CORROSION PERFORMANCE OF EPOXY-COATED MMFX BARS

By
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A Report on Research Sponsored by

MMFX Technologies, Inc.

Structural Engineering and Engineering Materials
SL Report 18-4a
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THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

The corrosion resistance of coated ASTM A1035 Type CL (2% Cr) and CM (4% Cr) steel bars produced by MMFX Technologies were evaluated in both cracked and uncracked concrete as well as in the rapid macrocell test. Coated bars were evaluated after simulating damage typical to that which would occur during normal handling and placement at a construction site. Bars were compared to the performance of epoxy-coated (ASTM A775) reinforcement from previous studies, and a life-cycle cost analysis over a 75-year design life was performed.

Both epoxy-coated bars tested (2% and 4% chromium) exhibited reduced disbondment of the coating at the end of testing compared to conventional epoxy-coated reinforcement. The 4% chromium coated bars also exhibited significantly lower corrosion rates relative to conventional epoxy-coated reinforcement, with corrosion rates between 15 and 30% of that of conventional ECR. Coated bars with 2% chromium performed comparably or slightly better than conventional epoxy-coated reinforcement (depending on the test method), but the differences were not statistically significant. The life-cycle cost analysis found that epoxy-coated MMFX with 4% chromium was the most cost-effective reinforcement of the bars in this study.

Keywords: chromium, concrete, corrosion, MMFX, reinforcing steel

ACKNOWLEDGEMENTS

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INTRODUCTION

This report describes the results of corrosion resistance testing of ASTM A1035 Type CM (4% Cr) and CL (2% Cr) epoxy-coated bars produced by MMFX Technologies. Specimens were evaluated in terms of corrosion rate, time to corrosion initiation, chloride threshold at initiation, and for epoxy-coated specimens, disbondment of the epoxy coating.

EXPERIMENTAL PROCEDURE

Two types of bars were tested in this study: epoxy-coated MMFX bars containing 4% and 2% chromium (ASTM A1035 type CM and CL, respectively). The chemical composition of the bars is provided in Table 1.

Table 1: Chemical composition of MMFX bars

Specimen	Chemical Composition of Product (%Wt)										
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Cu**	**Mo**	**V**	**N(PPM)**
MMFX-ECR(4%)	0.14	0.22	0.66	0.026	0.003	4.03	0.06	0.09	0.001	0.011	145
MMFX-ECR(2%)	0.264	0.242	0.73	0.02	0.0012	2.09	0.071	0.087	0.011	0.0064	68

Four tests were used to evaluate the reinforcement in this study: the Southern Exposure test, the cracked beam test, a modified Southern Exposure test (using a beam specimen), and the rapid macrocell test.

Southern Exposure, Cracked Beam, and Beam Specimens

Description

Three types of prismatic concrete specimens were cast in this study. Southern Exposure (SE) specimens (shown in Figure 1) have dimensions of 12 × 12 × 7 in. (305 × 305 × 178 mm). Two layers (mats) of reinforcement are used in the specimens. The top mat and bottom mat consisted of two and four No. 5 (No. 16) reinforcing bars, respectively. Bars were 12 in. (305 mm) long with 1-in. (25-mm) clear cover, spaced at 2.5 in. (64 mm) and centered within the prism. The top and bottom mats were electrically connected through a terminal box across a 10-ohm resistor via external wiring to allow for macrocell corrosion rate measurements. To allow the specimens to be ponded with salt solution, a 0.75 in. (19 mm) concrete dam was cast integrally with the specimens.

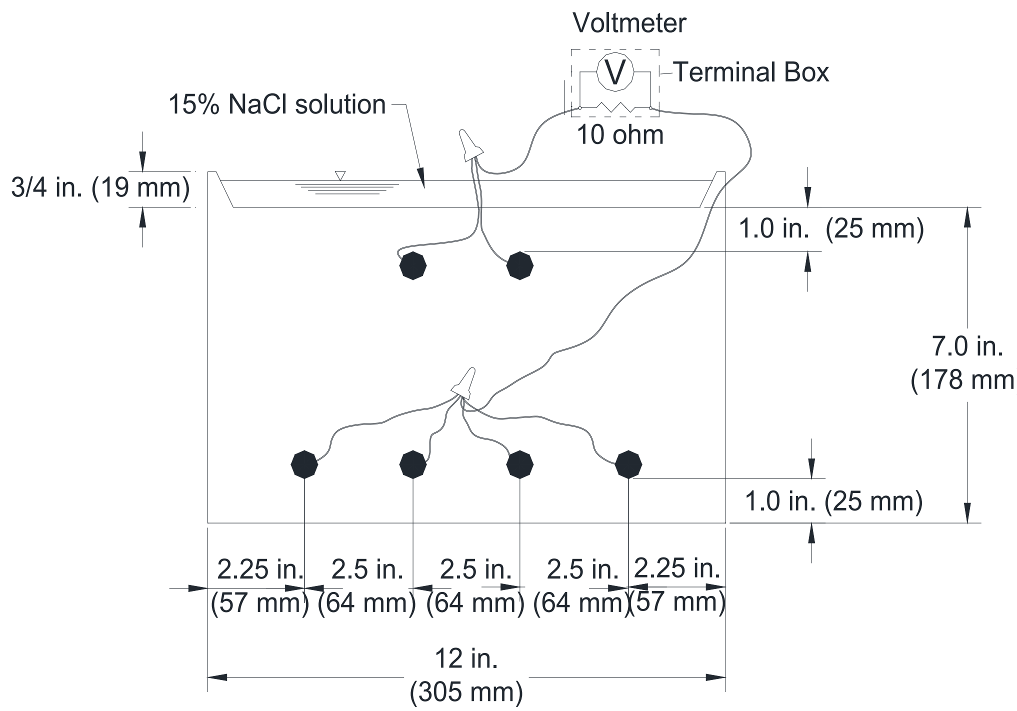

Figure 1– Southern Exposure (SE) specimen

Cracked beam (CB) and beam (B) specimens are half the width of Southern Exposure specimens and contain of two mats of reinforcement. The top mat is comprised of a single No. 5 (No. 16) bar and the bottom mat consists of two No. 5 (No. 16) bars. For cracked beam specimens, a simulated crack is made by inserting a 12-mil (0.3-mm), 6 in. (151 mm) long stainless steel shim centered in the mold and in contact with the top bar prior to casting. The shim wis removed 24 hours after casting. Beam specimens are similar to cracked beam specimens, but contain no crack. Cracked beam and beam specimens are shown in Figures 2 and 3, respectively.

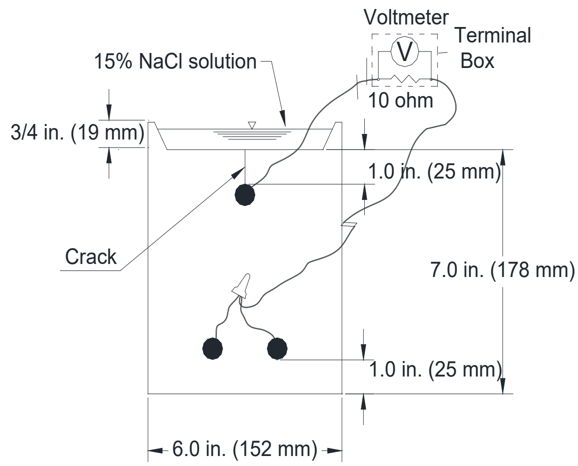

Figure 2— Cracked beam (CB) specimens

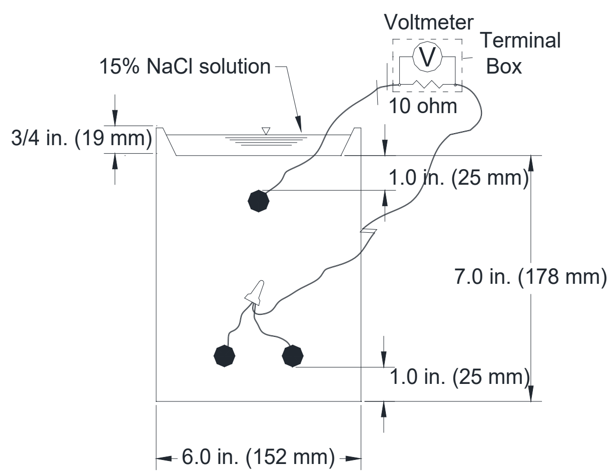

Figure 3— Beam (B) specimens

Test Procedure

To fabricate bench-scale specimens, reinforcing bars are cut to a length of 12 in. (305 mm), and both ends of each bar are drilled and tapped to a 0.75 in. (19 mm) depth with 10-24 threading. To simulate the effects of damage, all epoxy-coated reinforcement used in Southern Exposure, beam, and cracked beam specimens, as shown in Figure 4, is intentionally damaged using a 0.125 in. (3 mm) diameter four-flute drill bit. The epoxy layer is penetrated to a depth of 15 mils (0.4 mm), deep enough just to expose the underlying steel. The epoxy layer is penetrated with a total of ten holes on each bar, with five holes spaced every 2 in. (51 mm) on each side of a bar.

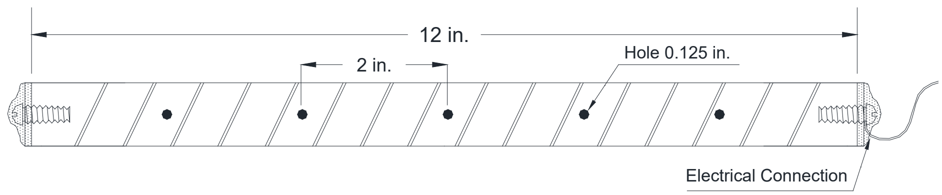

Figure 4— Damage pattern of epoxy-coated bar (plan view) in bench-scale tests

Epoxy-coated bars are rinsed with soapy water to remove any oil from bar surface. Forms were built from 0.75 in. (19 mm) plywood and comprised of four sides and a base. Since specimens are cast upside down, to build the dam around the top surface of a specimen, a tapered 10.5 × 10.5 × 0.75 in. (267 × 267 × 19 mm) plywood is attached and centered to the base for Southern Exposure molds. The width of this attached plywood was half for cracked beam and beam molds. Epoxy-coated bars are aligned in a way that the intentionally damaged sites face the top and bottom of the mold. All bars and molds are fabricated using 1.25 in. (32 mm) long 10-24 threaded stainless steel machine screws. Specimens are fabricated and cast in an inverted position. Concrete is placed in two layers, and each layer wis consolidated by internal vibration.

After casting, specimens are wet-cured for 3 days and air-cured for 25 days thereafter. Corrosion tests began 28 days after casting. Prior to testing, test bars are wired by connecting wire leads through 10-24 × 0.5 in. (13 mm) stainless steel screws and a No. 10 stainless steel washer. The four sides of specimens are coated with epoxy to protect the electrical connections and to prevent chloride ingress from the sides of the specimen. Both top and bottom mats of specimens are connected to a terminal box across a 10-ohm resistor.

The duration of the Southern Exposure, cracked beam, and beam tests is 96 weeks. The test consists of 12 weeks of wet-dry cycles followed by 12 weeks of continuously wet cycles. These two regimes are alternated and repeated until end of the test. During the wet-dry cycles, specimens are ponded with 15% NaCl solution and maintained at ambient room temperature for four days. At this point, macrocell corrosion rate, corrosion potentials, and linear polarization resistance (LPR) are measured, the salt solution is vacuumed off from the surface of the concrete specimens, and specimens are placed under a heat tent at 100 ± 3 °F (38 ± 2 °C) for 3 days. This procedure was repeated for 12 weeks. After 12 weeks of wet-dry cycles, specimens are continuously ponded with a 15% NaCl solution and kept covered at ambient room temperature for 12 weeks. Deionized water is added to the concrete to the ponding solution, as needed, to replace water lost due to evaporation. Readings are taken on a weekly basis.

Chloride Sampling and Analysis

To evaluate the critical chloride threshold of reinforcement, Southern Exposure and beam specimens are sampled upon corrosion initiation. Corrosion initiation on an uncoated bar is defined as a measured macrocell corrosion rate exceeding 0.3 μm/yr or a corrosion potential more negative than –0.275 V with respect to a saturated calomel electrode (SCE). These rules are not applicable for the coated bars, since corrosion initiation is restricted to the damaged sites and the bars exhibit lower corrosion rates upon corrosion initiation than uncoated bars. Furthermore, epoxy-coated bars may show more negative corrosion potentials than uncoated bars due to a lack of oxygen. Thus, a combination of a jump in macrocell corrosion rate and a drop in potential are used to determine corrosion initiation of epoxy-coated bars.

