}_{\text{CSE}}$ and slightly more positive than $-300 \text{ mV}_{\text{CSE}}$.

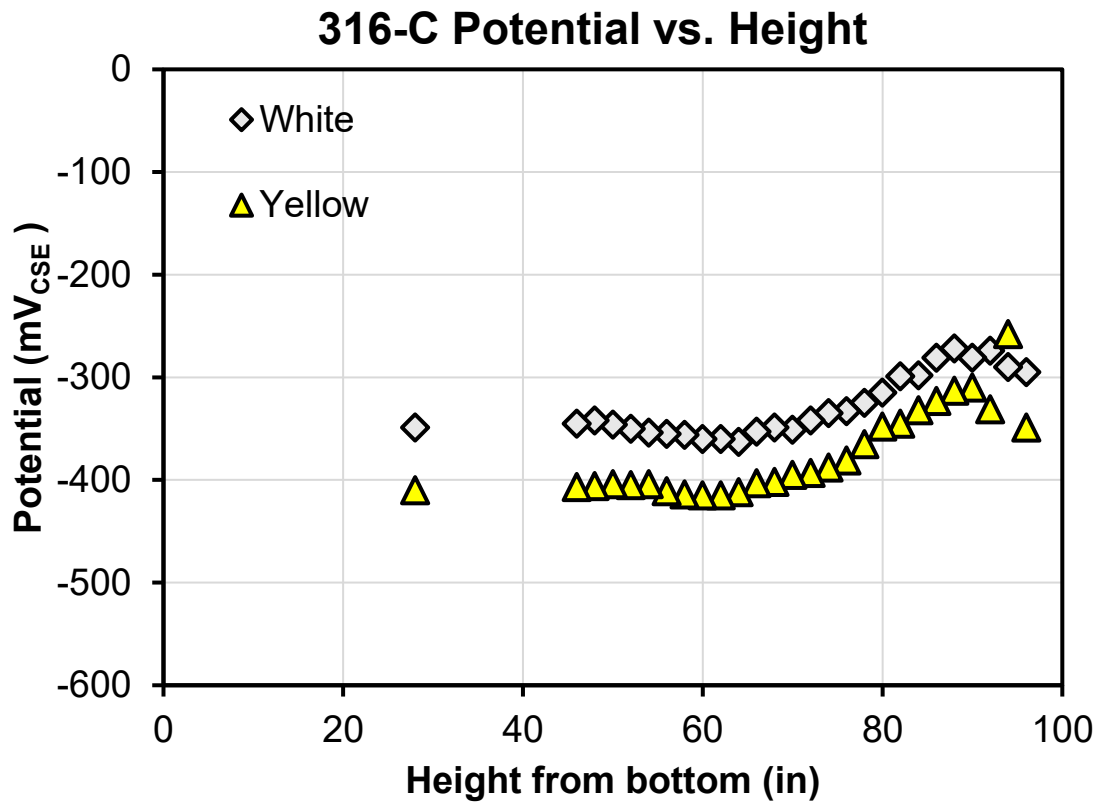


Figure 5-27. Avg. Rebar Potential vs height measured in column 316-C.

5.4.5 Column with Carbon Steel Rebars

The columns with carbon steel rebars show significantly wider cracks than the columns with MMFX, 3CR12 or 2101 rebars. Figure 5-28 shows the potential vs. height measured on two rebars of column A.

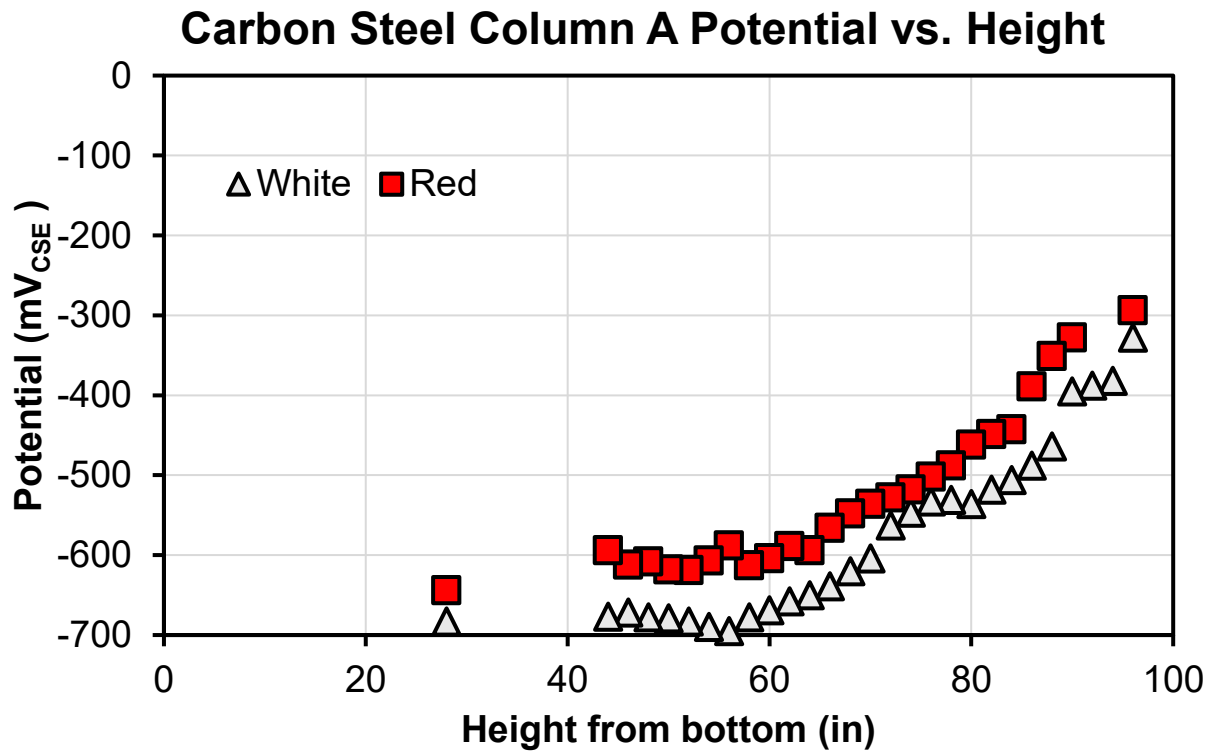


Figure 5-28. Avg. rebar potential vs height measured in column A (with carbon steel rebar).

5.5 CORES OBTAINED FROM CRESCENT BEACH COLUMNS

Selected columns with 3CR12, MMFX and 2101 rebars were cored. Cores were obtained from columns MMFX-A (Figure 5-29), 2101-A with the core obtained ~ 20 inches above the water line, (see Figure 5-30), 2101-B with the core obtained ~6 inches below the water line (Figure 5-31). These three cores had rebar segments that were later cleaned to assess corrosion extent.



Figure 5-29. Images show the core obtained from column MMFX-1. It included a rebar segment.



Figure 5-30. Image shows the core obtained from column 2101-A (~20 inches above WL).



Figure 5-31. Image shows the core obtained from column 2101-B (~6 inches below WL).

All three columns with 3CR12 rebars were cored, short cores were obtained from all three 3CR12 columns. The cores were obtained along the rebar and/or cracked section, but the core did not cut through the rebar. For columns B and C the cores were obtained from the back face (West face), for column A no notation was made as of which face was cored. Figure 5-32 shows pictures of the short cores and which column they correspond to. In addition, a long core was obtained from column A. The core penetrated the whole column, Figure 5-33 shows an image of this core.

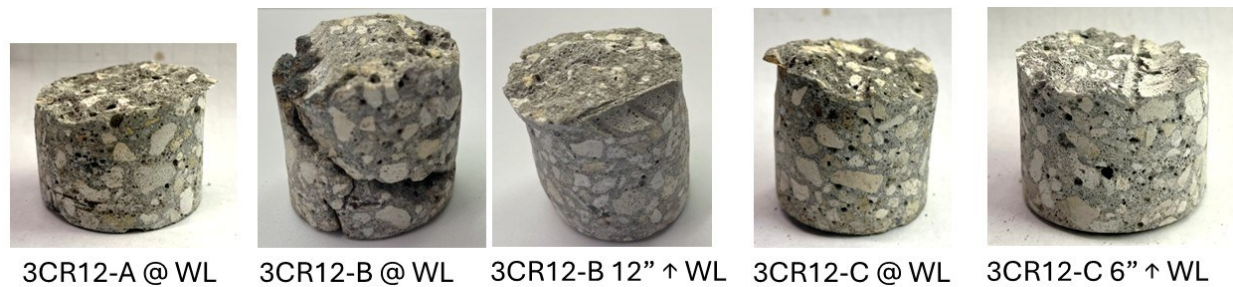


Figure 5-32. Image shows the cores obtained from columns with 3CR12 reinforcement.

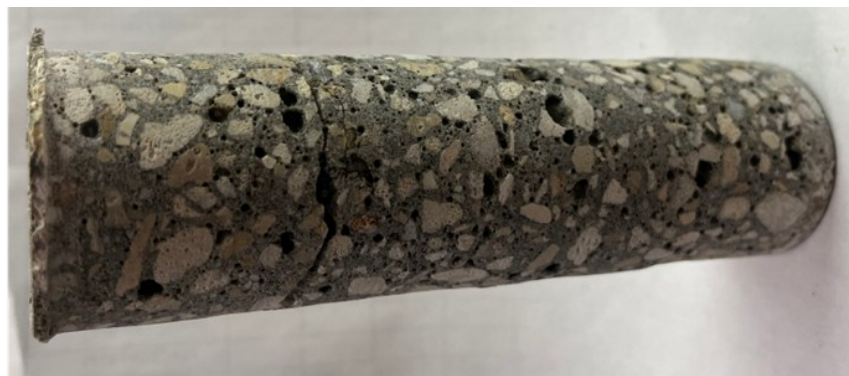


Figure 5-33. Image shows the core obtained from column 3CR12-A @ WL from the center of the column.

5.5.1 Chloride Profiles for Crescent Beach Samples

This section presents the chloride profiles for cores taken from the Crescent Beach Field site. FDOT considers 1.2 lbs/yd^3 as the critical chloride threshold (C_T) for corrosion initiation for black bars. (Note that 1.2 lbs/yd^3 is approximately 0.7 kg/m^3). Trejo [15] reported a chloride threshold for MMFX of 7.6 lbs/yd^3 (i.e., 4.5 kg/m^3). Gutierrez and Presuel [1] a chloride threshold of 42 lb/yd^3 (25 kg/m^3) for 2101 LDX.

Figure 5-34 and Figure 5-35 depict chloride profiles for one of the MMFX columns. Both profiles correspond to millings obtained from a concrete core. Figure 5-34 shows the profile from the column surface, whereas Figure 5-35 shows how the chloride evolved behind the rebar (rebar trace). Note that the chloride concentration at the rebar depth is two to three times the C_T reported by Trejo [15].

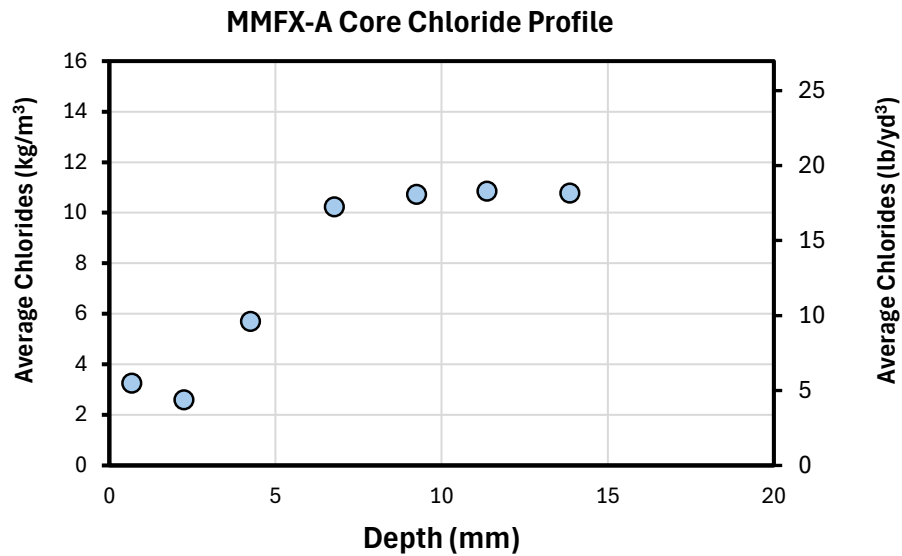


Figure 5-34. MMFX-A Core Chloride Profile.

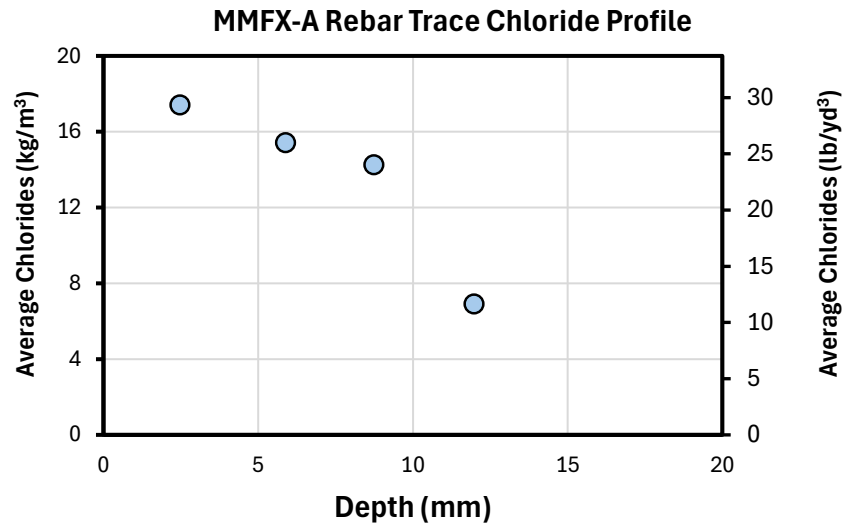


Figure 5-35. MMFX-A Rebar Trace Chloride Profile.

Figure 5-36 through Figure 5-38 depict chloride profiles for two of the 2101 columns, and Figure 5-39 through Figure 5-44 depict chloride profiles for three of the 3CR12 columns. Figure 5-36 and Figure 5-38 show chloride concentrations close to the rebar trace. No chloride profile from the surface was possible from the 2101-A core (see Figure 5-30). Some of the profiles are from the column surface and others refer to the chloride concentration close to the rebar trace. Each of the core profiles from the column surface followed a pattern of exhibiting lower chloride concentrations near the surface, generally increasing with depth into the concrete.

This might be in part due to the skin effect, as well as wetting and drying that takes place at the elevations cored. Profiles of rebar traces showed high chloride concentrations close to the rebar, decreasing with distance from the rebar. Note that in this case the millings were taken from the core section beyond/behind the rebar for 2101 cored columns. Maximum chloride concentrations for all cores and rebar traces remained under 20 kg/m^3 except for the rebar trace from column 2101-A, which reached a maximum chloride concentration of over 25 kg/m^3 closest to the rebar. The higher concentration might have resulted from a crack. The concrete cover on these columns is 25 mm (one inch). The chloride concentration close to the rebar for MMFX was close to 18 kg/m^3 , for 2101 was ranged between 15 kg/m^3 (Column B) and 25 kg/m^3 (Column A). The chloride concentration close to 3CR12 rebars ranged between 12 and 18 kg/m^3 . Recall that no rebar was obtained from columns with 3CR12 rebars. Core chloride profile shapes did not show typical Fickian behavior, and therefore Dapp was not calculated.

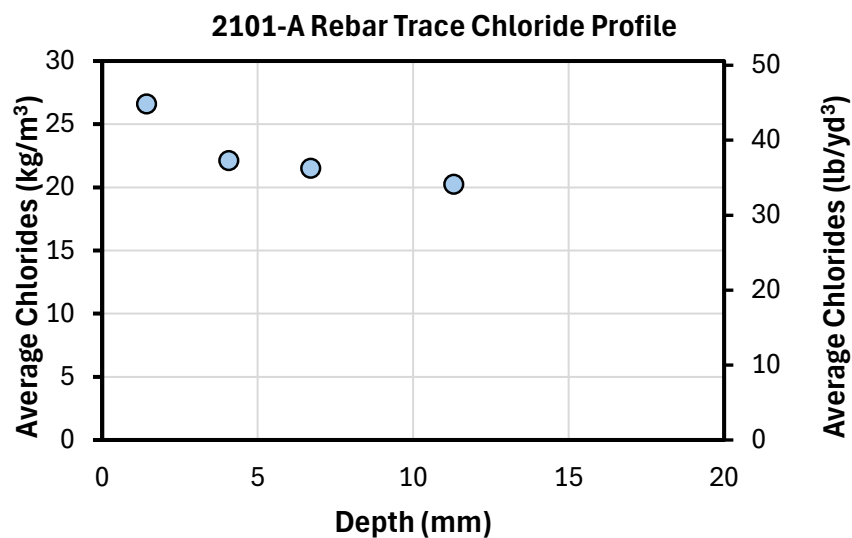


Figure 5-36. 2101-A Rebar Trace Chloride Profile.

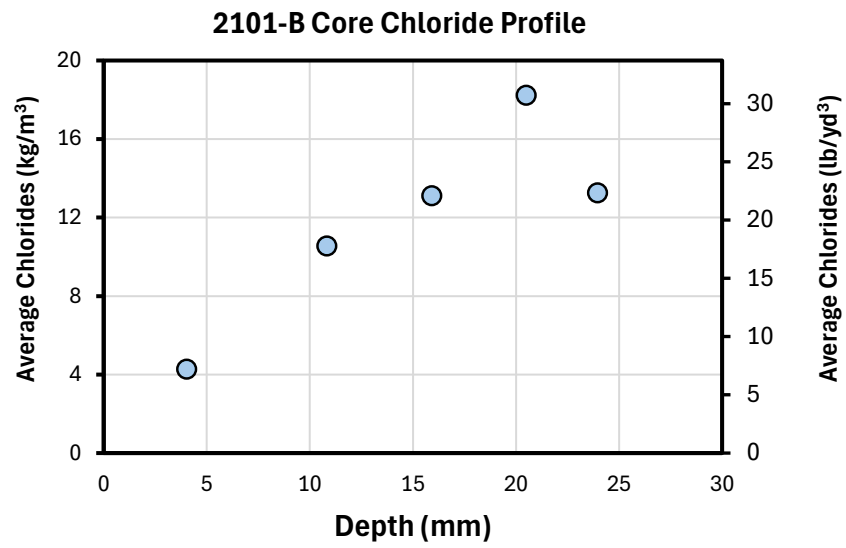


Figure 5-37. 2101-B Core Chloride Profile.

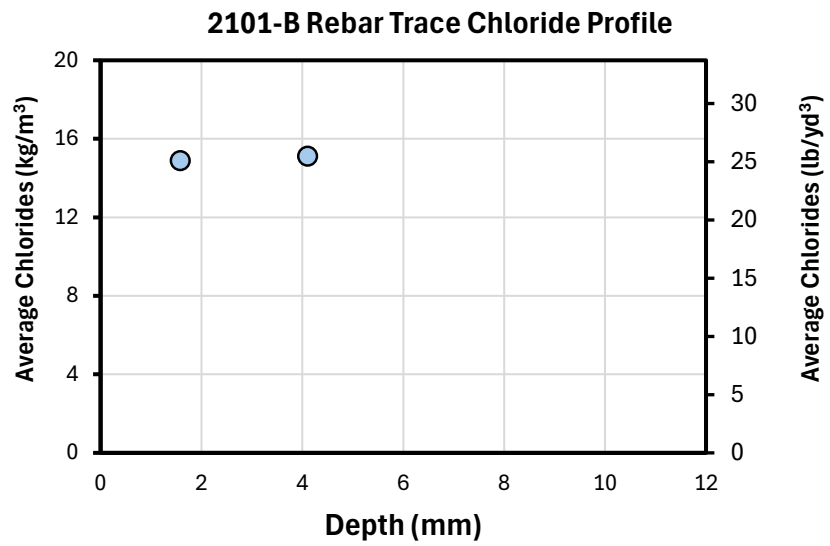


Figure 5-38. 2101-B Rebar Trace Chloride Profile.

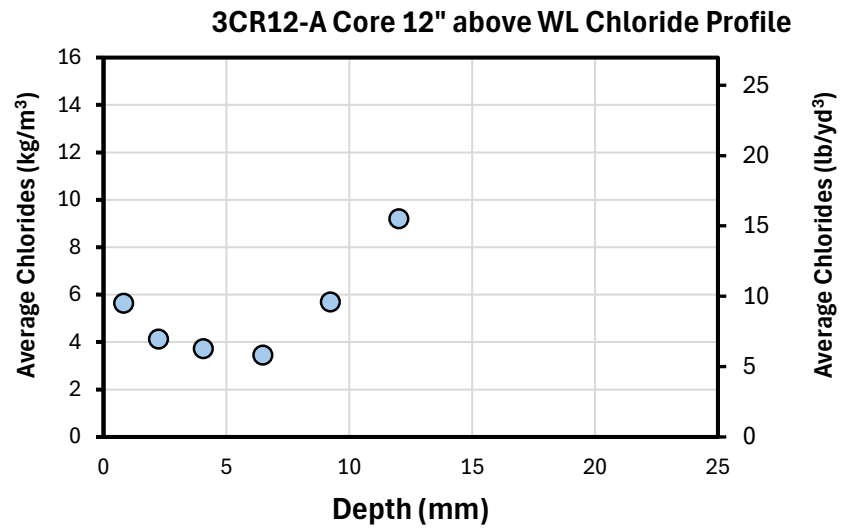


Figure 5-39. 3CR12-A (12" above water line) Chloride Profile.

One of the cores obtained from column 3CR12-A penetrated the whole column and did not touch any rebar. Figure 5-40 shows the profiles from both ends of the column. The concentration at the rebar depth appears to be between 12.5 kg/m³ and 14 kg/m³ (no counting increase in chloride concentration build up due to the rebar presence [16] [17] [1]).

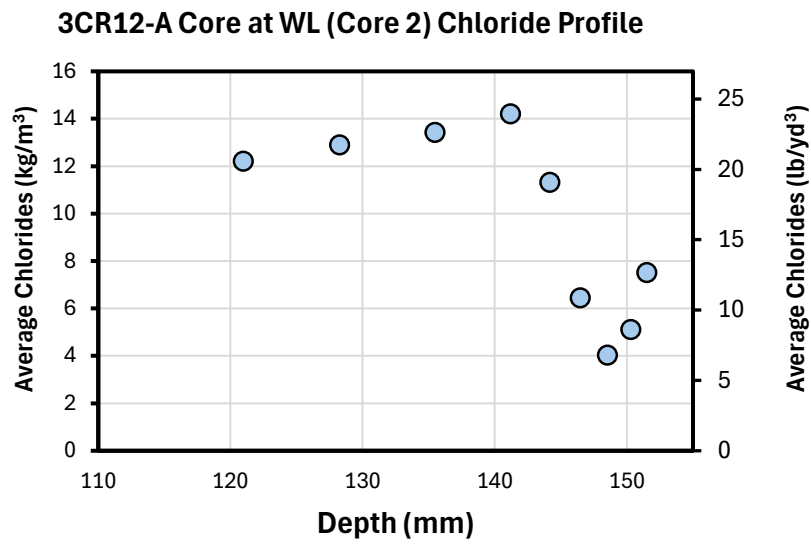
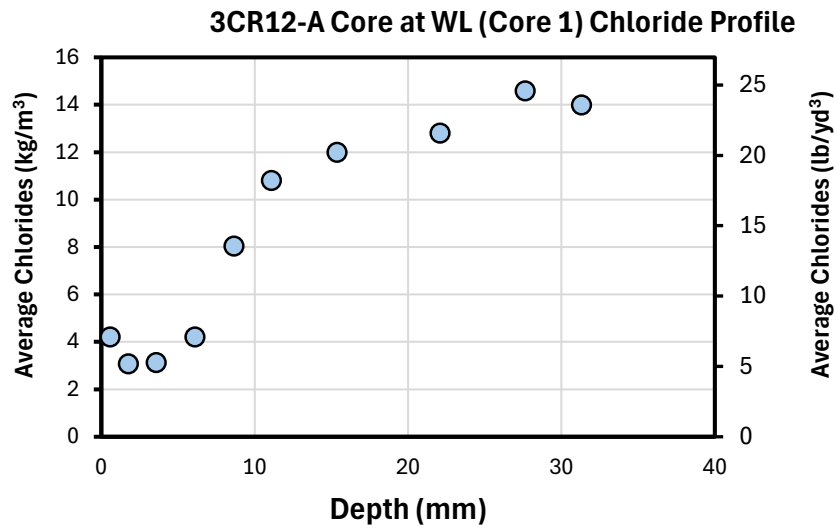


Figure 5-40. 3CR12-A @ WL(both sides) Chloride Profile.

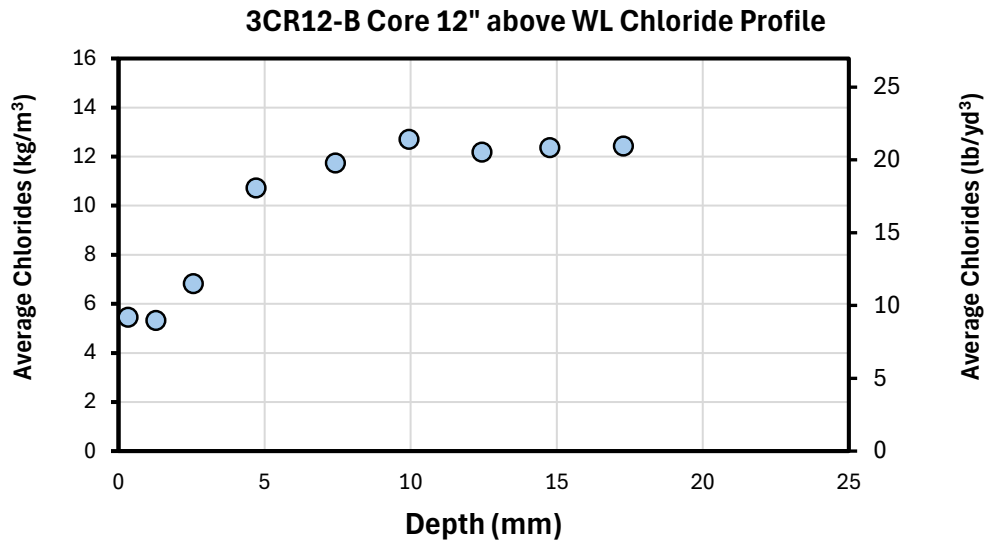


Figure 5-41. 3CR12-B Core 12" above WL Chloride Profile.

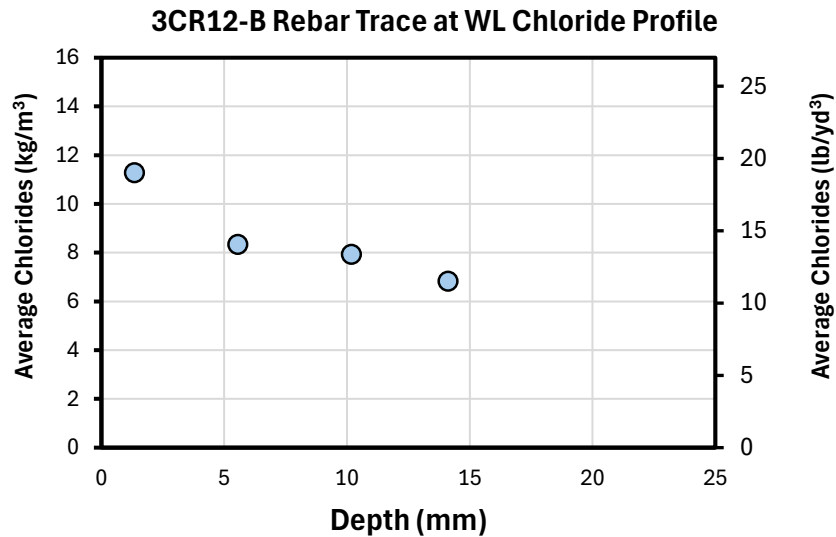


Figure 5-42. 3CR12-B Rebar Trace at WL Chloride Profile.

Figure 5-42 shows the rebar trace chloride concentration, in this case the layers were obtained toward the column surface, i.e., concrete in front of the rebar. Recall that no rebar segment was obtained from 3CR12 columns.

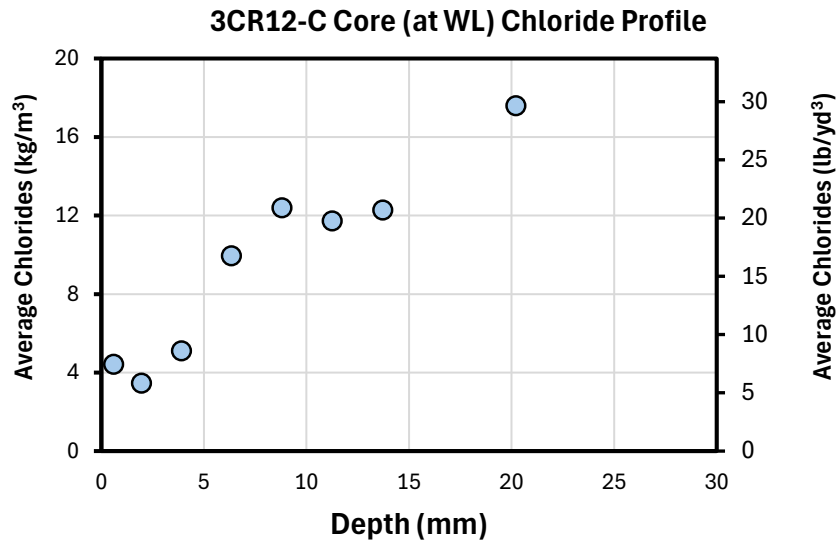


Figure 5-43. 3CR12-C Core (at water line) Chloride Profile.

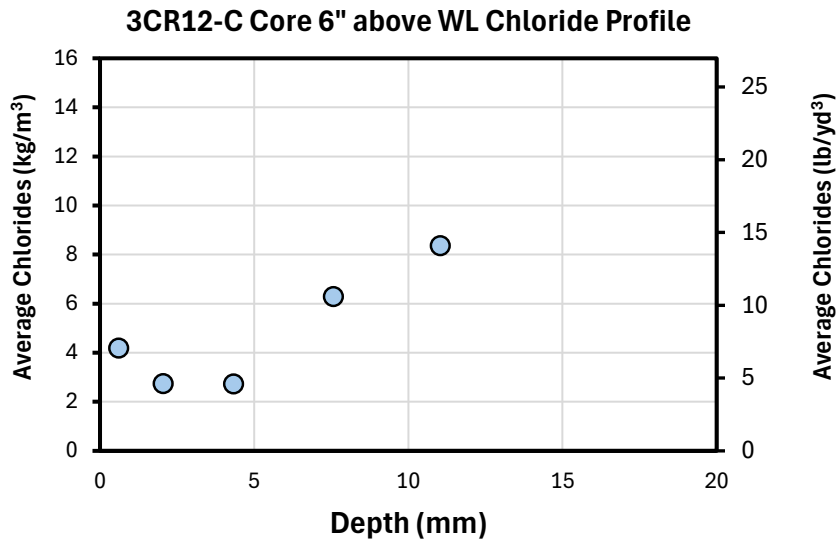


Figure 5-44. 3CR12-C Core (6" above water line) Chloride Profile.

5.5.2 Corrosion Extent on Rebar Segments After Additional Cleaning

Deliverable 3 included images of the rebars segments before and after cleaning. Figure 5-45, Figure 5-47, and Figure 5-49 show images of the MMFX rebar section, the 2101 Column A rebar section, and the 2101 Column B rebar section, respectively, after additional immersion time in the cleaning solution. Figure 5-46, Figure 5-48, and Figure 5-50 show close-up image(s) of the MMFX rebar section, the 2101 Column A rebar section, and the 2101 Column B rebar section, respectively, for the areas with more significant cross section loss.



Figure 5-45. MMFX rebar section after additional immersion in cleaning solution.

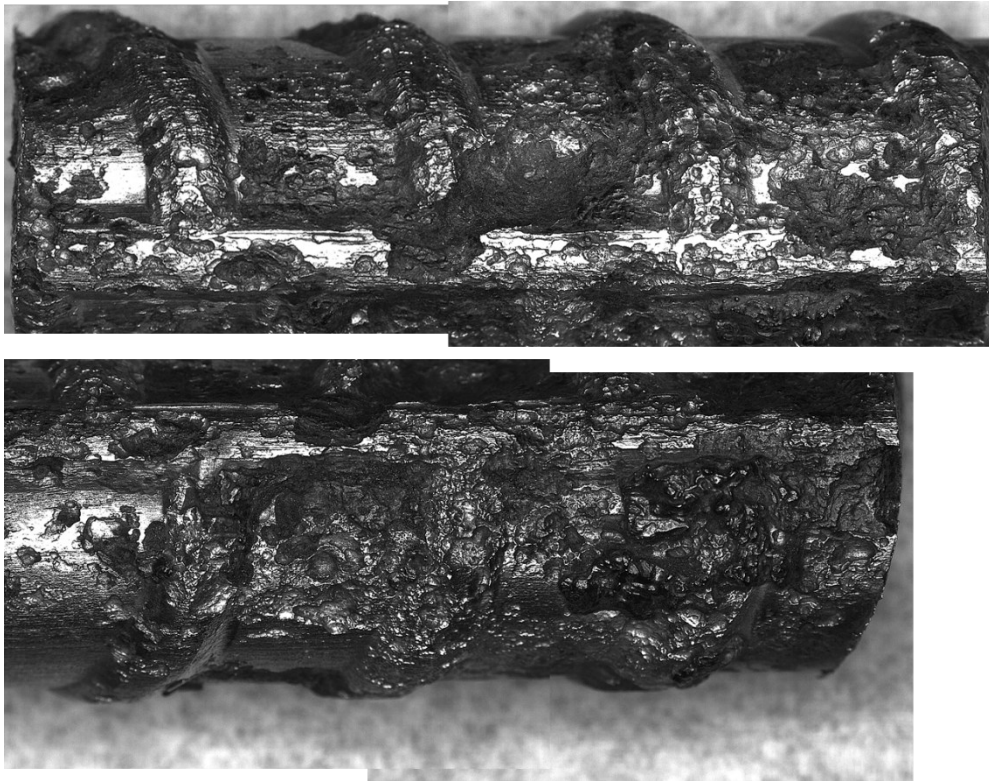


Figure 5-46. MMFX rebar section close-up of the region with most corrosion.



Figure 5-47. 2101 rebar section (Column A) after additional immersion in cleaning solution.



Figure 5-48. 2101 (Column A) rebar section close-up of the region with most corrosion.



Figure 5-49. 2101 rebar section (Column B) after additional immersion in cleaning solution.

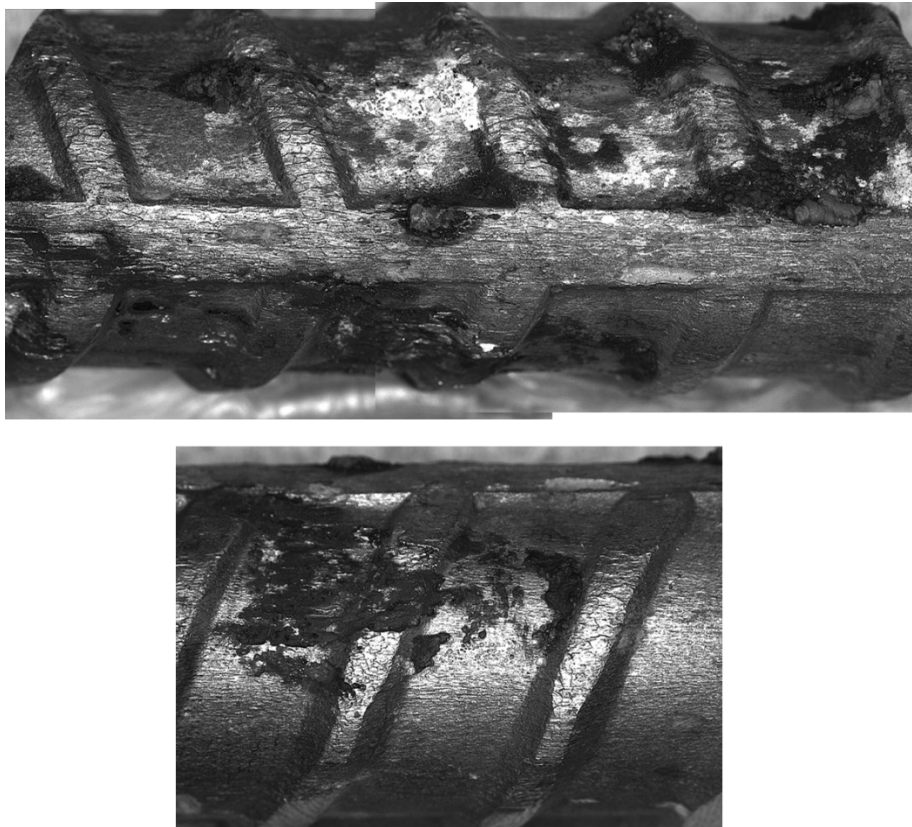


Figure 5-50. 2101 (Column B) rebar section close-up of the region with most corrosion.

5.6 SUMMARY

The columns with 2101, 3CR12 and MMFX rebars were observed to have cracks. The rebar potential vs. height and chloride profiles confirm that corrosion is likely taking place on these rebars located at the Crescent Beach field site. The columns with black bar are also corroding and the cracks are wider than for the columns with intermediate alloy rebars.

6 RESULTS – VISITS TO BRIDGES

This chapter describes the visits to two bridges with CRRBs. Two visits took place to the Jensen Beach Bridge (Bridges #890145): March 2025 and July 2025. SR30A Bridge (Bridge #510072 at St. Joseph's Bay area) visit took place during May 2025. Prior to the visit to the SR30A bridge, a meeting with FDOT took place to schedule the bridge visit. There are two bridges on SR30A with CRRB reinforcement, the second bridge in the Port St. Joseph's Bay area was reported not accessible, it was decided to visit only Bridge #510072.