Samples for chloride testing are taken using a 0.25 in. (6.4 mm) masonry drill bit so that the top of the bit is level with the top of the top mat of reinforcing steel (as shown in Figures 5 and 6 for Southern Exposure and beam specimens, respectively). Six samples (three from each side) are taken upon onset of corrosion and six samples at the test end life. At each sample site, concrete is initially drilled to a depth of 0.5 in. (13 mm) and the powdered concrete discarded. The specimen is then drilled to a depth of 2.5 in. (63 mm); this powdered sample (about 3 g) is transferred to a plastic bag for analysis. The water-soluble chloride content of concrete samples is measured per AASHTO T 260-94, "Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials."

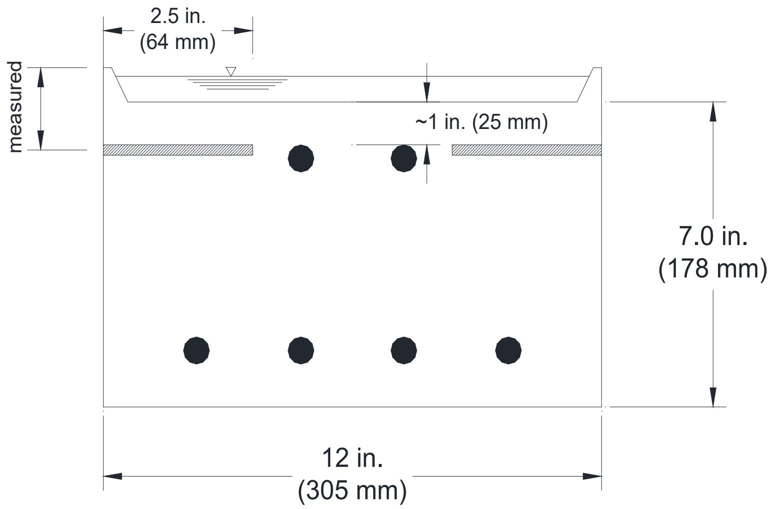

Figure 5— Southern Exposure specimen chloride sampling

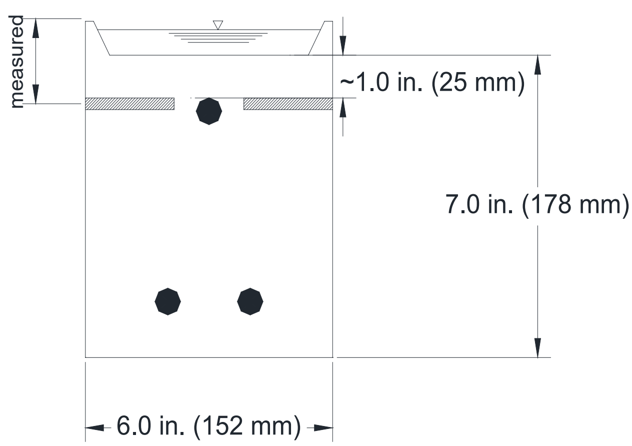

Figure 6— Beam specimen chloride sampling

Disbondment Test

To evaluate the integrity of the epoxy coatings, a disbondment test was performed after testing had been completed at sites of intentional damage. In the disbondment test, two cuts are made at a 45° angle with the axis of the bar using a utility knife, creating the shape of an 'X' with its center at the center of each damaged site. The edge of the knife is then used to attempt to remove any coating. The area of disbondment, if any, is measured using a transparent overlay grid marked in mm. If disbondment extends more than 0.5 in. (12.7 mm) from the hole in all directions (corresponding to an area of 1.05 $in.^2$ (677 mm^2)) the specimen is said to have experienced total disbondment.

Rapid Macrocell Test

Description

A rapid macrocell test set up is shown in Figure 7. This test exposes the bars to simulated concrete pore solution and enables chloride ions to reach the bar surface immediately; thus, accelerating the corrosion process. This test was first developed at the University of Kansas and is included in the Annex of ASTM A955 as a means of evaluating the corrosion resistance of stainless steel bars. The rapid macrocell test uses two containers. The container with the cathode consists of two No. 5 (No. 16) bars in a simulated concrete pore solution at a depth of 3 in. (76 mm). One liter of pore solution consists of 17.87 g of sodium hydroxide (NaOH) and 18.81 g of potassium hydroxide (KOH) dissolved in 974.8 g of deionized water (ASTM A955). The with the anode consists of a single No. 5 (No. 16) bar in a simulated pore solution with salt at the same depth as used for the cathode. The salt solution is created by adding 172.1 g of NaCl to one liter of pore solution. The anode and cathode bars are electrically connected through a terminal box across a 10-ohm resistor via external wiring to allow for electron flow and macrocell corrosion rate measurements. A salt bridge (ionic connection) is provided to allow ionic movement from cathode to anode. Air, scrubbed to remove any CO_2, is bubbled into the cathode. The test duration is 15 weeks, with the solutions changed every 5 weeks to maintain the pH. Macrocell corrosion rate and corrosion potential measurements (described below) are taken on a weekly basis; LPR is performed on a triweekly basis.

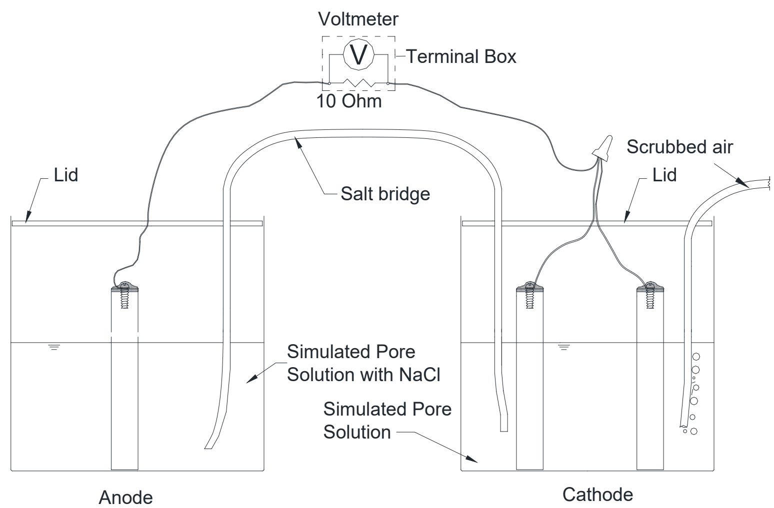

Figure 7— Rapid Macrocell Specimen

Test Procedure

To fabricate the rapid macrocell specimens, bars are first cut to 5 in. (127 mm) and one end of each bar is drilled and tapped to a 0.75 in. (19 mm) depth with 10-24 threading. Epoxy-coated bars are rinsed with soapy water to remove any oil and dirt. A wire is attached to the bar tapped end using a 0.5 in. (13 mm) 10-24 stainless steel machine screw and a No. 10 stainless steel washer. The electrical connection is epoxied using the 3M Scotchkote^{TM} rebar patch kit. For the epoxy-coated bars the untapped bare end is capped and epoxied. All epoxy-coated bars are intentionally damaged, as shown in Figure 8, as described for the bench-scale specimens. Bars are placed into the containers and electrically connected across a 10-ohm resistor via terminal box.

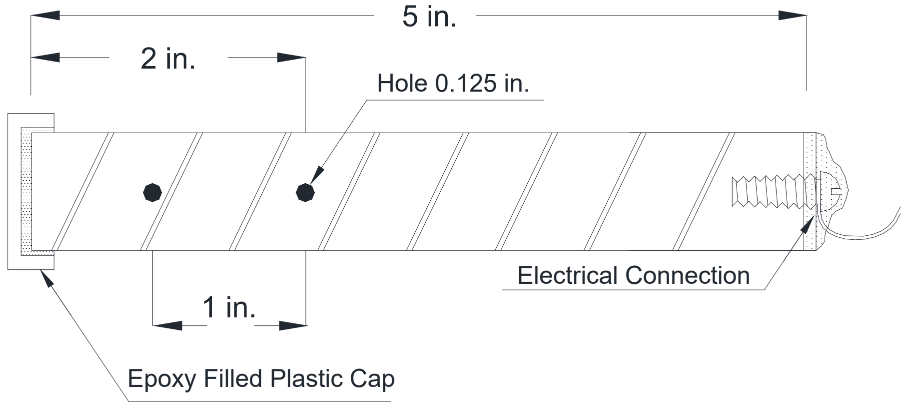

Figure 8— Damage pattern of epoxy-coated bar in rapid macrocell test

Corrosion Measurements

Macrocell Corrosion Rate:

To obtain the macrocell corrosion rate, the voltage drop between the anode and cathode of each specimen is taken across a 10-ohm resistor. The current density per unit area between two can be obtained using Ohm's Law:

$$i_{\mathrm{corr}} = 10^6 \times \frac{V}{RA} \tag{1}$$

where i_{corr} is current density (µA/cm^2); V is the measured voltage drop across the resistor (volts); R is the resistance of resistor (10 ohms); and A is the surface area of anode (cm^2). The top mat of steel is the anode in the bench-scale tests, and the single bar in the salt solution serves as the anode in the rapid macrocell tests.

The corrosion rate can be expressed as the thickness loss of steel per time. The relationship between current density and thickness loss is shown below per Faraday's Law:

$$r = k\frac{ia}{nF\rho} \tag{2}$$

where r is the corrosion rate (µm/year); k is a conversion factor (315360 (A.µm.s)/(µA.cm.yr)); a is the atomic weight of the corroding metal (g/mol); n is the number of electrons lost per atom of metal oxidized (2 for iron); F is Faraday's constant (96485 Coulombs/equivalent); and ρ is the density of metal (g/cm^3). By substituting proper values for iron, Eq. (3.2) simplifies to $r = 11.6i$ in μm/yr ($0.457i$ in mils/yr).

Corrosion Potential:

After measuring the voltage drop, the connection between anode and cathode across the resistor is disconnected for at least two hours to allow the potentials to stabilize, and then the corrosion potential of the top and bottom mat in bench-scale tests is measured using a saturated calomel electrode (SCE).

Linear Polarization Resistance:

In addition to the weekly voltage drop and corrosion potential measurements, linear polarization resistance (LPR) was measured on a monthly basis for bench-scale specimens and a triweekly basis for macrocell specimens. Linear polarization resistance is used to measure the total corrosion rate of reinforcement, including both macrocell corrosion (where the anode and cathode are on separate bars), and microcell corrosion, where the anode and cathode on the same bar. In a corroding specimen, both forms of corrosion are present simultaneously, and voltage drop readings do not measure microcell corrosion.

TEST PROGRAM

For all types of reinforcement, six Southern Exposure specimens, six cracked beam specimens, and six rapid macrocell tests were prepared. For each MMFX epoxy-coated bar, six beam specimens were cast in addition to the specimens listed above to allow for a more accurate determination of the critical chloride threshold of the reinforcement. The total number of MMFX test specimens in this study is listed in Table 2.

Table 2: MMFX Bar Test Specimens

Steel Designation[a]	SE[b]	CB[c]	B[d]	RM[e]	Total
MMFX-ECR(2%)	6	6	6	6	24
MMFX-ECR(4%)	6	6	6	6	24
Total	**12**	**12**	**12**	**12**	**48**

MMFX-ECR(2%) = Epoxy-coated MMFX steel containing 2% chromium
MMFX-ECR(4%) = Epoxy-coated MMFX steel containing 4% chromium
[b]SE = Sothern Exposure specimen
[c]CB = Cracked beam specimen
[d]B = Beam specimen
[e]RM = Rapid macrocell

The bench-scale specimens were cast with six batches of concrete. For each of the first three batches, two Southern Exposure and two cracked beam specimens were cast for each bar type. Batch 6 consisted of twelve beam specimens-six specimens of each coated bar type. The concrete used contained Type I/II portland cement with a water-cement ratio *(w/c*) of 0.45, a target air content of 6 ± 1%, and target slump of 3 ± 1 in. (75 ± 25 mm). Aggregate properties and mixture proportions are shown in Table 3. The average 28-day concrete compressive strength for batches 1 through 6 were 5550, 4650, 4250, 4530, 4770, and 4850 psi (38.2, 32.1, 29.3, 31.2, 32.9, and 33.4 MPa).

Table 3: Mix Proportions (SSD basis)

Water lb/yd^3 (kg/m^3)	Cement lb/yd^3 (kg/m^3)	Coarse Agg. lb/yd^3 (kg/m^3)	Fine Agg. lb/yd^3 (kg/m^3)	Air-entraining Agent oz/yd^3 (mL/m^3)
269 (160)	598 (355)	1484 (880)	1435 (851)	4.73 (183)

Bulk specific gravity of fine aggregate = 2.63
Bulk specific gravity of Coarse aggregate = 2.59

TEST RESULTS

Southern Exposure Specimens

Macrocell Corrosion Rate

The macrocell corrosion rates of Southern Exposure specimens for the epoxy-coated MMFX bars containing 4% chromium (SE-MMFX-ECR(4%)) and 2% chromium (SE-MMFX-ECR(2%)) based on total area of the bar are shown in Figures 9 and 10, respectively. The maximum corrosion rates based on total area for the SE-MMFX-ECR(4%) and SE-MMFX-ECR(2%) specimens through week 96 ranged from 0.122 to 0.625 μm/yr and 0.187 to 0.918 μm/yr, respectively.

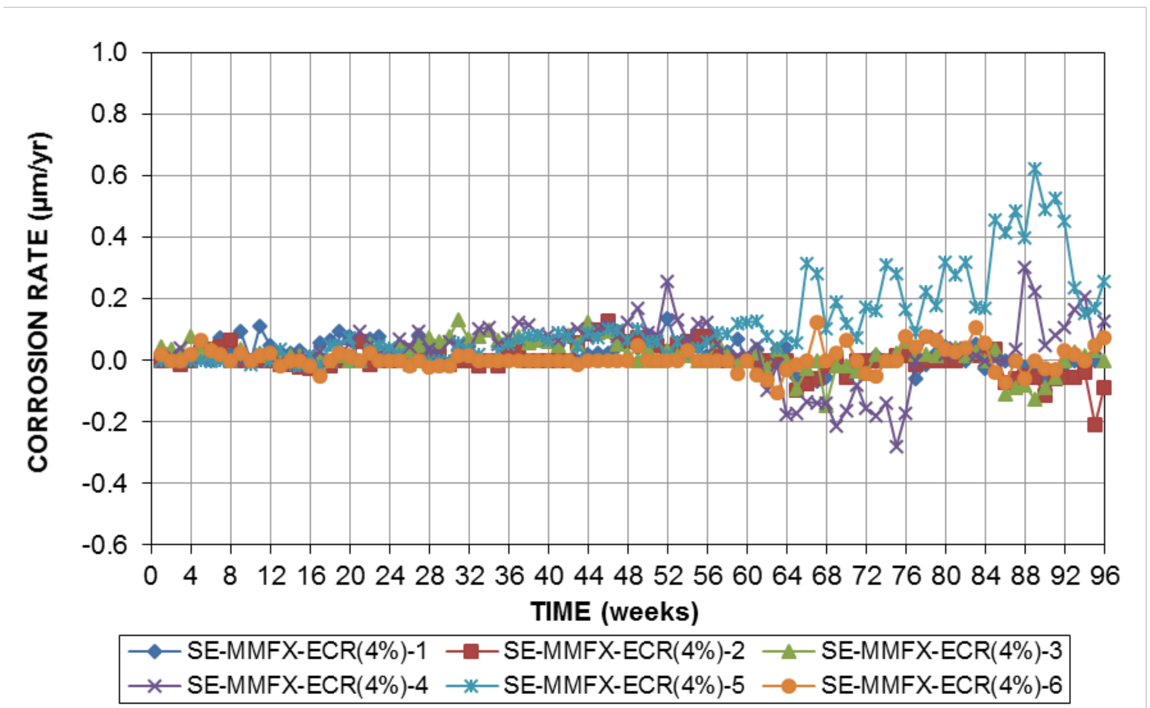

Figure 9— Macrocell corrosion rates (μm/yr) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

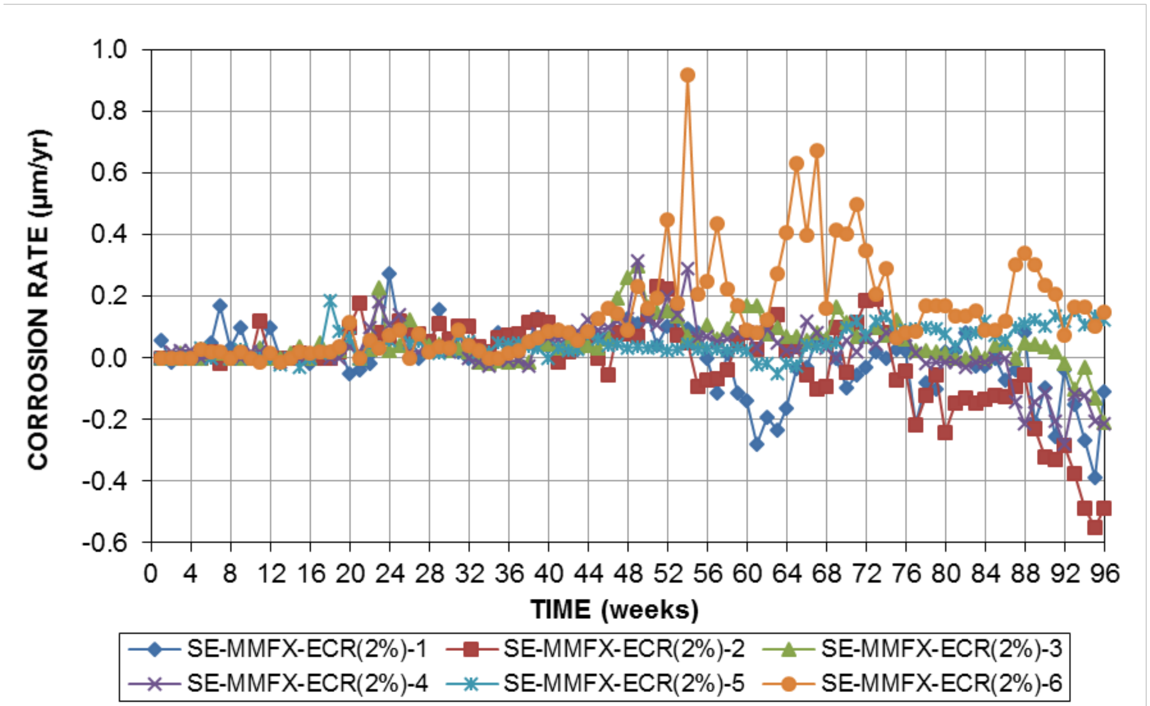

Figure 10— Macrocell corrosion rates (µm/yr) based on total area of the reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

The macrocell corrosion rates based on total area are calculated based on the assumption that the entire surface area of the bar is corroding. However, since for the epoxy-coated bars corrosion is more likely to occur on the damaged area of the bar, it is useful to calculate the corrosion rates based on the assumption that only damaged area of the bar is corroding. Figures 11 and 12 show the macrocell corrosion rates for the SE-MMFX-ECR(4%) and SE-MMFX-ECR(2%) specimens, respectively, based on the exposed area of the reinforcement. The corrosion rate based on exposed area at the holes for bars with 10 penetrations through the epoxy on each bar is 192 times the corrosion rate based on total bar area. The maximum corrosion rates based on exposed area for the SE-MMFX-ECR(4%) and SE-MMFX-ECR(2%) specimens through week 96 ranged from 23.4 to 120 µm/yr and 35.8 to 176.3 µm/yr, respectively.

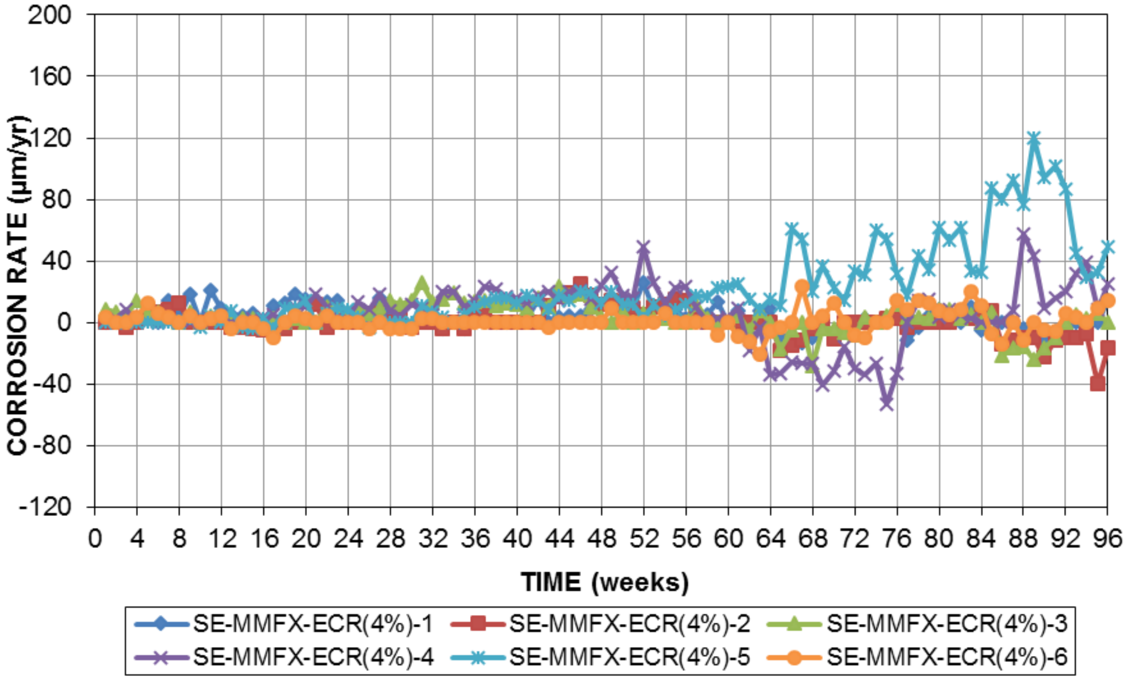

Figure 11— Macrocell corrosion rates (µm/yr) based on exposed area of the reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

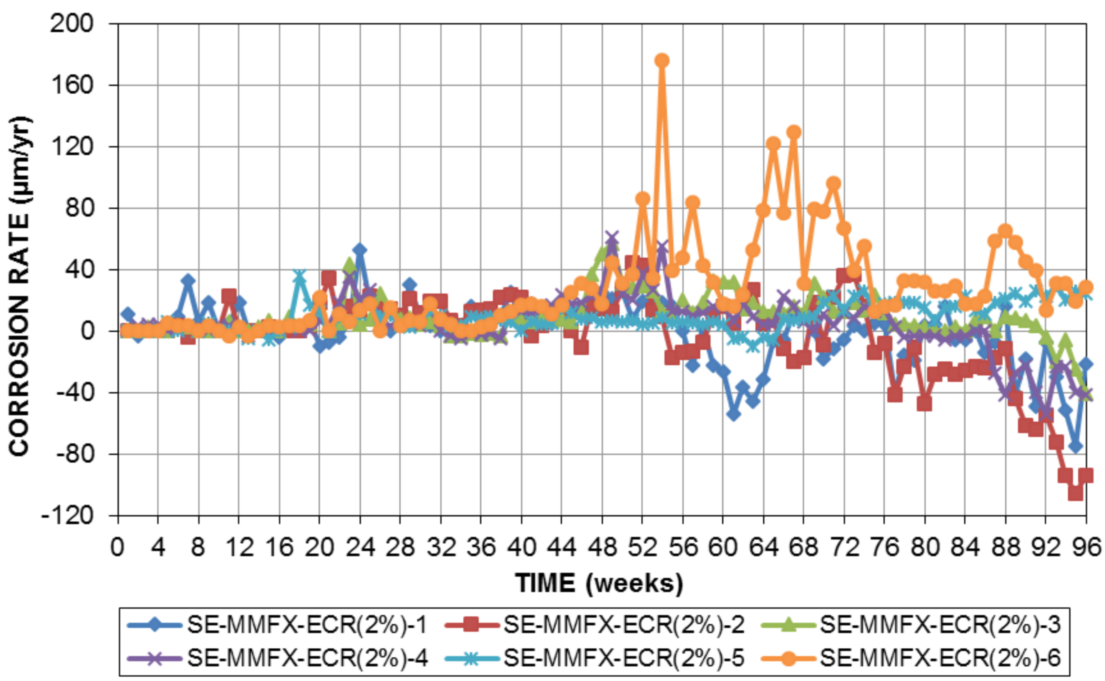

Figure 12— Macrocell corrosion rates (µm/yr) based on exposed area of the reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

Figure 13 shows the average corrosion rate for the Southern Exposure specimens based on exposed area. Based on exposed area, the epoxy-coated bars with 2% nominal chromium content exhibited average corrosion rates of 10.0 µm/yr or less through week 23. Between weeks 23 and 96, the corrosion rates on these specimens fluctuated between –33.0 and 46.9 µm/yr. The epoxy-coated bars with 4% nominal chromium content exhibited a maximum average corrosion rate of 20.1 µm/yr at week 89.