The SR30A Bridge is not instrumented. Electrical contact(s) to the reinforcement were made by drilling to the rebar depth (see section 6.1 below describing the bridge visit).

The Jensen Beach Bridge is instrumented in Bents 10, 11 and 12. Bents 11 and 12 are accessible, but a boat is needed to access Bent 10.

6.1 VISIT TO BRIDGE #510072, SR30A BRIDGE ST. JOSEPH'S BAY AREA

The visit to SR30A bridge (#510072) took place during May 2025. Figure 6-1 below shows an image of the bridge and the bulk-head on each side. The red circles show the approximate locations where drilling took place to locate the reinforcement. Figure 6-2 shows a picture of the hole made at site one, a crack is also visible, but it is believed not to be due to corrosion.



Figure 6-1. Picture of SR30A Bridge (510072) taken from the marina, left dot location 1, right dot is location 2.

A portable GPR was used to locate the rebar, drilling then took place. An electrical connection was made. The rebar potential was obtained at a few locations, including reinforcement vs. a reference electrode in the water. A Copper/Copper sulfate reference was used. Visual inspection

of each drilled hole appears to show corrosion resistant rebar (i.e., not black rebar). Surface resistivity measurements also were taken at a few locations close to where the drilling took place.

6.1.1 Location One

The rebar potential values measured suggest passive reinforcing steel. The magnitude of the values measured at the first location suggest that the contact might not have been very good. The reading with the electrode in the water was $-0.003 V_{CSE}$. The values measured ranged between $-0.017 V_{CSE}$, and $-0.006 V_{CSE}$. The surface resistivity measured ranged between 10 and 15 $k\Omega\text{-cm}$.



Figure 6-2. Drilled hole to access rebar at location one. A crack was visible transverse to the phone shade.

6.1.2 Location Two (South Side)

The rebar potential with the reference electrode in the water was $-0.282 V_{CSE}$. At locations close to the site drilled the values ranged between -0.081 and $-0.146 V_{CSE}$. A better contact with the reinforcement was achieved. The surface resistivity ranged between 7 and 16 $k\Omega\text{-cm}$.

6.1.3 Additional Observations

Several cracks were observed on the bulk-heads and documented with photographs. Figure 6-3, Figure 6-4 and Figure 6-5 show images of where the cracks are located. These are not believed to be due to corrosion of the reinforcement.



Figure 6-3. South side of the bridge, showing several cracks (moisture allows for observation).



Figure 6-4. Close-up of two of the cracks (moisture allows for observation).



Figure 6-5. South side of the bridge under the deck, showing several cracks (moisture allows observation).

6.2 FIELD VISIT TO JENSEN BEACH BRIDGE

This section summarizes the previous and the two visits that took place as part of the current project.

6.2.1 Prior Visits to Jensen Beach Bridge

A report was submitted to FDOT by a contractor [11] that was charged with visiting and assessing the Jensen Beach Bridges (up to 2020) over time. In here the focus is on the substructure elements that contains 2101LDX rebars, since the bridge deck section with MMFX was not visited during the recent visits. The 2020 report indicates that during the field visits the performance monitoring consisted of periodic visual inspections and sounding surveys to identify and track changes in crack development and any concrete delamination and spalls. The instrumented elements allowed for measuring corrosion potentials to determine the presence of any corrosion activity and measuring the electrical resistivity of the concrete as a means of indirectly assessing concrete quality and chloride penetration.

As part of the prior study, concrete core samples were obtained to directly observe the condition of the reinforcement and to determine the chloride content at various depths in the concrete. Findings for the instrumented part of the bridge reinforced with 2101LDX were compared to similar data obtained for standard ASTM A 615 black bars that were used on other similar components of the bridges and under the same environmental conditions. Monitoring started in 2003, and annual visits took place during the initial 10 years, and then once in 2016 and once

more in 2019. The report indicates that they observed no difference in corrosion resistance between 2101LDX and black bars in the column and footings.

The report also indicated the following observations. Listed and reproduced from the report [11]:

- Chlorides have infiltrated the concrete on the columns, footings, and top and bottom surfaces of the deck, but the chloride content at the reinforcing steel depth in all of the components is still less than the corrosion threshold for black bars.
- No corrosion was found on the 2101LDX SS bars or MMFX bars that were exposed in cored holes. Although a minor amount of corrosion was observed on the black bars in the columns, footing, and deck, it is believed that the observed corrosion existed at the time of construction and is not the result of ongoing active corrosion.
- Corrosion potentials for the 2101LDX SS bars in the columns and footings are notably more negative than for the black bars, but currently there is no indication that the more negative potentials imply an earlier onset of corrosion will occur for the 2101LDX SS bars compared to the black bars.
- Corrosion potentials for the 2101LDX SS bars in the columns and footing at Pier 12 are more negative than those for the same type of bars in the columns and footing at Pier 11. The significance, if any, of this difference is unknown.

6.2.2 Jensen Beach Bridge– Potential vs. Height

This section presents the potential vs. height measured at the Jensen Beach Bridge columns that are instrumented. Bent 11 and Bent 12 contain 2101 rebars. The plots in Figure 6-6 and Figure 6-7 show the potential vs. height measured on columns of Bent 11 and Bent 12, respectively. One core was obtained during the July 2025 trip from Bent 11 south column south face. The chlorides profile measured on this core suggests that there are very little or no chlorides at the rebar depth (Figure 6-18). This is likely also the case at the other elevations. However, the rebar potentials are showing values that range between $-450 \text{ mV}_{\text{CSE}}$ to $-300 \text{ mV}_{\text{CSE}}$, which for carbon steel rebars would suggest active corrosion. It is hypothesized that the rebar from the footer is also not active, but due to oxygen concentration limitations the rebars at the footer are at a more negative potential. The footer rebars are likely polarizing the rebars in the column to the negative measured values. Passive stainless steel is polarized more easily at lower current levels than carbon steel. It is important to note that the concrete resistivity values measured on these columns (Figure 6-11 and Figure 6-12) suggest a dry concrete and/or with supplementary cementitious materials (most concrete resistivity values during the March 2025 visit were greater than $50 \text{ k}\Omega\text{-cm}$).

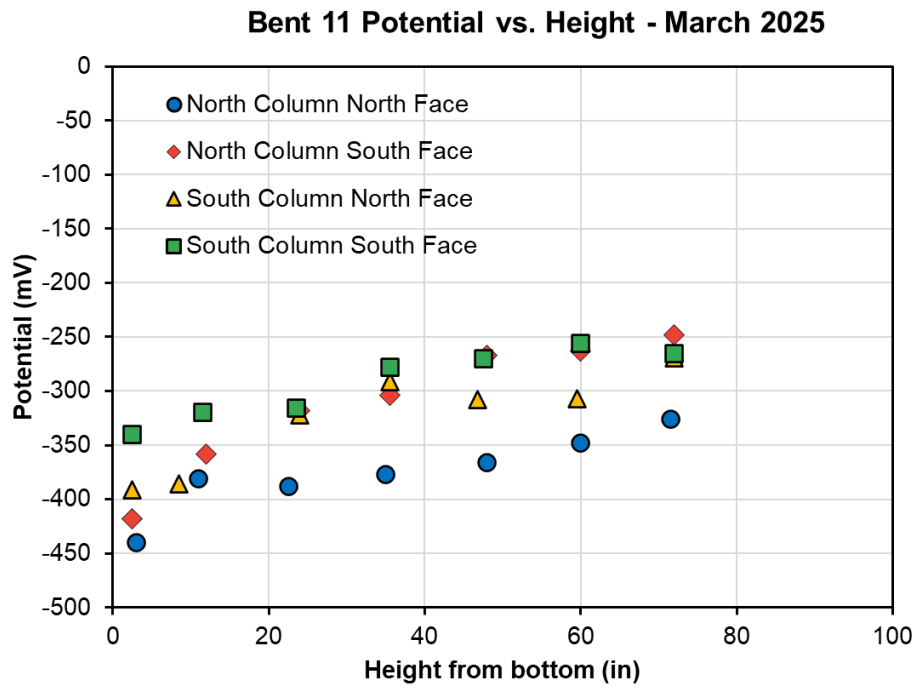


Figure 6-6. Bent 11 rebar potential vs. height.

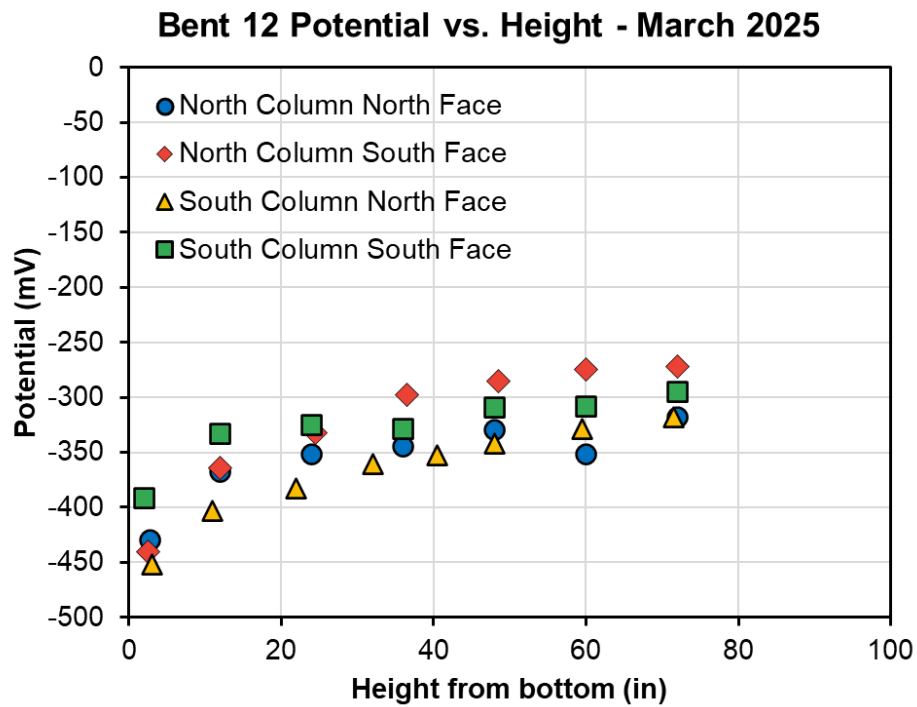


Figure 6-7. Bent 12 rebar potential vs. height.

During the visit on July 8, 2025, the FDOT field team brought one of its boats and measurements were made on the columns in Bent 10. The column in Bent 10 has carbon steel rebars, and except for the lowest elevation, all other rebar potential values were more positive than -250 mVcse. This can be observed from the plots in Figure 6-8. Figure 6-8 shows that at the lowest elevation the rebar ranged between -300 and -250 mVcse. It is known that carbon steel rebars require more current to be polarized when compared to stainless steels.

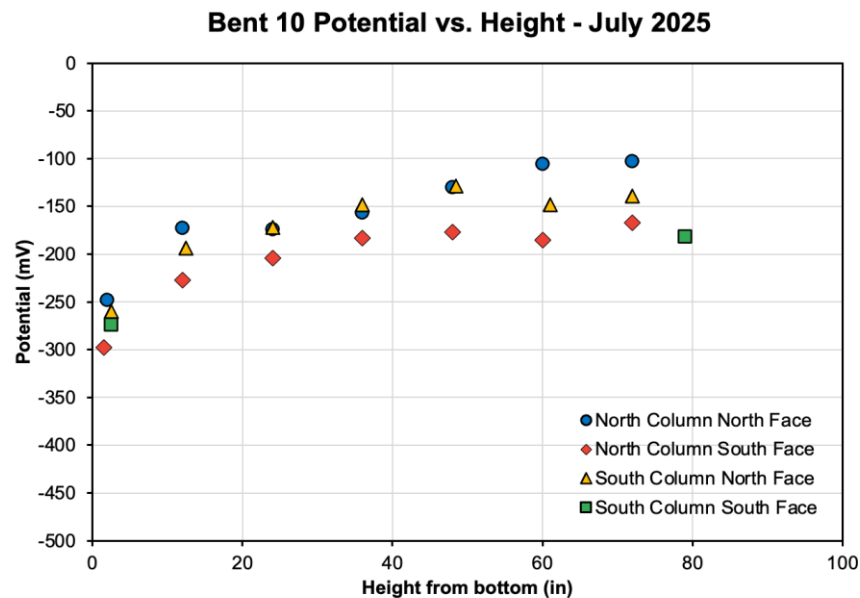


Figure 6-8. Bent 10 rebar potential vs. height.

Figure 6-9 and Figure 6-10 show the rebar potential vs. height measured during the July 2025 visit on the columns from Bent 11 and Bent 12, respectively. The rebar potential values measured during the July trip are comparable to those measured during the March 2025 visit (all rebar potential values shown in this chapter are vs. CSE).

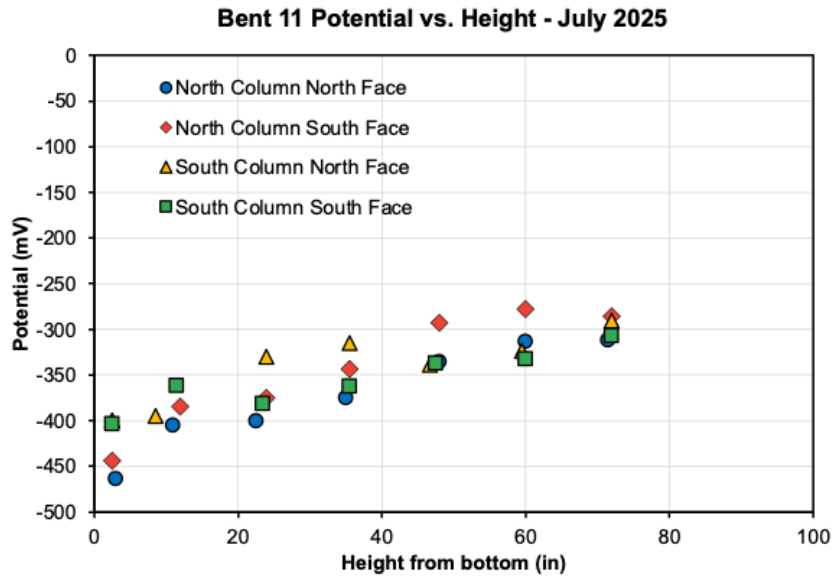


Figure 6-9. Bent 11 rebar potential vs. height.

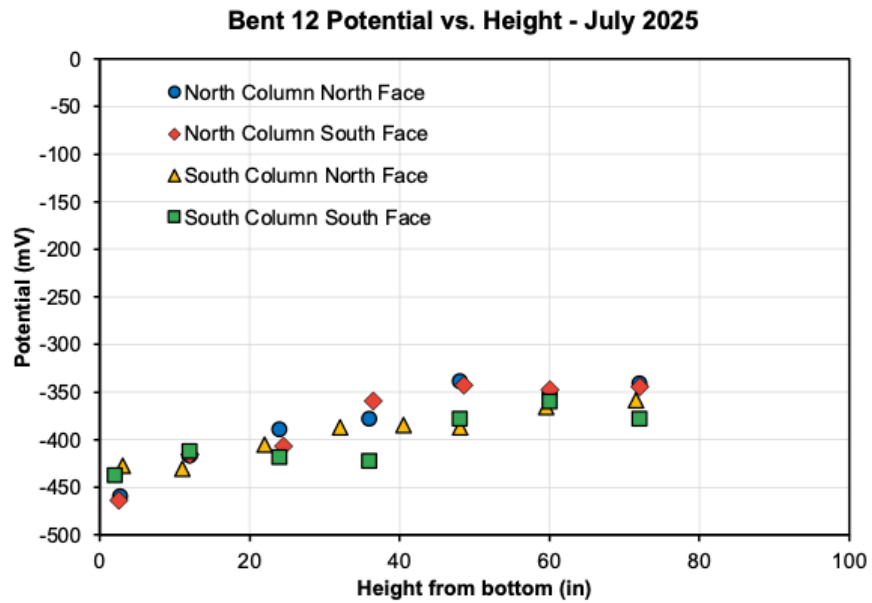


Figure 6-10. Bent 12 rebar potential vs. height.

6.2.3 Concrete Resistivity Measured on the Columns of the Jensen Beach Bridge

Concrete resistivity values were measured on the columns. A proceq resistivity meter was used to measure the surface resistivity on the columns. During the trip that took place March 2025, only columns in Bents 11 and Bent 12 were measured. Whereas during the trip that took place July 8, 2025: the resistivity of columns in Bent 10 were also measured.

Figure 6-11 and Figure 6-12 show the concrete resistivity vs. height measured on the columns of Bent 11 and Bent 12, respectively. The values in most cases were greater than 50 KΩ-cm. The exception was the concrete on the North column North face from Bent 12, which displayed values ranging from 15 KΩ-cm to 72 KΩ-cm.

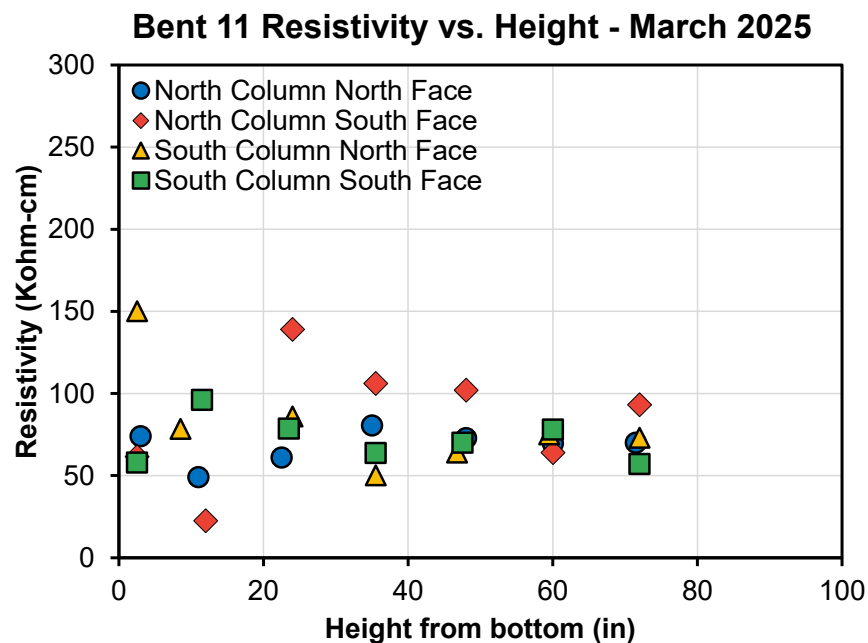


Figure 6-11. Bent 11 concrete resistivity vs. height.

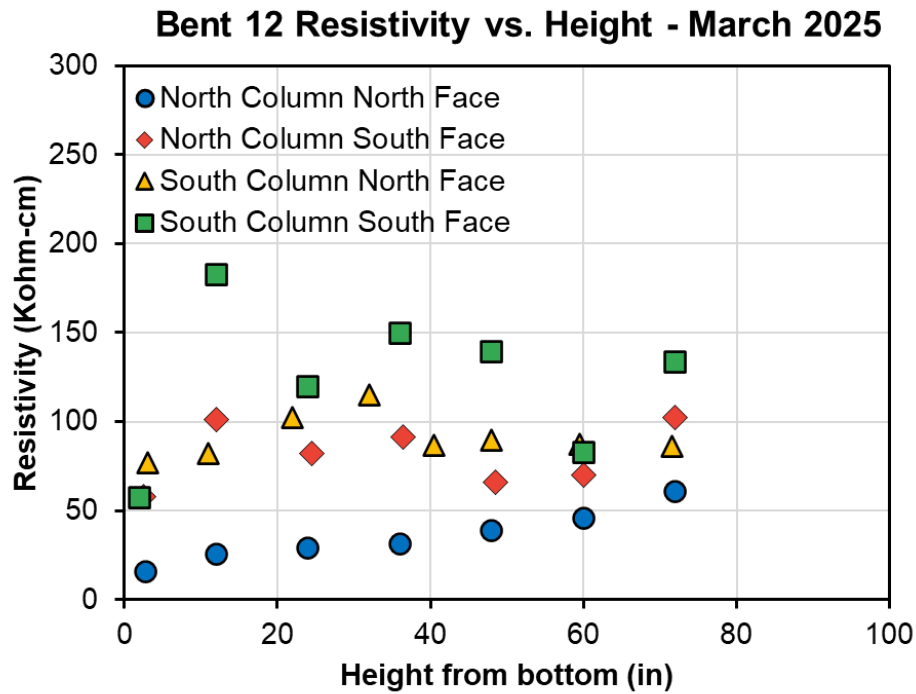


Figure 6-12. Bent 12 concrete resistivity vs. height.

Figure 6-13 shows the concrete resistivity measured on the columns with carbon steel rebar located on Bent 10. The smallest value was measured on the North Column North face at 60 inch elevation was 33 KΩ-cm. Most values were greater than 50 Kohm-cm and in some cases were as high as 150 KΩ-cm. The range of values suggest that the moisture content varies greatly from column to column, and also with elevation. Figure 6-14 and Figure 6-15 shows the concrete resistivity values measured on the columns of Bent 11 and Bent 12, respectively. The concrete resistivity values tended to be somewhat higher at some elevations during the July visit compared to the values measured during the March visit. During the July visit, the Bent 12 North Column North Face showed values close to 100 KΩ-cm.

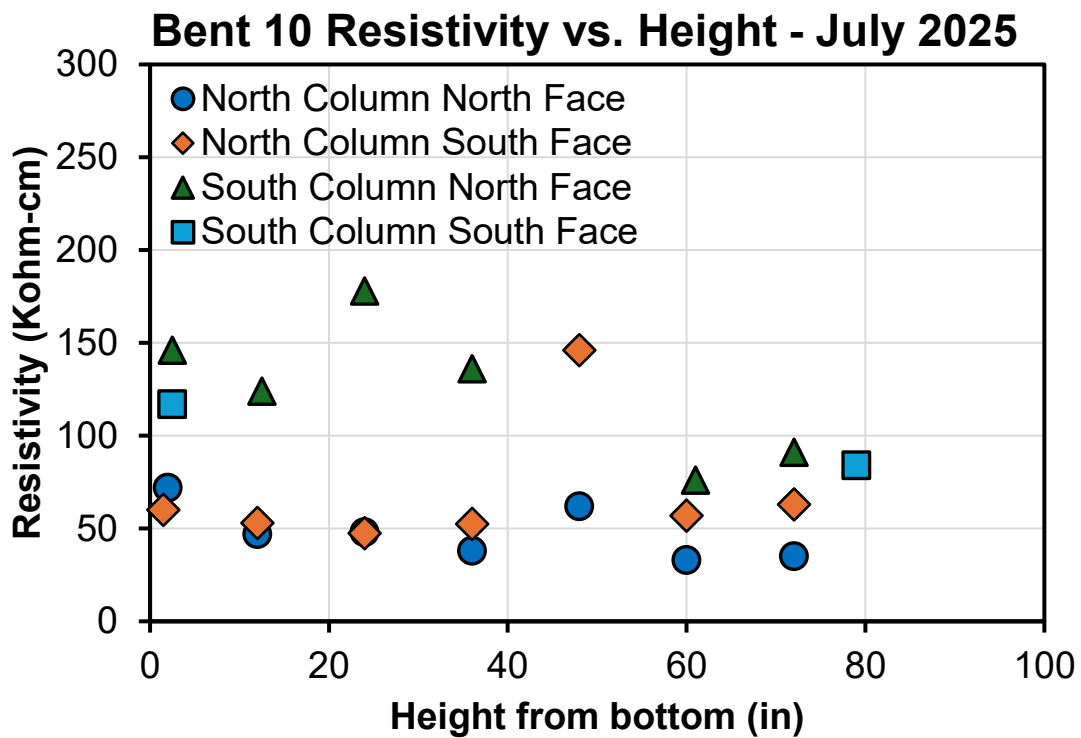


Figure 6-13. Bent 10 concrete resistivity vs. height.

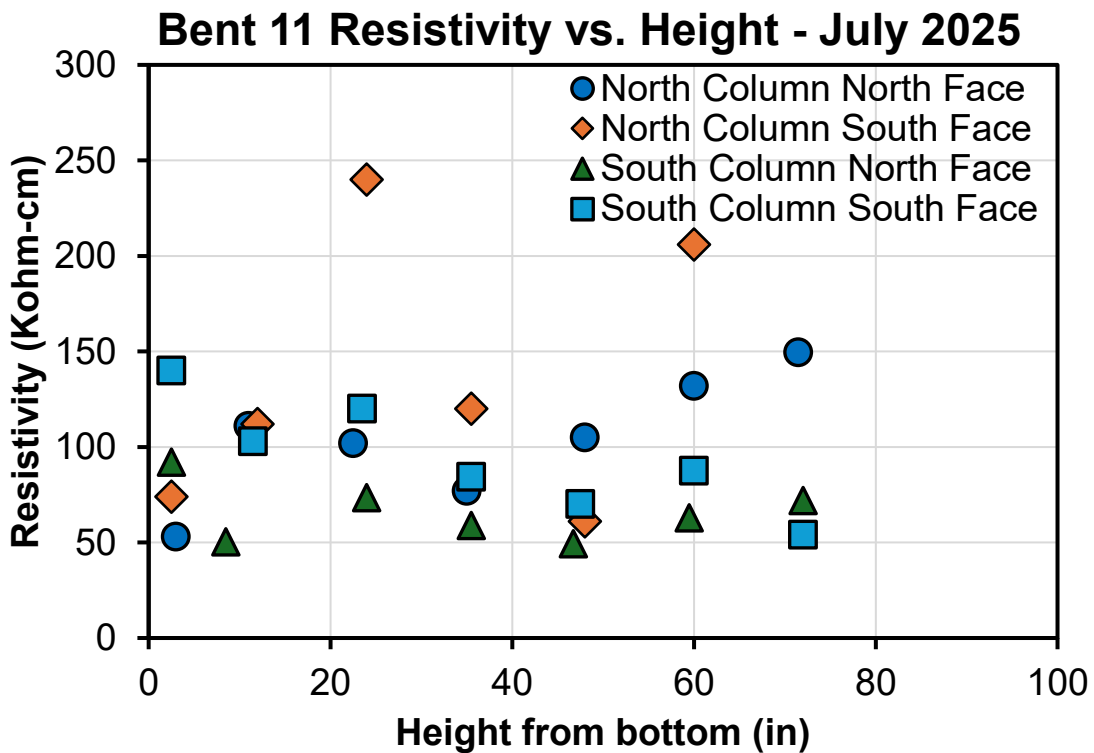


Figure 6-14. Bent 11 concrete resistivity vs. height.

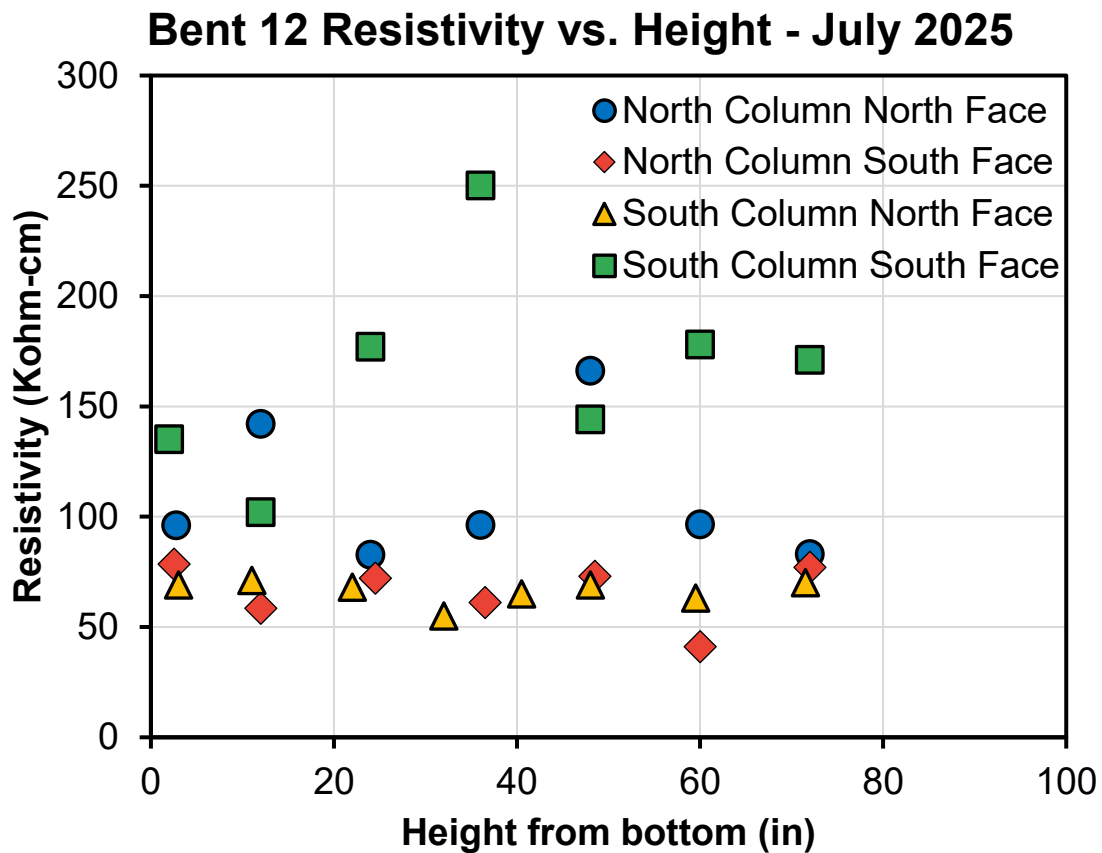


Figure 6-15. Bent 12 concrete resistivity vs. height.

6.2.4 Chloride Profiles for Jensen Beach Bridge Samples

This section presents the chloride profiles for cores taken from the Jensen Beach Causeway Bridge site. Figure 6-16 depicts the chloride profile for a core taken from the north footer of bent 11, 25 inches above the marine growth. Figure 6-17 depicts the chloride profile for another core taken from the north footer of bent 11, 5 inches above the marine growth. Figure 6-18 depicts the chloride profile for a core taken from the south face of the south column of bent 11, 12 inches above the bottom of the column. Each of the core profiles followed a pattern of exhibiting high chloride concentration near the surface, generally decreasing with depth into the concrete.

Figure 6-16 and Figure 6-17 reveal that the chloride concentration decreased significantly faster with depth for the north footer core 25 inches above the marine growth compared to the core from the same footer 5 inches above the marine growth. As Figure 6-17 demonstrates, the chloride concentration for the core 5 inches above the marine growth hovers consistently near 30 kg/m³ for the first 10 mm. This is likely because the area closer to the marine growth remains submerged or wet for longer periods of time, resulting in a higher chloride surface concentration that then appears to have penetrated about 10 mm. On the other hand, because the area at the

higher elevation experiences more wetting and drying cycles, the chloride surface concentration is higher, and thus Figure 6-16 shows that the concentration decreases by over half in the same depth range of 0 mm to 10 mm. There appears to be a local maximum at 15 mm depth.

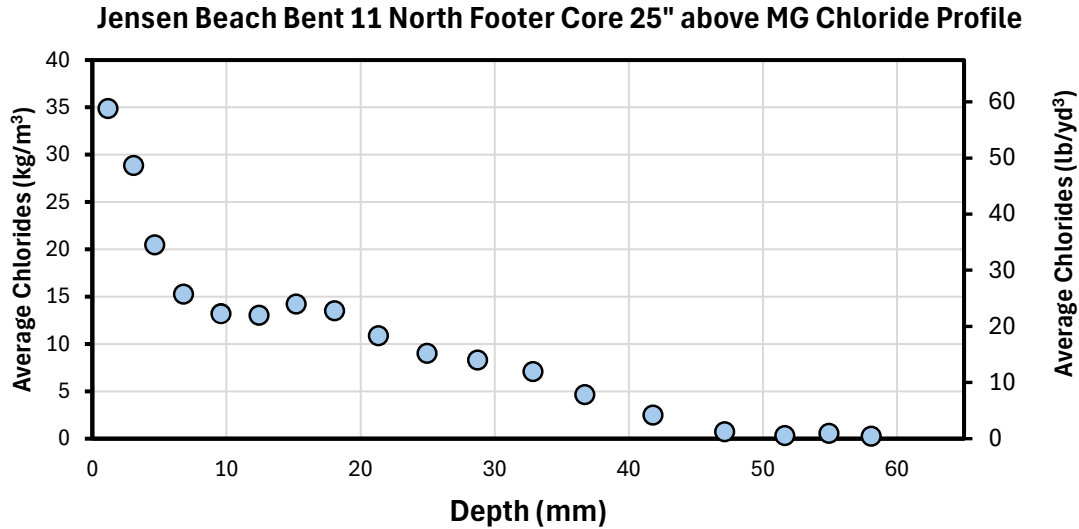


Figure 6-16. Chloride profile of Jensen Beach bent 11 north footer core (25" above marine growth).

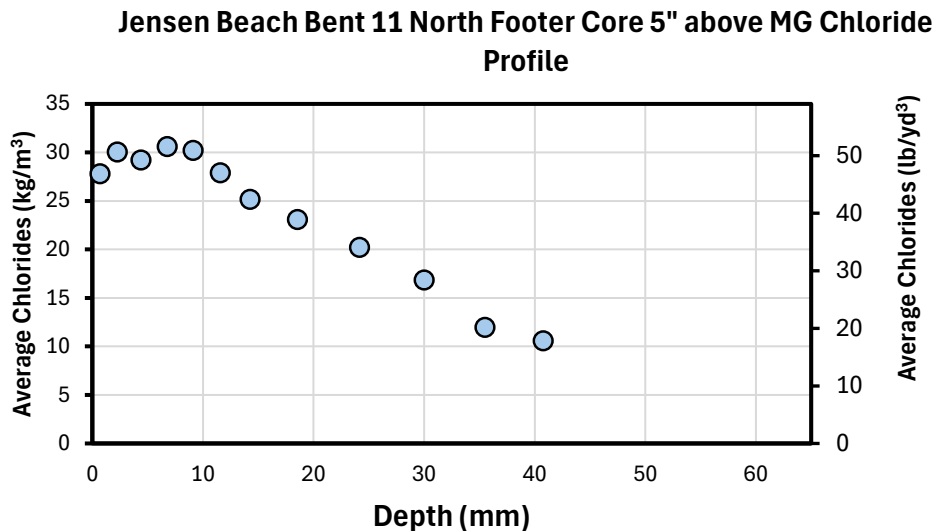


Figure 6-17. Chloride profile - Jensen Beach bent 11 north footer core (5" above marine growth).

The chloride profile from the core obtained on the column is a few feet above the footer and the chlorides likely reach the surface from ocean spray (breaking of the waves on the footer). The columns have a paint coating that might have slowed the chloride penetration, but it can be observed in Figure 6-18 that there is a considerable chloride amount that has penetrated the first

20 mm of the concrete. If the rebar depth is 75 mm (i.e. 3 inches), then the chloride at the rebar depth is expected to be very low currently. The Dapp (apparent diffusion coefficient) was calculated assuming 21 years of exposure, a Co of 0.2 kg/m³. Table 6-1 shows the calculated Cs, Dapp in cm²/s and in in²/year, as well as the residual and the number of layers removed (#LaRem – Number of Layers Removed) to obtain a good fit.

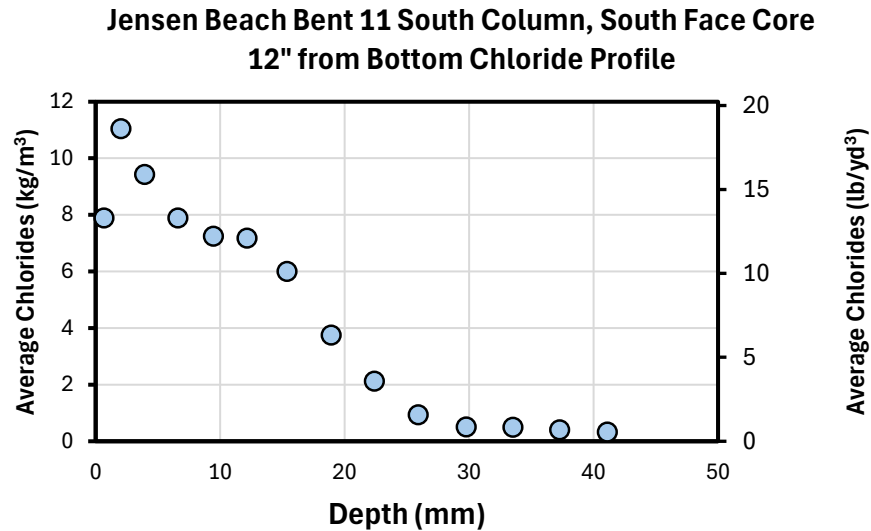


Figure 6-18. Chloride profile of Jensen Beach bent 11 south column, south face core (12" above bottom).

Table 6-1. Jensen Beach bent 11, D_{app} from cores obtained.

Core Location	Cs (kg/m ³)	Dapp (cm ² /s)	Dapp in ² /y	Residual	#LaRem
N Footer 5" above MG	34.9	1.23E-08	0.06	14.053	2
N Footer 25" above MG	17.8	1.25E-08	0.06	8.291	3
S Column	12.2	2.24E-09	0.01	6.381	2

6.3 SUMMARY

The rebars at instrumented columns at the Jensen Beach Bridge do not seem to be corroding, based on the chloride concentration observed at the rebar depth. The 2101LDX duplex stainless steel rebars in the columns show negative rebar values, but are not believed to be due to active corrosion, rather the passive stainless steel is being polarized by the rebars in the footers (that are under saturated concrete and likely under mass transport limitations causing low rebar potential).

7 FORENSIC ANALYSIS – SDS SAMPLES

This chapter presents the forensic analysis performed on the SDS samples that were terminated. The initial section is upon terminating the samples, followed by a section after removing the rebar and cleaning the rebars. Several images in these sections were previously published in the 2026 AMPP conference proceedings [18]. The final section presents average chloride concentrations of milled rebar traces.

7.1 REBAR CONDITION UPON EXPOSURE

7.1.1 4-CCRV-3CR12-2

This section presents photos of sample 4-CCRV-3CR12-2 immediately after termination, including each rebar and its rebar trace in the concrete. Figure 7-1 presents the top-facing side of the top row of rebars while Figure 7-2 shows the bottom-facing side of the top row. Because this sample had a simulated crevice, there are 6 rebars in the top row instead of 3. The top-facing side displayed the most severe corrosion, concentrated near the midpoint of the rebars. This is because the sample also had a simulated crack, which helped facilitate the initial chloride ingress. Red rust stains appear on both the concrete and the rebars. Extensive pitting and cross-section loss is present on the top-facing side of all the rebars in the top row, with rebars B1 and B2 having the most severe pits. As Figure 7-1 shows, the corrosion products that accumulated on rebars B1 and B2 caused a large crack inside the concrete. Figure 7-2 shows that no or very little corrosion is apparent on the bottom-facing sides of the rebars. As expected, corrosion was present at the exposed ends of each rebar (outside the concrete) in both the top and bottom rows.

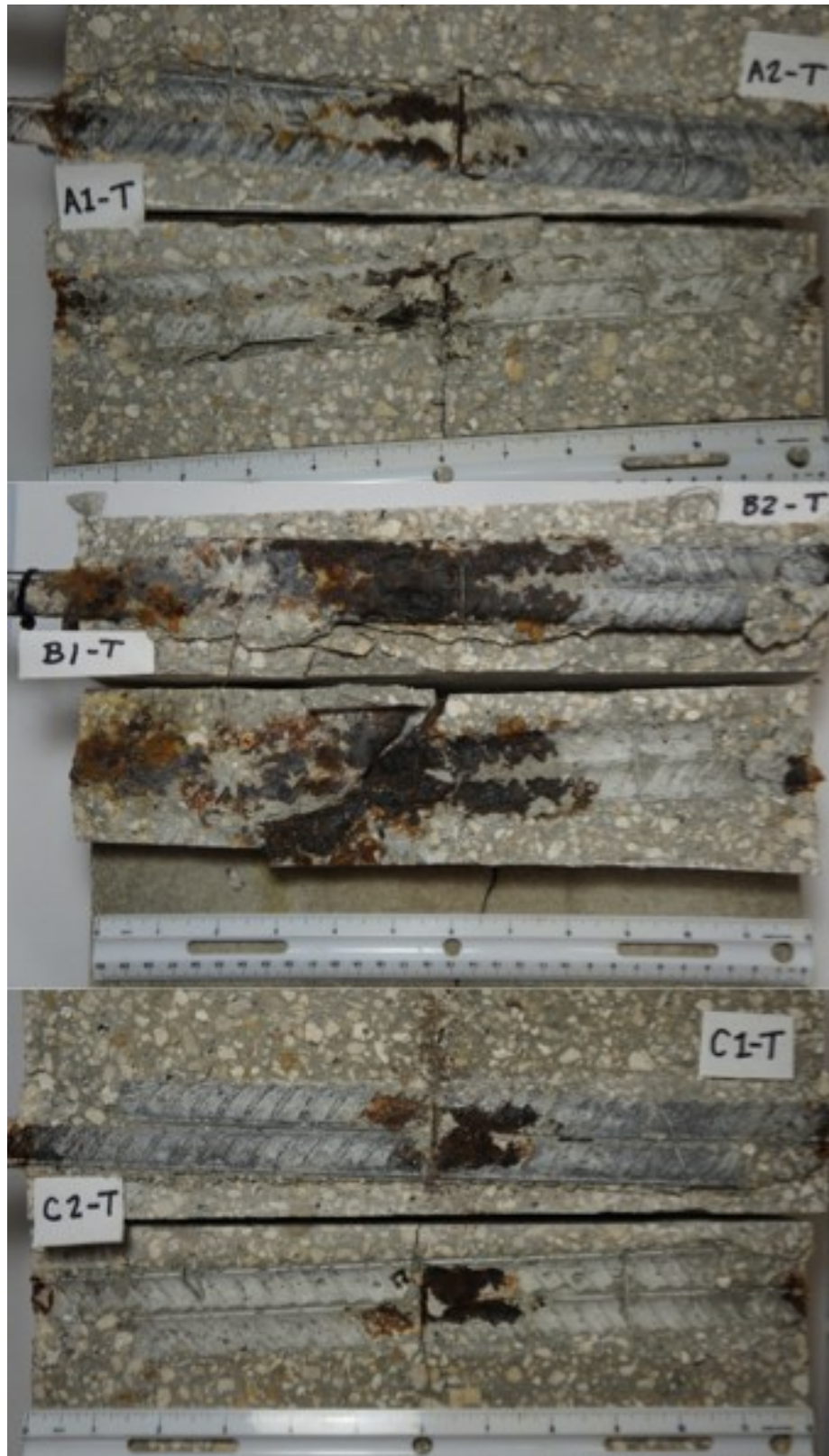


Figure 7-1. 4-CCRV-3CR12-2 top row, top-facing rebars and concrete rebar traces.

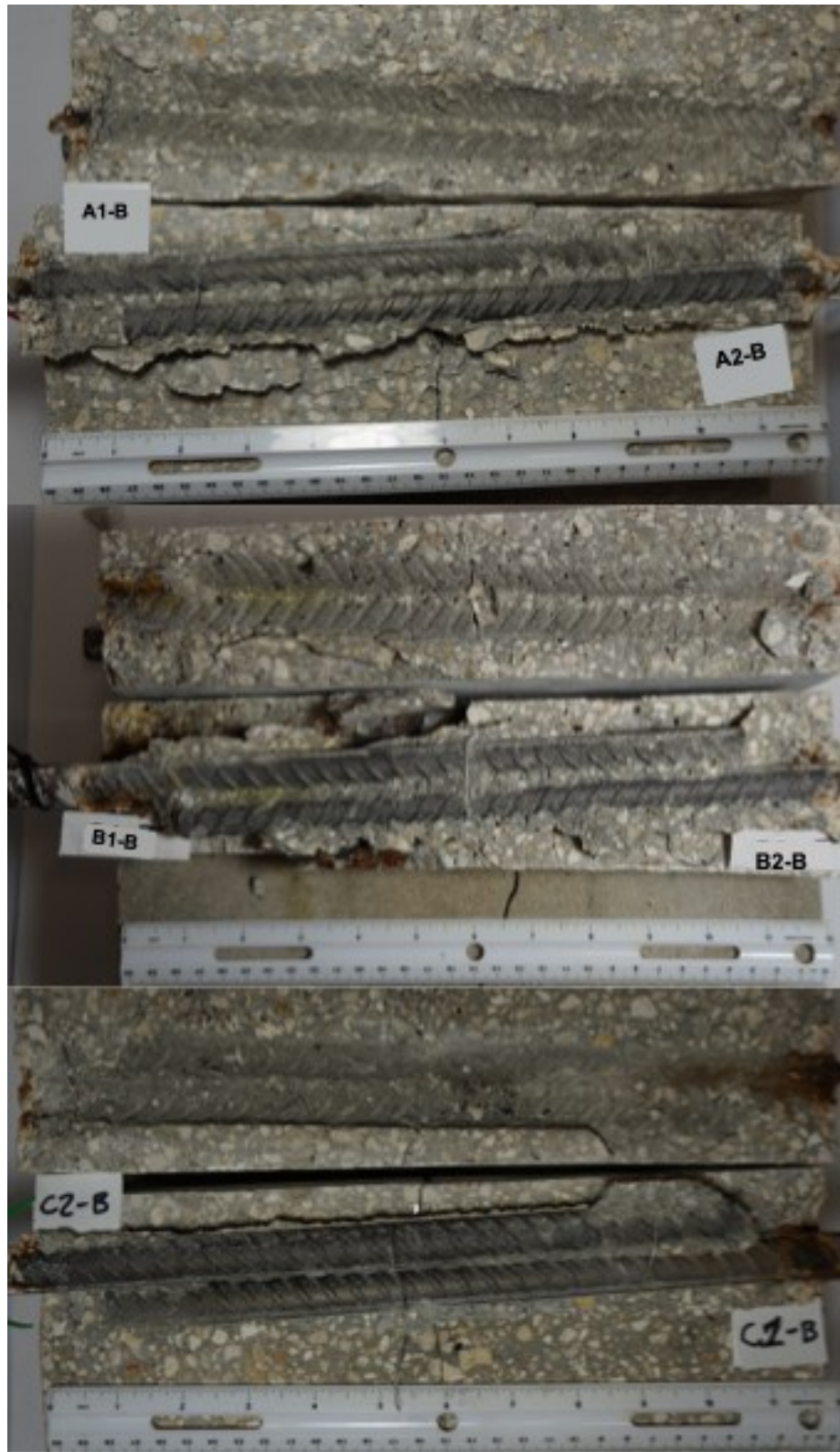


Figure 7-2. 4-CCRV-3CR12-2 top row, bottom-facing rebars and concrete rebar traces.

Figure 7-3 shows the top-facing side of the bottom row of rebars while Figure 7-4 shows the bottom-facing side of the bottom row. Similar to the top row, the top-facing rebar side of the bottom row displayed significantly more corrosion than the bottom-facing side. Red rust stains appear on the top faces of rebars D and E and their rebar traces. Rebars D and E displayed several pits on their top faces. Figure 7-3 shows that rebar E showed the most severe corrosion out of the three rebars in the bottom row likely because it was directly under rebars B1 and B2. Figure 7-4 shows that the bottom-facing side of rebar E had one area with red rust stain in the rebar close to the concrete end. The bottom side of rebar D showed little to no corrosion. Similarly, rebar F showed not to very little corrosion, both on its top face and bottom face.



Figure 7-3. 4-CCRV-3CR12-2 bottom row, top-facing rebars and concrete rebar traces.

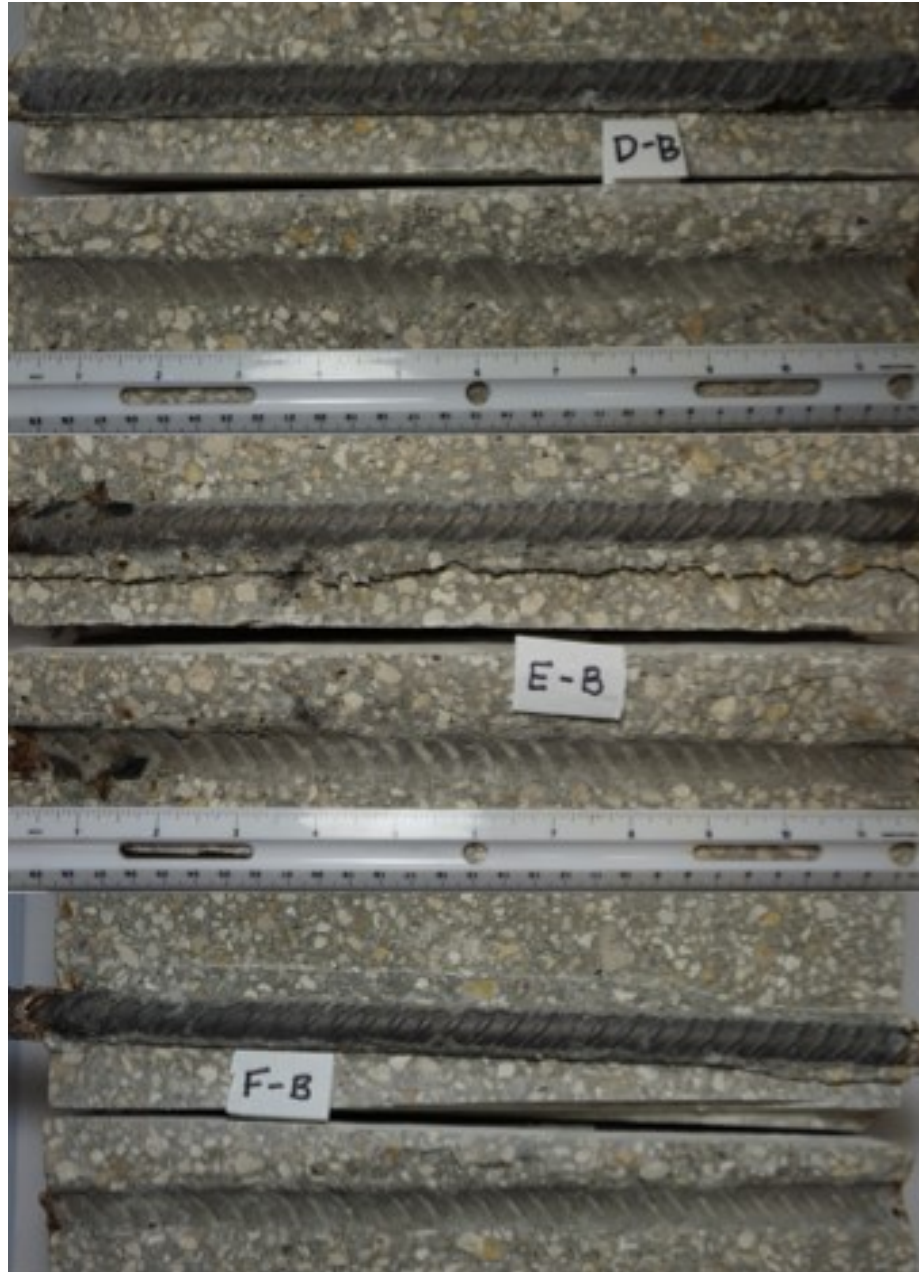


Figure 7-4. 4-CCRV-3CR12-2 bottom row, bottom-facing rebars and concrete rebar traces.

7.1.2 CREV-CT2-2

This section presents photos of sample CREV-CT2-2 immediately after termination, including each rebar and its rebar trace in the concrete. Figure 7-5 presents the top-facing side of the top row of rebars while Figure 7-6 shows the bottom-facing side of the top row. This sample also had a simulated crevice. Rust stains on the rebars and cracks in the concrete are evident on both the top-facing and bottom-facing sides, concentrated near the ends of the rebar. Because the 316 cladding did not cover the ends of the rebars (i.e., no end-caps were used), the carbon steel core was exposed and began corroding, both inside and outside of the concrete. The end of rebar B1

that was embedded in the concrete within the solution reservoir showed evidence of corrosion and corrosion product buildup, which likely caused the crack in the concrete seen in Figure 7-5. The rebar ends embedded in the concrete were within the solution reservoir above. Rust stains in the concrete are evident from the bottom faces of the rebars in Figure 7-6 but are not as severe as the top faces. Figure 7-5 and Figure 7-6 both show that the clad portions of the rebars remained in good condition and did not show any evidence of corrosion.

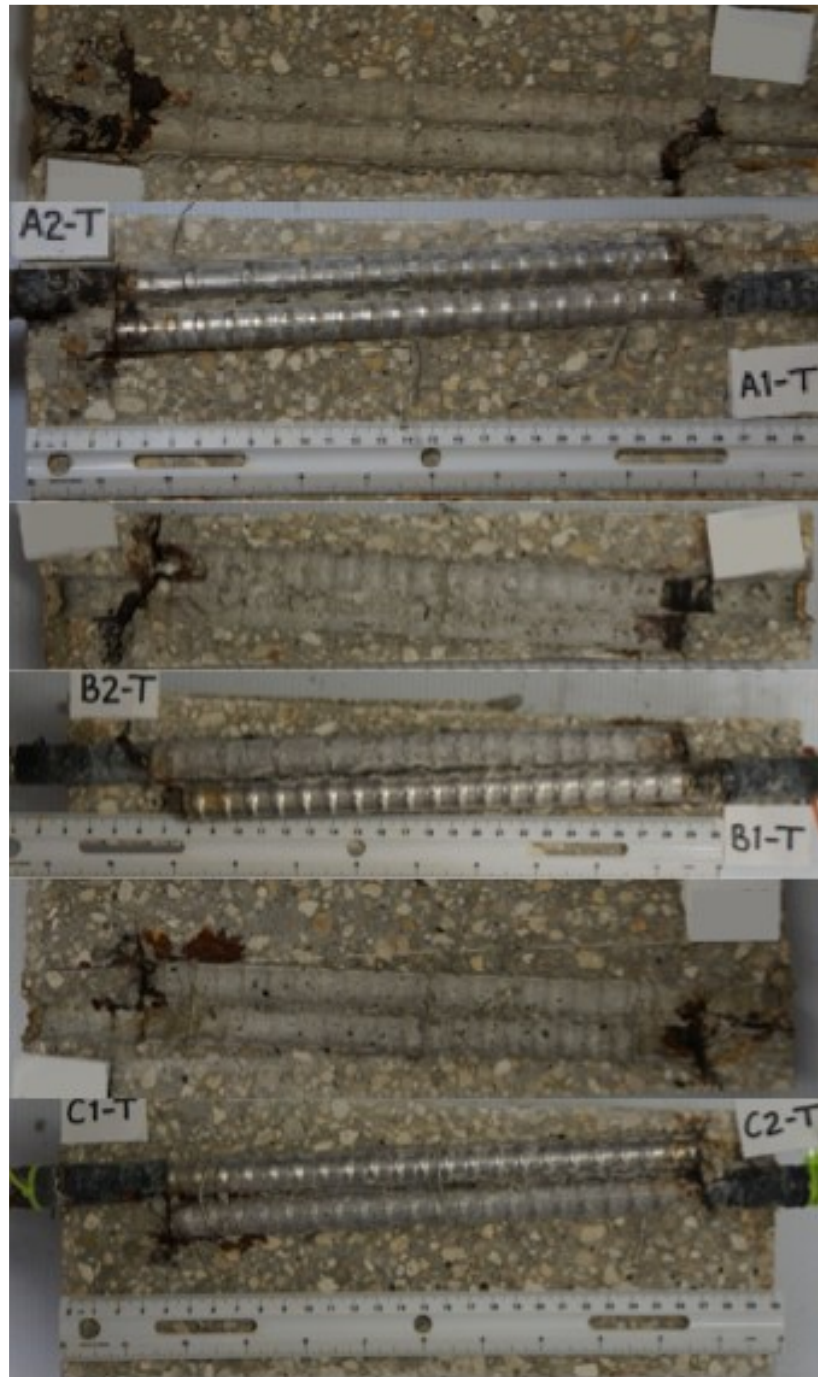


Figure 7-5. CREV-CT2-2 top row, top-facing rebars and concrete rebar traces.

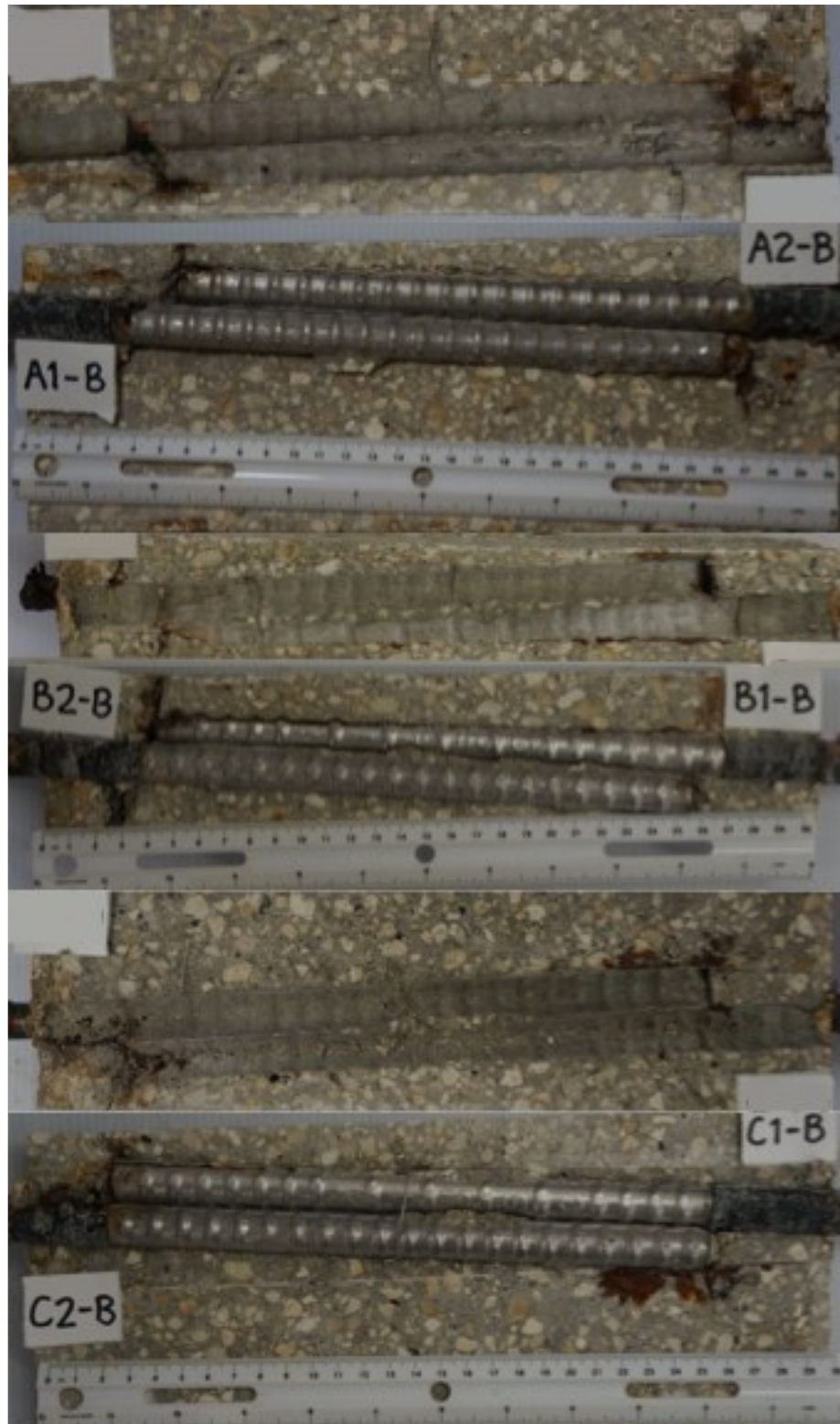


Figure 7-6. CREV-CT2-2 top row, bottom-facing rebars and concrete rebar traces.

Figure 7-7 presents the top-facing side of the bottom row of rebars while Figure 7-8 shows the bottom-facing side of the bottom row. The uncovered ends of the rebars showed evidence of corrosion, which is expected given their exposure to the environment. The portions of rebar inside the concrete showed no corrosion. The rebars had shrinkage sleeves on each end.

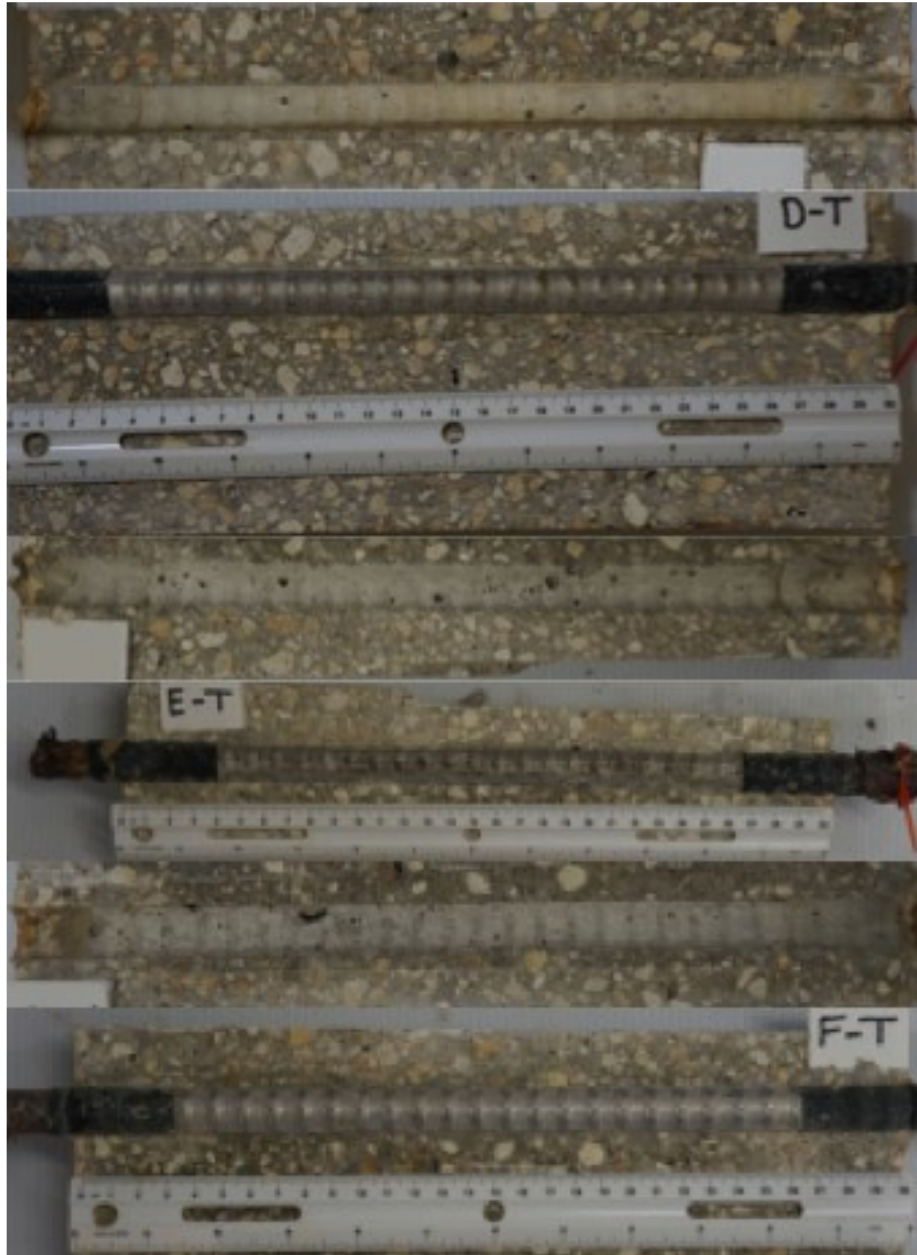


Figure 7-7. CREV-CT2-2 bottom row, top-facing rebars and concrete rebar traces.

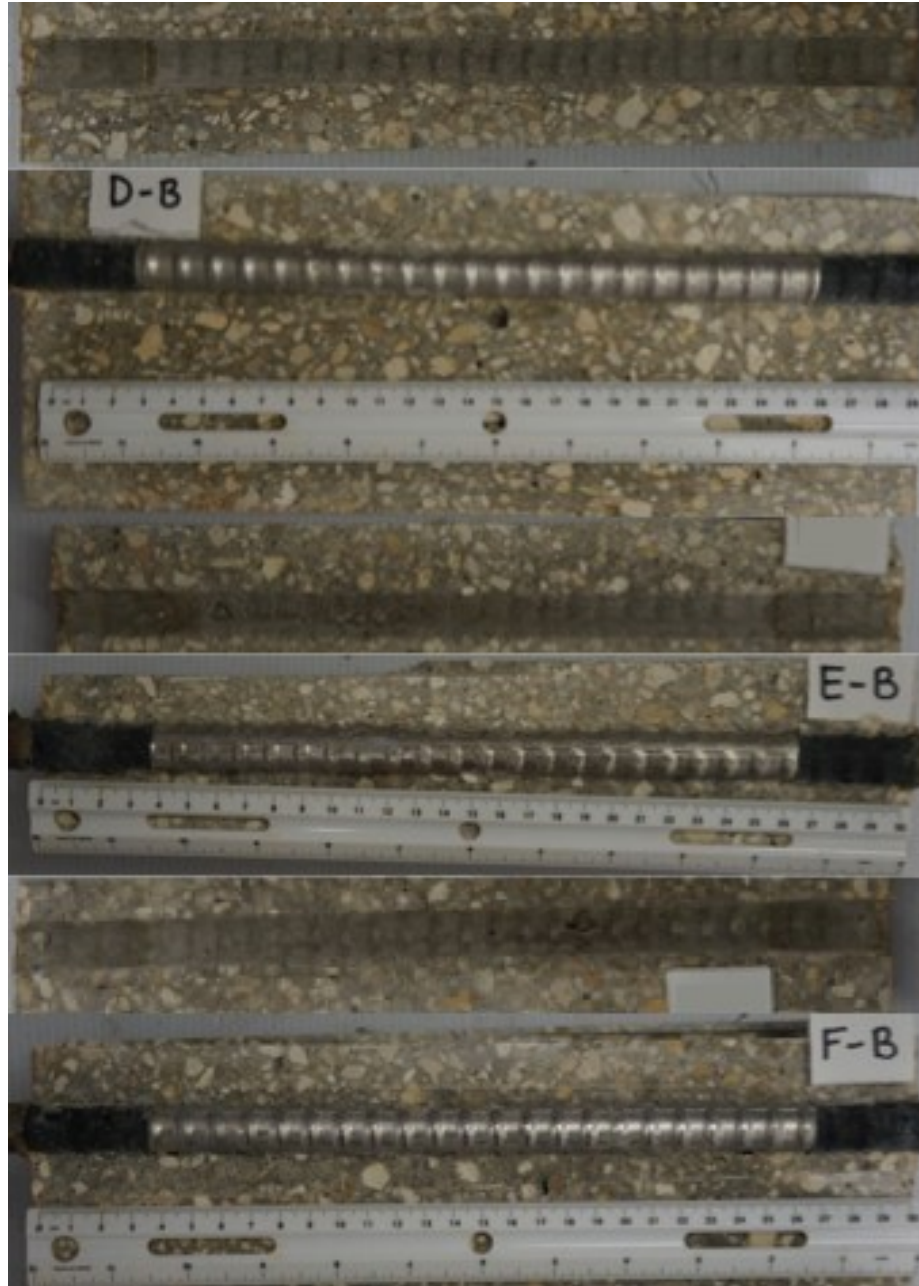


Figure 7-8. CREV-CT2-2 bottom row, bottom-facing rebars and concrete rebar traces.

7.1.3 4-CCON-CT2-1

This section presents photos of sample 4-CCON-CT2-1 immediately after termination, including each rebar and its rebar trace in the concrete. In this sample, only rebars C and consequently F were terminated. Rebar C showed consistently more negative corrosion potential values and corrosion rates than the other two rebars in the top row. Figure 7-9 shows the top-facing sides of rebars C and F as well as their concrete rebar traces. The simulated crack in the concrete surface is visible in rebar C's rebar trace. Rust stains are also apparent in this sample as shown in the concrete rebar trace of C in Figure 7-9 about 3 inches (7.6 cm) away from the simulated crack in

the center. The top-facing side of rebar C shows a corrosion spot on the cladding, which caused the rust stain on the concrete. The crack in the concrete facilitated chloride ingress, however the rust spot is away from the simulated crack. It is hypothesized that a defect in the clad allowed corrosion to initiate at that location. No signs of corrosion are visible on the top-facing side of rebar F.

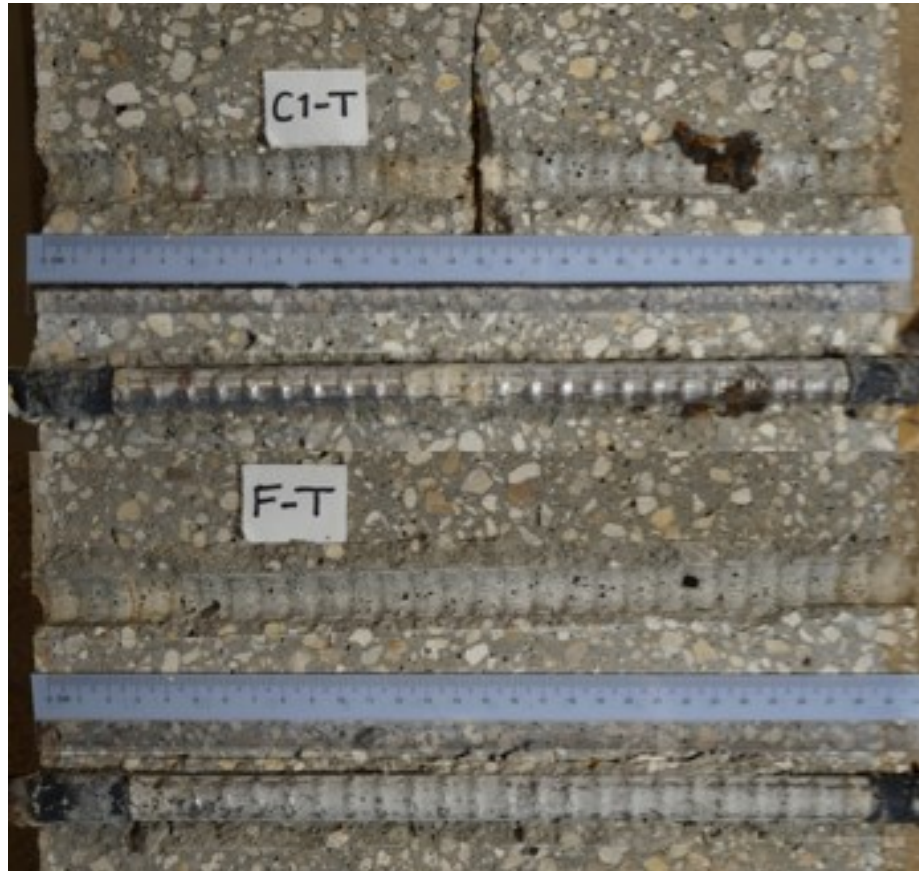


Figure 7-9. 4-CCON-CT2-1 top-facing, top and bottom rebars and concrete rebar traces.

Figure 7-10 shows the bottom-facing sides of rebars C and F as well as their concrete rebar traces. The simulated crack in the concrete surface is again visible under rebar C. More rust stains are apparent in the concrete rebar trace of C, close to the shrinkage sleeve. The bottom-facing side of rebar C shows corrosion on the end of the rebar. It is possible that the corrosion stain close to the shrinkage wrap was due to crevice corrosion. Outside of the concrete, corrosion on the uncoated rebar ends likely initiated because the carbon steel core was exposed. No signs of corrosion are visible on the bottom-facing side of rebar F.

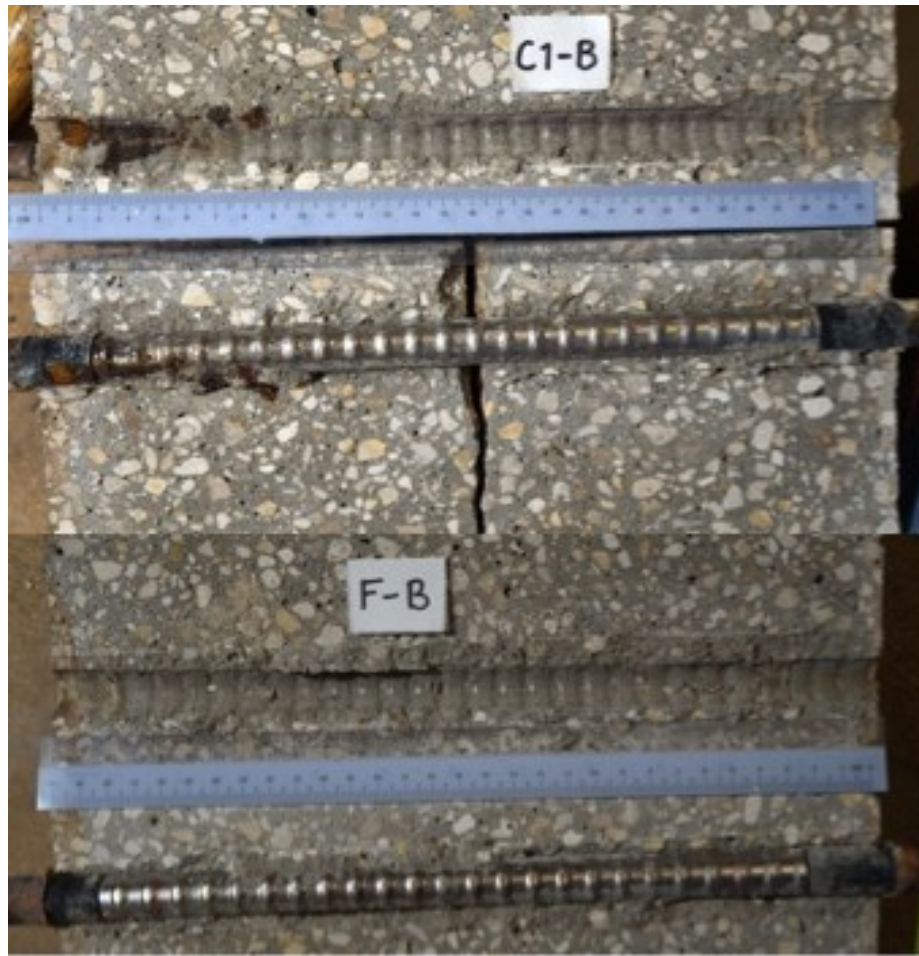


Figure 7-10. 4-CCON-CT2-1 bottom-facing, top and bottom rebars and concrete rebar traces.

7.1.4 BCCD-CT2-1

This section presents photos of sample BCCD-CT2-1 after termination, including each rebar and its rebar trace in the concrete. During the preparation of this sample, holes of 3 mm diameter were drilled in the cladding 25 mm apart. The rebars in the bottom row are black steel with no cladding. Figure 7-11 and Figure 7-12 show the top-facing and bottom-facing sides, respectively, of the top row of rebars. Figure 7-11 shows that corrosion appears to be concentrated around the drilled holes, where chlorides were able to reach the carbon steel core. There are several rust stains on the concrete, stemming from the corrosion on the rebar. Corrosion stains are observed on the 316 cladding surrounding the holes. The bottom faces also showed corrosion around the holes, but they were less severe than the top side. The exception to this is the bottom of rebar B, under which a large crack formed, as Figure 7-12 shows. The crack was likely caused by corrosion of the carbon steel rebar E, from the bottom row.