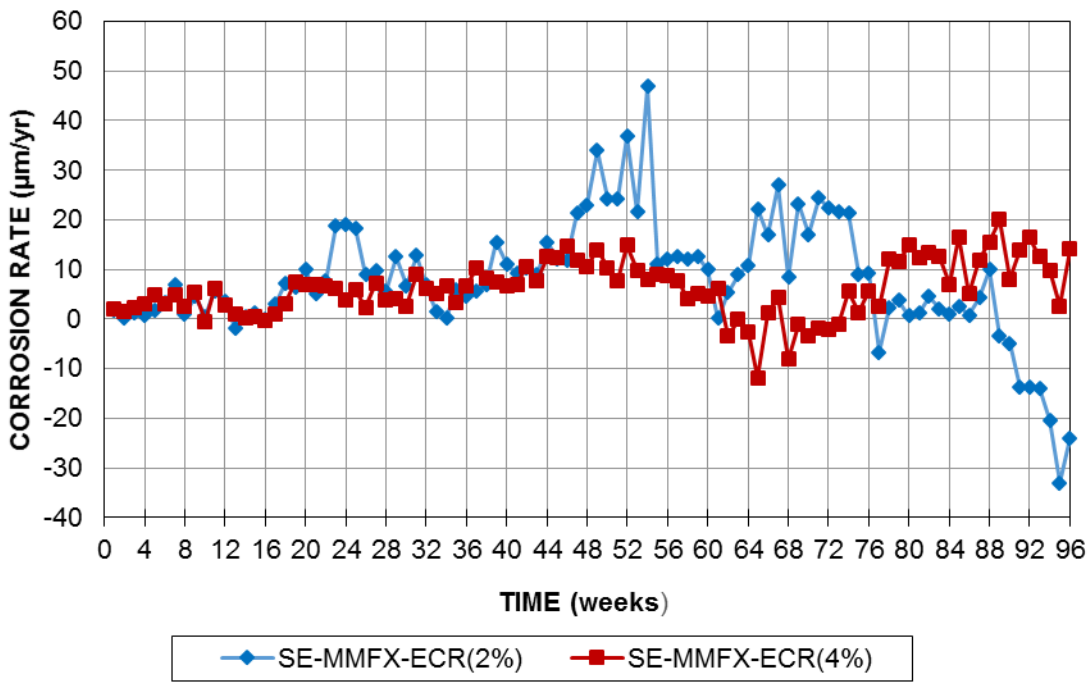

Figure 13— Average corrosion rate (µm/yr) based on exposed area versus time for Southern Exposure specimens containing epoxy-coated MMFX bars

The average and individual corrosion losses for the Southern Exposure specimens through end of the test (week 96) are tabulated in Table 4. Corrosion losses were obtained by integrating corrosion rates with respect to time; that is, corrosion loss is the accumulated amount of thickness of steel that is corroded over time. Based on exposed area, the average corrosion losses for the MMFX-ECR(2%) and MMFX-ECR(4%) specimens were 14.7 and 11.4 µm, respectively.

Table 4: Corrosion loss (μm) for Southern Exposure specimens

Specimen	Corrosion Loss (μm)-Total Area						Average	Std. Dev.
	Week 96		Week 96		Week 96			
	1	2	3	4	5	6		
MMFX-ECR(2%)	-0.007	-0.024	0.089	0.045	0.089	0.267	0.076	0.105
MMFX-ECR(4%)	0.037	0.002	0.036	0.055	0.217	0.01	0.059	0.080
	Corrosion Loss (μm)-Exposed Area							
MMFX-ECR(2%)	-1.3	-4.7	17	8.6	17.1	51.3	14.7	45.8
MMFX-ECR(4%)	7.1	0.4	6.9	10.6	41.7	1.8	11.4	22.3

Linear Polarization Resistance (LPR)

Corrosion rates based on total area obtained from LPR test results on Southern Exposure specimens with MMFX epoxy-coated specimens containing 4% and 2% chromium are shown in Figures 14 and 15, respectively. Based on total area, the maximum corrosion rates for specimens SE-MMFX-ECR(4%) and SE-MMFX-ECR(2%) through week 96 ranged from 0.1 to 0.42 μm/yr and 0.22 to 0.72 μm/yr, respectively.

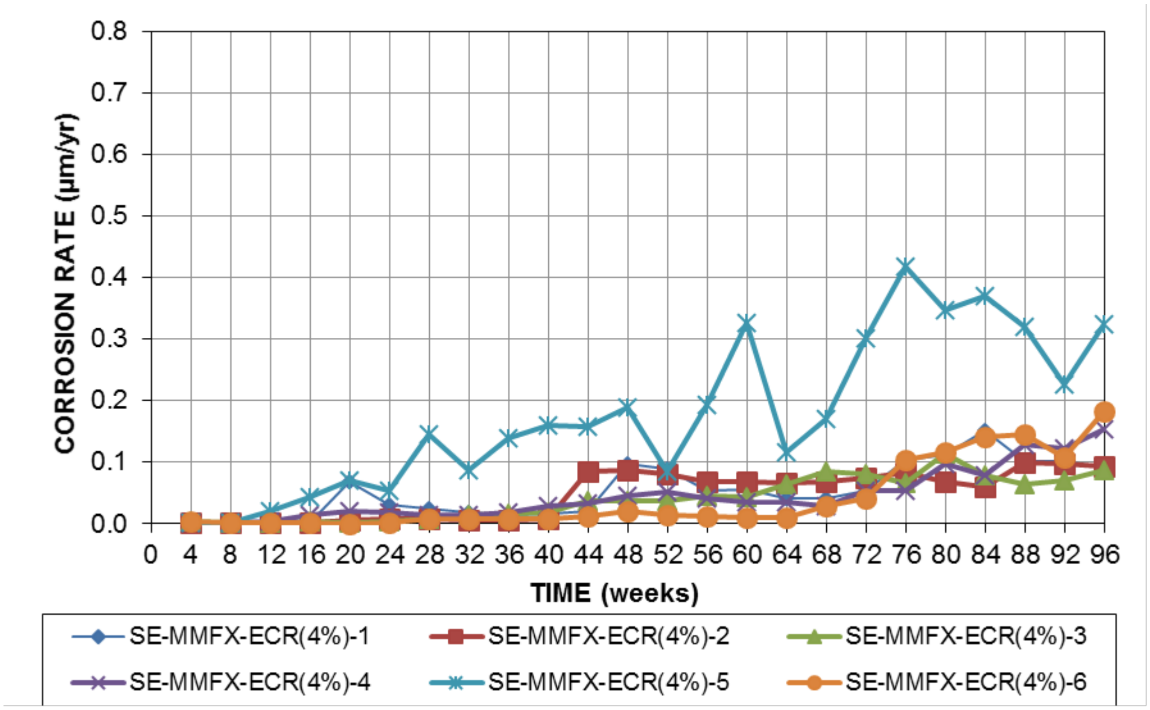

Figure 14— LPR test corrosion rates (µm/yr) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

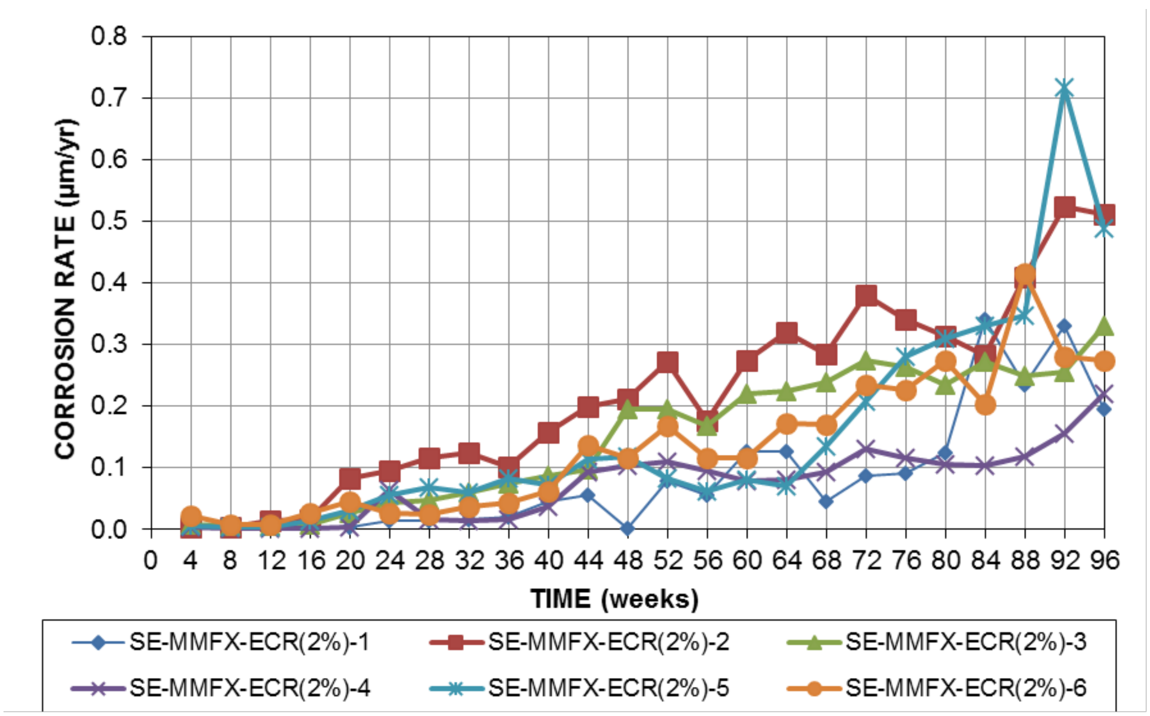

Figure 15— LPR test corrosion rates (µm/yr) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

Figure 16 shows the average corrosion rate for the Southern Exposure specimens containing epoxy-coated bars based on exposed area obtained from the LPR test results. Corrosion rates tended to increase throughout the test. Based on exposed area, the epoxy-coated bars with 2% nominal chromium content exhibited a maximum average corrosion rate of 72 µm/yr at week 88. The epoxy-coated bars with 4% nominal chromium content exhibited a maximum average corrosion rate of 29.7 µm/yr at week 96.

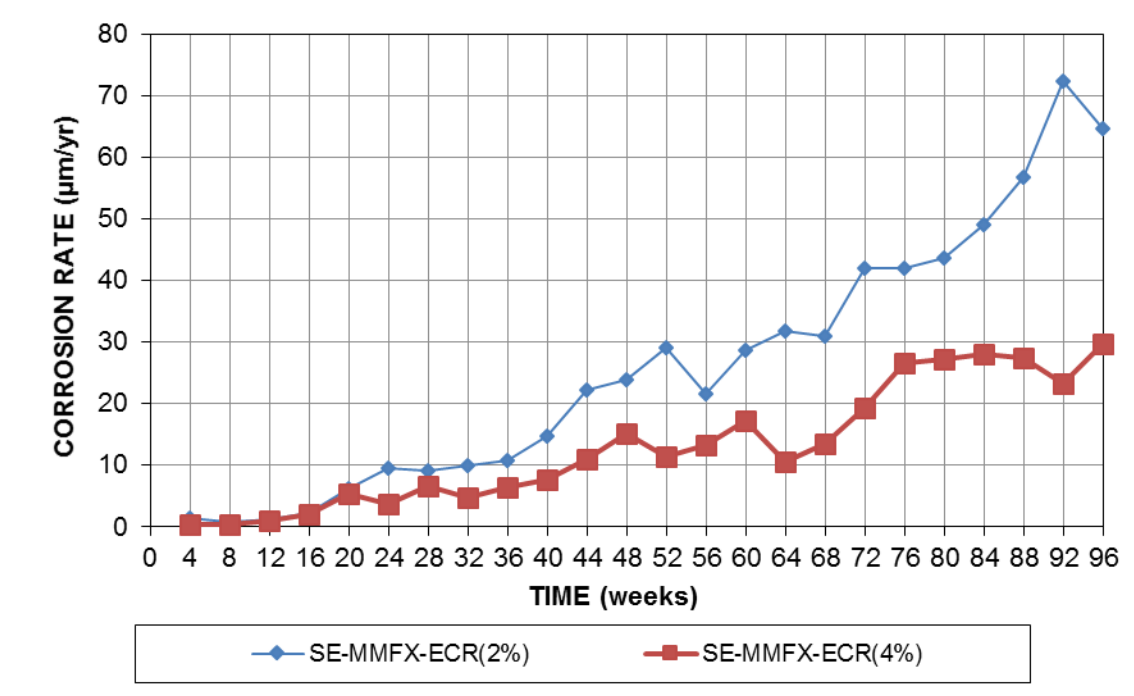

Figure 16— Average LPR test corrosion rate (µm/yr) based on exposed area versus time for Southern Exposure specimens containing epoxy-coated MMFX bars

The average and individual corrosion losses obtained from LPR test results for the Southern Exposure specimens through end of the test (week 96) are tabulated in Table 5. Based on exposed area, the average corrosion losses for the MMFX-ECR(2%) and MMFX-ECR(4%) specimens were 48 and 24 µm, more than three times and two times as much as obtained from macrocell corrosion rates, respectively.