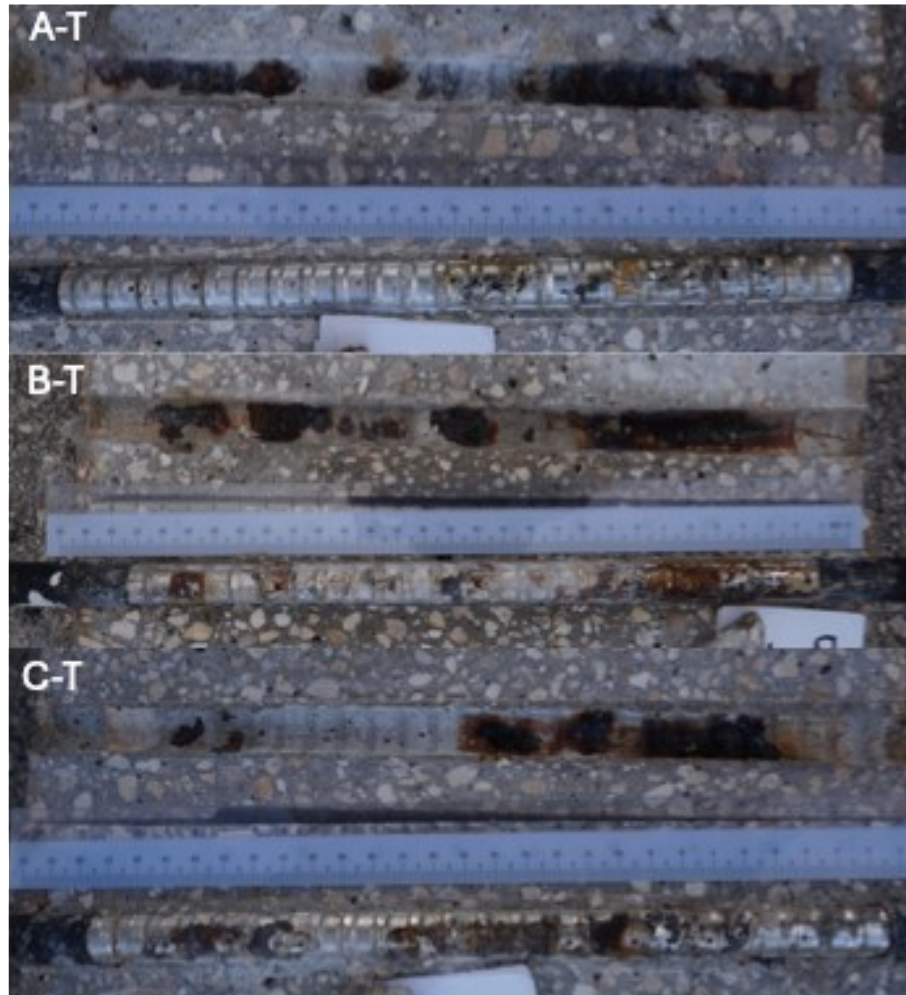


Figure 7-11. BCCD-CT2-1 top-facing, top rebars and concrete rebar traces.

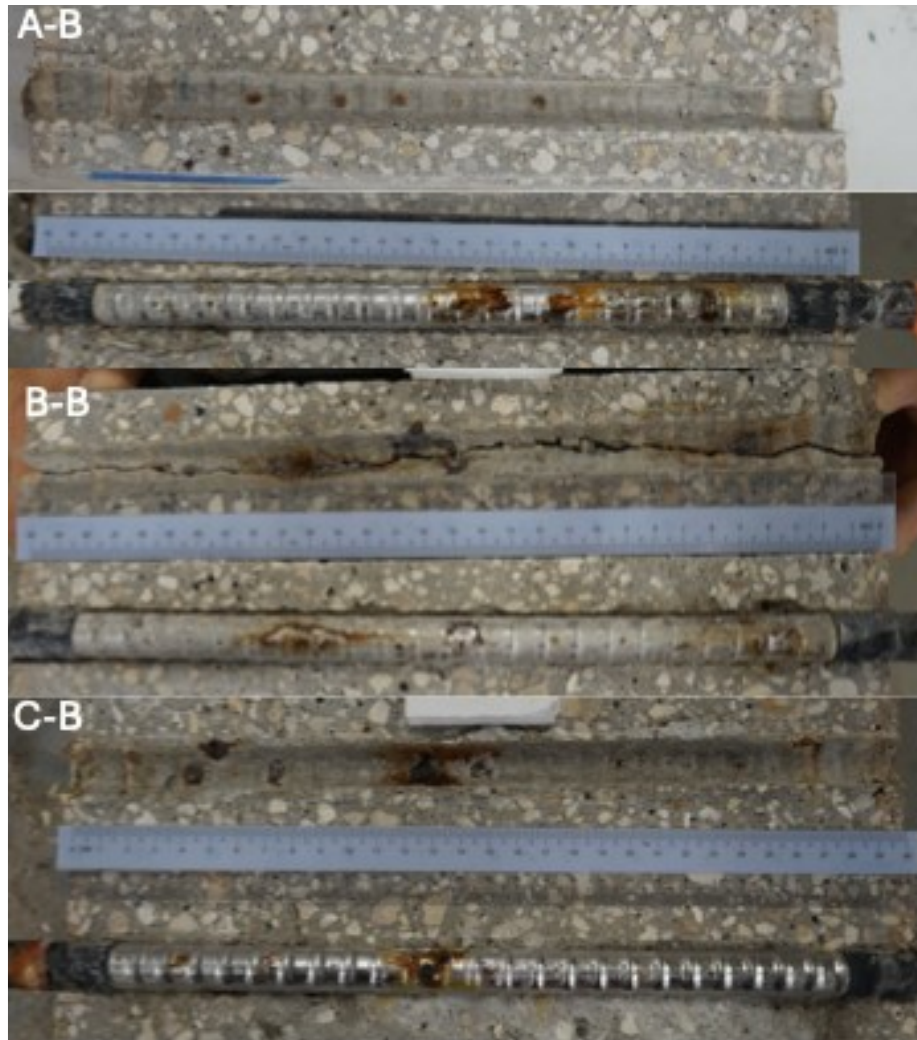


Figure 7-12. BCCD-CT2-1 bottom-facing, top rebars and concrete rebar traces.

Figure 7-13 and Figure 7-14 show the top-facing and bottom-facing sides, respectively, of the bottom row of carbon (black) steel rebars. Extensive corrosion is evident in these photos. Each rebar showed severe mass loss on the exposed ends and substantial corrosion product accumulation along the entire length of each rebar. The concrete trace of each rebar was thoroughly stained with rust. Several sections with cross-section loss were apparent on each rebar. Rebar E appeared to experience the most severe damage, which probably caused the previously mentioned crack above it (caused by Rebar E).

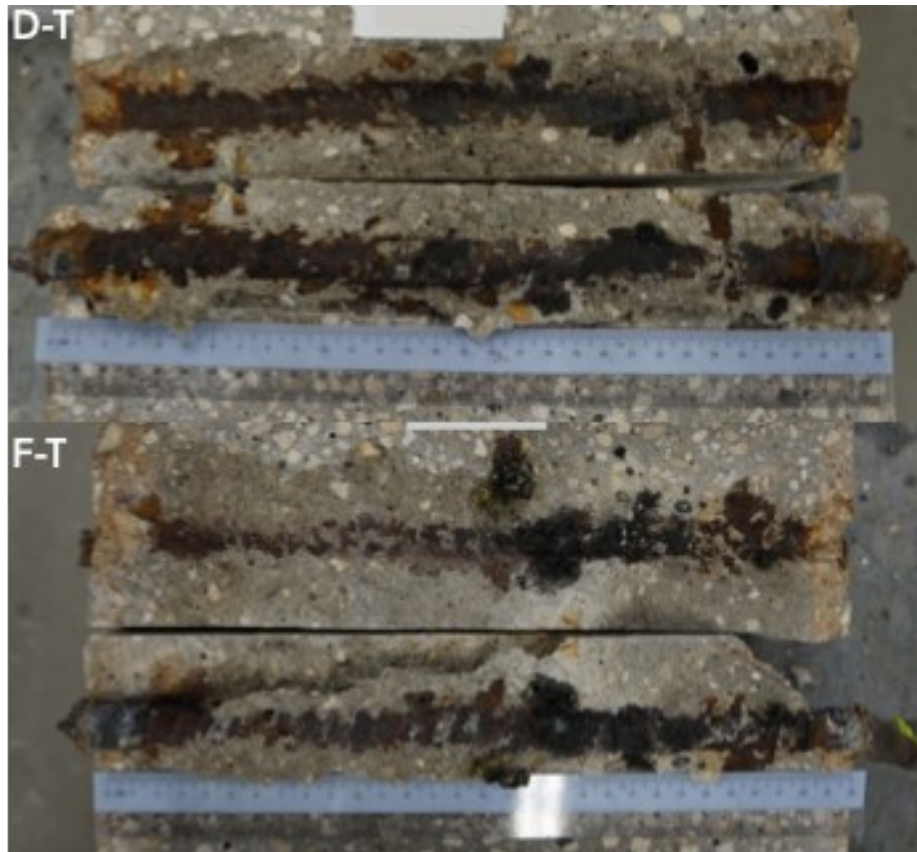


Figure 7-13. BCCD-CT2-1 top-facing, bottom rebars and concrete rebar traces.

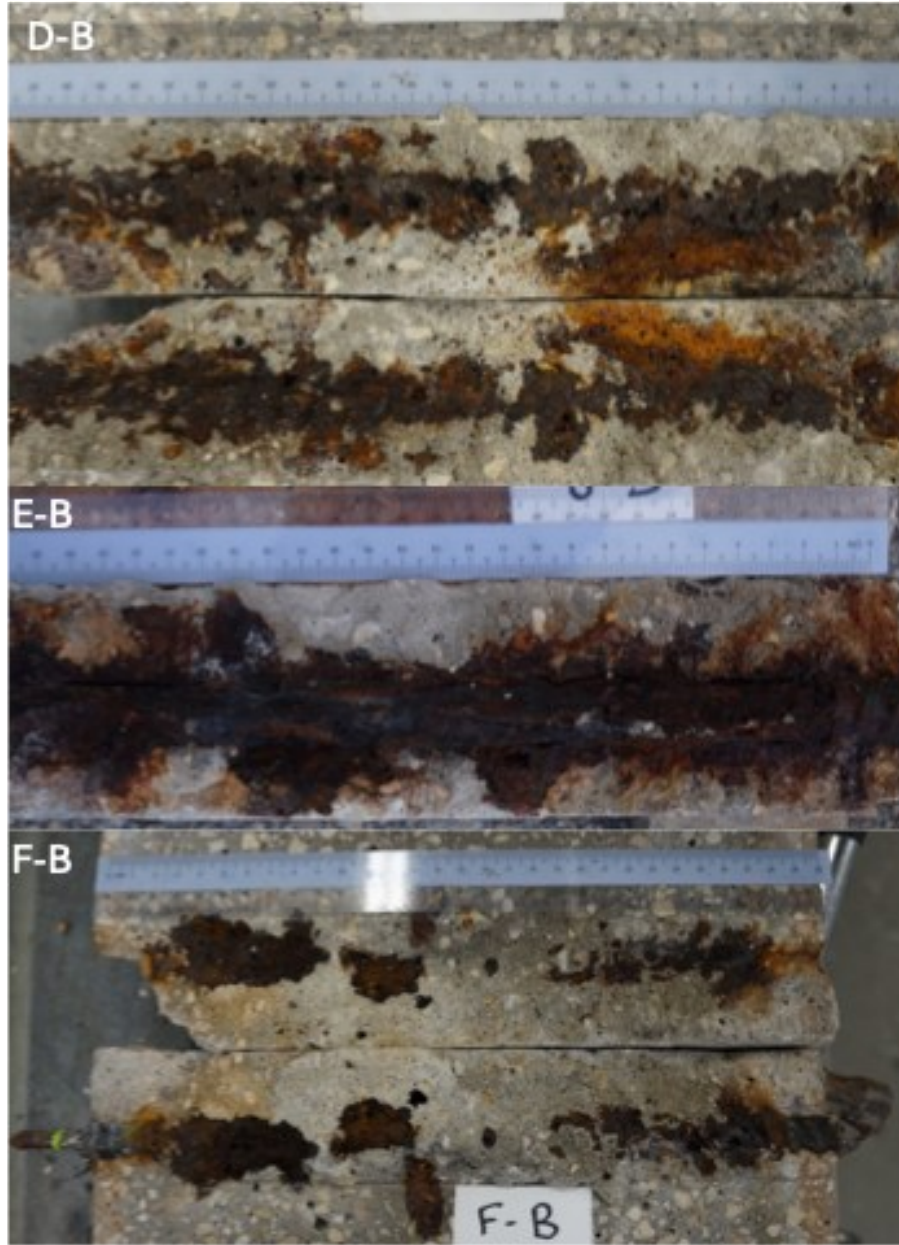


Figure 7-14. BCCD-CT2-1 bottom-facing, bottom rebars and concrete rebar traces.

7.1.5 CSDB-CT2-1

This section presents photos of sample CSDB-CT2-1 after termination, including each rebar and its rebar trace in the concrete. This sample was also prepared with drilled holes of 3 mm diameter in the cladding 25 mm apart, with a simulated crack in the concrete. In this sample all rebars in both rows are clad type 2. Figure 7-15 and Figure 7-16 show the top-facing and bottom-facing sides, respectively, of the top row of rebars. Figure 7-15 shows rust stains on the concrete that stemmed from the corrosion in the drilled holes. The corrosion on the rebars is most severe near the concrete crack, where the chlorides would have most easily penetrated and accumulated. Some of the cladding surrounding the holes was stained by the corrosion, as seen in Figure 7-15.

The longitudinal crack in the concrete rebar trace of top-facing rebar C formed during the termination process while trying to open the sample. The bottom faces exhibited less severe corrosion, but the carbon steel beneath the drilled holes still exhibited some corrosion and rust stains were present on the concrete surrounding the drilled holes. It is also apparent that not all drilled holes had bleeding of corrosion products.

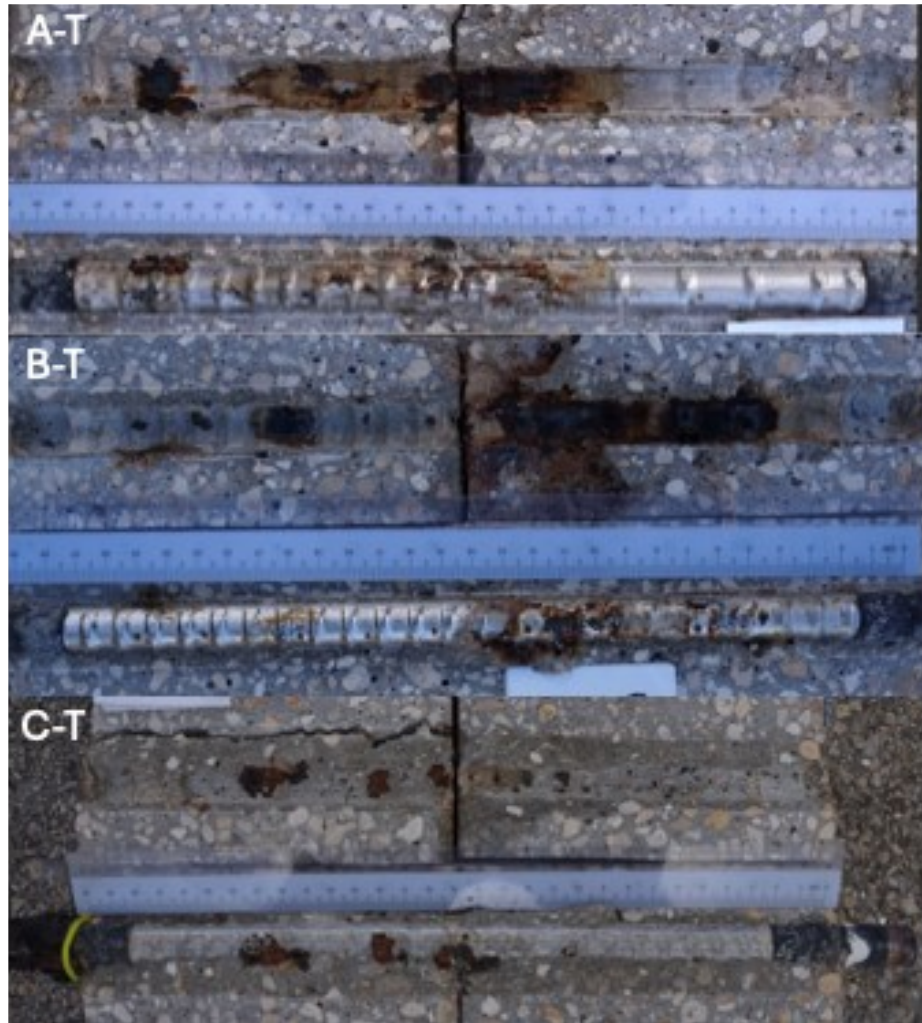


Figure 7-15. CSDB-CT2-1 top-facing, top rebars and concrete rebar traces.



Figure 7-16. CSDB-CT2-1 bottom-facing, top rebars (excluding rebar A) and concrete rebar traces.

Figure 7-17 presents the top-facing side of the bottom row of rebars while Figure 7-18 shows the bottom-facing side of the bottom row. The uncovered ends of the rebars showed evidence of corrosion, which is expected given their exposure to the environment. The portions of rebar inside the concrete showed no corrosion and the cladding remained in good condition.

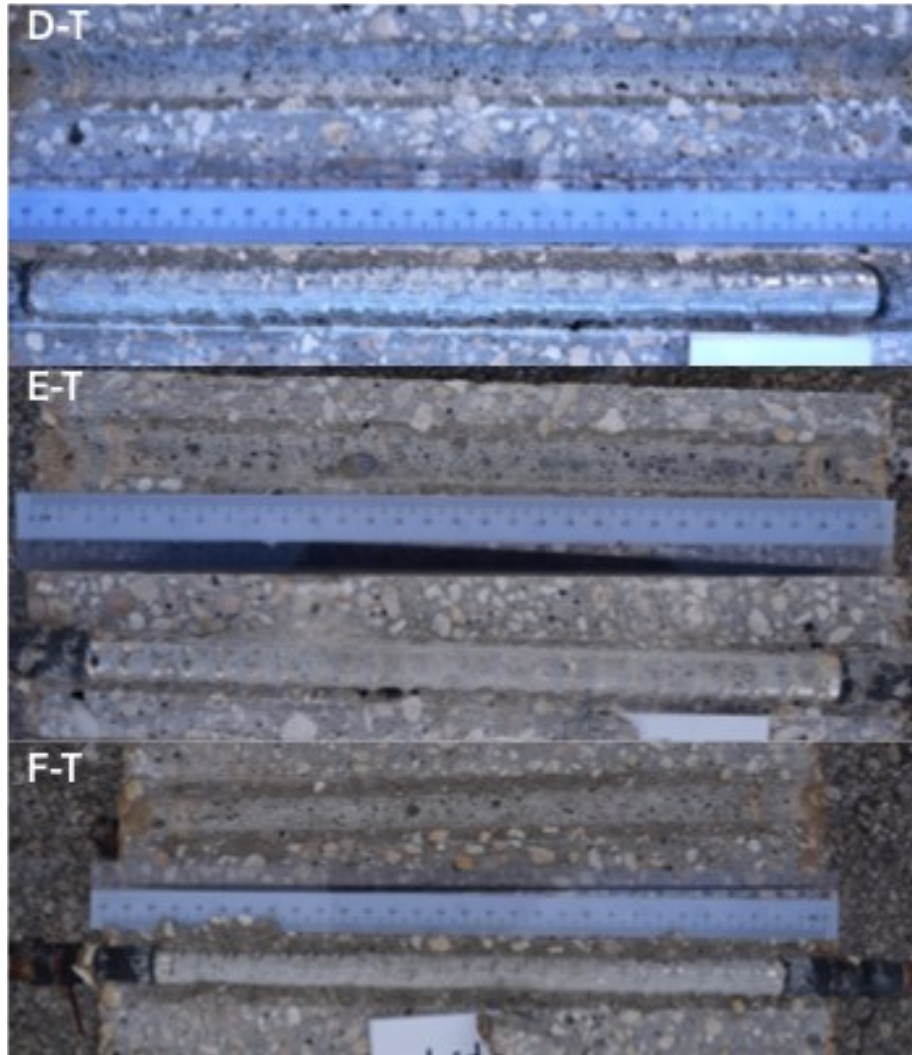


Figure 7-17. CSDB-CT2-1 top-facing, bottom rebars and concrete rebar traces.

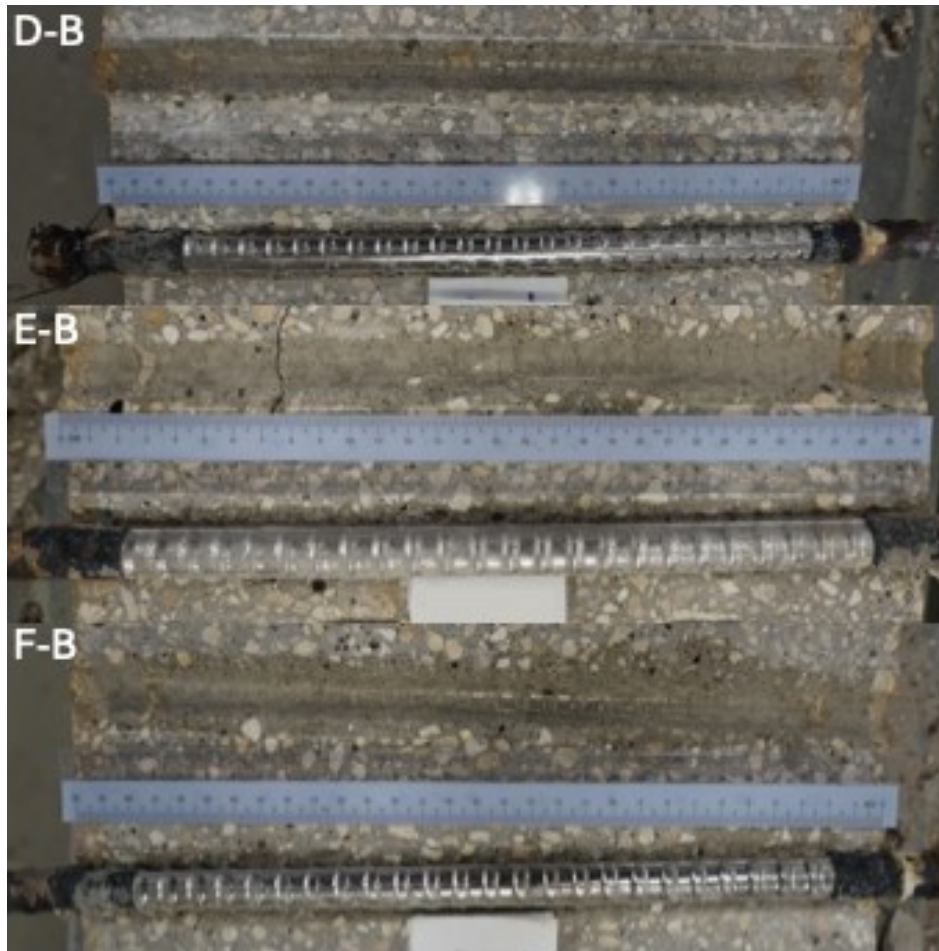


Figure 7-18. CSDB-CT2-1 bottom-facing, bottom rebars and concrete rebar traces.

7.1.6 304 Rebars and 316 Rebar

In addition, one 316 rebar and two 304 rebars were obtained from samples not described above. The 304 and 316 rebars were obtained from SDS samples that had black carbon steel rebars in the second row and that caused the concrete to crack in the upward direction, allowing these rebars to be removed. Images documenting the corrosion extent in the 316, and 304 rebars are included in this section. Figure 7-19 shows one 316 rebar and two 304 rebars. The 316 rebar showed no corrosion and the two 304 rebars still had some concrete paste attached to them. The images are of the top side. Figure 7-20 shows an image of the bottom side for one of the 304 rebars. Figure 7-21 shows a close-up of the only red rust (pit) observed on the 316 rebar. It is possible that the pits developed after the concrete surrounding them had cracked. Figure 7-22 shows close-ups for the 304 rebars; there were a few small pits that might have formed after the concrete had completely separated due to the crack caused by the bottom carbon steel rebars.



Figure 7-19. Images of one 316 SS rebar and two 304 SS rebars before cleaning.



Figure 7-20. Bottom-facing side of 304SS rebar before cleaning, showing some corrosion.



Figure 7-21. Closeups of pitting corrosion on 316SS rebar.



Figure 7-22. Closeups of pitting corrosion on 304SS rebars.

7.2 ANALYSIS AFTER REBAR CLEANING

7.2.1 4-CCRV-3CR12-2

This section presents photos of the rebars from sample 4-CCRV-3CR12-2 after cleaning. Figure 7-23 presents the top-facing side of the top row of rebars while Figure 7-24 shows the bottom-facing side of the top row. Because the top-facing side was closest to the simulated crack and the NaCl reservoir, this side displayed the most severe corrosion, concentrated near the midpoint of the rebars. Extensive pitting and cross-section loss is present on the top-facing side of all the rebars in the top row, with rebars B1 and B2 having the most severe cross-section loss. Table 11-3 through Table 11-11 in Section 11.3.1 of APPENDIX C: QUANTITATIVE MEASUREMENTS OF CORROSION DAMAGE TO SDS SAMPLES lists the diameter loss experienced by the most prominent corrosion site/pits in each rebar. Figure 7-24 shows that very little corrosion is apparent on the bottom-facing sides of the rebars, with the exception of some pits near the exposed ends of each rebar.



Figure 7-23. 4-CCRV-3CR12-2 top row, top-facing rebars after cleaning.

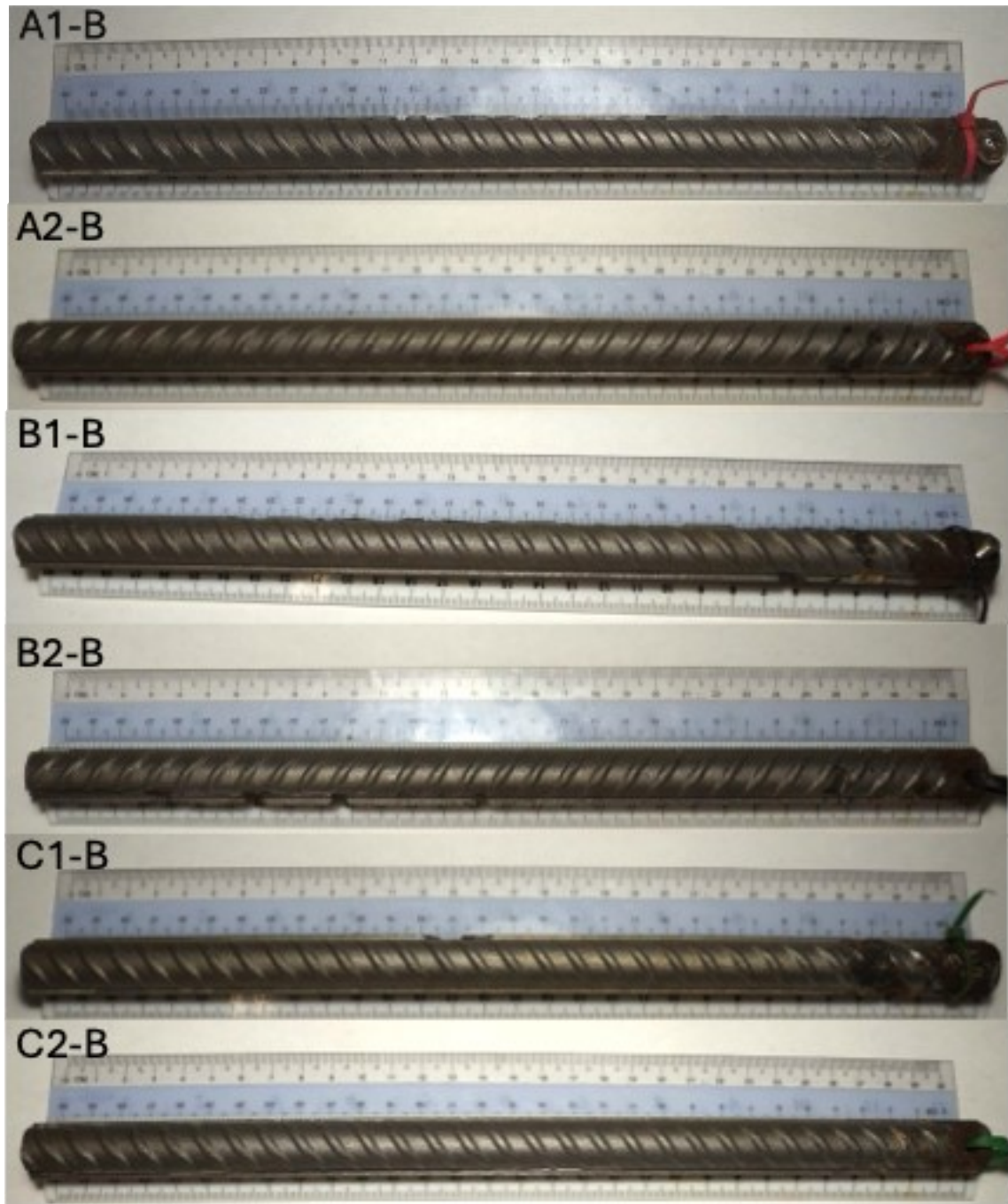


Figure 7-24. 4-CCRV-3CR12-2 top row, bottom-facing rebars after cleaning.

Figure 7-25 shows the top-facing side of the bottom row of rebars and Figure 7-26 shows the bottom-facing side of the bottom row. Again, the top-facing side displayed the most severe corrosion, concentrated near the midpoint of the rebars. The top faces of rebars D and E had extensive corrosion sites, with rebar E being the more severe of the two. Rebar E was likely the worst because it was directly under rebars B1 and B2, which were the most damaged rebars of the top row. Rebar F had little corrosion on either side. The cross-section loss observed on rebars

D and E is significantly less than what was observed on the rebars on the top row. The bottom faces of rebars D and E showed little corrosion, except for some pits (small corrosion sites) near one of the ends of rebar E, as Figure 7-26 shows.

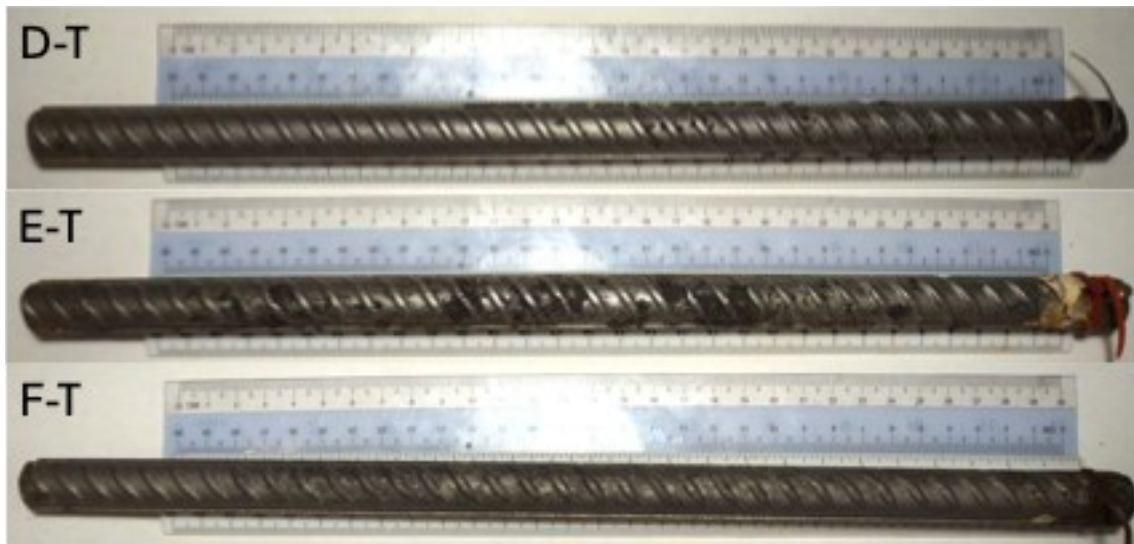


Figure 7-25. 4-CCRV-3CR12-2 bottom row, top-facing rebars after cleaning.



Figure 7-26. 4-CCRV-3CR12-2 bottom row, bottom-facing rebars after cleaning.

The following section presents closeup photos of the corrosion experienced by the rebars from sample 4-CCRV-3CR12-2. Figure 7-27 shows the pits present on rebars A1 and A2. Out of the two rebars, most cross-section loss was experienced by the top-facing side of rebar A1. Several pits are present on the top face of rebar A2 as well.



Figure 7-27. Rebars A1 and A2 closeups (top and bottom).

Figure 7-28 shows the corrosion extent present on rebar B1 while Figure 7-29 shows the corrosion extent on rebar B2. Rebar B1 experienced the most cross-section loss out of all rebars in the sample, mainly on the top face. The deepest corrosion spot is shown in the first image of Figure 7-28. Rebar B1 suffered a loss of almost half its diameter in a few locations due to corrosion (see Table 11-5 for pit depths of this rebar). The top side of rebar B2 also showed extensive number of corrosion sites, albeit less severe than rebar B1.

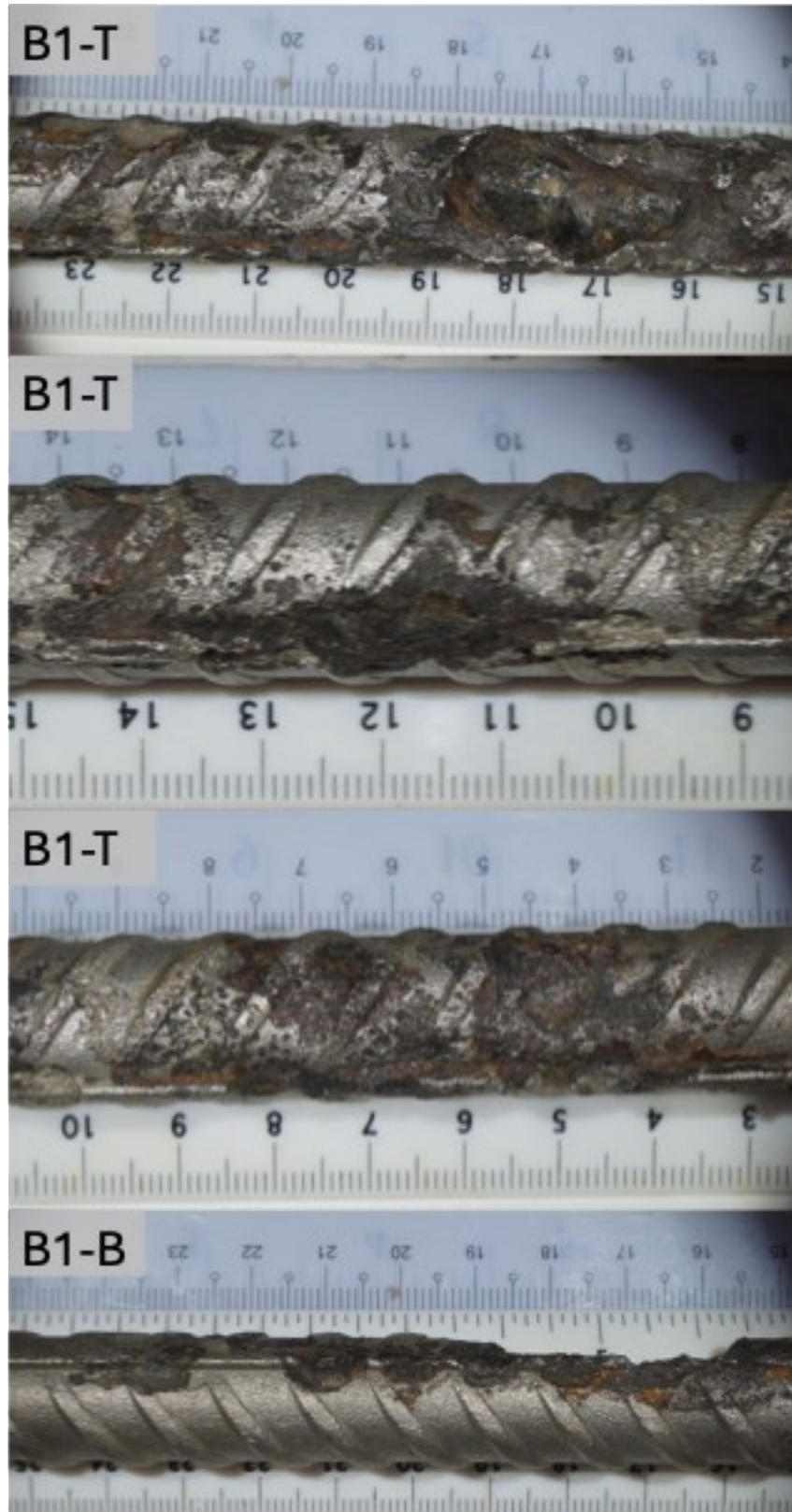


Figure 7-28. Rebar B1 closeups (top and bottom or side image).



Figure 7-29. Rebar B2 closeups (top and bottom).

Figure 7-30 shows the corrosion present on rebars C1 and C2. Corrosion was less severe on these rebars than the rest of the rebars in the top row of this sample. Areas of pitting (small corrosion sites) extended about 5.5 cm on the top faces of each rebar, but the diameter loss was not as significant as the A or B rebar pairs.

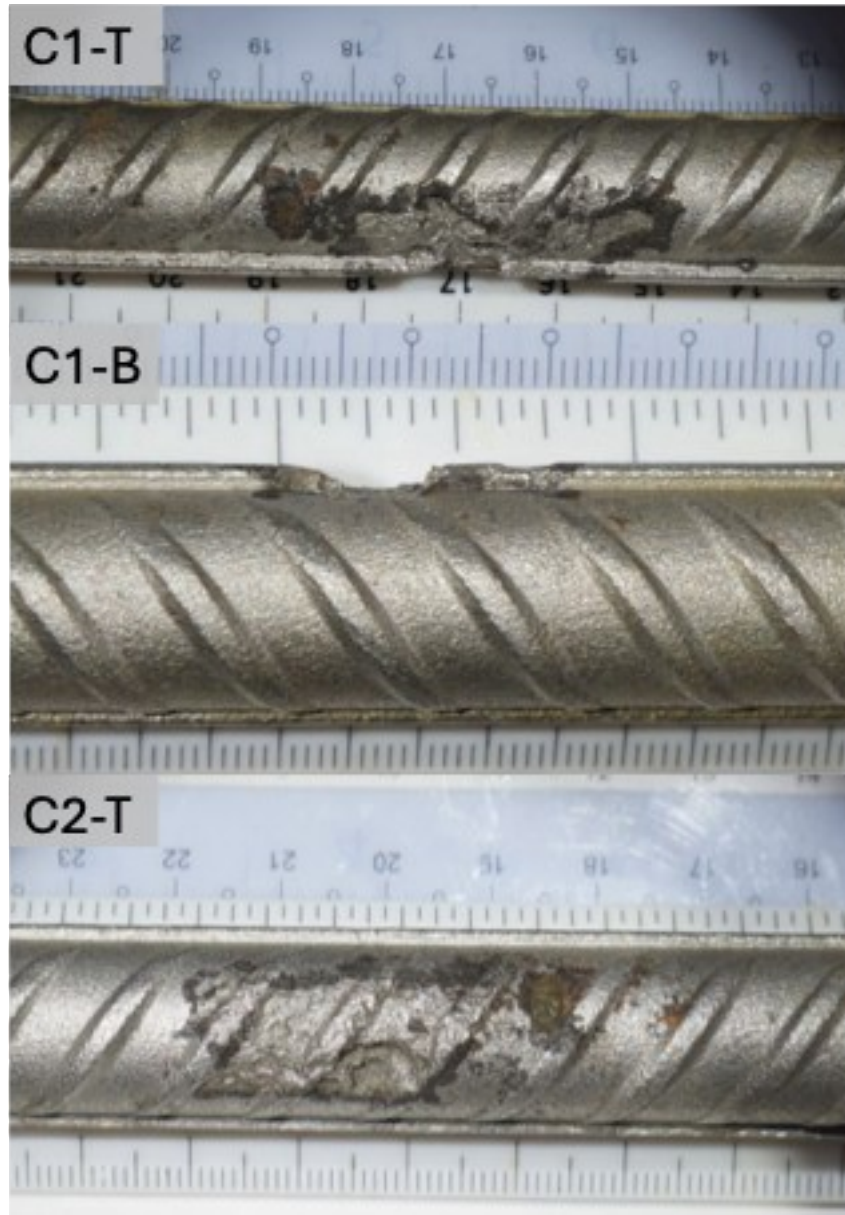


Figure 7-30. Rebars C1 and C2 closeups.

Figure 7-31 shows the corrosion present on rebars D and E. Several small pits can be seen on the top face of rebar D, however rebar E experienced the most extensive corrosion and cross-sectional loss from the rebars in the bottom row. As previously mentioned, this is likely due to rebar E's position under rebars B1 and B2. The concentration of chlorides was probably highest near rebars B1 and B2 due to cracks caused by the corrosion products accumulated in these two rebars, giving rebar E the shortest and most direct diffusion path from that region.

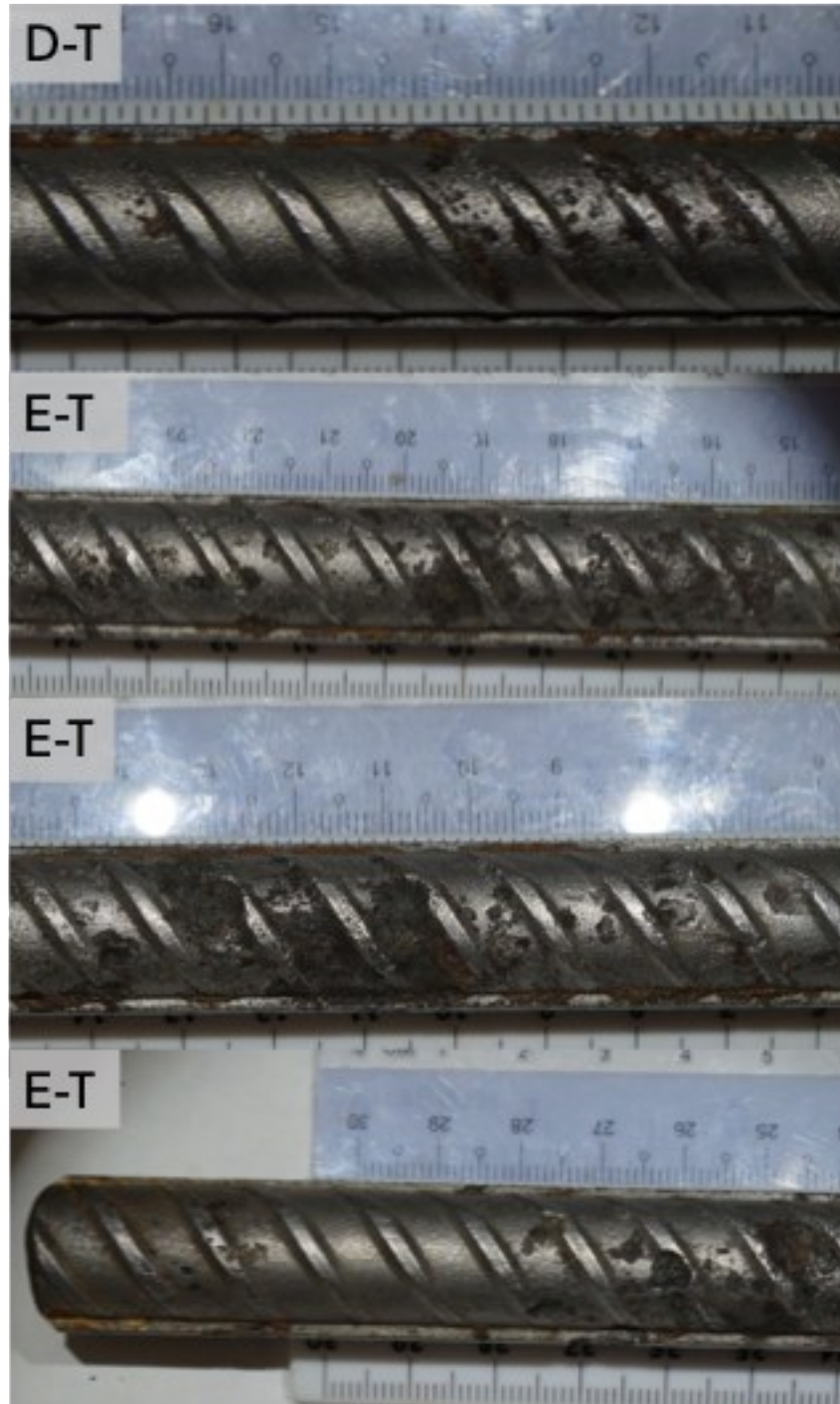


Figure 7-31. Notable closeups of 3CR12 bottom row rebars.

7.2.2 CREV-CT2-2

This section presents photos of the concrete cracks in the top row of rebars from sample CREV-CT2-2 before cleaning. Also shown in this section are two photos of the embedded rebar ends after cleaning. In this sample, corrosion began taking place at the unclad ends of each rebar. The

penetration depth at the rebar ends due to pitting (followed by more general corrosion) is recorded in Table 11-12, which can be found in Section 11.3.2 of APPENDIX C: QUANTITATIVE MEASUREMENTS OF CORROSION DAMAGE TO SDS SAMPLES. The rebar ends that were embedded in the concrete to simulate a crevice began corroding likely due to chloride ingress, as they were within the reservoir. The corrosion products accumulated and expanded within the concrete, causing several cracks inside the sample. Rust stains were evident on both the concrete and the cladding. The most significant crack was caused by the corrosion from the embedded unclad end of rebar B1. Figure 7-32 shows a large crack formed from rebar B1's embedded end. In Figure 7-33, a crack formed near the exposed end of rebar A2. This crack likely stemmed from the corrosion that leached out from the embedded end of rebar B1, which was directly next to A2.



Figure 7-32. Concrete fracture caused by corrosion from rebar B1.

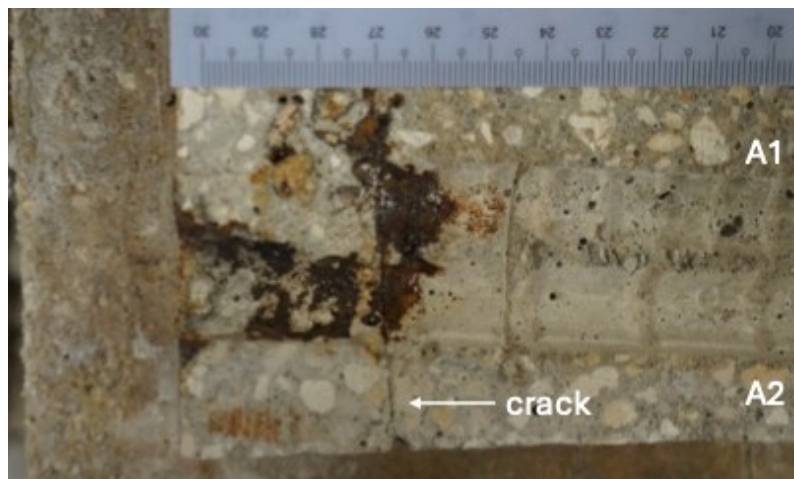


Figure 7-33. Concrete crack near rebar A2, likely caused by corrosion from rebar B1.

Figure 7-34 shows the concrete crack formed above the top face of rebars C1 and C2. The crack likely propagated from the corrosion of the embedded end of rebar C1.



Figure 7-34. Concrete crack caused by corrosion from rebar C1.

Figure 7-35 and Figure 7-36 show closeups of the rebar ends, after cleaning, that caused the cracks. Figure 7-35 shows the embedded, unclad end of rebar B1 which caused the crack shown in Figure 7-32 and likely caused the crack near rebar A2 in Figure 7-33. The loss of cross section due to corrosion at the end of rebar B1 extended 6 mm deep, as noted in Table 11-12. Figure 7-36 shows the embedded, unclad end of rebar C1 which caused the crack shown in Figure 7-35. The loss of cross section due to corrosion at the end of rebar C1 was less extensive than that of B1; the penetration depth was approximately 3.5 mm, as noted in Table 11-12.

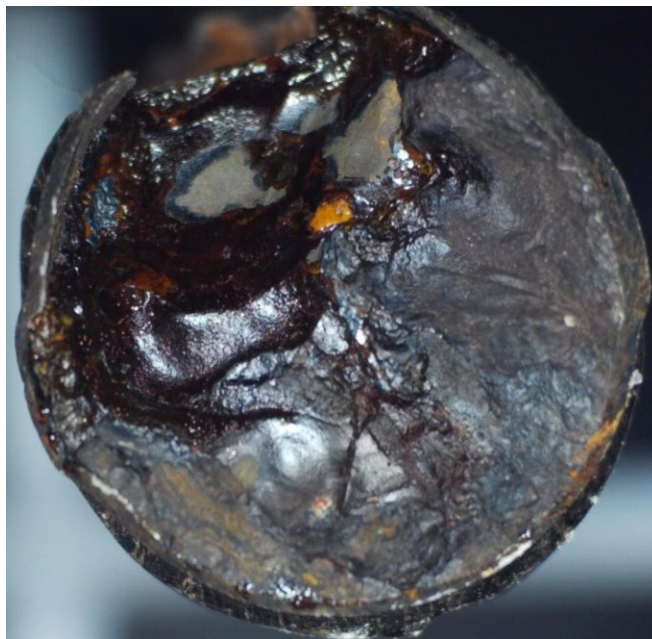


Figure 7-35. Corrosion of unclad, embedded rebar end of rebar B1 after cleaning.



Figure 7-36. Corrosion of unclad, embedded rebar end of rebar C1 after cleaning.

7.2.3 4-CCON-CT2-1

This section presents photos of rebar C from sample 4-CCON-CT2-1 after cleaning. The rebars (rebar F not shown) were cleaned using the same way explained in the methodology. Figure 7-37 presents both sides of rebar C while Figure 7-38 depicts a closeup photo of several shallow red rust pits in the cladding in top face of rebar C. The original damage to the rebar likely occurred during the preparation of the rebar when the cladding was being clamped on around the carbon steel core of the rebar. It is likely there was a small holiday. Residual stresses from this process likely resulted in weak spots in the cladding, possibly facilitating the mild corrosion depicted in Figure 7-38 during the sample's exposure period. The damage extends about 1.5 cm along the length of the rebar, with a maximum diameter loss of approximately 0.19 mm.



Figure 7-37. Both sides of 4-CCON-CT2-1 rebar C.



Figure 7-38. Closeup of pits on cladding, top face of 4-CCON-CT2-1 rebar C.

7.2.4 BCCD-CT2-1

This section presents the rebars on the top side of sample BCCD-CT2-1. The rebars were cleaned in the same way as described in the methodology but immersed for longer periods of time (up to a day). In Section 11.3.3 of APPENDIX C: QUANTITATIVE MEASUREMENTS OF CORROSION DAMAGE TO SDS SAMPLES, Table 11-13, Table 11-14, and Table 11-15 list the hole depths for BCCD-CT2-1 while Table 11-16, Table 11-17, and Table 11-18 list the spaces between the holes. Some of the holes were too deep for the microscope to fully analyze closely. The holes were counted starting from the zip tie section of the rebar. For example, hole 1 would be the first hole after the zip tie along the rebar, and hole 2 would be the one to the right of that.

The top sides of rebars A, B, and C were examined first. Rebar A, shown in Figure 7-39, did not show significant signs of corrosion along the top side after cleaning. The two deepest holes on the top side of rebar A were holes 1 at 3 millimeters and hole 9 at 5.2 millimeters, which are shown in Figure 7-40 and Figure 7-41. Hole 9 shows an initial smaller diameter closer to the surface, and it becomes larger towards the bottom of the hole, while hole 1 was uniform in diameter throughout.



Holes 6 (left) and 7 (right)

Figure 7-39. Top side of rebar A and select segments of sample BCCD-CT2-1.

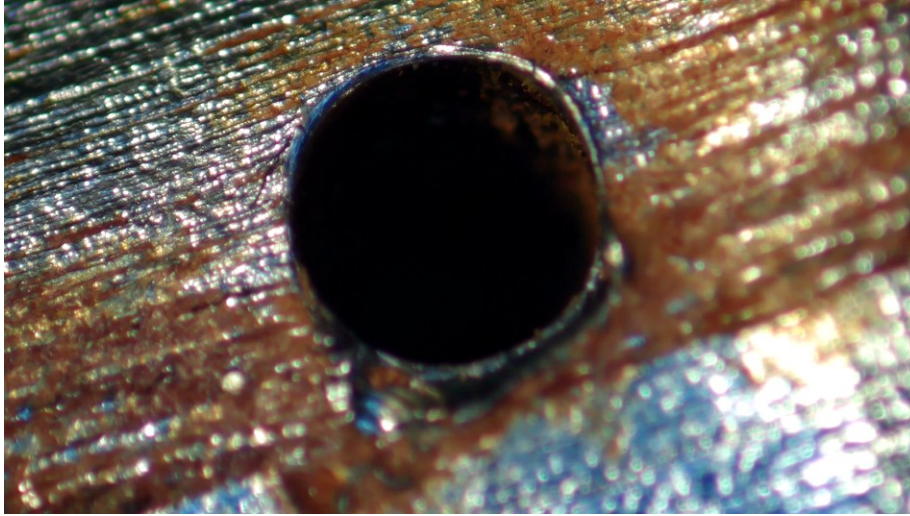


Figure 7-40. Hole 1 on top side of rebar A of sample BCCD-CT2-1.

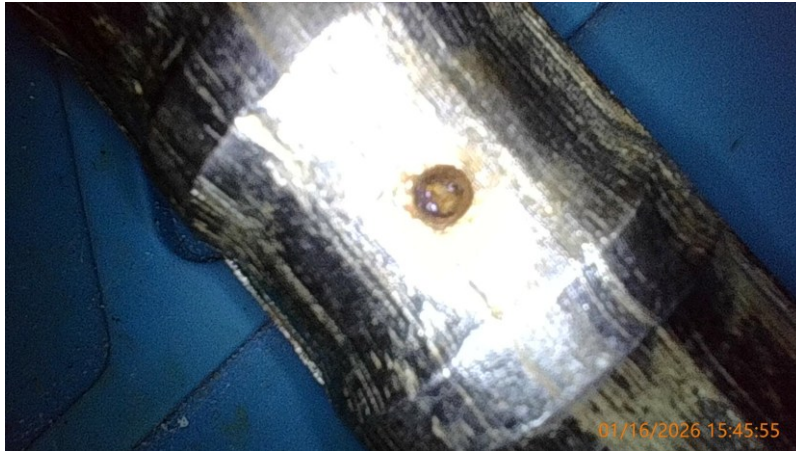


Figure 7-41. Hole 9 on top side of rebar A of sample BCCD-CT2-1.

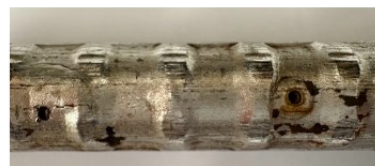
Rebar B in Figure 7-42 showed significantly more amounts of corrosion left over on the top side after cleaning compared to rebar A and C. Holes 7 and 9 were the deepest holes at 1.5 millimeters and 2.3 millimeters respectively. As depicted in Figure 7-43, hole 9 also shows evidence of pitting corrosion, as the hole diameter is not uniform at each depth, and appears to be smaller towards the surface compared to the deeper parts. This side of rebar B had two bumps beneath hole 7 and hole 10. There was a crack in the bump of hole 10 that was filled with corrosion products as well. Hole 10 is depicted in Figure 7-44.



Holes 1,2,3 (left to right)



Holes 6 (left) and 7 (right)



Holes 8 (left) and 9 (right)

Figure 7-42. Top side of rebar B and select segments of sample BCCD-CT2-1.

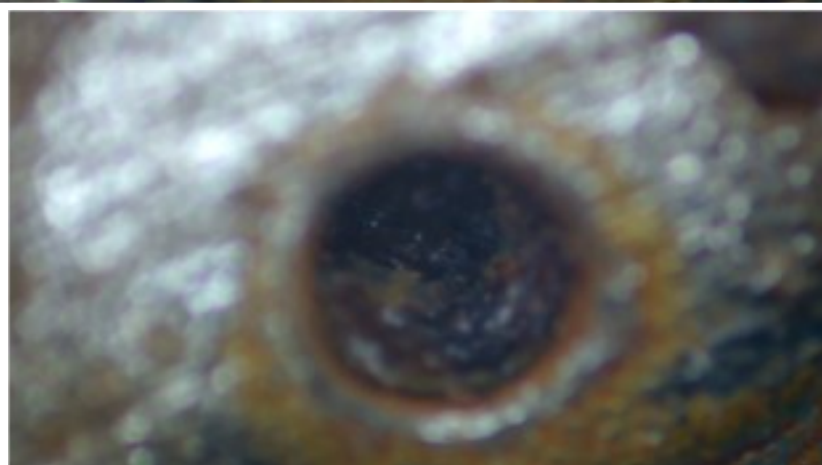
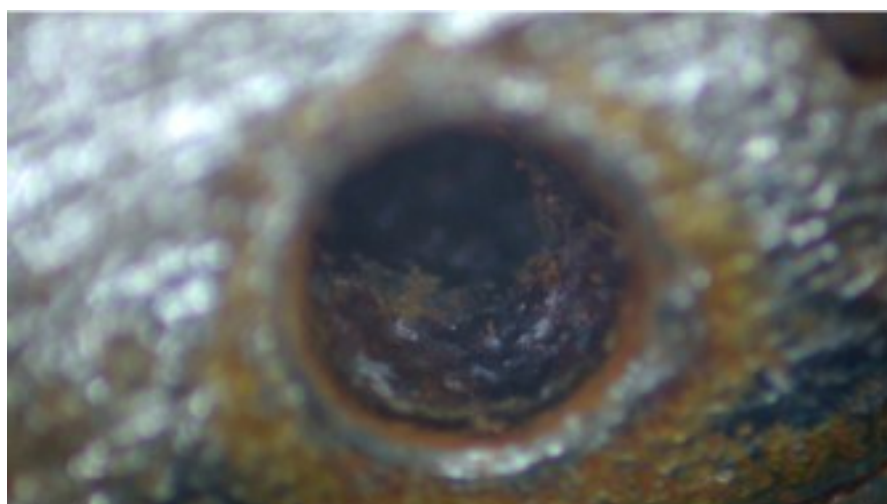


Figure 7-43. Hole 9 on top side of rebar B of sample BCCD-CT2-1.

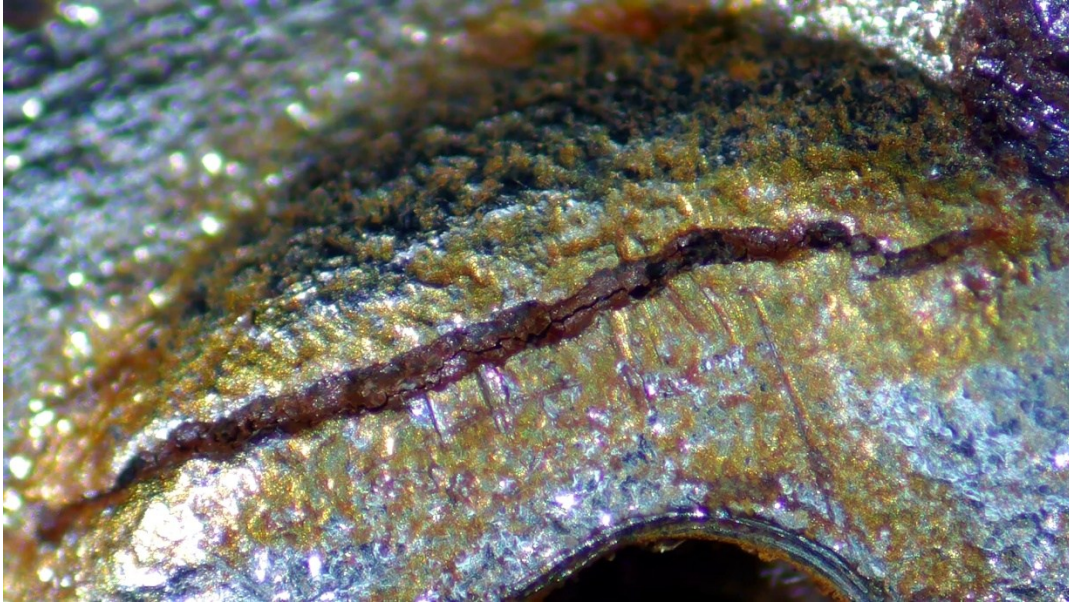


Figure 7-44. Bump with crack in hole 10 on top side of rebar B of sample BCCD-CT2-1.

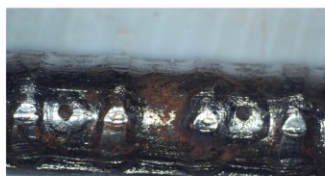
Figure 7-45 shows the top side of rebar C. There was some corrosion throughout the middle of the surface from holes 1 to 7. Holes 1 and 2 were also slightly deformed. The holes on the top side of rebar C did not have large depths, and the largest one was hole 2 at 1.2 millimeters, which is shown in Figure 7-46. This side had several bumps with cracks in them along the holes. Hole 3 is an example shown in Figure 7-47.



Holes 1,2, 3 (left to right)



Holes 6 (left) and 7 (right)



Holes 1 (left) and 2 (right)
(before cleaning)



Holes 4 (left) and 5 (right)



Holes 6 (left) and 7 (right)
(before cleaning)

Figure 7-45. Top side of rebar C and select segments of sample BCCD-CT2-1.

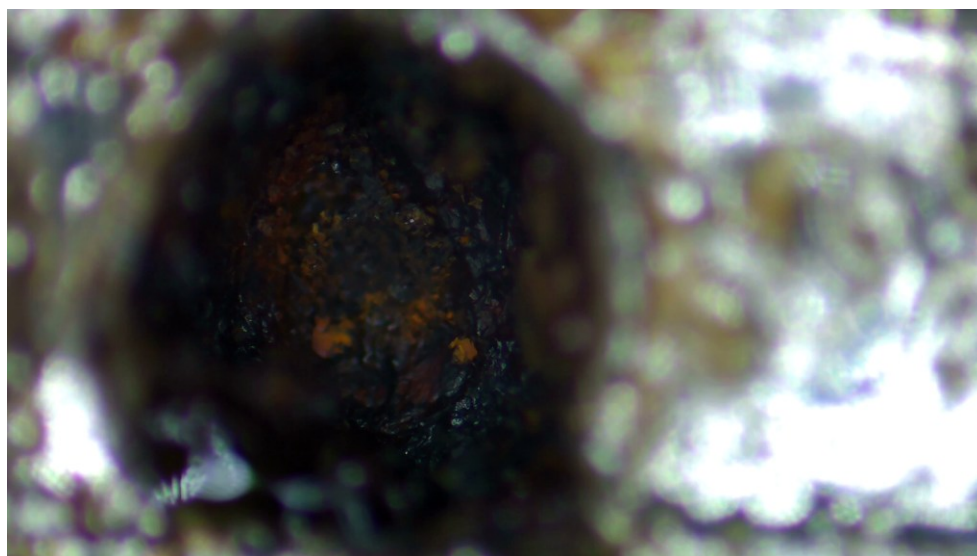


Figure 7-46. Hole 2 on top side of rebar C of sample BCCD-CT2-1.

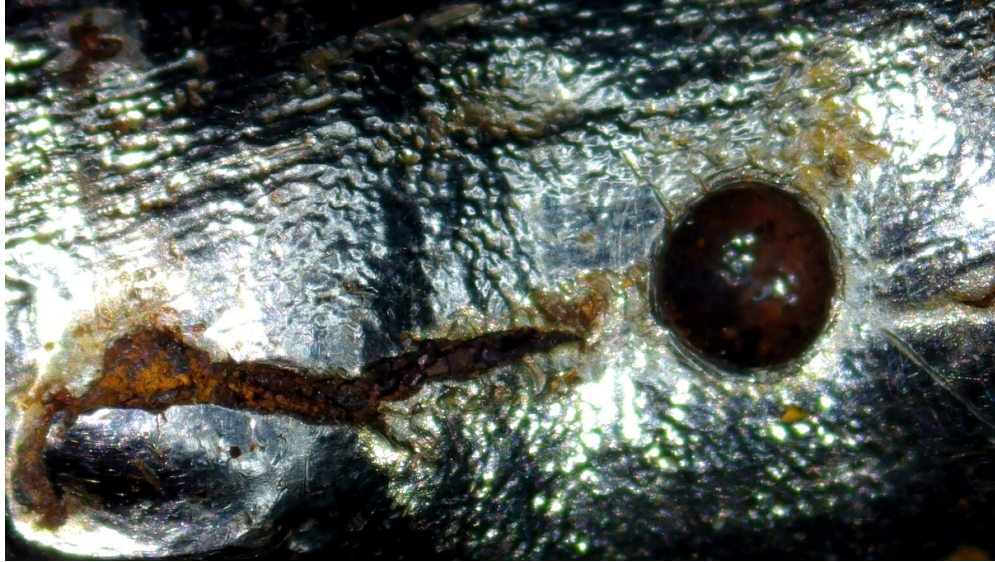


Figure 7-47. Bump with crack in hole 3 on top side of rebar C of sample BCCD-CT2-1.

The bottom sides of each top rebar in sample BCCD-CT2-1 are analyzed in the following section. Overall, the amount of corrosion products on these sides was less than the top sides after cleaning. The bottom side of rebar A in Figure 7-48 did not show major signs of corrosion after it was cleaned, with only some spots left over. The only hole that had a major depth was hole 5 at 3.3 millimeters, which is shown in Figure 7-49. It is important to note that this hole had a relatively uniform diameter throughout, unlike some other rebars. Hole 9 had a slight bump beneath the hole as well, which is visible in Figure 7-48.

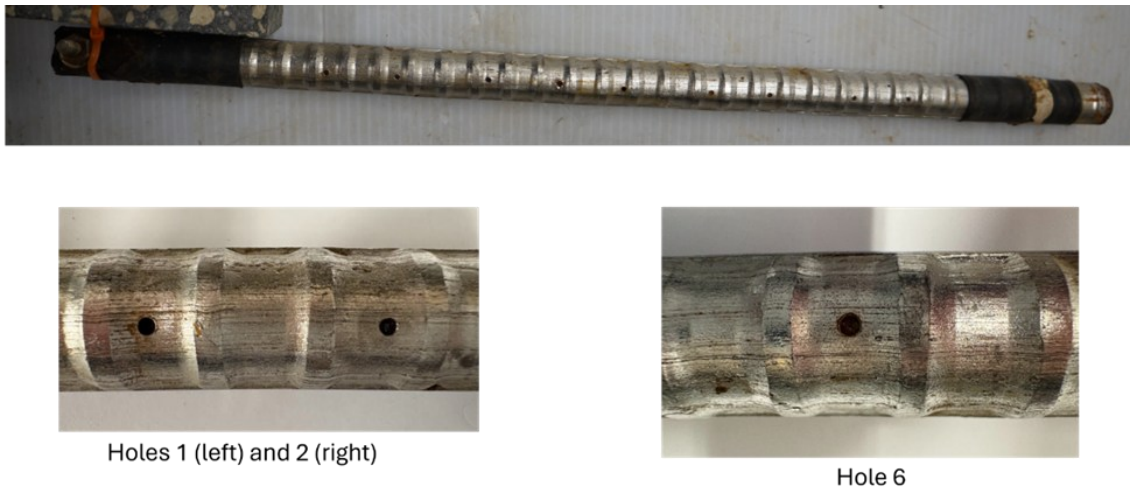


Figure 7-48. Bottom side of rebar A and select segments of sample BCCD-CT2-1.

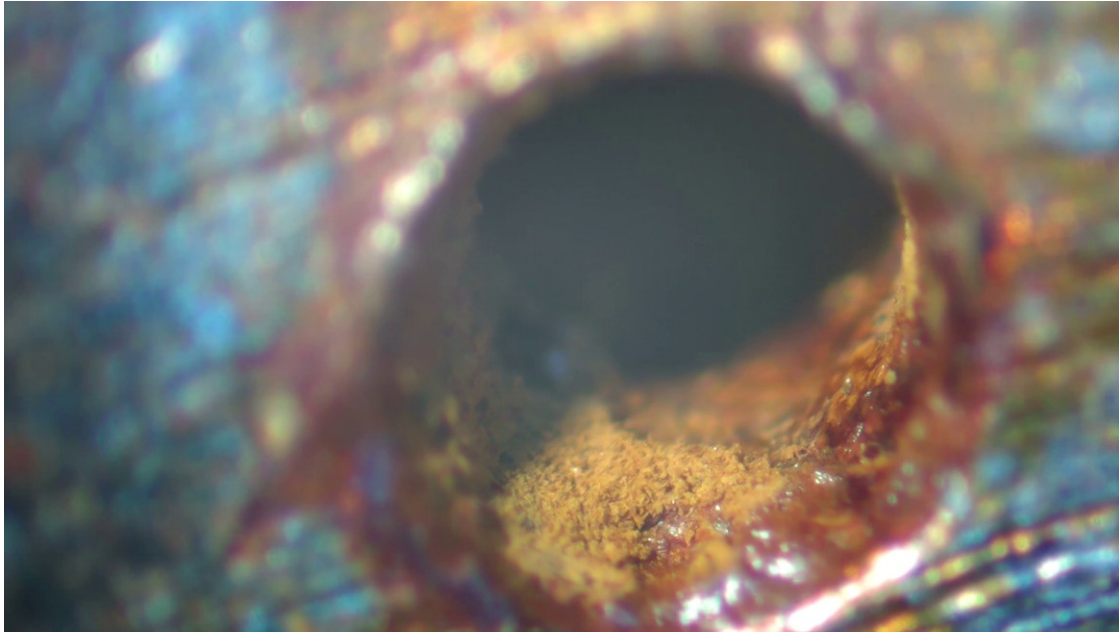
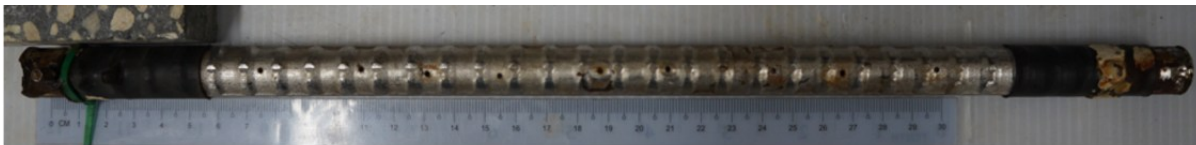


Figure 7-49. Hole 5 on bottom side of rebar A of sample BCCD-CT2-1.

The bottom side of rebar B in Figure 7-50 showed some notable stains and leftover corrosion product after cleaning, although not as much as the top side. Hole 7 is an example of a hole that was clogged with corrosion product that was unable to be fully cleaned. A picture before the full cleaning of the rebar shows the corrosion product above hole 7. The deepest hole was hole 2 at 3.9 millimeters, followed by hole 3 at 2.5 millimeters. Hole 2 was very narrow due to a buildup of corrosion product along the edges. Hole 3 is depicted in Figure 7-51. This side also had some bumps beneath the holes, but none of them had cracks going through them.



Holes 5 (left) and 6 (right)



Holes 7 (left) and 8 (right) (before cleaning)



Holes 7 (left) and 8 (right)

Figure 7-50. Bottom side of rebar B and select segments of sample BCCD-CT2-1.

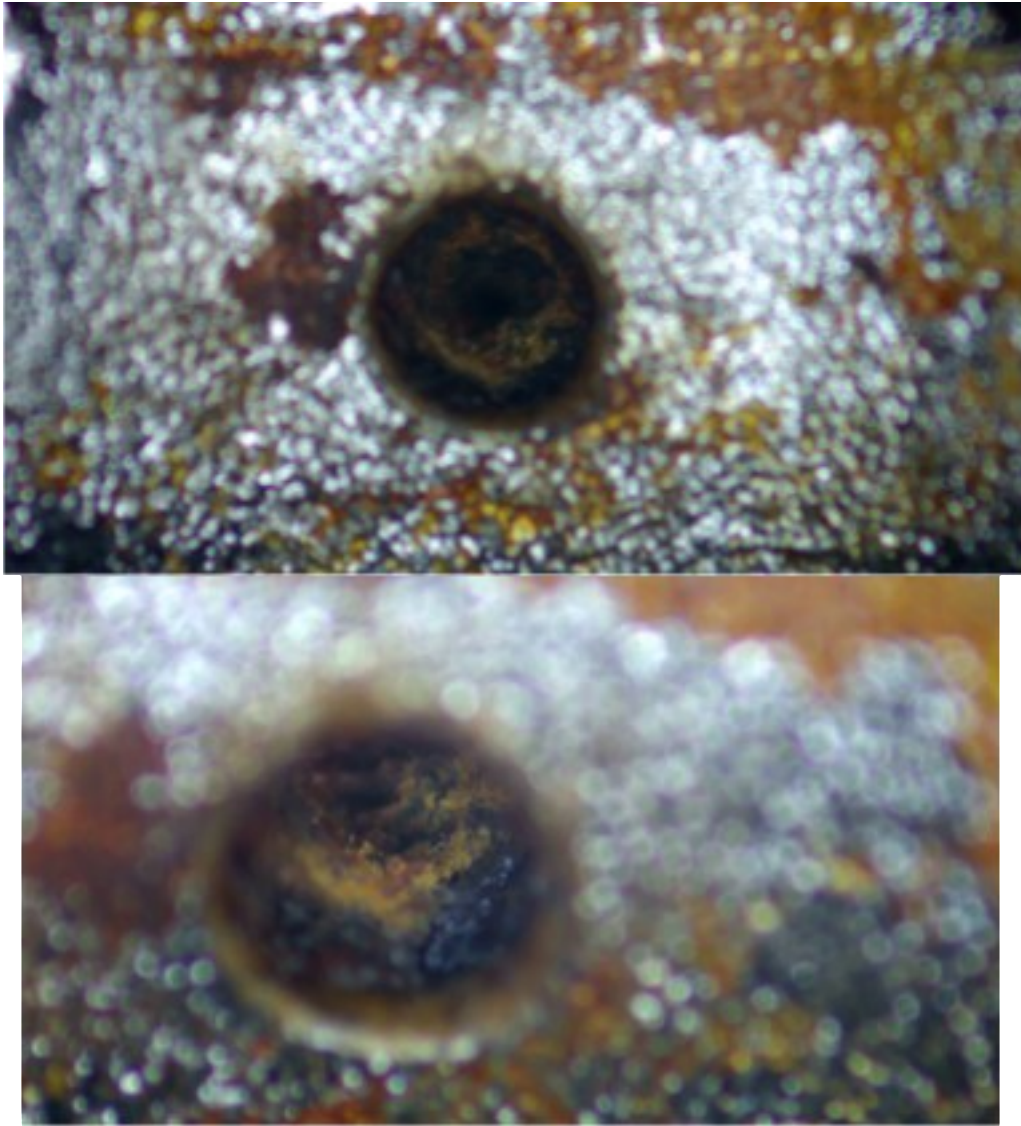


Figure 7-51. Hole 3 on bottom side of rebar B of sample BCCD-CT2-1.

The bottom side of rebar C in Figure 7-52 had a hole deformation that occurred on hole 6 and slightly on hole 7. This side also had relatively shallow holes. The two deepest holes were 4 and 6 both at 2.2 millimeters. Figure 7-53 and Figure 7-54 show that holes 4 and 6 could also be subject to pitting corrosion, as the hole shape is irregular and changes at different depths. There were slight bumps beneath a few holes, and remnants of a bump around hole 6, which seemed to have broken from corrosion that occurred inside of it.



Holes 6 (left) and 7 (right)

Figure 7-52. Bottom side of rebar C and select segments of sample BCCD-CT2-1.



Figure 7-53. Hole 4 on bottom side of rebar C of sample BCCD-CT2-1.