Table 5: Corrosion loss (µm) for Southern Exposure specimens based on LPR test results

Specimen	Corrosion Loss (µm)-Total Area						Average	Std. Dev.
	Week 96		Week 96		Week 96			
	1	2	3	4	5	6		
MMFX-ECR(2%)	0.155	0.400	0.275	0.135	0.288	0.246	0.250	0.097
MMFX-ECR(4%)	0.100	0.088	0.075	0.084	0.328	0.076	0.125	0.010
	Corrosion Loss (µm)-Exposed Area							
MMFX-ECR(2%)	29.8	77.0	52.9	26.0	55.2	47.3	48.0	18.6
MMFX-ECR(4%)	19.1	16.8	14.4	16.1	63.0	14.5	24.0	19.2

Corrosion Potential

The average top mat corrosion potentials (with respect to a copper-copper sulfate electrode) for the Southern Exposure specimens are shown in Figure 7. The average bottom mat corrosion potentials are exhibited in Appendix A. The average top mat potential for all specimens was near –0.34 V at the start of the test. The potential of the MMFX (ECR)-2% specimens gradually increased to –0.28 V by week 9 and exhibited drops in potential thereafter, reaching –0.62 V at week 96. Likewise, the potential of the MMFX-ECR(4%) specimens gradually increased to –0.24 V by week 7, but exhibited drops in potential after week 7 and decreased to –0.58 V through week 96. The drops in potential correspond to the initiation of corrosion for a specimen in the series.

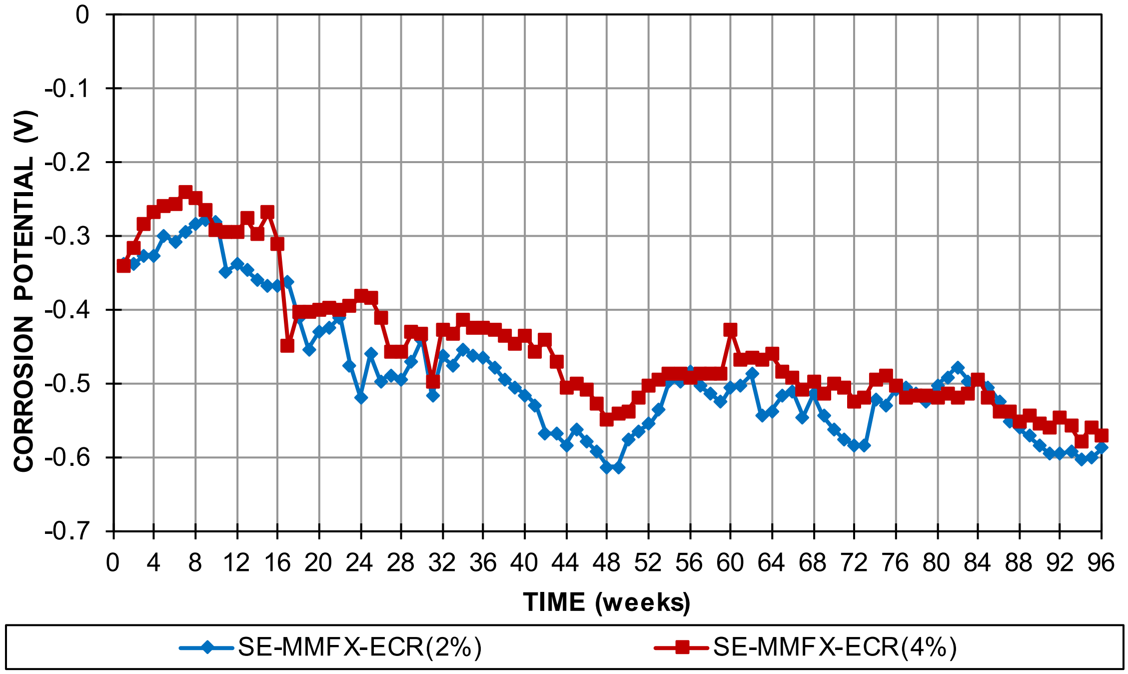

Figure 17—Top mat (anode) corrosion potential (CSE) versus time for Southern Exposure specimens containing epoxy-coated MMFX bars

Autopsy

Upon completion of the test (96 weeks), the Southern Exposure specimens were sampled to measure the final chloride content and then autopsied and photographed. Figure 18 shows top mat epoxy-coated reinforcement of Southern Exposure specimens (Specimen SE-MMFX-ECR(4%)-5) before disbondment. Corrosion products were visible on some of intentionally damaged sites of reinforcement after autopsy. However, corrosion products were more obvious on the underlying steel after the disbondment test. The top mat and a representative bar from the bottom mat of SE-MMFX-ECR(4%)-5 after the disbondment test are shown in Figures 19 and 20, respectively. Figures 21 and 22 present top bars and a bottom bar of SE-MMFX-ECR(2%)-5, respectively, after the disbondment test. Visible corrosion products, after the disbondment test, on the underlying steel of top mat bars in Figures 19 and 21 are indicated by ovals.

Figure 18— Southern Exposure MMFX-ECR(4%)-5 top bars before disbondment test after 96 weeks

Figure 19— Southern Exposure MMFX-ECR(4%)-5 top bars after disbondment test after 96 weeks

Figure 20— Southern Exposure MMFX-ECR(4%)-5 bottom bar after disbondment test after 96 weeks

Figure 21— Southern Exposure MMFX-ECR(2%)-5 top bars after disbondment test after 96 weeks

Figure 22— Southern Exposure MMFX-ECR(2%)-5 bottom bar after disbondment test after 96 weeks

The disbonded area for the top bars from the MMFX-ECR(4%) and MMFX-ECR(2%) Southern Exposure specimens are tabulated in Tables 6 and 7, respectively. For each bar, the disbondment test was performed at three intentionally damaged sites, two of which were chosen from the upper surface of the bar, as it was oriented in the specimen, and the third from the bottom surface. The average disbondment of MMFX-ECR(4%) top bars, 0.55 in^2 (358 mm^2), was 20% less than the disbondment for MMFX-ECR(2%), 0.69 in^2 (447 mm^2), however, a wide variation betweeen specimens was observed.

Table 6: Disbonded area and total corrosion loss at week 96 for the MMFX-ECR(4%) top bars in Southern Exposure specimens

Specimen	Total Corrosion Loss (µm)	Top side 1 (in^2)	Top side 2 (in^2)	Bottom side (in^2)	Average (in^2)
1	0.100	1.05	0.54	0.32	0.42
		0.19	0.21	0.22	
2	0.088	1.05	0.39	0.41	0.49
		0.25	0.28	0.31	
3	0.075	1.05	0.21	0.20	0.41
		0.61	0.25	0.15	
4	0.084	1.05	1.05	1.05	0.98
		0.62	1.05	1.05	
5	0.328	0.33	0.15	0.23	0.54
		1.05	1.05	0.43	
6	0.076	0.11	0.24	0.01	0.53
		0.95	0.36	0.29	
Average	0.125				0.55

Table 7: Disbonded area and total corrosion loss at week 96 for the MMFX-ECR(2%) top bars in Southern Exposure specimens

Specimen	Total Corrosion Loss (µm)	Top side 1 (in^2)	Top side 2 (in^2)	Bottom side (in^2)	Average (in^2)
1	0.155	0.79	0.26	0.17	0.73
		1.05	1.05	1.05	
2	0.4	0.39	0.17	0.59	0.41
		0.85	0.34	0.12	
3	0.275	0.73	0.50	0.22	0.67
		1.05	1.00	0.53	
4	0.135	0.27	1.05	0.87	0.63
		0.59	0.15	0.87	
5	0.288	0.91	1.05	1.05	1.03
		1.05	1.05	1.05	
6	0.246	1.05	0.59	0.41	0.70
		1.05	0.24	0.83	
Average	0.250				0.69

Cracked Beam Specimens

Macrocell Corrosion

The macrocell corrosion rates of cracked beam specimens for the epoxy-coated MMFX bars containing 4% chromium (CB-MMFX-ECR(4%)) and 2% chromium (CB-MMFX-ECR(2%)) based on total area of the bar are shown in Figures 23 and 24, respectively. The maximum corrosion rates based on total area for the CB-MMFX-ECR(4%) and CB-MMFX-ECR(2%) specimens through week 96 ranged from 0.389 to 1.43 µm/yr and 0.602 to 2.08 µm/yr, respectively.

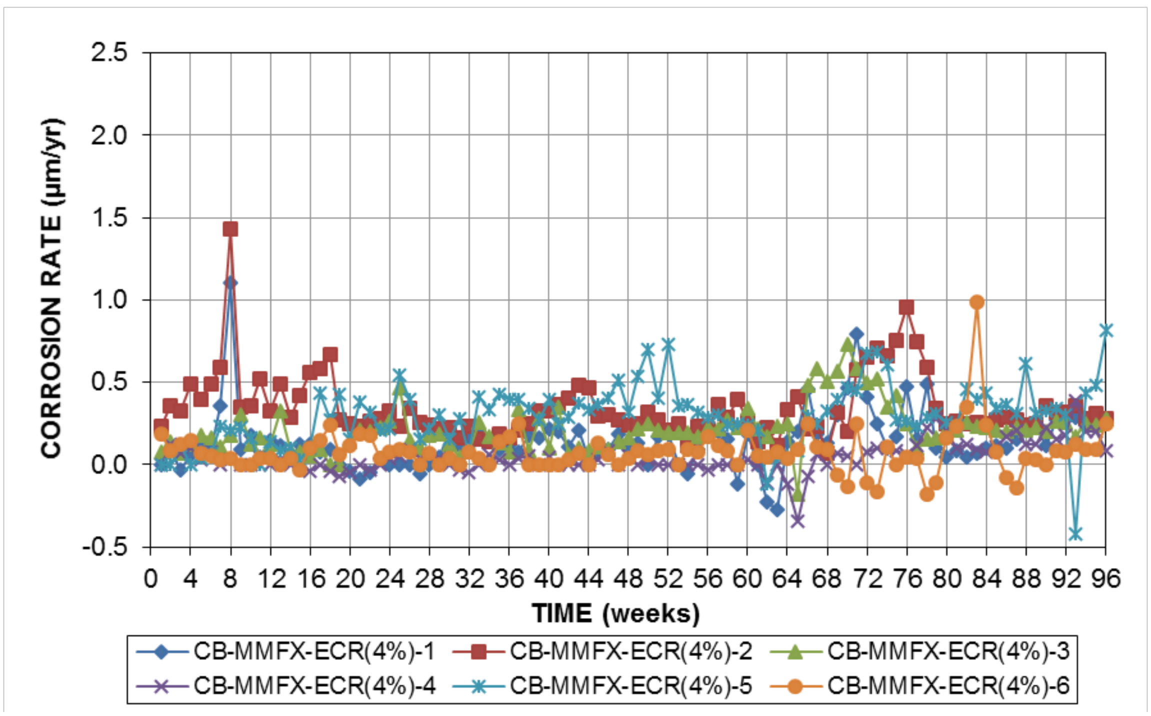

Figure 23— Macrocell corrosion rates based on total area (µm/yr) for cracked beam specimens containing MMFX-ECR(4%) bars

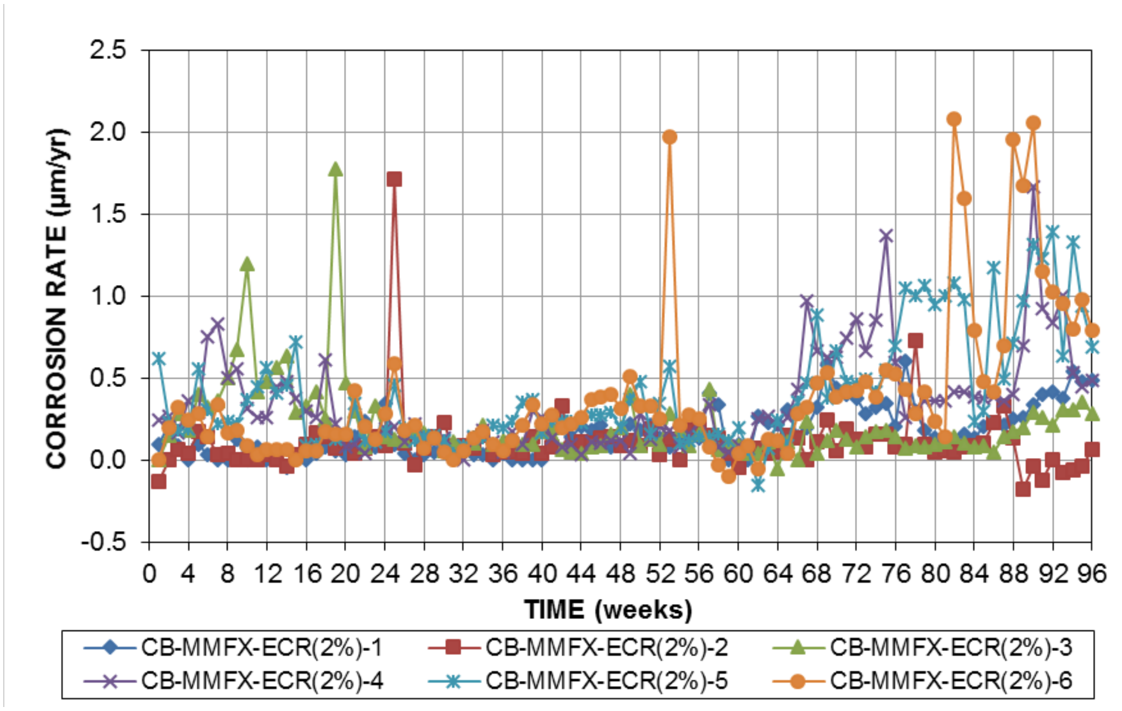

Figure 24— Macrocell corrosion rates based on total area (µm/yr) for cracked beam specimens containing MMFX-ECR(2%) bars

Figures 25 and 26 show the macrocell corrosion rates for the CB-MMFX-ECR(4%) and CB-MMFX-ECR(2%) specimens, respectively, based on exposed area of the reinforcement. The maximum corrosion rates based on exposed area for the CB-MMFX-ECR(4%) and CB-MMFX-ECR(2%) specimens through week 96 ranged from 74.6 to 275 µm/yr and 116 to 399 µm/yr, respectively.

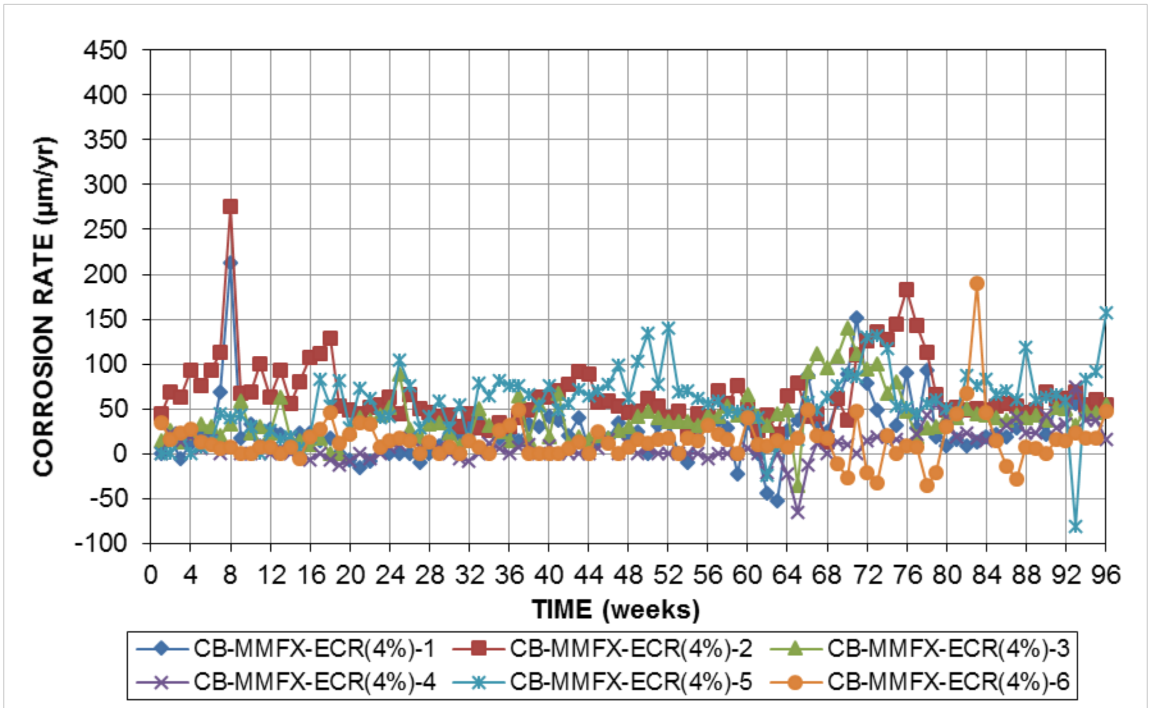

Figure 25— Macrocell corrosion rates based on exposed area (μm/yr) for cracked beam specimens containing MMFX-ECR(4%) bars

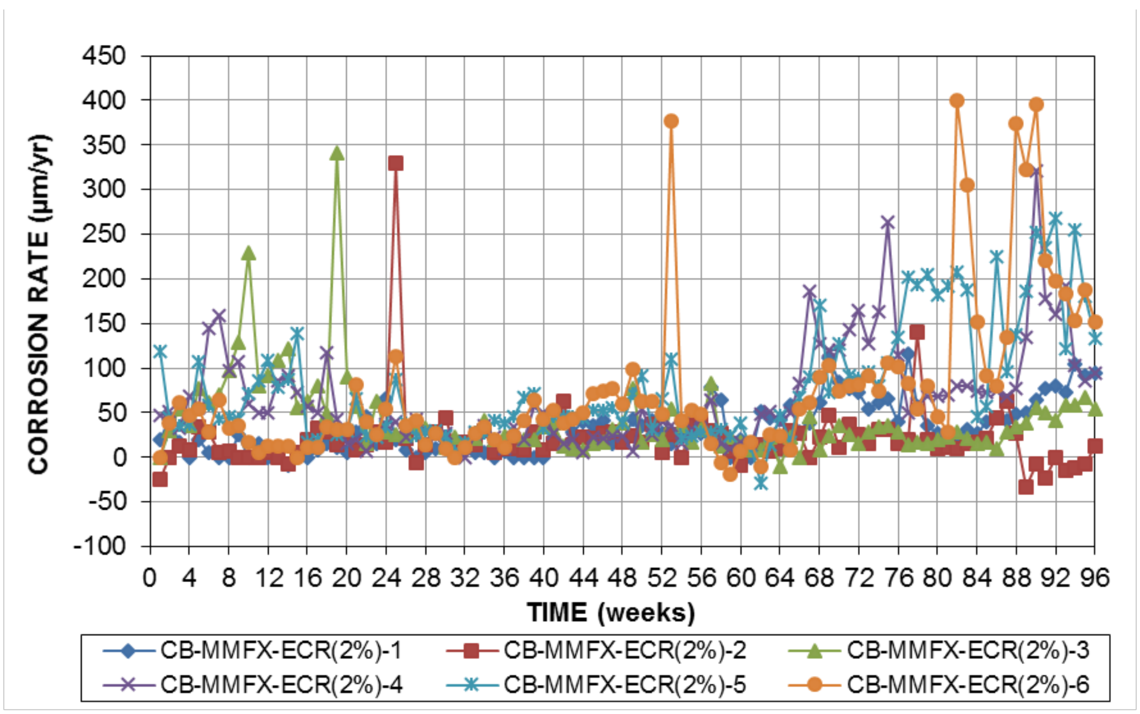

Figure 26— Macrocell corrosion rates based on exposed area (μm/yr) for cracked beam specimens containing MMFX-ECR(2%) bars

Figure 27 shows the average corrosion rates for the cracked beam specimens. Based on exposed area, the corrosion rate of epoxy-coated bars with 2% nominal chromium content fluctuated between 0 and 180 µm/yr; bars with 4% chromium content had rates between 0 and 95 µm/yr.

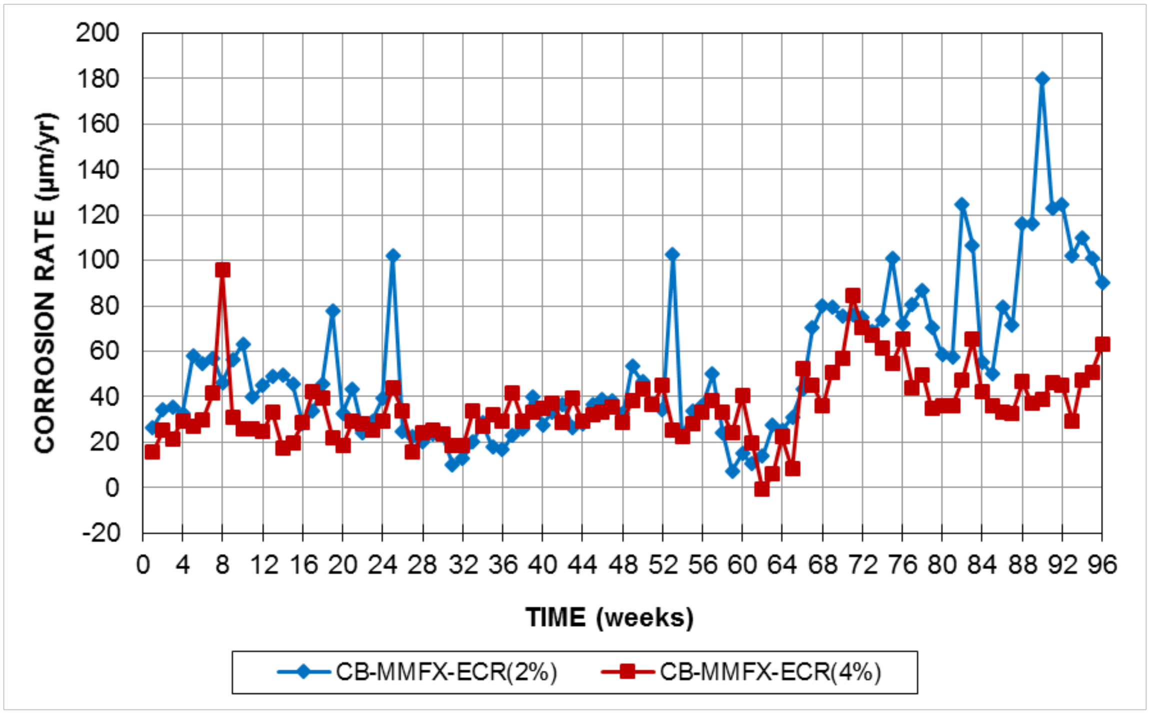

Figure 27— Average corrosion rate (µm/yr) based on exposed area versus time for cracked beam specimens containing epoxy-coated MMFX bars

The average and individual corrosion losses for the cracked beam specimens through end of the test (week 96) are tabulated in Table 8. Based on exposed area, losses for the MMFX-ECR(2%) and MMFX-ECR(4%) specimens ranged from 37.0 to 147 µm, with an average of 97.1 µm, and 15.8 to 123 µm, with an average loss of 65.4 µm, respectively.

Table 8: Corrosion loss (µm) for cracked beam specimens

Specimen	Corrosion Loss (µm)-Total Area						Average	Std. Dev.
	Week 96		Week 96		Week 96			
	1	2	3	4	5	6		
MMFX-ECR(2%)	0.315	0.193	0.401	0.644	0.767	0.715	0.506	0.235
MMFX-ECR(4%)	0.262	0.638	0.390	0.082	0.546	0.127	0.341	0.224
	Corrosion Loss (µm)-Exposed Area							
MMFX-ECR(2%)	60.5	37.0	76.9	124	147	137	97.1	45.1
MMFX-ECR(4%)	50.3	123	74.9	15.8	105	24.4	65.4	43.1

Linear Polarization Resistance (LPR)

The corrosion rates based on total area obtained from the LPR test results on cracked beam specimens with MMFX epoxy-coated specimens containing 4% and 2% chromium are shown in Figures 28 and 29, respectively. Based on total area, the maximum corrosion rates for specimens CB-MMFX-ECR(4%) and CB-MMFX-ECR(2%) through week 96 ranged from 0.28 to 3.76 µm/yr and 0.66 to 9.95 µm/yr, respectively.