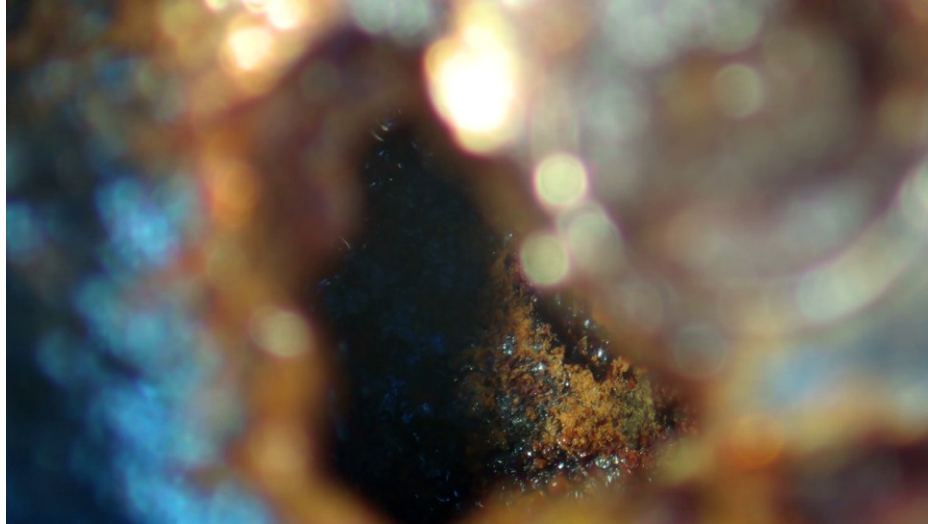


Figure 7-54. Hole 6 on bottom side of rebar C of sample BCCD-CT2-1.

7.2.5 CSDB-CT2-1

This section analyzes the individual rebars on the top row of sample CSDB-CT2-1. It presents the top and bottom sides of each rebar. The rebars were cleaned with the same method as described in previous sections but immersed for longer periods of time (up to a day). After the full cleaning, the amount of corrosion on these rebars was similar to sample BCCD-CT2-1. In Section 11.3.4 of APPENDIX C: QUANTITATIVE MEASUREMENTS OF CORROSION DAMAGE TO SDS SAMPLES, Table 11-19, Table 11-20, and Table 11-21 list the hole depths for CSDB-CT2-1 while Table 11-22, Table 11-23, and Table 11-24 list the spaces between the holes.

The top sides of each rebar in CSDB-CT2-1 are presented and analyzed below. Figure 7-55 shows the top side of rebar A, with corrosion still present along holes 4, 5 and 6-9 after the full cleaning. A large crack in the rebar formed along holes 4 and 5, which allowed a crevice suitable for corrosion to take place. The corrosion around hole 9 was the most pronounced and persistent after cleaning. These images are consistent with the images taken right after termination, as most of the corrosion in the concrete and the rebar were found around these holes. Only hole 1 had a large depth of 4 millimeters and is depicted in Figure 7-56. The two images in the figure show that the diameter of the hole slightly changed at greater depths of the hole as corrosion penetrated through.

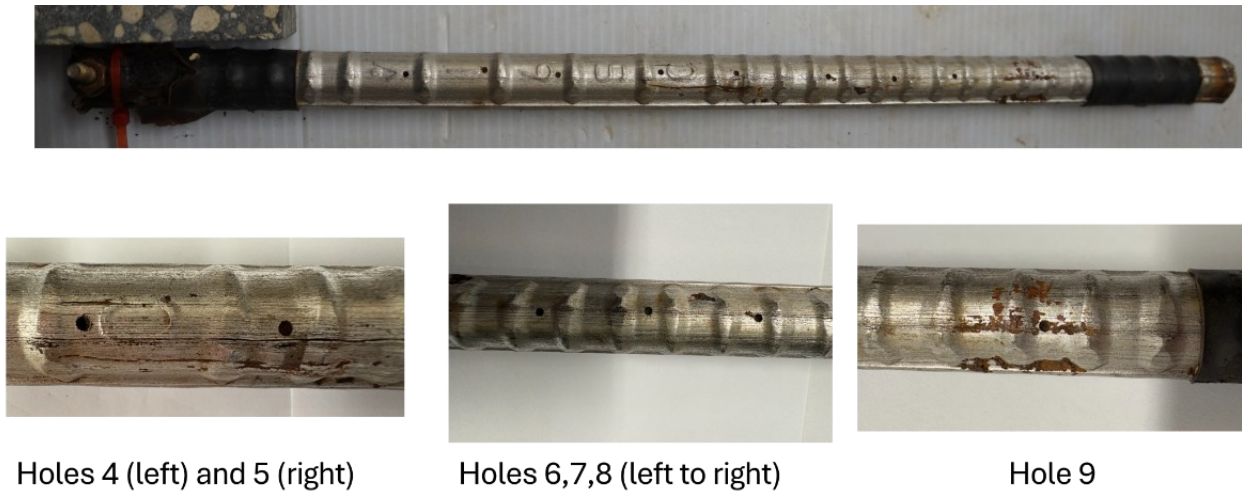


Figure 7-55. Top side of rebar A and select segments of sample CSDB-CT2-1.

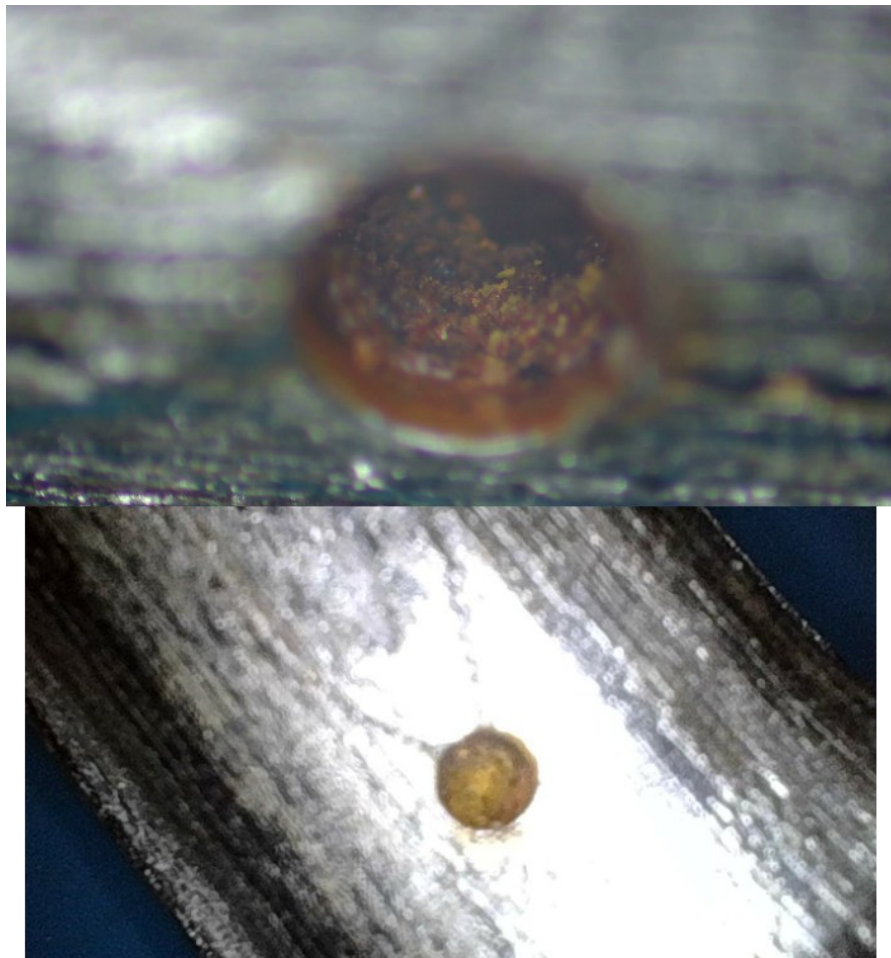


Figure 7-56. Hole 1 on top side of rebar A of sample CSDB-CT2-1.

Figure 7-57 shows the top side of rebar B. It shows remnants of corrosion mainly around hole 7, with the remaining holes showing very little corrosion after cleaning. The damage caused by corrosion penetrated past the circumference of hole 7, indicating that there was significant corrosion that may have originated from this area and spread out, which is consistent with the images after termination. The rest of the holes looked quite similar to holes 2 and 3. None of the holes, including hole 7, had very large depths, as none of them surpassed 1 millimeter. Figure 7-58 depicts hole 2, which had a depth of 1 millimeter. This rebar was the only one from sample CSDB-CT2-1 that had bumps protruding right beneath the holes. There were several bumps present on the top and the bottom side of rebar B in this sample.

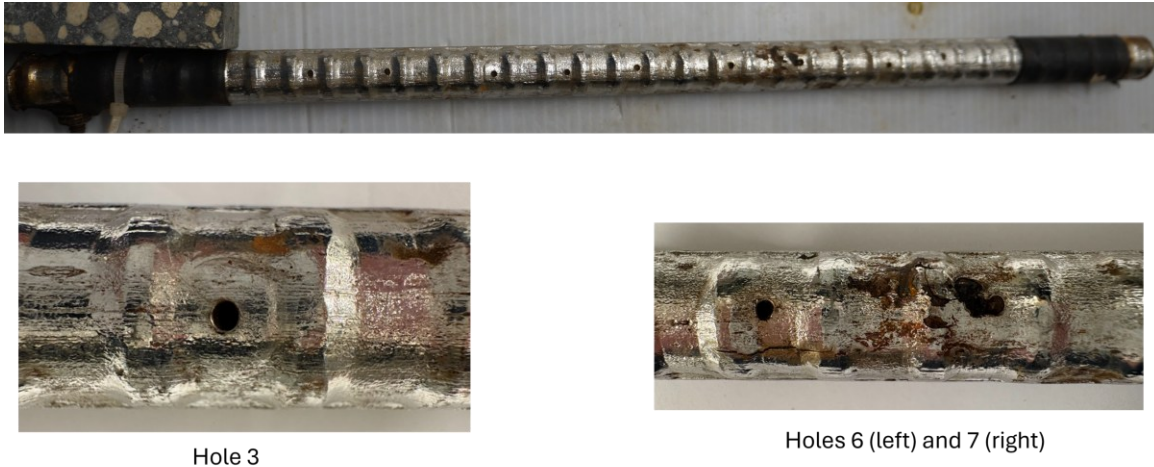


Figure 7-57. Top side of rebar B and select segments of sample CSDB-CT2-1.

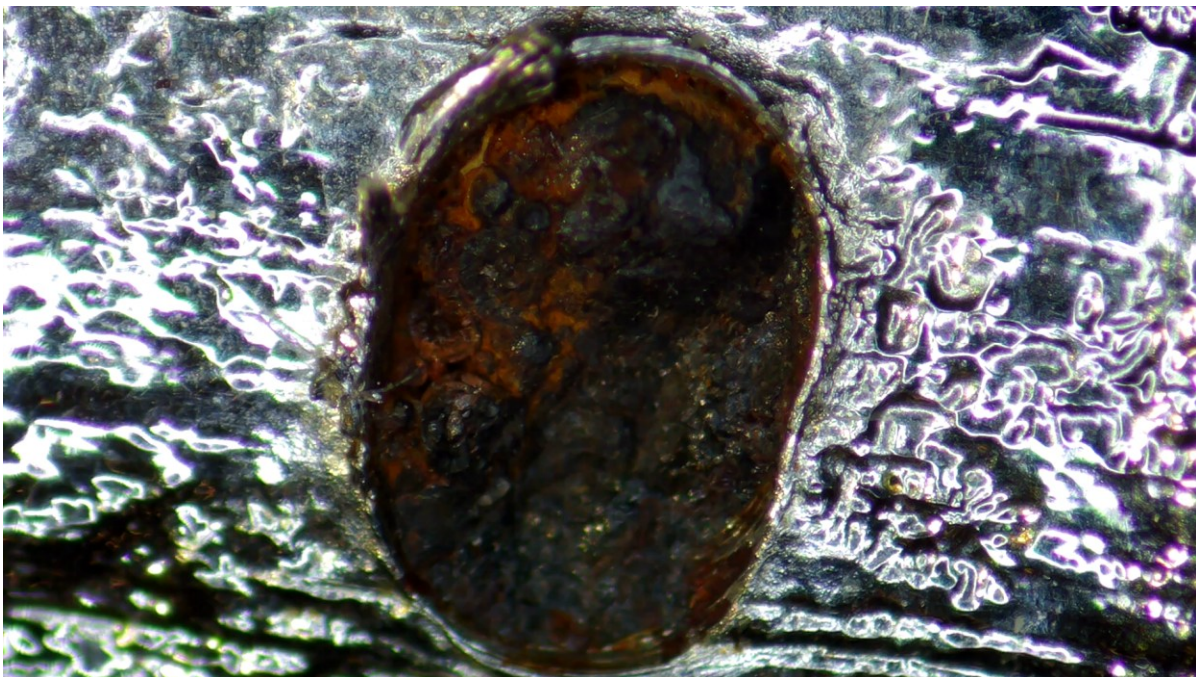


Figure 7-58. Hole 2 on the top side of rebar B of sample CSDB-CT2-1.

Figure 7-59 shows the top part of rebar C, which did not have signs of significant corrosion after cleaning. Some spots were visible around holes 2, 3, and 5 after initial cleanings, but they were removed after. After all the cleanings were done, this side of the rebar did not show significant signs of corrosion and showed much less compared to the top sides of rebar A and B of this sample. The only hole on the top side of rebar C that had a relatively large depth was hole 8 at 2.5 millimeters, which is depicted in Figure 7-60. This hole also shows changes in shape at different depths.



Figure 7-59. Top side of rebar C and select segments of sample CSDB-CT2-1.

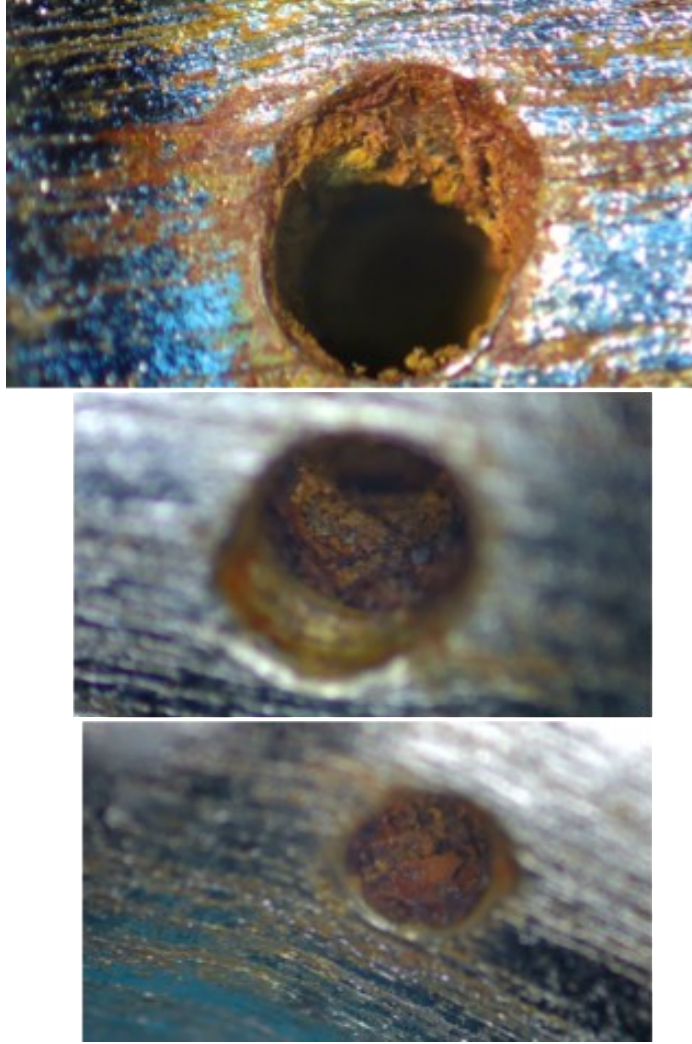


Figure 7-60. Hole 8 on top side of rebar C of sample CSDB-CT2-1.

The next set of figures shows the bottom sides of each top rebar in sample CSDB-CT2-1. Figure 7-61 shows the bottom side of rebar A. This rebar did have notable hole depths of 3.5 millimeters for hole 1 and 2 millimeters for hole 7. Both also showed a change in diameter at varying hole depths. This can be seen with the outer, darker ring of corrosion product in the photo that surrounds the deeper, more illuminated section at the bottom. This suggests evidence of pitting corrosion. These holes are depicted in Figure 7-62 and Figure 7-63.



Holes 5 (left) and 6 (right)



Hole 8

Figure 7-61. Bottom side of rebar A and select segments of sample CSDB-CT2-1.



Figure 7-62. Hole 1 on bottom side of rebar A of sample CSDB-CT2-1.

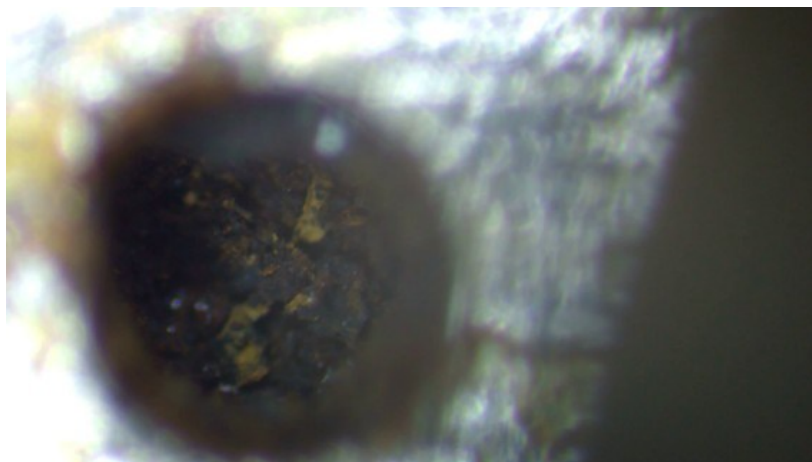
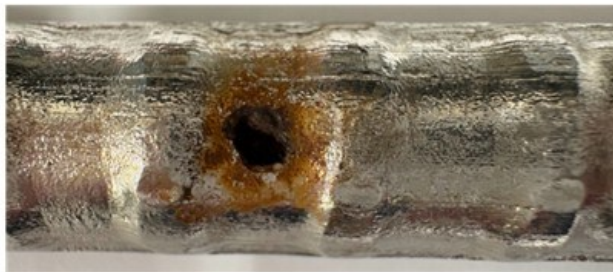


Figure 7-63. Hole 7 on bottom side of rebar A of sample CSDB-CT2-1.

There were prominent stains on the bottom side of rebar B after cleaning, and some remnants of corrosion product as well, albeit less than the top side. Hole 1 on the bottom of rebar B was damaged and expanded due to corrosion. It also had significant staining around it as well. This is consistent with the corrosion exhibited by the images of the concrete right after the sample was terminated. Rebar B and selected segments are shown in Figure 7-64, where other examples of persistent corrosion can be seen. Hole 1 had a depth of 2 millimeters, and hole 5 had a depth of 2.3 millimeters, and they are displayed in Figure 7-65 and Figure 7-66. These holes also had changes in shape at different depths. As mentioned with the top side of rebar B of this sample, there were several bumps on this side beneath the holes. This side also had a bump to the side of hole 6. The bump had a large crack going through it with corrosion product inside. The crack is displayed below in Figure 7-67.



Hole 1

Figure 7-64. Bottom side of rebar B and select segments of sample CSDB-CT2-1.

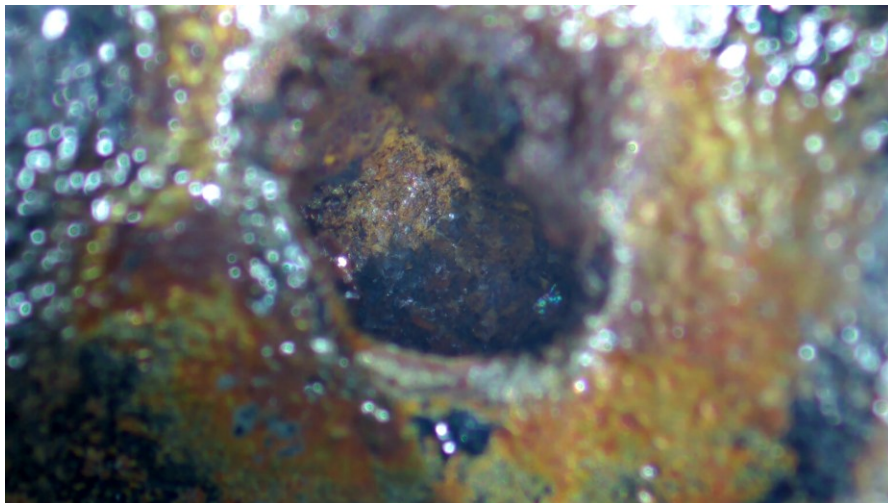


Figure 7-65. Hole 1 on bottom side of rebar B of sample CSDB-CT2-1.

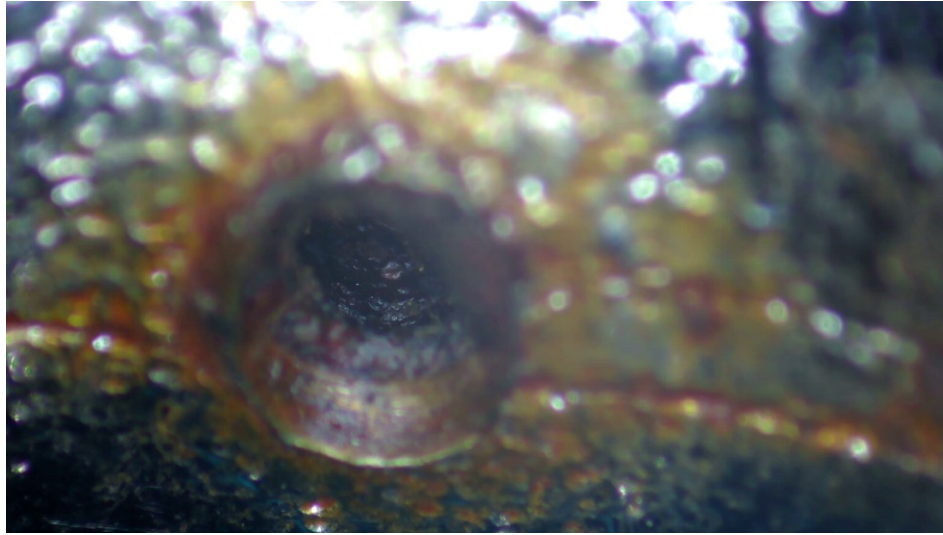


Figure 7-66. Hole 5 on bottom side of rebar B of sample CSDB-CT2-1.

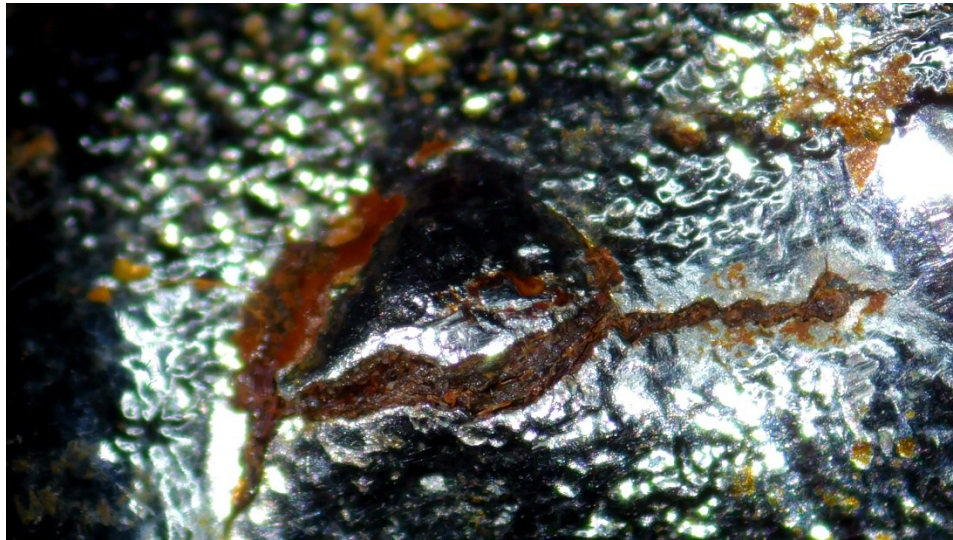


Figure 7-67. Bump with crack next to Hole 6 on bottom side of rebar B of sample CSDB-CT2-1.

Figure 7-68 shows the bottom side of rebar C. This side also had stains after the rebar was fully cleaned with trace amounts of corrosion product as seen around holes 1 and 2 in the figure. This side of the rebar also had multiple holes of significant depth. Hole 3 was 3 millimeters deep, Hole 5 was 2 millimeters deep, Hole 6 was 2.8 millimeters, hole 8 was 4.5 millimeters, and hole 9 was 3.6 millimeters deep. Figure 7-69, Figure 7-70, and Figure 7-71 show holes 3, 8, and 9, which were the three deepest ones. They all showed varying hole diameters along the hole depth.



Holes 1 (left) and 2 (right)

Figure 7-68. Hole 3 on bottom side of rebar C of sample CSDB-CT2-1.

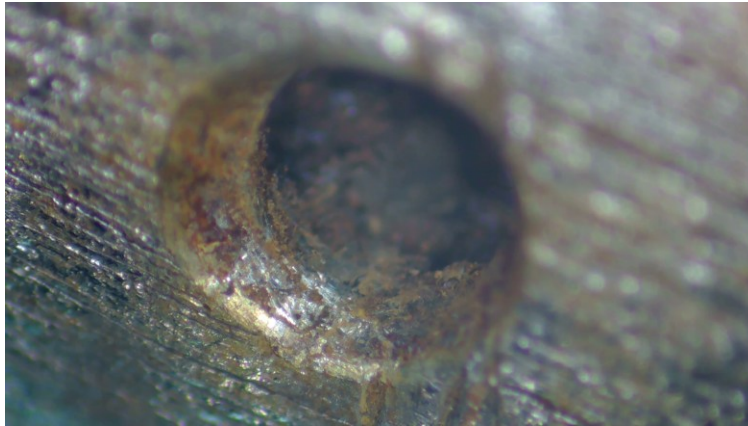


Figure 7-69. Hole 3 on bottom side of rebar C of sample CSDB-CT2-1.

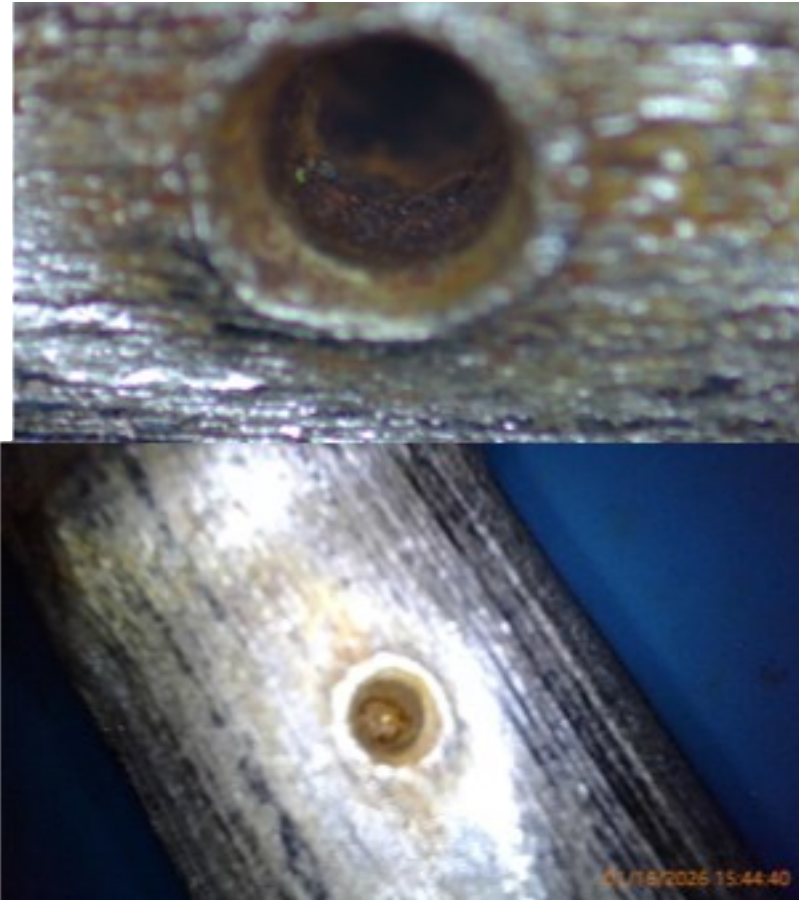


Figure 7-70. Hole 8 on bottom side of rebar C of sample CSDB-CT2-1.

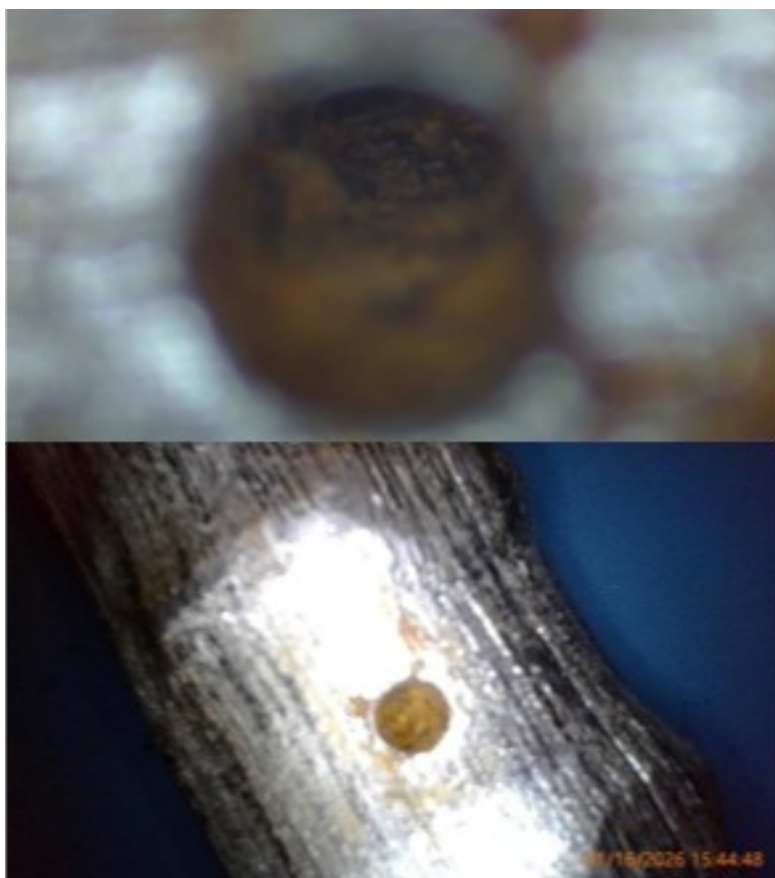


Figure 7-71. Hole 9 on bottom side of rebar C of sample CSDB-CT2-1.

7.3 REBAR TRACE CHLORIDE CONCENTRATIONS

Several rebar traces of terminated samples were milled (with a flat end-mill) the concrete powder was collected and titrated to determine chloride concentrations. Table 7-1 lists the sample, rebar, trace location, and average chloride concentration $[Cl^-]$ of the rebar trace. The “Top” rebar trace location refers to the concrete section that was originally just above the rebar, while the “Bottom” rebar trace location refers to the concrete section just below the rebar. The top rebar trace of sample 4-CCRV-3CR12-2 rebar B had too many rust stains to yield enough powder for a titration, therefore some of the top rebar trace of rebar A was milled and combined. Due to the small amount of powder generated by rebar traces, most samples only had one specimen to titrate and one duplicate. Samples that yielded enough powder also had a triplicate specimen that was titrated.

The bottom rebar traces of CSDB-CT2-1 rebar E had a higher average chloride concentration than the top rebar trace of the same rebar. The reason for this is not clear, but likely it has to do with the overall chloride profile through the concrete depth after the extensive exposure time (~20 years). Possibly, the higher wt% of NaCl used in the initial 10 years of the SDS study combined with long periods of not adding any solution to the reservoir resulted in downward chloride diffusion and accumulation at the bottom of the sample.

Table 7-1. Average chloride concentrations of terminated SDS samples' rebar traces.

Sample	Rebar(s)	Rebar Trace Location	Average [Cl⁻] (kg/m³)	Average [Cl⁻] (lb/yd³)
4-CCRV-3CR12-2	A and B	Top	11.87	20.01
4-CCRV-3CR12-2	B	Bottom	10.37	17.48
4-CCRV-3CR12-2	E	Bottom	18.93	31.91
CREV-CT2-2	B	Top	15.63	26.35
CSDB-CT2-1	B	Top	18.83	31.74
CSDB-CT2-1	B	Bottom	17.53	29.55
CSDB-CT2-1	E	Top	14.70	24.78
CSDB-CT2-1	E	Bottom	21.50	36.24
4-CCON-CT2-1	C	Top	16.29	27.46
BCCD-CT2-1	C	Top	11.84	19.96

8 FORENSIC ANALYSIS – FDOT-SMO SAMPLES

8.1 VISUAL OBSERVATIONS OF SAMPLES BEFORE FORENSIC ANALYSIS

The following sections show images of the concrete surface of the samples selected for forensic analysis before they were terminated. The front and back of each sample, as well as notable cracks, were documented.

8.1.1 STD3-2101-B (Tombstone)

Figure 8-1 shows the front and back side of sample STD3-2101-B. A crack without visible corrosion formed on the front face over bar 3 at the top of the sample extending down about 5 5/8" toward the right face. There was also a crack on the right face from the top of the sample with corrosion extending about 2.5" and then extending diagonally down towards the front face by about 3.5." This is shown in Figure 8-2.



Figure 8-1. Front and back side of sample STD3-2101-B before termination.



Figure 8-2. Right side crack of sample STD3-2101-B before termination.

8.1.2 STD3-2304-B (Tombstone)

Figure 8-3 shows the front and back side of sample STD3-2304-B. There was a crack with a bleed out on the back side below where the waterline was.

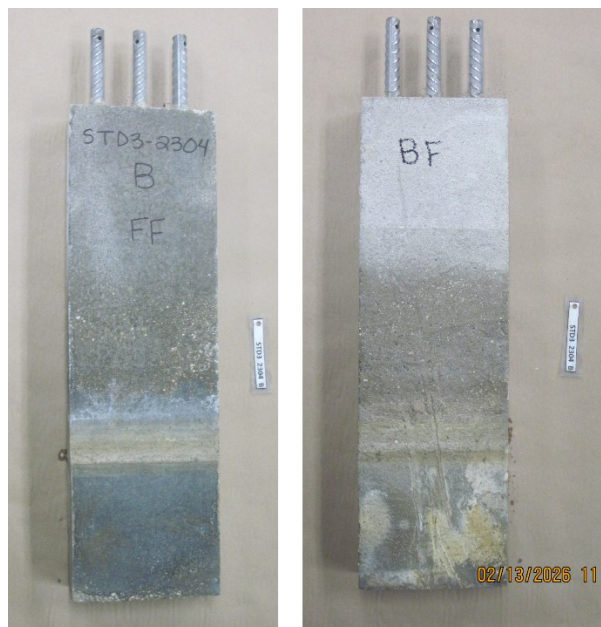


Figure 8-3. Front and back side of sample STD3-2304-B before termination.

8.1.3 BENT-STD3-304-C (Tombstone)

Figure 8-4 and Figure 8-5 show the back and front side of sample BENT-STD3-304-C, respectively. There were cracks with white bleed out on all sides of the sample above the waterline.



Figure 8-4. Back side of sample STD3-SMI-D before termination.



Figure 8-5. Front side of sample BENT-STD3-304-C before termination.

8.1.4 STD3-SMI-D (Tombstone)

Figure 8-6 shows the back side of sample STD3-SMI-D and Figure 8-7 shows multiple images of the front side. There was a crack with white bleed out on the front face below the waterline over bar 3. The front side also had a big spot of corrosion with bleed out over bar 3 above the waterline. The crack there had a length of about 6.0" and width of 0.012". There were corrosion spots at a width of 1.0" and a length about 3.0", and small spots of corrosion on the bottom over bar 3.



Figure 8-6. Back side of sample STD3-SMI-D before termination.



Figure 8-7. Front side of sample STD3-SMI-D before termination.

8.1.5 STD3-3CR12-E (Tombstone)

Figure 8-8 shows the front and back of sample STD3-3CR12-E. There was a crack with white bleed out on the bottom left corner of the front side below the waterline extending to the left face, which is shown in Figure 8-9. There was no corrosion in this crack.



Figure 8-8. Front and back side of sample STD3-3CR12-E before termination.



Figure 8-9. Back side crack of sample STD3-3CR12-E before termination.

8.1.6 STD3-MMFX-B (Tombstone)

Figure 8-10 shows the front side and back side of sample STD3-MMFX-B. Figure 8-11 shows a close-up of the crack that was observed on the front face.

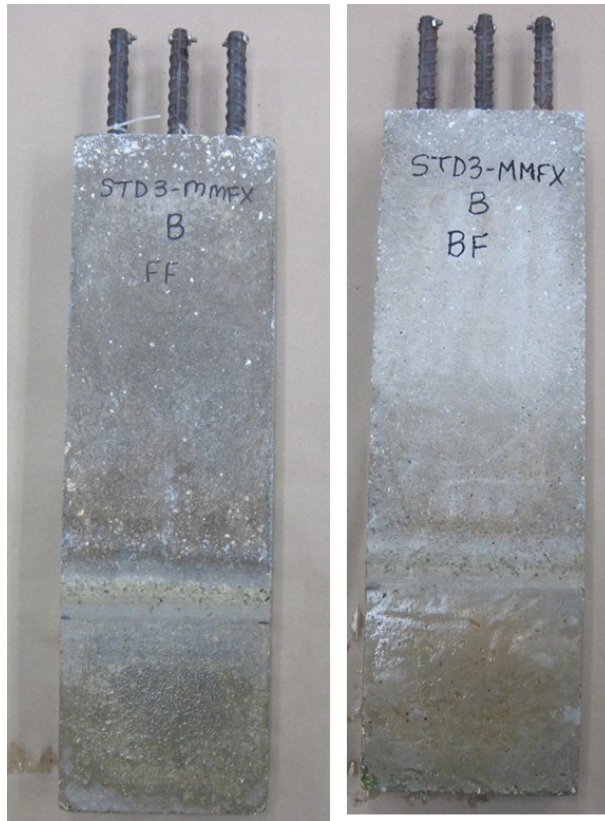


Figure 8-10. Front and back side of sample STD3-MMFX-B before termination.



Figure 8-11. Crack observed on the front side of sample STD3-MMFX-B before termination.

8.1.7 ELEV-MMFX-A (3-Bar Square)

Figure 8-12 shows the front side of sample ELEV-MMFX-A with a bleed out evident on the bottom area. Figure 8-13 shows the back side. No noticeable corrosion took place, and there were no visible cracks.



Figure 8-12. Front side of sample ELEV-MMFX-A before termination.



Figure 8-13. Back side of sample ELEV-MMFX-A before termination.

8.1.8 UBDB-SMI-B (G109)

Figure 8-14 shows the top and bottom trace left by the u-bar in sample UBDB-SMI-B. An up-close image of the top side is shown in Figure 8-15, which shows slight marks of corrosion in the middle of the U.

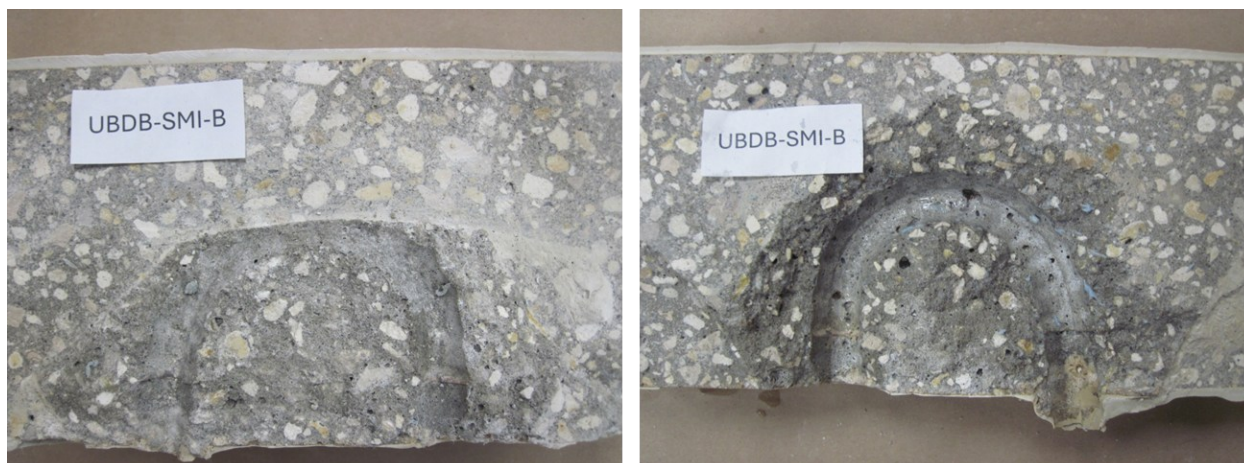


Figure 8-14. Top (left) and bottom (right) trace of sample UBDB-SMI-B (G109).

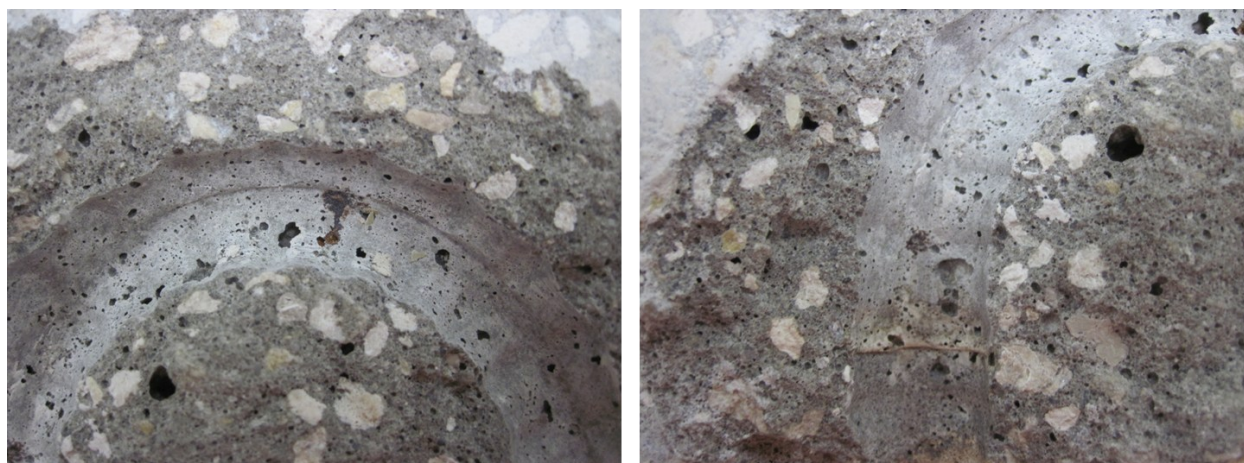


Figure 8-15. Top trace and close-up of sample UBDB-SMI-B (G109).

8.2 VISUAL OBSERVATIONS OF CORROSION ON BARS AFTER TERMINATION

The following sub-sections present further analysis of the samples mentioned in section 5. Visual observations of corrosion on certain rebars were reported. The figures show individual corrosion spots on rebars, and images of the rebars together in their entirety.

8.2.1 STD3-2101-B (Tombstone)

Figure 8-16 shows all the rebars from sample STD3-2101-B. There were notable signs of corrosion on rebars 2 and 3, while rebar 1 had no corrosion. Figure 8-17 and Figure 8-18 show corrosion spots from multiple angles on rebars 2 and 3, respectively. Rebar 2 and 3 had corrosion where the bar exits the concrete. There was no corrosion on the bar at, above, or below the waterline on the bar.



Figure 8-16. All rebars of sample STD3-2101-B.



Figure 8-17. Close up of corrosion spot on rebar 2 of sample STD3-2101-B at multiple angles.



Figure 8-18. Close up of corrosion spot on rebar 3 of sample STD3-2101-B at multiple angles.

8.2.2 STD3-2304-B (Tombstone)

Figure 8-19 shows all the rebars from sample STD3-2304-B. Rebar 2, shown in Figure 8-20, had notable corrosion at the bottom of the bar extending 2" up from the bottom of the bar and the spot itself is about 1/2" wide. Rebars 1 and 3 had no corrosion.



Figure 8-19. All rebars of sample STD-2304-B.



Figure 8-20. Close up corrosion spot on rebar 2 of sample STD-2304-B.

8.2.3 BENT-STD3-304-C (Tombstone)

Figure 8-21 shows all the rebars of sample BENT-STD3-304-C. Rebar 1 had corrosion near the top of the bar where the bar exits the concrete, which is shown in Figure 8-22. There was a corrosion spot on the bar at about 3" above the bend that had a length of 0.25", and a width of about 0.25".

Rebar 2, shown in Figure 8-23, had corrosion on the bottom of the bar that covers about 1/3 of the bottom; there was no other corrosion on the bar. Rebar 3, shown in Figure 8-24 had two spots of corrosion on the bar; one at approximately the waterline and one below the waterline; the topmost spot was about 13.5" down from the top of the bar; the bottom most spot was about 17 and 1/8" down from the top of the bar.



Figure 8-21. All rebars of sample BENT-STD3-304-C.



Figure 8-22. Close up corrosion spots on rebar 1 of sample BENT-STD3-304-C.



Figure 8-23. Close up corrosion spot on end of rebar 2 of sample BENT-STD3-304-C.

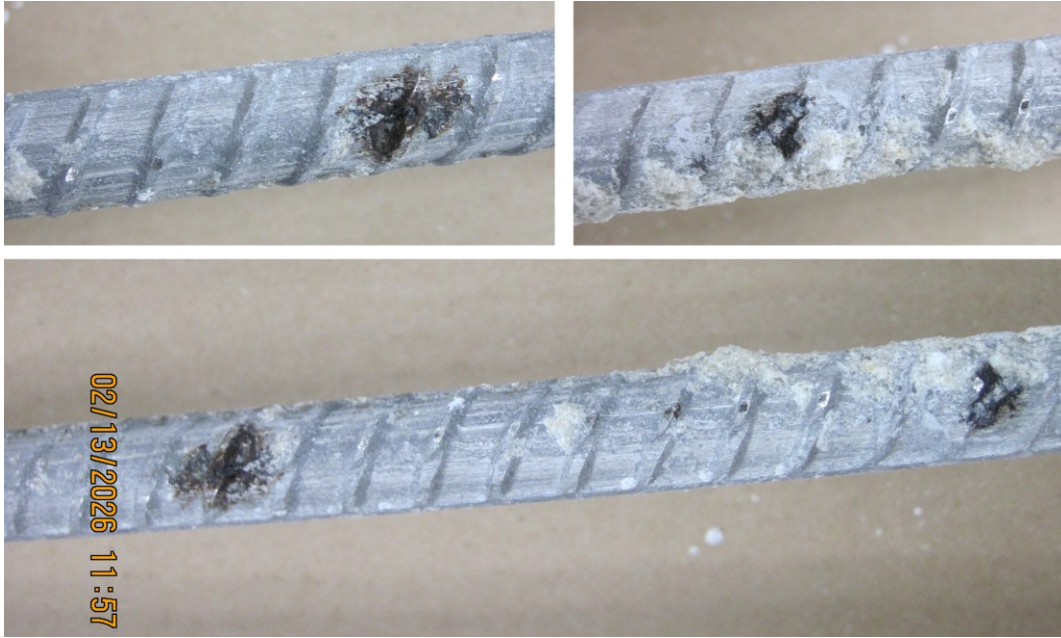


Figure 8-24. Close up corrosion spots on rebar 3 of sample BENT-STD3-304-C.

8.2.4 STD3-SMI-D (Tombstone)

Figure 8-25 shows the rebars of sample STD3-SMI-D as well as corrosion on rebar 3. Rebar 3 had a spot of corrosion on the bar near the bottom about $\frac{1}{8}$ " up from the bottom extending to $\frac{7}{8}$ " of the bar length with a width of about $\frac{3}{16}$ ". There was also corrosion on the bar at about 5.75" up from the bottom of the bar extending up to about 8.5", covering about $\frac{1}{2}$ of the bar at that spot. Rebar 1 had corrosion at about 6.75" up from the bottom of the bar extending up to 7 and $\frac{7}{8}$ " with a width of about half of the bar at that spot. Rebar 2 had corrosion on the bar covering the bottom 2 and $\frac{5}{16}$ " and about $\frac{1}{3}$ of the bar at that location.



Figure 8-25. All rebars and close up image of corrosion spot on rebar 3 of sample STD3-SMI-D.

8.2.5 STD3-3CR12-E (Tombstone)

Figure 8-26 shows all rebars of sample STD3-3CR12-E. Figure 8-27 shows corrosion spots on rebars 1 and 2. Rebar 1 had a spot of corrosion at the bottom of the bar extending about 7/8" up from the bottom and covering about 1/3 of the bar at that location. There was corrosion on rebar 2 starting approximately 2.75" up from the bottom of the bar and extending up to about 7.25" from the bottom of the bar; corrosion covers approximately 3/4 of the bar at that location. Figure 8-28 shows multiple large corrosion spots on rebar 3.



Figure 8-26. All rebars of sample STD3-3CR12-E.



Figure 8-27. Corrosion spots on rebar 1 (right 2 images) and 2 (left) of sample STD3-3CR12-E.

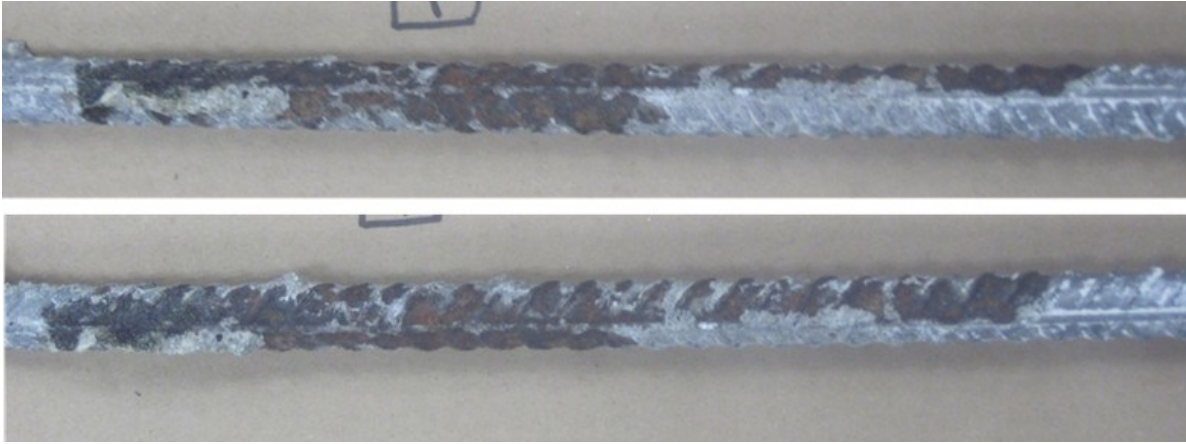


Figure 8-28. Corrosion spots on rebar 3 of sample STD3-3CR12-E.

8.2.6 STD3-MMFX-B (Tombstone)

Figure 8-29 shows all rebars of sample STD3-MMFX-B. Figure 8-30 shows corrosion spots on rebars 1, Figure 8-31 shows the corrosion spots observed on rebar 2 (bottom of the rebar), and. Figure 8-32 shows the corrosion spots observed on rebar 3.



Figure 8-29. All rebars of sample STD3-MMFX-B.

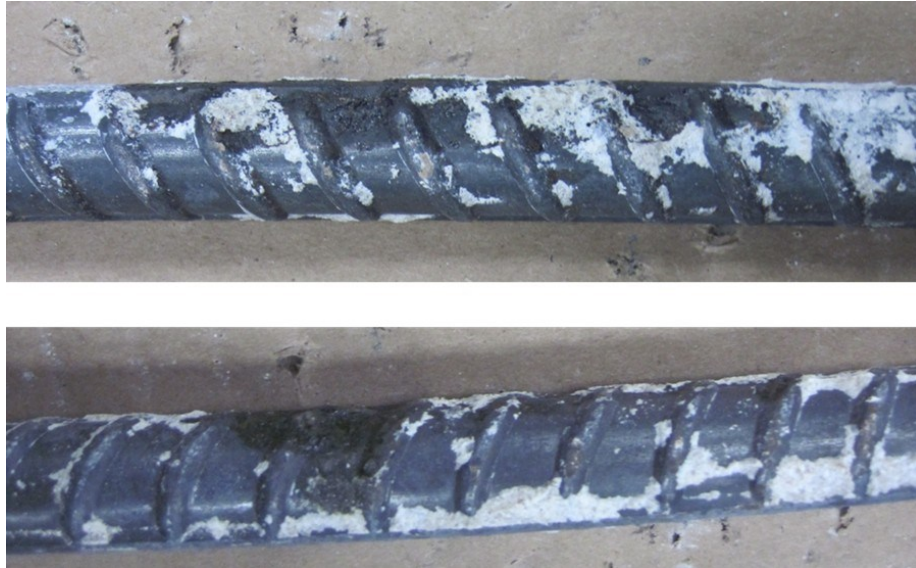


Figure 8-30. Corrosion spots observed on rebar 1 of sample STD3-MMFX-B.



Figure 8-31. Corrosion spots observed on rebar 2 of sample STD3-MMFX-B.



Figure 8-32. Corrosion spots observed on rebar 3 of sample STD3-MMFX-B.

8.2.7 ELEV-MMFX-A (3-Bar Square)

Figure 8-33 shows the rebars from sample ELEV-MMFX-A. Each rebar in this sample had corrosion. Figure 8-34 shows corrosion on rebar 1. There was corrosion on the bar about 3.25" up from the bottom of the bar which extended to $\frac{3}{8}$ " up from the bottom with a width of $\frac{1}{2}$ ". Figure 8-35 shows the corrosion on rebar 2. There was corrosion on the bar about 3.5" up from the bottom of the bar extending to about $\frac{2}{3}$ " around the bar at that location. Figure 8-36 shows the corrosion spots on rebar 3, which was about $\frac{1}{8}$ " up from the bottom extending to approximately $\frac{3}{4}$ " and 1" up from the bottom. There was also a spot of corrosion about 3.5" up from the bottom of the bar extending 1" up on the bar. Corrosion covered approximately $\frac{3}{4}$ of the bar at that location.



Figure 8-33. All rebars of sample ELEV-MMFX-A.



Figure 8-34. Corrosion spots on rebar 1 of sample ELEV-MMFX-A.

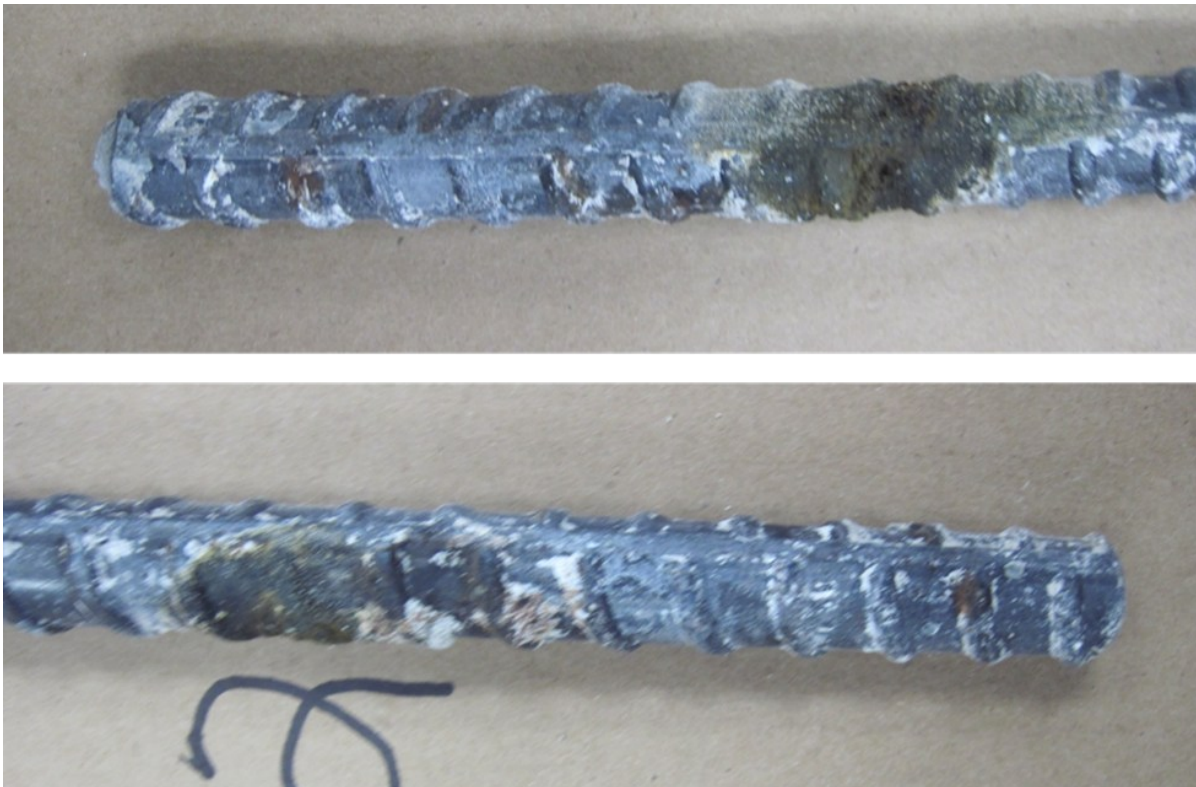


Figure 8-35. Corrosion spots on rebar 2 of sample ELEV-MMFX-A.

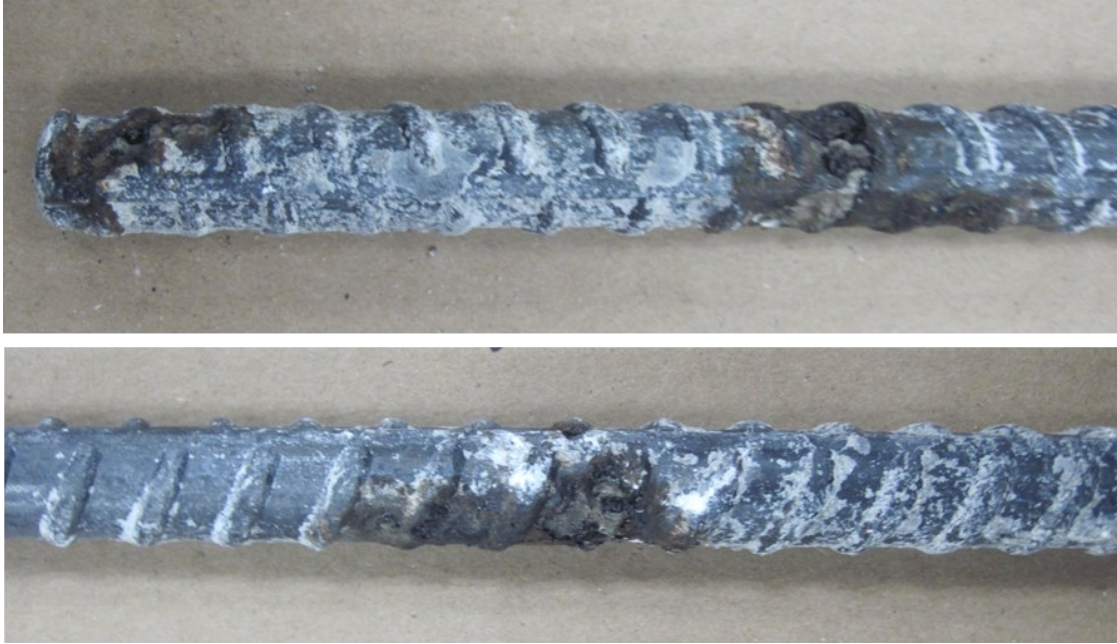


Figure 8-36. Corrosion spots on rebar 3 of sample ELEV-MMFX-A.

8.2.8 UBDB-SMI-B (G109)

Figure 8-37 and Figure 8-38 show the top and bottom sides of the u-bar in sample UBDB-SMI-B, respectively. There was corrosion on the left arm of the bar on the bottom side at about 3/4" length and about 1/2" wide. The top side had tiny spots of corrosion in one of the pin holes on the bent part of the bar and a tiny spot of corrosion 1/8" away.

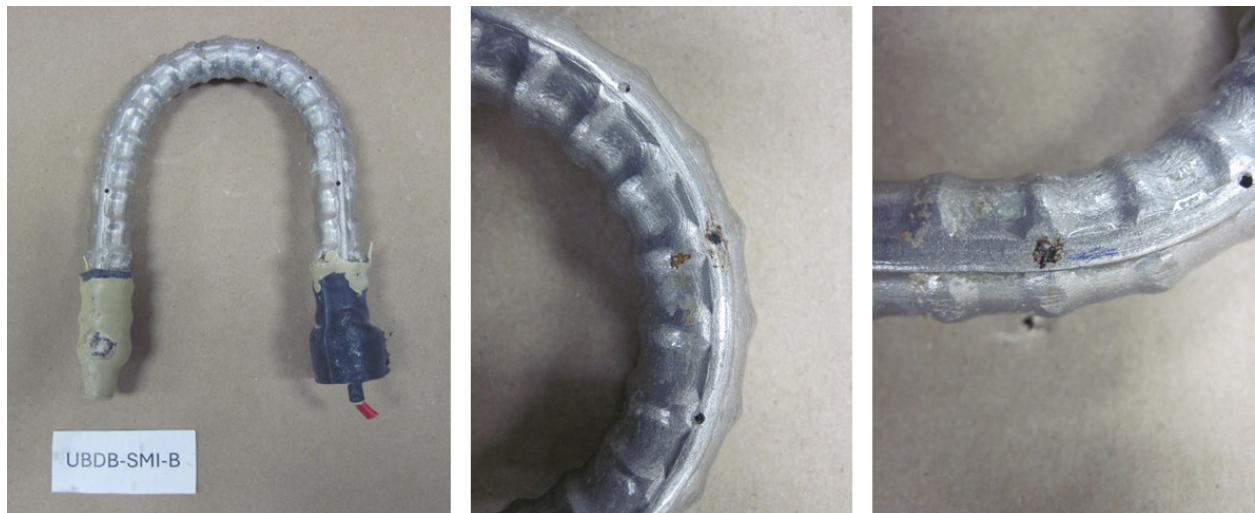


Figure 8-37. Corrosion spots on top side of sample UBDB-SMI-B (G109).



Figure 8-38. Corrosion spots on bottom side of sample UBDB-SMI-B (G109).

8.3 VISUAL OBSERVATIONS OF CORROSION ON BARS AFTER TERMINATION AND CLEANING

The sections below show the rebars from the FDOT-SMO samples that had noticeable corrosion sites. Each sample had three associated rebars, but some are not shown in this section mainly because they did not have any major corrosion damage. The length scale that each of the rebars were measured on, starts from the side with the bolt connection and then ends at the other end of the rebar, as seen in the following images. One exception exists for the rebars with the bent geometry, as the length scale starts from the bolt connection to the end of the rebar without including the bent portion, as shown in the photos. The rebars were cleaned with vinegar through immersion and scrubbing. This process was repeated when necessary.

Sections 8.3.1 to 8.3.7 show the forensic analysis for the samples with the Tombstone geometry samples after the rebars have been cleaned. Section 8.3.8 follows, showing the rebars after cleaning from the 3-bar square sample and G-109 modified sample.

8.3.1 STD3-2101-B (Tombstone)

Figure 8-39 shows all three rebars of sample STD3-2101-B as an example of the rebars after cleaning has taken place.



Figure 8-39. All rebars of sample STD3-2101-B after cleaning.

Rebars 2 and 3 showed corrosion sites, and rebar 3 showed the largest surface area affected. There was also one smaller affected area on rebar 2. Figure 8-40 and Figure 8-41 show rebar 2 and 3 respectively. Rebar 1 did not have any major areas of pitting or corrosion damage.



Figure 8-40. Corrosion spot observed on rebar 2 of STD3-2101-B.

The corrosion site on rebar 2 occurred from a length of about 3.5 inches to about 4 inches on the length scale defined above. The small wedge along the bar was eroded off, as seen in the top middle section of Figure 8-40. Otherwise, the corrosion site itself was not very deep and was mainly surface level damage.

Rebar 3 (Figure 8-41) had a larger area of corrosion damage that spanned from around 3.5 inches to just over 5 inches on the length scale. The affected area spanned around the entire circumference of the rebar, and it varied in length around the circumference as seen in the images. The rebar cross section loss was much deeper compared to the damage on rebar 2. The corrosion products at rebar 3 caused the concrete to crack as described in Section 8.1.1.



Figure 8-41. Full length of rebar 3 and notable areas of corrosion damage of sample STD3-2101-B.

8.3.2 STD3-2304-B (Tombstone)

Figure 8-42 and Figure 8-43 show images of rebars 2 and 3, respectively after cleaning the rebars removed from sample STD-2304-B. Figure 8-42 shows that Rebar 2 had one major corroding area at the rebar end. The corrosion site length is a little longer than the spacing between three rebar ribs. The corrosion site covered a small fraction of the rebar circumference. The corrosion site was about $1/10^{\text{th}}$ of an inch in depth. Figure 8-43 shows the full length and close-up of the shallow corroding sites observed on Rebar 3.



Figure 8-42. Corrosion spot observed on rebar 2 of sample STD3-2304-B.

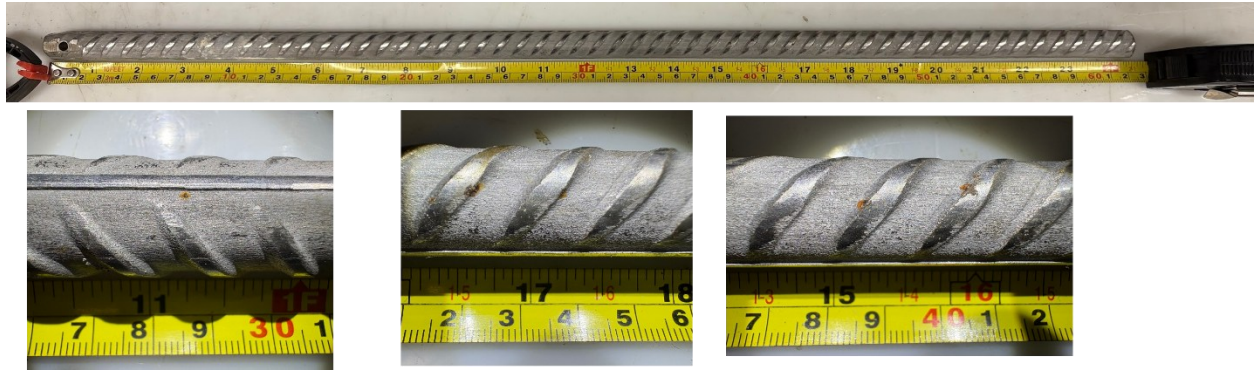


Figure 8-43. Sample STD3-2304-B - full length of rebar 3 and corrosion sites.

Rebar 3 did not have any major areas of corrosion, and it only had very little corrosion spots scattered throughout the rebar, which are documented in Figure 8-43. The spots had very shallow depths and did not result in significant damage to the rebar.

8.3.3 BENT-STD3-304-C (Tombstone)

Figure 8-44 and Figure 8-45 show images of rebars 1 and 3, respectively from sample STD3-304-C (BENT). Rebar 2 did not show any notable signs of corrosion damage. As shown in Figure 8-45, rebar 1 had a few small areas of corrosion damage. The largest one occurred at around 3.75 to 3.9 inches on the length scale. The others were small divots in different areas of the rebar. The one on the left of Figure 8-44 occurred at about 15.2 inches on the length scale and the one on the right at 16.1 inches, note that there was cross section loss at these sites.

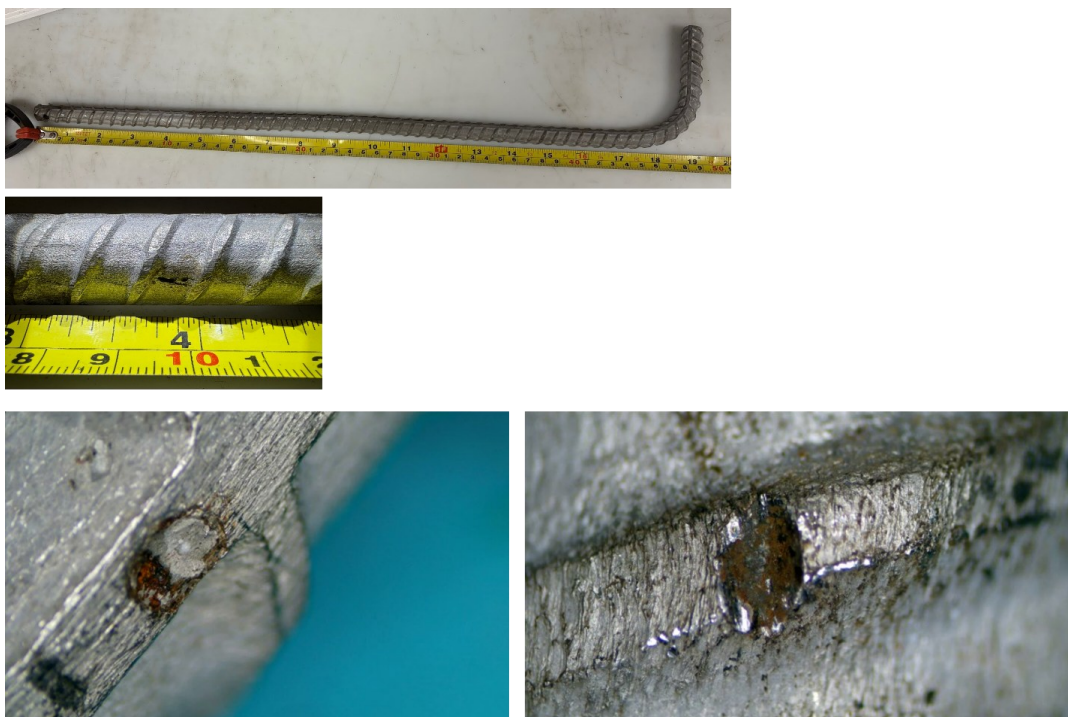


Figure 8-44. STD3-304-C (BENT) - full length of rebar 1 and corroding locations.

Rebar 3 only showed one area with significant corrosion damage as can be observed in Figure 8-45. The corrosion site location was 13.8 inches on the length scale. It had a larger depth compared to the corrosion sites in rebar 1, but the corrosion sites on both rebars were still quite shallow.



Figure 8-45. STD3-304-C (BENT) rebar 3 corroding site after cleaning.

8.3.4 STD3-SMI-D (Tombstone)

Figure 8-46 and Figure 8-47 show rebars 1 and 3, respectively from sample STD3-SMI-D. Rebar 1 did not show any major signs of corrosion apart from one very large pit that spanned from roughly 16.3 inches to 16.7 inches on the length scale. The pit was about 0.25 inches in depth.

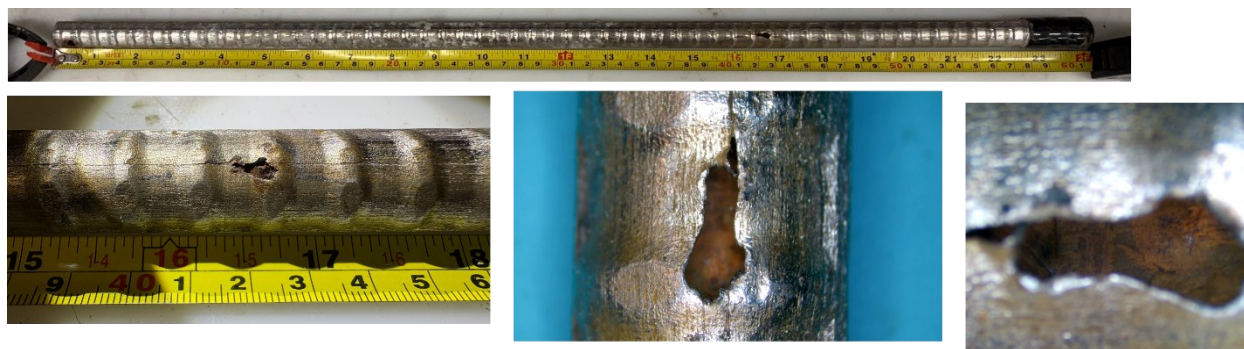


Figure 8-46. STD3-SMI-D - full length of rebar 1 and notable corroding site after cleaning.

Rebar 3 had a few minor damage sites from corrosion, and one small, but deep pit that occurred 20 inches on the length scale, which is shown on the bottom left of Figure 8-47. The rest of the damage was minor and did not result in any deep pits, as shown with an example on the bottom middle of Figure 8-47.

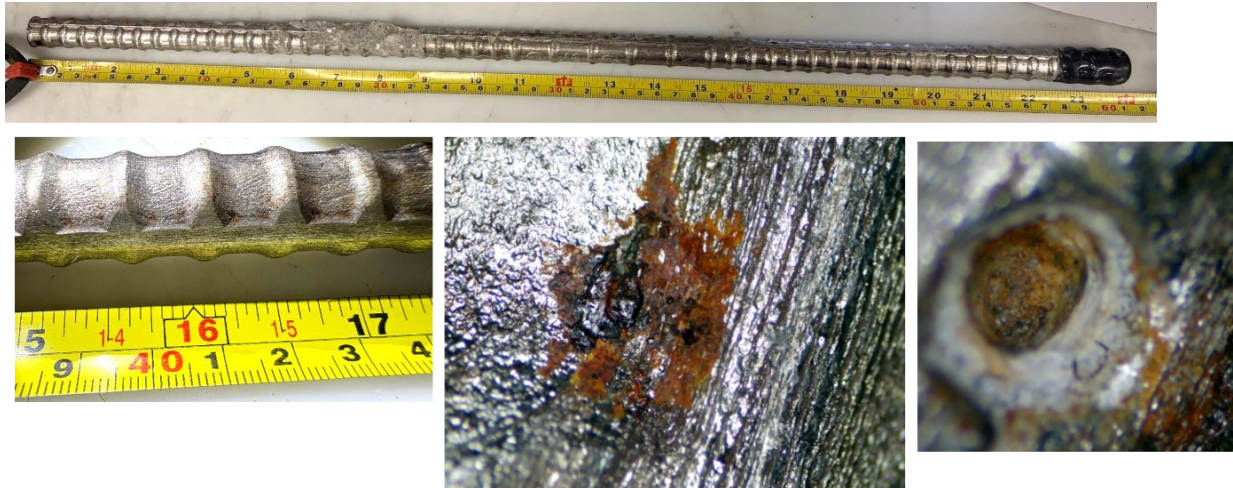


Figure 8-47. STD3-SMI-D - full length of rebar 3 and notable areas of corrosion damage.

8.3.5 STD3-3CR12-E (Tombstone)

Below are notable areas of corrosion damage on rebars 1 and 3 from sample STD3-3CR12-E. Rebar 2 did not show any major damage. Figure 8-48 shows rebar 1, which had minor specs of damage in a few places along its length. The only major area of damage occurred at the end of the rebar at around 2 feet on the length scale, as seen below. The damage did not span around the rebar and stayed on the displayed side.



Figure 8-48. STD3-3CR12-E - full length of rebar 1 and notable areas of corrosion damage.

Figure 8-49 shows rebar 3, which had major damage along a large section of the rebar. The damage spanned from about 5.5 inches to about 15.7 inches on the length scale. Although the damage covered a large surface area, the corroding sites after cleaning were not very deep.



Figure 8-49. STD3-3CR12-E - full length of rebar 3 and notable areas of corrosion damage.

8.3.6 STD3-MMFX-B (Tombstone)

The following figures show rebars 1, 2, and 3 from the STD3-MMFX-B. The measuring tape was located in the opposite end for the rebars on this sample. Each of the rebars showed significant corrosion damage along large sections of them. Figure 8-50 shows rebar 1, which had two major corroded areas that occurred at the rebar end and from about 6 inches to 10 inches on the length scale shown. The site between 6 and 10 inches extended most of the rebar circumference. Major corrosion sites occurred at the very beginning, and at the end of this damaged region.



Figure 8-50. STD3-MMFX-B - full length of rebar 1 and notable areas of corrosion damage.

Figure 8-51 shows rebar 2, which had damage at the rebar end. The damage was somewhat deep and spanned about 2.3 inches (see close-ups). The damage was localized to that area and was only found on one side of the rebar.



Figure 8-51. STD3-MMFX-B - full length of rebar 2 and notable areas of corrosion damage.