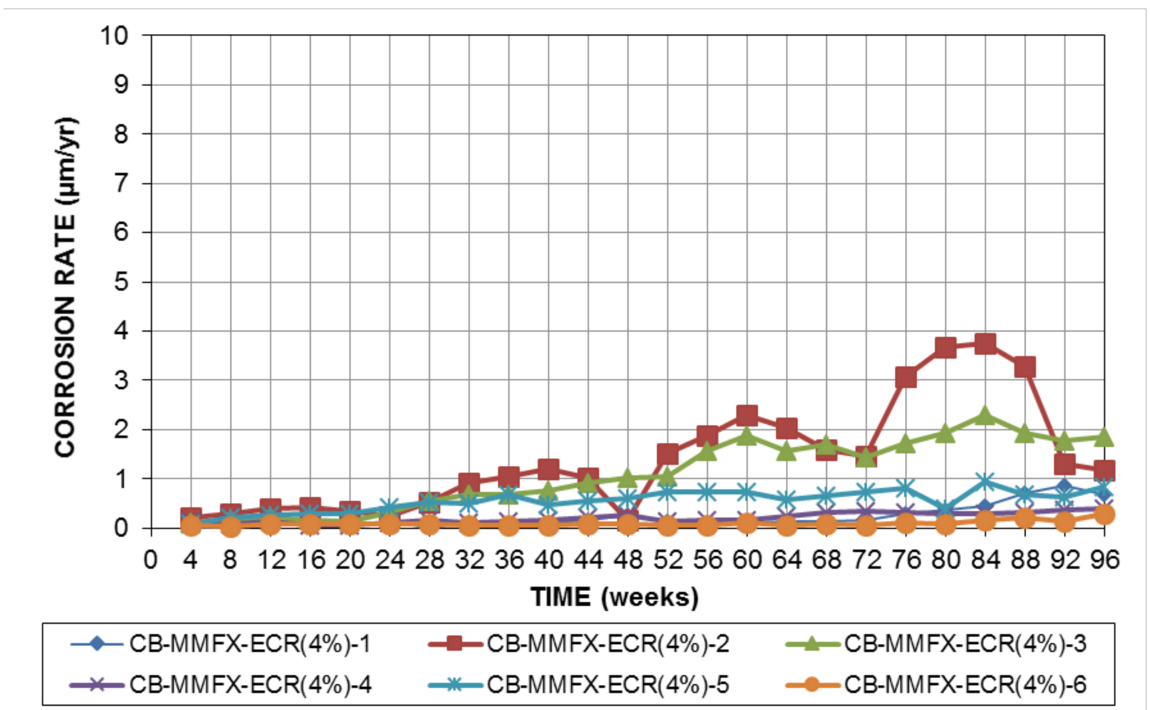

Figure 28— LPR test corrosion rates (µm/yr) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(4%) bars

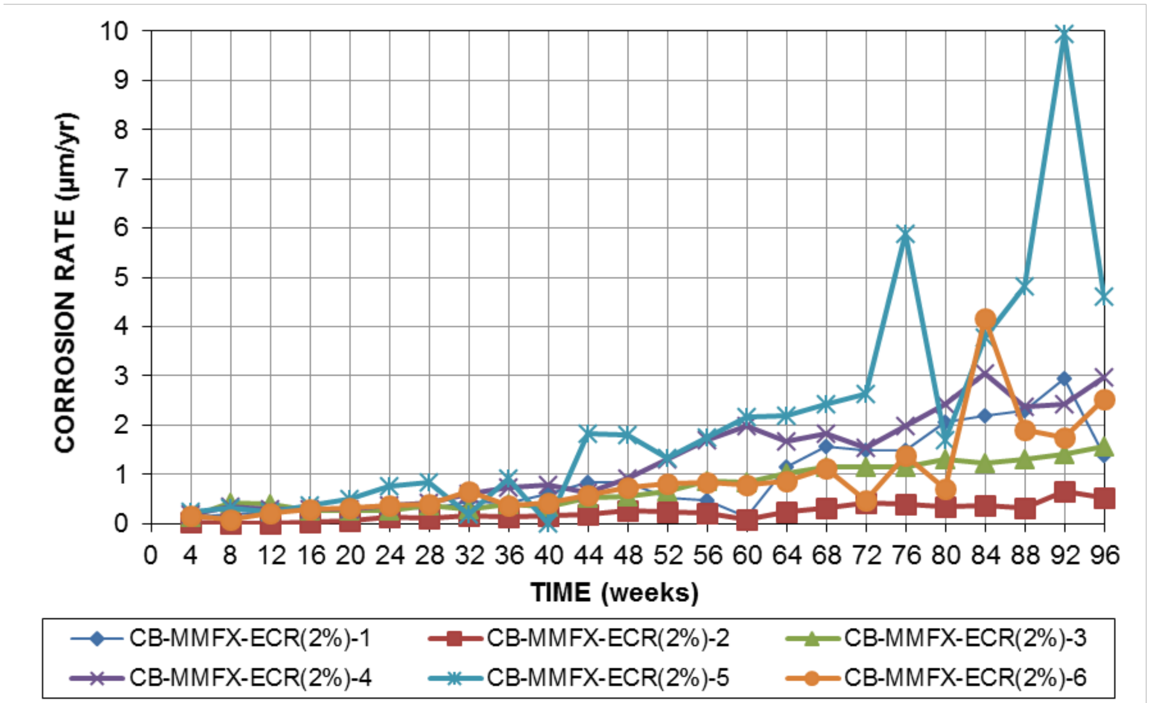

Figure 29— LPR test corrosion rates (μm/yr) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

Figure 30 shows the average corrosion rates for the cracked beam specimens based on exposed area obtained from the LPR test results. As shown, up to week 40, the average corrosion rate for CB-MMFX-ECR(2%) was similar to that of CB-MMFX-ECR(4%). After week 40, CB-MMFX-ECR(2%) exhibited greater corrosion rates than CB-MMFX-ECR(4%), and the difference between the two increased over time. Based on exposed area, the epoxy-coated CB-MMFX-ECR(2%) and CB-MMFX-ECR(4%) specimens exhibited maximum corrosion rates of 613 μm/yr and 253 μm/yr at weeks 92 and 84, respectively.

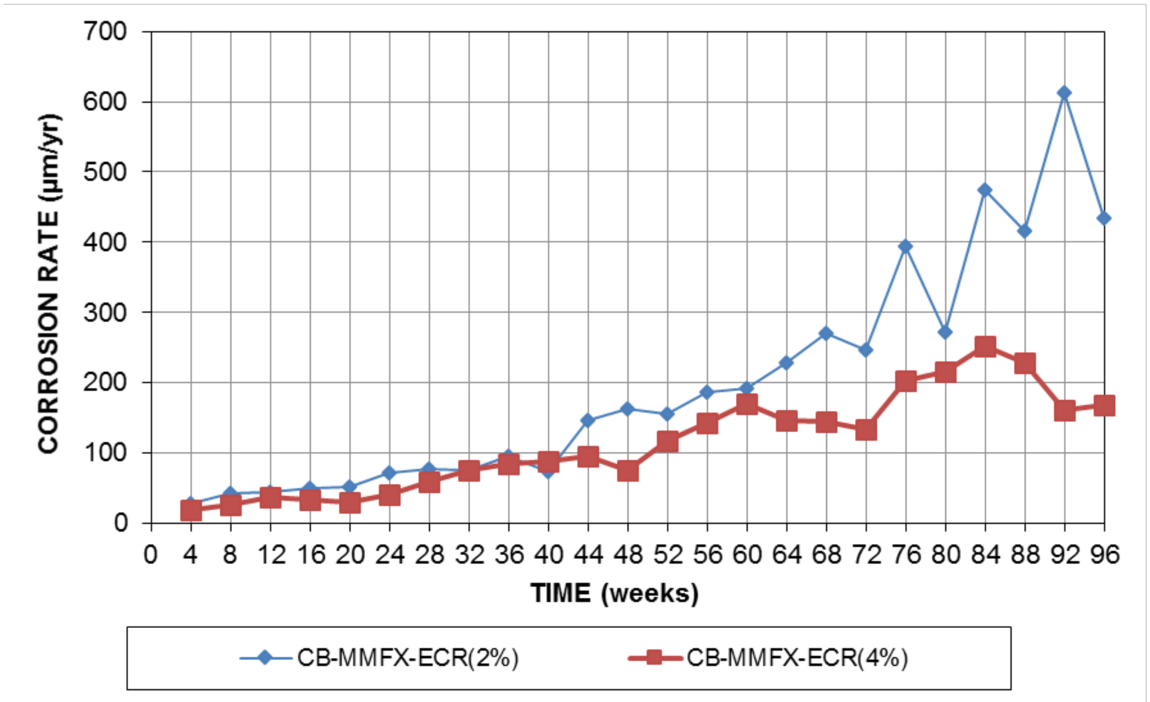

Figure 30— Average LPR test corrosion rate (µm/yr) based on exposed area versus time for cracked beam specimens containing epoxy-coated MMFX bars

The average and individual corrosion losses for the cracked beam specimens obtained from LPR test results through the end of test (week 96) are tabulated in Table 9. Based on exposed area, losses for the MMFX-ECR(2%) specimens ranged from 79.2 to 756 µm, with an average of 370 µm, about 3.8 times the value based on macrocell corrosion rates. The corrosion losses for the MMFX-ECR(4%) specimens ranged from 32.5 to 500 µm, with an average loss of 212 µm, about 3.2 times that obtained from macrocell corrosion rates.

Table 9: Corrosion loss (µm) for cracked beam specimens based on LPR test results

Specimen	Corrosion Loss (µm)-Total Area						Average	Std. Dev.
	Week 96		Week 96		Week 96			
	1	2	3	4	5	6		
MMFX-ECR(2%)	1.74	0.413	1.38	2.40	3.94	1.69	1.93	1.18
MMFX-ECR(4%)	0.397	2.60	2.03	0.385	1.03	0.170	1.10	1.00
	Corrosion Loss (µm)-Exposed Area							
MMFX-ECR(2%)	335	79.2	265	461	756	324	370	226
MMFX-ECR(4%)	76.2	500	390	74.0	198	32.5	212	192

Corrosion Potential

The average top mat corrosion potentials (with respect to a copper-copper sulfate electrode) for the cracked beam specimens are shown in Figure 31. The specimens with all bar types exhibited potentials near –0.47 V at the start of the test. The average potential of the MMFX-ECR(2%) specimens dropped to near –0.60 V up to week 11 and gradually increased up to week 24. After week 24, potentials again decreased, ranging between –0.53 V and –0.70 V by week 96. The potentials of the MMFX-ECR(4%) specimens exhibited similar potentials as MMFX-ECR(2%) through week 96. The potentials indicate that the specimens initiated corrosion in the first week of testing.

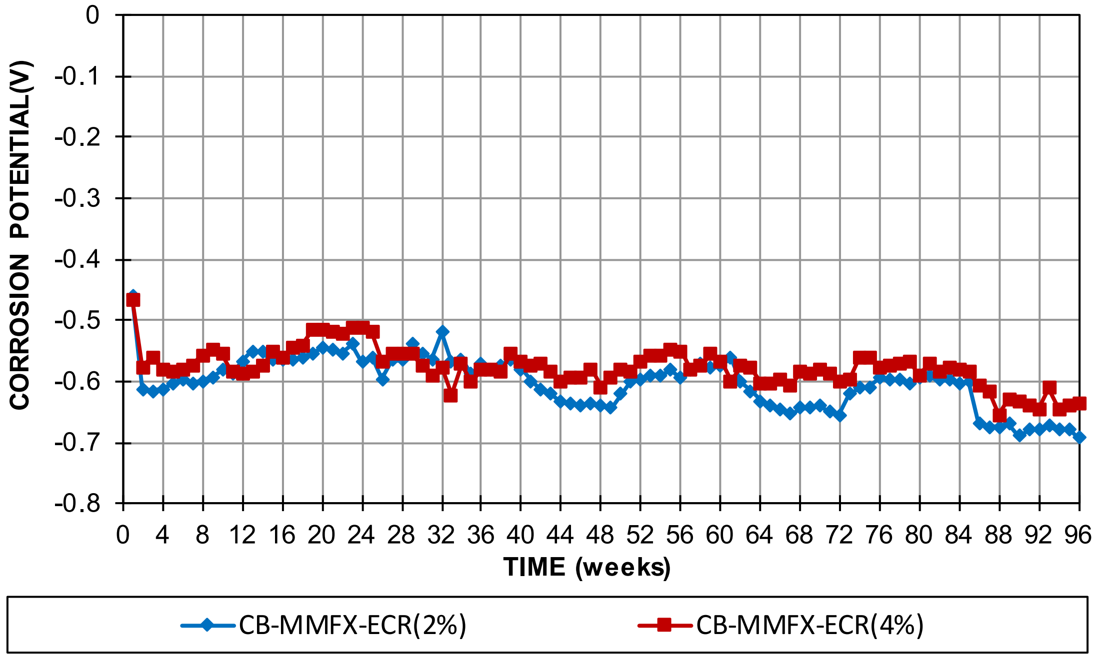

Figure 31— Top mat (anode) corrosion potential (CSE) versus time for cracked beam specimens containing epoxy-coated MMFX bars

Autopsy Results

Upon completion of the test (96 weeks), the cracked beam specimens were autopsied and photographed. Disbondment tests were performed on the epoxy-coated bars for the top bars, as well as one representative bottom bar for each specimen. Top and bottom bars from cracked beam specimens containing 2% and 4% chromium (CB-MMFX-ECR(2%)-2 and CB-MMFX-ECR(4%)-5) are shown in Figures 32 through 35. Most of the top mat bars containing 2% chromium experienced total disbondment between the epoxy layer and the underlying steel. Corrosion products under the disbonded epoxy were also widespread for this reinforcement (Figure 51). Bottom mat bars containing 2% chromium, however, did not exhibit significant disbondment or visible corrosion products (Figure 52). Top mat reinforcement of specimens with bars containing 4% chromium did not show as much disbondment as reinforcement with 2% chromium; however, corrosion products were still visible under the disbonded epoxy. Bottom mat bars containing 4% chromium also exhibited less this disbondment than top mat bars, although corrosion products were visible in some cases (Figure 54). For CB-MMFX-ECR(4%)-5 top and bottom bars, visible corrosion products are indicated by ovals in Figures 53 and 54, respectively.