Figure 8-52 shows rebar 3, which had one large section with corrosion damage, located 19 inches from the side with the drilled hole. The corrosion site extended about two inches in length. The damaged area was somewhat deep as can be observed on the close-up. It cover most of the rebar circumference.



Figure 8-52. STD3-MMFX-B - full length of rebar 3 and notable areas of corrosion damage.

8.3.7 ELEV-MMFX-A (3-Bar Square)

The following rebar images after cleaning the rebar removed from ELEV-MMFX-A 3-Bar Square sample. Each of the three rebars of this sample had some corrosion damage. Figure 8-53 shows rebar 1, which had very little damage, and only contained one small corrosion site, a deep pit occurred at around 18.8 inches on the length scale.

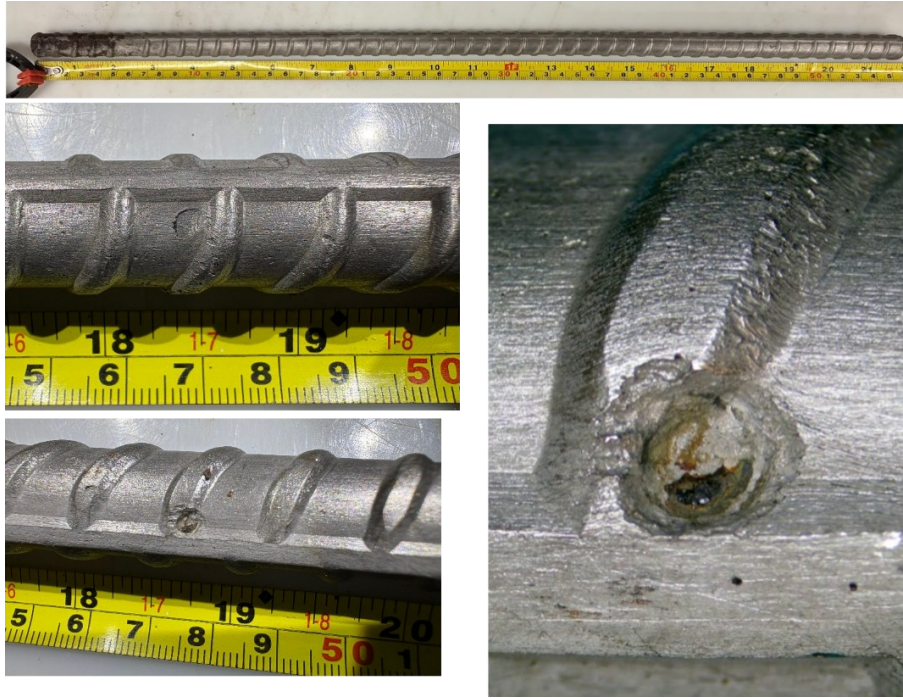


Figure 8-53. ELEV-MMFX-A - full length of rebar 1 and notable areas of corrosion damage.

Figure 8-54 shows rebar 2. Rebar 2 had more significant damage at around 18.5 inches on the length scale. The rebar had two deep corrosion sites in that location, and other wider areas of damage on the other side around the same area on the length scale. Figure 8-55 shows rebar 3, which had the most severe damage out of all three rebars. It had multiple deep sites around 21 to 22 inches on the length scale, as well as a wide section of cross-section loss around that area as well. It also had damage at the end that spread unevenly to about an inch long.



Figure 8-54. ELEV-MMFX-A - full length of rebar 2 and notable areas of corrosion damage.



Figure 8-55. ELEV-MMFX-A - full length of rebar 3 and notable areas of corrosion damage.

8.3.8 UBDB-SMI-B (G109)

Figure 8-56 shows the bottom side of the U-bar from sample UBDB-SMI-B. Before the rebar was cleaned, there was corrosion build-up on the left side of this rebar face. This section was the only area of major corrosion build-up on the entire rebar. After this rebar area was cleaned, the hole drilled below this area was photographed and shown on the very right side of the figure. The hole resembled the others, and some of them were clogged with corrosion products and some were not. The two holes depicted below are representative of how the holes throughout the rebar looked.



Top most on left side



Left most

Figure 8-56. Rebar removed from UBDB-SMI-B sample: left top side full U rebar view and two close-up of the drilled holes.

9 CONCLUSIONS

9.1 SDS SAMPLES AT FAU

Most monitored 316, CT1, CT2, 304 and 2304 rebars were found not to be corroding.

A few samples with CT2 rebars that had been drilled were found to be corroding. CT2 rebars were found to be corroding and to have progressed to the point that cracks were visible at the concrete surface (CREV geometry) due to rebars ends not being capped.

The two remaining samples with 3CR12 rebars were found to be corroding. Interestingly the corrosion extent was not the same on all rebars. One possible explanation for this could be that the rebar that was observed to have more cross-section loss acted as sacrificial protection for the other rebars when interconnected.

Little or no corrosion was observed on the 304 and 316 rebars that were removed from samples that had carbon steel on the second row.

9.2 SAMPLES EXPOSED AT FDOT-SMO

All terminated samples had at least one rebar that corroded. Samples with MMFX were found to have the worst corrosion (i.e., the rebar corrosion extent both before cleaning and after cleaning). 3CR12 rebars showed corrosion on two of the rebars and the areas with corrosion were less than observed on MMFX rebars.

Two 2101 rebars were found with corrosion; in this case, the corrosion sites were close to the top of the sample away from the immersed region. In the Tombstone sample, corrosion on rebar 3 caused a crack. One 2304 rebar showed corrosion on rebar 2, and corrosion was located at the embedded lower point of the rebar. Two CT2 rebars were found to have corroded at locations where holidays or defects were present. After cleaning, the bent 304 rebars showed small corrosion spots.

9.3 FIELD COLUMNS

All columns with BB, 2101, 3CR12 and MMFX rebars were found with concrete cracks along the rebar length. One of the columns with 2101 rebar experienced a spall between the two visits. It is important to note that the 2101 rebar had mill scale which likely allowed corrosion to initiate at a low chloride threshold. The cores obtained from columns with MMFX rebars (1) and 2101 rebars (2) contained rebar segments. The rebar segments showed a significant amount of cross section loss on some sections of the rebar, but other parts of the rebar had no corrosion. The localized nature of corrosion on intermediate corrosion resistant rebars proceeded to the extent that an x-crit larger than what causes cracks took place on all the columns with 2101, 3CR12 and MMFX. The mixed potential that develops between the areas with oxygen and the areas that are partially or fully saturated appear to interact in such a way that the corrosion process is supported once it has been initiated.

9.4 VISITED BRIDGES

It is the authors' opinion that, based on the chloride profiles and concrete surface resistivity, the Jensen Beach Bridge columns and footers with 2101 rebars are not corroding. The chloride concentration at the rebar depth observed from the profiles is below the expected chloride threshold for 2101 alloy. Based on the inspection during the visit to Bridge #510072, SR30A Bridge at St. Joseph's Bay area, the 316 rebar at Bridge #510072 is likely not corroding. During the visits to the bridges, it was observed that both bridges had cracks that are not related to corrosion.

10 REFERENCES

- [1] F. Presuel-Moreno, J. Zielske, Y. Wu and V. Casas, "Analysis and Estimation of Service Life of Corrosion Prevention Materials Using Diffusion, Resistivity, and Accelerated Curing for New Bridge Structures: Volume 1: Corrosion Prevention Materials (Monitoring and Forensic Examination)," Florida Department of Transportation Research Center, Tallahassee, FL, Report BDK-79-977-02, 2013.
- [2] U. Angst, O. B. Isgor, C. M. Hansson, A. Sagüés and G. M. R, "Beyond the chloride threshold concept for predicting corrosion of steel in concrete," *Appl. Phys. Rev.*, vol. 9, no. 1, 2022.
- [3] F. Presuel-Moreno, R. G. Powers and W. H. Hartt, "Corrosion Resistant Alloys for Reinforced Concrete," Florida Department of Transportation Research Center, Tallahassee, FL, Final Report BD228, 2008.
- [4] W. H. Hartt, R. G. Powers, D. K. Lysogorski, M. Paredes and Y. P. Virmani, "Job Site Evaluation of Corrosion-Resistant Alloys for Use as Reinforcement in Concrete," Federal Highway Administration, U.S. Department of Transportation, Washington, DC, FHWA-HRT-06-078, 2006.
- [5] P. Castro-Borges, O. Traconis de Rincon, E. I. Moreno, A. A. Torres-Acoasta, M. Martinez-Madrid and A. Knudsen, "Performance of a 60-Year-Old Concrete Pier with Stainless Steel Reinforcement," *Materials Performance*, pp. 50-55, October 2022.
- [6] S. R. Sharp, L. J. Lundy, H. Nair, C. D. Moen, J. B. Johnson and B. E. Sarver, "Acceptance Procedures for New and Quality Control Procedures for Existing Types of Corrosion Resistant Reinforcing Steel," VTRC, Virginia Department of Transportation, Richmond, VA, Final Report VCTIR 11-R21, 2011.
- [7] Virginia Department of Transportation, "Instructional and Informational Memorandum: Corrosion Resistant Reinforcing Steels (CRR)," IIM-S&B-81.11, Richmond, VA, 2026.
- [8] World Steel Association, "Stainless steel rebar applications in architecture, building and construction," [Online]. Available: <https://worldstainless.org/applications/architecture-building-and-construction-applications/stainless-steel-rebar/>.
- [9] K. Cornell, "Key elements of Kenaston Overpass in Winnipeg reinforced with stainless steel rebar," *The Stainless Rebar Standard*, 2014.

- [10] S. Rizkalla, P. Zia, H. Seliem and G. Lucier, "Evaluation of MMFX Steel for NCDOT Concrete Bridges," North Carolina Department of Transportation, Raleigh, NC, FHWA/NC/2006-31, 2005.
- [11] I. Lasa, M. Duncan and W. Scannell, "Field Evaluation of MMFX and 2101LDX Stainless Steel Reinforcement," Florida Department of Transportation Corrosion Research Laboratory, Gainesville, FL, Final Interim Performance Report, 2020.
- [12] F. Presuel-Moreno, G. Pimentel, S. Zapata and R. Taylor, "Current State of Simulated Desk Slab Samples Cast with Corrosion Resistant Alloys (>16 years)," in *TriDurLE Year 3*, August 2024.
- [13] R. Taylor, "Corrosion Monitoring and Analysis of Reinforced Concrete: Corrosion Resistant Alloys After Long Term Exposure to Chlorides," Master's thesis, Florida Atlantic University, 2023.
- [14] FDOT, "Florida Method of Test for Determining Low-Levels of Chloride in Concrete and Raw Materials in FM 5-516," Florida Department of Transportation, 2023.
- [15] D. Trejo and R. G. Pillai, "Accelerated Chloride Threshold testing: Part II - Corrosion-Resistant Reinforcement," *ACI Materials Journal*, vol. 101, no. 1, pp. 57-64, 2004.
- [16] S. C. Kranc, A. A. Sagüés and F. Presuel-Moreno, "Decreased Corrosion Initiation Time of Steel in Concrete Due to Reinforcing Bar Obstruction of Diffusional Flow," *ACI Materials Journal*, vol. 99, pp. 51-53, 2002.
- [17] H. Yu and W. H. Hartt, "Effects of Reinforcement and Coarse Aggregates on Chloride Ingress into Concrete and Time-to-Corrosion: Part 1—Spatial Chloride Distribution and Implications," *Corrosion*, vol. 63, no. 9, pp. 843-849, 2007.
- [18] F. Presuel-Moreno and S. Mavrak, "Characterization of various corrosion resistant rebars embedded in concrete after 20 years of exposure," in *AMPP 2026 Conference*, Houston, TX, 2026.

11 APPENDICES

11.1 APPENDIX A: NAMES OF SDS SAMPLES AT FAU

Table 11-1. List of all monitored SDS samples at FAU.

ID	Rebar Type	Older ID	Status
103	304SS	6-CREV-304-1	Not terminated
104	304SS	6-CREV-304-2	Not terminated
201	CT2	4-STD2-CT2-1	Not terminated
202	CT2	4-STD2-CT2-2	Not terminated
203	CT2	4-STD2-CT2-3	Not terminated
204	CT2	4-STD1-CT2-1	Not terminated
205	CT2	4-STD1-CT2-2	Not terminated
206	CT2	4-STD1-CT2-3	Not terminated
207	CT2	4-CCON-CT2-1	Rebar C terminated
208	CT2	4-CCON-CT2-2	Not terminated
209	CT2	4-CCON-CT2-3	Not terminated
210	CT2	4-CREV-CT2-1	Not terminated
211	CT2	4-CREV-CT2-2	Not terminated
212	CT2	4-CREV-CT2-3	Not terminated
213	CT2	4-CCRV-CT2-1	Not terminated
214	CT2	4-CCRV-CT2-2	Not terminated
215	CT2	USDB-CT2-1	Not terminated
216	CT2	USDB-CT2-2	Not terminated
217	CT2	USDB-CT2-3	Not terminated

ID	Rebar Type	Older ID	Status
218	CR12	4-CCRV-3CR12-2	Terminated
219	CR12	4-CCRV-3CR12-3	Not terminated
220	304SS	6-CCRV-304-1	Not terminated
221	304SS	6-CCRV-304-2	Not terminated
222	304SS	6-CCON-304-1	Not terminated
224	304SS	6-CCRV-304-3	Not terminated
225	304SS	6-WB-304-1	Not terminated
226	304SS	6-CREV-304-3	Not terminated
227	CT2	CREV-CT2-1	Not terminated
228	CT2	CREV-CT2-2	Terminated
301	316SS	1-STD2-316-1	Not terminated
302	316SS	1-STD2-316-2	Not terminated
303	316SS	1-STD2-316-3	Not terminated
304	CT1	1-STD2-CT1-1	Not terminated
305	CT1	1-STD2-CT1-2	Not terminated
306	CT1	1-STD2-CT1-3	Not terminated
307	316SS	1-STD1-316-1	Not terminated
308	316SS	1-STD1-316-2	Not terminated
309	316SS	1-STD1-316-3	Not terminated
310	CT1	1-STD1-CT1-1	Not terminated
311	CT1	1-STD1-CT1-2	Not terminated
312	CT1	1-STD1-CT1-3	Not terminated

ID	Rebar Type	Older ID	Status
313	316SS	2-PICK-316-2	Not terminated
314	316SS	2-PICK-316-3	Not terminated
315	CT2	BCCD-CT2-1	Terminated
316	CT2	BCCD-CT2-2	Not terminated
317	316SS	PICK-316	Not terminated
318	316SS	PICK-316	Not terminated
319	316SS	PICK-316	Not terminated
320	316SS	2-STD2-316-1	Not terminated
321	316SS	2-STD2-316-2	Not terminated
322	316SS	2-STD2-316-3	Not terminated
323	316SS	3-CCON-316-1	Not terminated
324	316SS	3-CCON-316-2	Not terminated
325	316SS	3-CCON-316-3	Not terminated
326	316SS	3-CCRV-316-1	Not terminated
327	316SS	CCON-316-?	Not terminated
328	316SS	CCON-316-?	Not terminated
329	316SS	CCON-316-?	Not terminated
330	316SS	3-CCRV-316-2	Not terminated
331	316SS	3-CREV-316-1	Not terminated
332	316SS	3-CREV-316-2	Not terminated
333	316SS	3-CREV-316-3	Not terminated
334	2304SS	5-STD1-2304	Not terminated

ID	Rebar Type	Older ID	Status
335	304SS	6-STD1-304-1	Not terminated
336	304SS	6-STD1-304-2	Not terminated
337	304SS	6-STD1-304-3	Not terminated
338	304SS	6-STD2-304-1	Not terminated
339	304SS	6-STD2-304-2	Not terminated
341	CT2	CSDB-CT2-2	Not terminated
342	CT2	CSDB-CT2-1	Terminated
343	304SS	6-STD2-304-3	Not terminated
344	304SS	6-CCON-304-2	Not terminated
345	304SS	6-CCON-304-3	Not terminated
346	304SS	6-WB-304-2	Not terminated

11.2 APPENDIX B: REBAR POTENTIAL MEASUREMENTS IN 2025

Table 11-2. Comprehensive list of electrically disconnected rebar potential measurements from January, February, and May 2025.

Date	1/2025	1/2025	1/2025	2/2025	2/2025	2/2025	5/2025	5/2025	5/2025
ID	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})
102	-	-	-	-90.6	-91.3	-114	-91.57	-90.29	-86.81
103	-163.1	-434	-161.6	-184.9	-347	-209.7	-166.84	-390.41	-163.21
104	-189.8	-258.9	-164.7	-177.7	-258.5	-194.5	-151.03	-183.5	-156.36
202	-127.8	-129	-141.7	-144.7	-150.9	-157.1	-125.29	-101.38	-101.26
203	-91.9	-51.7	-48.5	-46.7	-43.6	-58.7	-133.26	-3.17	-88.07
207	-	-	-	-105.2	-60.7	-284	-251.09	-183.81	-280.75
210	-	-	-	-	-	-	-46.32	-84.36	-86.69
211	-152.8	-156.1	-151.9	-159.3	-164.5	-161	-104.09	-93.41	-94.67
213	-147	-158.6	-160.6	-161.6	-173.1	-170.9	-67.05	-97.38	-55.09
214	-176	-179.6	-179.5	-134.4	-142	-139.5	-180.24	-173.32	-123.03
215	-	-	-	-401	-211.5	-171.5	-360.57	-334.11	-327.29
217	-	-	-	-171.5	-102.6	-137.4	-215.3	-54.99	-68.21
218	-456	-403	-440	-513	-459	-476	-433.29	-386.95	-409.42
219	-460	-470	-458	-432	-497	-472	-436.85	-496.58	-513.26
220	-380	-177.1	-173.1	-361	-231.7	-138.3	-340	-278.01	-187.89
221	-399	-175.4	-163	-358	-153.1	-159.2	-358.47	-192.06	-187.16
222	-191.1	-190.2	-190	-217.4	-222.5	-248.3	-125.64	-137.27	-152.67
225	-424	-211.5	-307	-399	-198.3	-210.7	-	-	-
226	-149.9	-334	-151.5	-135.7	-309	-166.3	-150.59	-265.81	-203.44

Date	1/2025	1/2025	1/2025	2/2025	2/2025	2/2025	5/2025	5/2025	5/2025
ID	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})
227	-258.2	-345	-393	-261.5	-401	-454	-294.42	-307.1	-455.03
228	-428	-426	-280	-409	-403	-273	-326.15	-348.9	-212.54
301	-70.8	-76.4	-69.7	-3.6	-8.6	-1.4	-1.65	-74.24	-62.29
302	-76.1	-77.9	-81.2	-82.3	-74.8	-77.6	-138.96	-223.12	-59.81
303	-66.6	-81.7	-81.1	-9.2	-23	-28.3	-10.79	-13	-82.17
304	-245.2	-113.9	-311	-167.6	-594	-154.8	-73.07	-53.31	-194.25
305	-100	-111.1	-79.8	-45.1	-58.6	-56	-111.4	-101.15	-154.72
306	-84.7	-87	-161.5	-39.5	-36.3	-39.3	-267.58	-60.51	-116.72
307	-92.7	-95.1	-92.4	-35.9	-45.4	-67.6	-89.46	-55.39	-52.67
309	-145.4	-141	-124.1	-180.5	-205.1	-179.9	-127.15	-126.77	-130.56
311	-127.7	-68.9	-142.4	-239.1	-185.1	-234.1	-242.03	-210.59	-195.66
312	-33.5	-12.6	-17.5	-46.9	-22.7	-27.8	-97	-139.58	-116.29
313	-187.3	-142.7	-209.4	-225.6	-249.4	-211.7	-239.56	-363.58	-286.1
314	-121.4	-217.4	-64.5	-178.5	-71	-59.9	-208.33	-142.18	-127.34
315	-	-	-	-517	-147.1	-233.3	-287.88	-210.32	-118.3
316	-	-	-	-512	-329	-416	-347.5	-278.13	-327.16
317	-99.1	-204.6	-105.7	-42.8	-112.9	-34.5	-96.61	-104.73	-153.19
318	-63.9	-73.2	-68.9	-4.9	-16	-9.6	-70.27	-83.86	-79.09
319	-79.4	-85.5	-81.2	-139	-137.4	-132.8	-68.34	-68.38	-102.15
320	-34.6	-33.9	-33.6	-75.7	-78.2	-75.4	-70.46	-69.23	-156.59
321	-171.3	-99.9	-93.1	-48.7	-70.1	-58.2	-125.88	-77.1	-73.63
322	-51	-48.7	-59.4	-13.9	-9	-12.6	-85.92	-155.92	-83.23

Date	1/2025	1/2025	1/2025	2/2025	2/2025	2/2025	5/2025	5/2025	5/2025
ID	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})	Rebar A (mV _{CSE})	Rebar B (mV _{CSE})	Rebar C (mV _{CSE})
323	-47.7	-49.4	-45.1	-30.3	-48.3	-41	-77.55	-70.64	-139.3
324	-	-	-	-88.7	-97.9	-98.1	-84.34	-85.7	-76.51
325	-	-	-	-144.1	-149.8	-161.2	-73.48	-75.98	-77.93
326	-59.3	-156.1	-69.8	-77.2	-143.1	-76.4	-120.64	-178.7	-122.05
327	-	-	-	-148.9	-176.7	-146.4	-176.02	-97.44	-90.07
328	-124.4	-107.2	-109.1	-218.6	-209.9	-206	-128.32	-349.7	-212.34
329	-67.7	-88.2	-47.1	-195	-201.1	-161.7	-118.55	-210.48	-256.93
331	-142.1	-151.3	-143.5	-189.2	-188.4	-189.8	-125.67	-122.52	-130.45
336	-97.1	-103.3	-99	-95.8	-97.6	-108.1	-212.16	-205.73	-201.09
337	-106.8	-135.8	-131	-207.7	-210.2	-204.8	-229.32	-238.11	-224.66
338	-130	-132.1	-136	-105	-116.5	-109.2	-117.21	-149.98	-79.49
339	-133	-139.9	-140.8	-178.9	-172.9	-168.7	-129.94	-129.13	-126.84
341	-284	-469	-461	-279	-442	-423	-277.47	-316.19	-334.31
342	-229	-201	-413	-405	-297	-418	-256.72	-253.53	-391.88
343	-125.1	-127.5	-125.6	-67.9	-56.3	-55.7	-119.55	-121.47	-127.74
344	-130.5	-131.8	-132.5	-126.7	-128.4	-167.6	-125.28	-201.64	-214.78
345	-135.4	-135.8	-131.9	-99.4	-101.8	-99.4	-273.03	-182.79	-123.67
346	-197	-144.4	-178	-300	-228.6	-363	-272.57	-156.94	-277.88

11.3 APPENDIX C: QUANTITATIVE MEASUREMENTS OF CORROSION DAMAGE TO SDS SAMPLES

11.3.1 4-CCRV-3CR12-2

Table 11-3. Rebar A1 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	4	0.63
Top	18.1	1.82
Top	18.4	2.51
Bottom	3.7	0.83

Table 11-4. Rebar A2 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	18.25	0.63
Top	19.6	0.98
Bottom	3.3	0.95

Table 11-5. Rebar B1 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	4.5	1.74
Top	11	0.96
Top	13.2	0.33
Top	16.6	7.59
Bottom	6.1	1.1
Bottom	7.4	2.22
Bottom	22.3	0.52

Table 11-6. Rebar B2 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	4.3	0.4
Top	15.3	1.11
Top	20	1.21
Top	22.6	2.26
Top	25.6	1.78

Table 11-7. Rebar C1 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	15.1	1.33
Top	16.5	1.13
Top	18.3	0.53
Bottom	3.5	0.65

Table 11-8. Rebar C2 of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	3.5	0.52
Top	18.4	1.52
Top	19.8	1.4

Table 11-9. Rebar D of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	6.2	0.35
Top	10.35	0.82

Table 11-10. Rebar E of sample 4-CCRV-3CR12-2 diameter losses due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	7.4	0.75
Top	12.5	0.89
Top	14.3	0.62
Top	17.6	0.7
Top	21.1	0.45
Top	26.4	0.19
Bottom	4	0.4
Bottom	6.5	1.03

Table 11-11. Rebar F of sample 4-CCRV-3CR12-2 diameter loss due to pitting corrosion.

Face	Position (cm)	Diameter loss (mm)
Top	3.2	1.19

11.3.2 CREV-CT2-2

Table 11-12. CREV-CT2-2 corrosion penetration depths at unclad rebar ends.

Rebar - Location Relative to Concrete	Penetration Depth (mm)
A1 - Outside	1.5
A1 - Inside	2
A2 - Outside	45
A2 - Inside	1.5
B1 - Outside	1.75
B1 - Inside	6
B2 - Outside	1.75
B2 - Inside	2.5
C1 - Outside	4
C1 - Inside	3.5
C2 - Outside	14
C2 - Inside	2

11.3.3 BCCD-CT2-1

Note: For all tables in this section, holes without listed depths were less than 0.1 cm.

Table 11-13. Hole depths of sample BCCD-CT2-1 rebar A.

Rebar A – Top Face		Rebar A – Bottom Face	
Hole	Hole Depth (cm)	Hole	Hole Depth (cm)
1	0.3	1	0.1
2	0.2	2	
3	0.11	3	0.15
4	0.1	4	0.11
5		5	0.33
6		6	
7		7	
8		8	
9	0.52	9	

Table 11-14. Hole depths of sample BCCD-CT2-1 rebar B.

Rebar B – Top Face		Rebar B – Bottom Face	
Hole	Hole Depth (cm)	Hole	Hole Depth (cm)
1	0.1	1	0.11
2	0.1	2	0.39
3		3	0.25
4		4	
5		5	
6		6	
7	0.15	7	
8		8	0.1
9	0.23	9	

Table 11-15. Hole depths of sample BCCD-CT2-1 rebar C.

Rebar C – Top Face		Rebar C – Bottom Face	
Hole	Hole Depth (cm)	Hole	Hole Depth (cm)
1		1	0.17
2	0.12	2	0.1
3		3	
4		4	0.22
5	0.12	5	
6		6	0.22
7	0.1	7	
8	0.1	8	0.1
9	0.1	9	

Table 11-16. Rebar A of sample BCCD-CT2-1: spaces between holes and hole orientation.

Rebar A – Top Face			Rebar A – Bottom Face		
Hole	Distance from Zip Tie End (cm)	Space Between (cm)	Hole	Distance from Zip Tie End (cm)	Space Between (cm)
1	8.9	0	1	8.9	0
2	11.1	2.2	2	11.2	2.3
3	14.2	3.1	3	14.2	3
4	16.4	2.2	4	16.6	2.4
5	18.5	2.1	5	18.8	2.2
6	21.7	3.2	6	21.8	3
7	23.8	2.1	7	23.9	2.1
8	26.6	2.8	8	27.1	3.2
9	28.9	2.3	9	29.2	2.1

Table 11-17. Rebar B of sample BCCD-CT2-1: spaces between holes and hole orientation.

Rebar B – Top Face			Rebar B – Bottom Face		
Hole	Distance from Zip Tie End (cm)	Space Between (cm)	Hole	Distance from Zip Tie End (cm)	Space Between (cm)
1	7.35	0	1	8	0
2	8.9	1.55	2	11.3	3.3
3	11	2.1	3	13.85	2.55
4	13.67	2.67	4	15.6	1.75
5	16.4	2.73	5	18.7	3.1
6	18.6	2.2	6	20.75	2.05
7	21.75	3.15	7	24.05	3.3
8	23.9	2.15	8	26.2	2.15
9	25.9	2	9	29.7	3.5
10	29	3.1			

Table 11-18. Rebar C of sample BCCD-CT2-1: spaces between holes and hole orientation.

Rebar C – Top Face			Rebar C – Bottom Face		
Hole	Distance from Zip Tie End (cm)	Space Between (cm)	Hole	Distance from Zip Tie End (cm)	Space Between (cm)
1	8.55	0	1	8.7	0
2	10.65	2.1	2	10.6	1.9
3	13.3	2.65	3	13.1	2.5
4	16.1	2.8	4	16	2.9
5	18.32	2.22	5	18.4	2.4
6	21.45	3.13	6	20.4	2
7	23.54	2.09	7	23.5	3.1
8	25.87	2.33	8	25.6	2.1
9	28.8	2.93	9	28.9	3.3

11.3.4 CSDB-CT2-1

Note: For all tables in this section, holes without listed depths were less than 0.1 cm.

Table 11-19. Hole depths of sample CSDB-CT2-1 rebar A.

Rebar A – Top Face		Rebar A – Bottom Face	
Hole	Hole Depth (cm)	Hole	Hole Depth (cm)
1	0.4	1	0.35
2		2	
3		3	
4		4	0.12
5		5	0.09
6		6	0.1
7		7	0.2
8	0.1	8	0.08
9	0.1	9	

Table 11-20. Hole depths of sample CSDB-CT2-1 rebar B.

Rebar B – Top Face		Rebar B – Bottom Face	
Hole	Hole Depth (cm)	Hole	Hole Depth (cm)
1		1	0.2
2		2	
3	0.1	3	
4		4	
5		5	0.23
6	0.1	6	
7		7	
8		8	
9	0.1	9	

Table 11-21. Hole depths of sample CSDB-CT2-1 rebar C.

Rebar C – Top Face		Rebar C – Bottom Face	
Hole	Hole Depth (cm)	Hole	Hole Depth (cm)
1	0.1	1	
2	0.1	2	0.15
3		3	0.3
4		4	
5		5	0.2
6		6	0.28
7	0.1	7	
8	0.25	8	0.45
9		9	0.36

Table 11-22. Rebar A of sample CSDB-CT2-1: spaces between holes and hole orientation.

Rebar A – Top Face			Rebar A – Bottom Face		
Hole	Distance from Zip Tie End (cm)	Space Between (cm)	Hole	Distance from Zip Tie End (cm)	Space Between (cm)
1	8.9		1	9.1	
2	11.8	2.9	2	11.3	2.2
3	13.5	1.7	3	13.5	2.2
4	16.6	3.1	4	16.5	3
5	18.9	2.3	5	18.9	2.4
6	21.85	2.95	6	21.9	3
7	24.2	2.35	7	24.1	2.2
8	26.4	2.2	8	26.8	2.7
9	29.4	3	9	29.5	2.7

Table 11-23. Rebar B of sample CSDB-CT2-1: spaces between holes and hole orientation.

Rebar B – Top Face			Rebar B – Bottom Face		
Hole	Distance from Zip Tie End (cm)	Space Between (cm)	Hole	Distance from Zip Tie End (cm)	Space Between (cm)
1	8.9		1	8.1	
2	10.6	1.7	2	11.1	3
3	13.6	3	3	13.3	2.2
4	15.8	2.2	4	15.6	2.3
5	18	2.2	5	18.7	3.1
6	21	3	6	20.9	2.2
7	23.3	2.3	7	24	3.1
8	26.9	3.6	8	26.2	2.2
9*	28.5	1.6	9	28.4	2.2

Table 11-24. Rebar C of sample CSDB-CT2-1: spaces between holes and hole orientation.

Rebar C – Top Face			Rebar C – Bottom Face		
Hole	Distance from Zip Tie End (cm)	Space Between (cm)	Hole	Distance from Zip Tie End (cm)	Space Between (cm)
1	8.7		1	8.7	
2	10.9	2.2	2	10.9	2.2
3	13.1	2.2	3	13.9	3
4	16.8	3.7	4	16.3	2.4
5	18.5	1.7	5	19.2	2.9
6	21.5	3	6	21.8	2.6
7	23.8	2.3	7	23.9	2.1
8	26	2.2	8	26.6	2.7
9	29	3	9	29	2.4

* Hole 9 in rebar B's top face was slightly off center compared to the other holes in the cladding.

11.4 APPENDIX D: ADDITIONAL PLOTS FROM FIELD COLUMNS

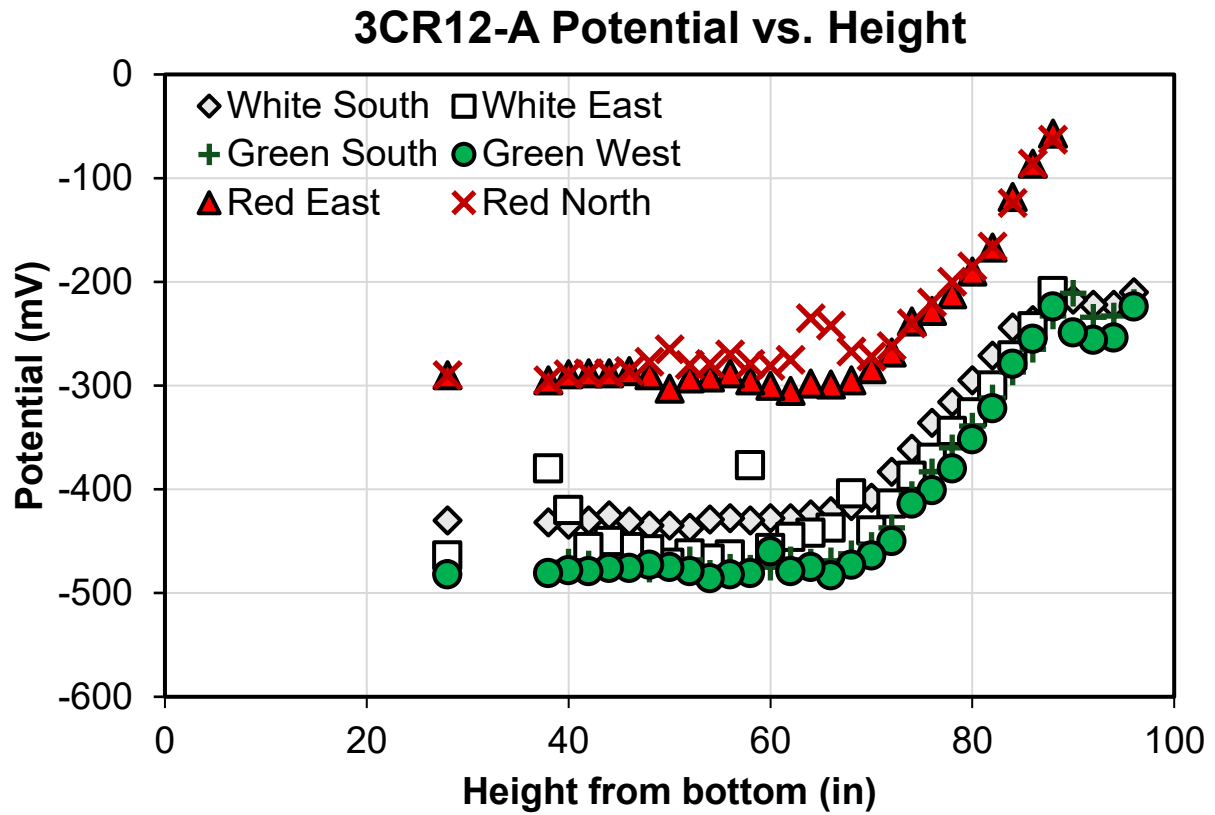


Figure 11-1. Rebar potential vs. height measured in column 3CR12-A. Two column faces per wire were measured and plotted.

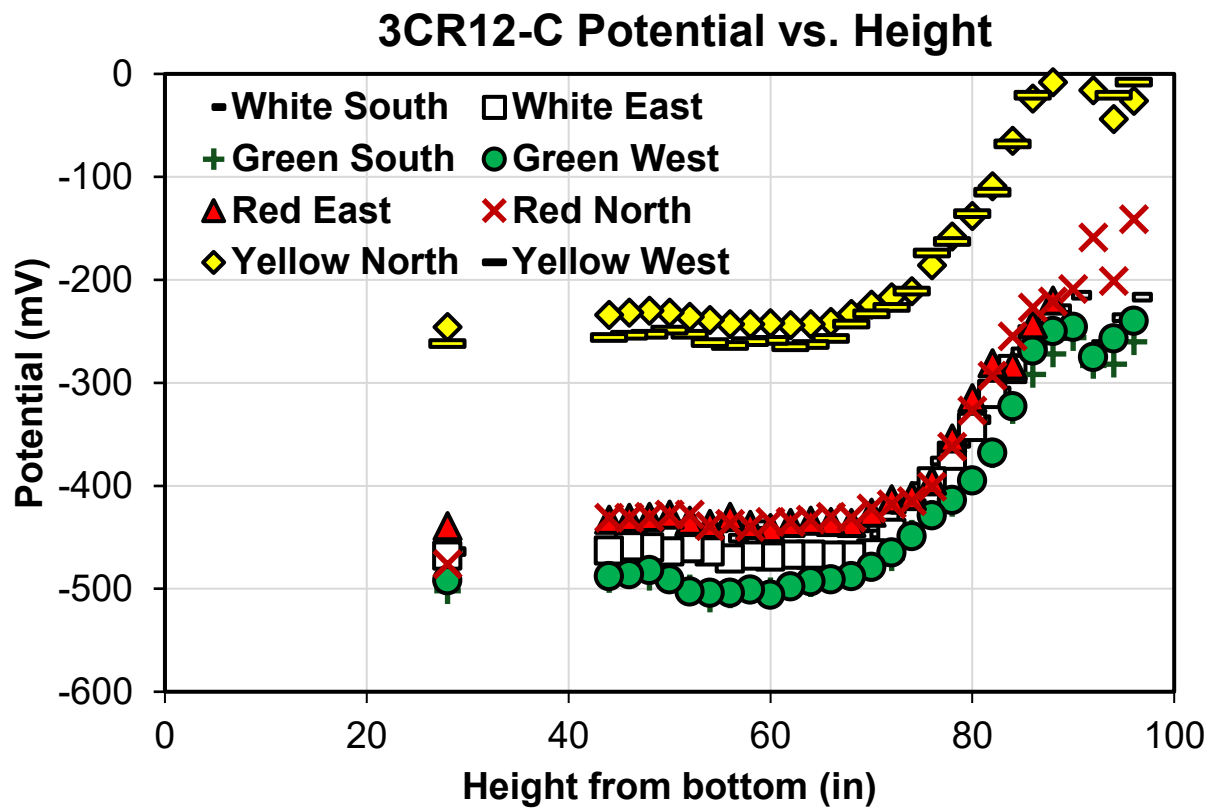


Figure 11-2. Rebar potential vs. height measured in column 3CR12-C. Two column faces per wire were measured and plotted.