Figure 32— Cracked beam MMFX-ECR(2%)-2 top bar after disbondment test after 96 weeks

Figure 33— Cracked beam MMFX-ECR(2%)-2 bottom bar after disbondment test after 96 weeks

Figure 34— Cracked beam MMFX-ECR(4%)-5 top bar after disbondment test after 96 weeks

Figure 35— Cracked beam MMFX-ECR(4%)-5 bottom bar after disbondment test after 96 weeks

The disbonded area for the top bar of MMFX-ECR(4%) and MMFX-ECR(2%) cracked beam specimens are tabulated in Tables 10 and 11, respectively. For bars that experienced total disbondment, the disbonded area was treated as 1.05 in.^{2} (677 mm^2), the maximum area measured at each disbondment site. The average disbondment of MMFX-ECR(4%) top bars was 0.71 in^2 (454 mm^2). All but one tested site for top bars containing 2% chromium experienced total disbondment, resulting in an average disbondment of 0.98 in^2 (634 mm^2).

Table 10: Disbonded area at week 96 for the MMFX-ECR(4%) top bar in cracked beam specimens

Specimen	Top side 1 (in^2)	Top side 2 (in^2)	Bottom side (in^2)	Average (in^2)
1	1.05	1.05	0.85	0.98
2	1.05	1.05	1.05	1.05
3	1.05	1.05	0.61	0.90
4	1.05	0.11	0.31	0.49
5	0.80	0.58	0.62	0.67
6	0.17	0.13	0.11	0.14
Average				0.71

Table 11: Disbonded area at week 96 for the MMFX-ECR(2%) top bar in cracked beam specimens

Specimen	Top side 1 (in^2)	Top side 2 (in^2)	Bottom side (in^2)	Average (in^2)
1	1.05	1.05	1.05	1.05
2	1.05	1.05	1.05	1.05
3	1.05	0.62	1.05	0.91
4	1.05	1.05	0.77	0.96
5	1.05	1.05	1.05	1.05
6	1.05	1.05	0.55	0.88
Average				0.98

Rapid Macrocell (RM) Specimens

Macrocell Corrosion

The individual corrosion losses at the end of the test (week 15) of the epoxy-coated bars containing 2% and 4% chromium are tabulated in Table 12. The average corrosion loss during the test for the epoxy-coated bars (based on the total area) is shown in Figure 36. Corrosion losses were obtained by integrating the macrocell corrosion rates with respect to time. After 15 weeks, corrosion loss of MMFX-ECR(4%) was 0.21 µm, less than half of corrosion loss of MMFX-ECR(2%), 0.45 µm.

Table 12: Corrosion loss (µm) for rapid macrocell specimens

Specimen	Corrosion Loss (µm)-Total Area						Average	Std. Dev.
	Week 15		Week 15		Week 15			
	1	2	3	4	5	6		
MMFX-ECR(2%)	0.296	0.524	0.500	0.502	0.310	0.577	0.451	0.118
MMFX-ECR(4%)	0.378	0.175	0.212	0.189	0.145	0.156	0.209	0.086

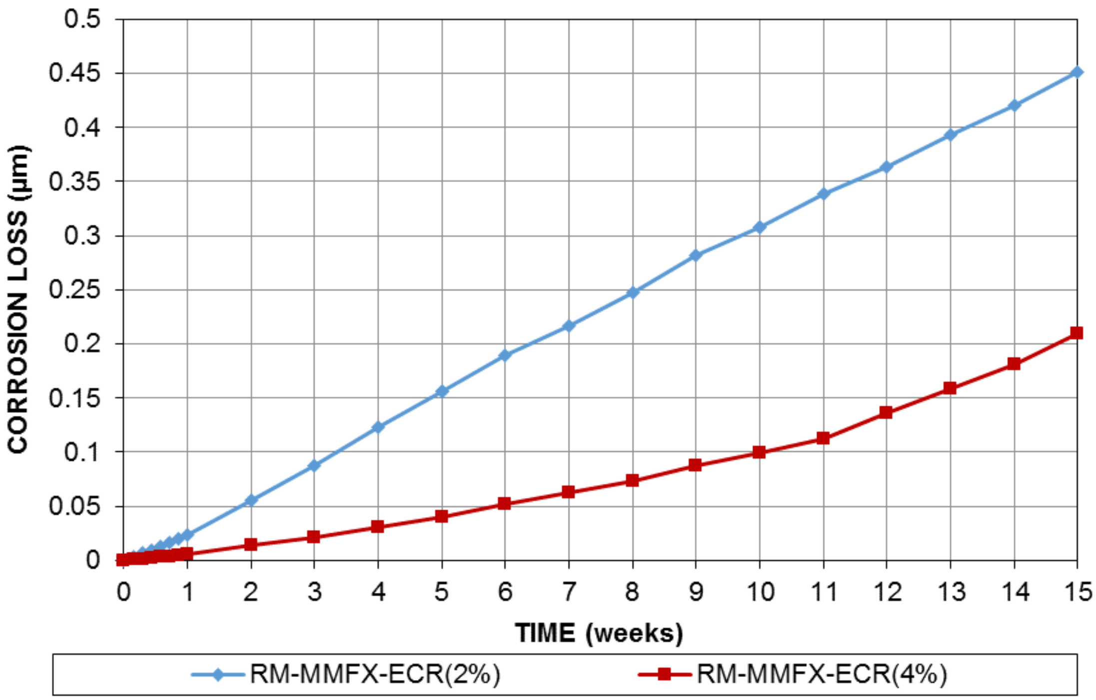

Figure 36— Average corrosion loss (µm) versus time for rapid macrocell tests containing epoxy-coated MMFX bars based on total area.

Linear Polarization Resistance (LPR)

Figures 37 and 38 show the average corrosion rate and loss, respectively, from LPR test results for the rapid macrocell specimens based on total area. For epoxy-coated bars, the corrosion loss of MMFX-ECR(4%), 0.33 µm, was about one third of the one for MMFX-ECR(2%), 1.07 µm. A comparison between the corrosion loss of reinforcement based on macrocell corrosion and LPR test results shows that for MMFX-ECR(4%) and

MMFX-ECR(2%), corrosion losses based on LPR test results were two and 1.5 times greater than that based on macrocell corrosion, respectively.

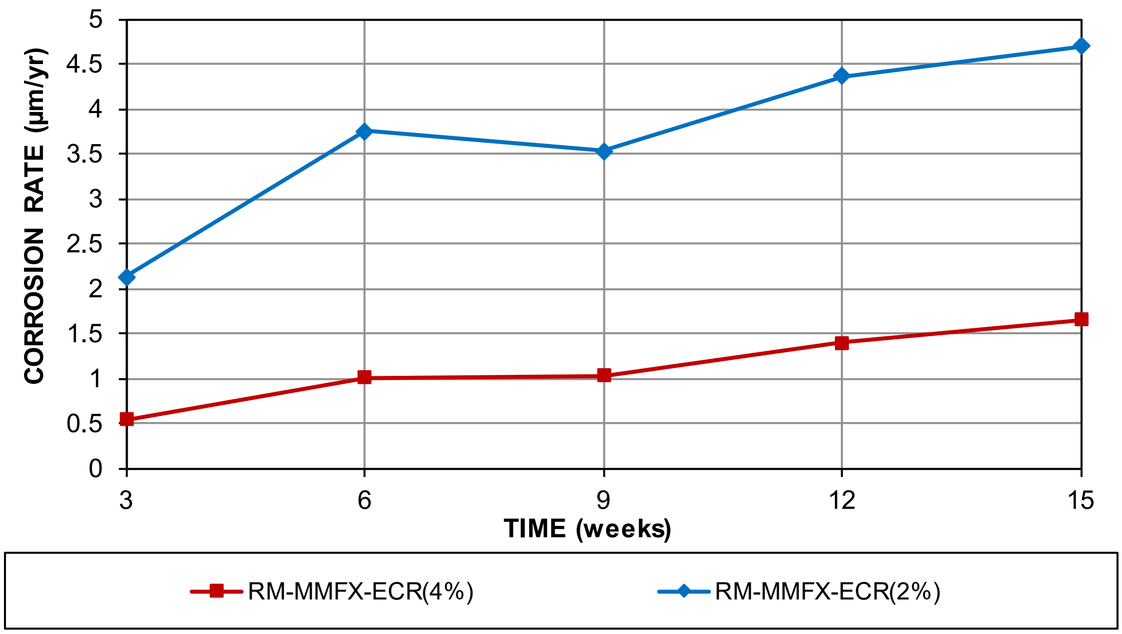

Figure 37— Average corrosion rates (μm/yr) versus time for rapid macrocell tests containing MMFX bars based on total area from LPR test results

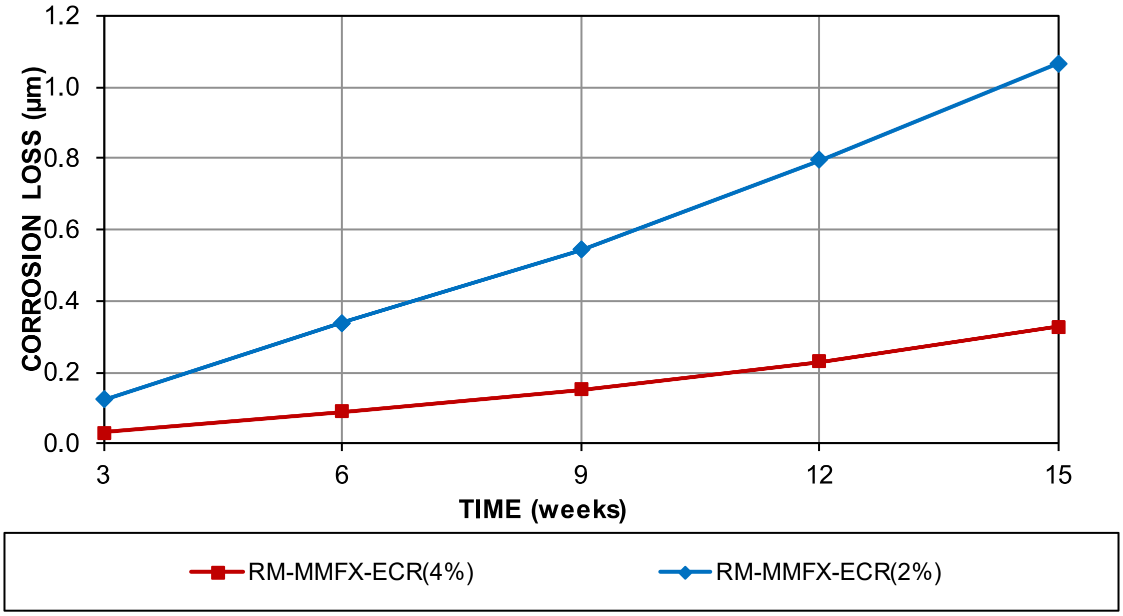

Figure 38— Average corrosion loss (µm) versus time for rapid macrocell tests containing MMFX bars based on total area from LPR test results

Table 13: Corrosion Loss (µm) for rapid macrocell specimens based on LPR test results

Specimen	Corrosion Loss (µm)-Total Area						Average	Std. Dev.
	Week 15		Week 15		Week 15			
	1	2	3	4	5	6		
MMFX-ECR(2%)	1.01	1.03	1.51	0.97	0.85	1.03	1.07	0.23
MMFX-ECR(4%)	0.56	0.20	0.07	0.35	0.42	0.35	0.33	0.17

Corrosion Potential

The average anode corrosion potentials taken with respect to a saturated calomel electrode (SCE) are shown in Figure 39. The potential of epoxy-coated MMFX-ECR(2%) and MMFX-ECR(4%) specimens decreased from –0.56 V to –0.61 V and –0.51 V to –0.57 V, respectively, during the first week of testing and remained there throughout the testing period.

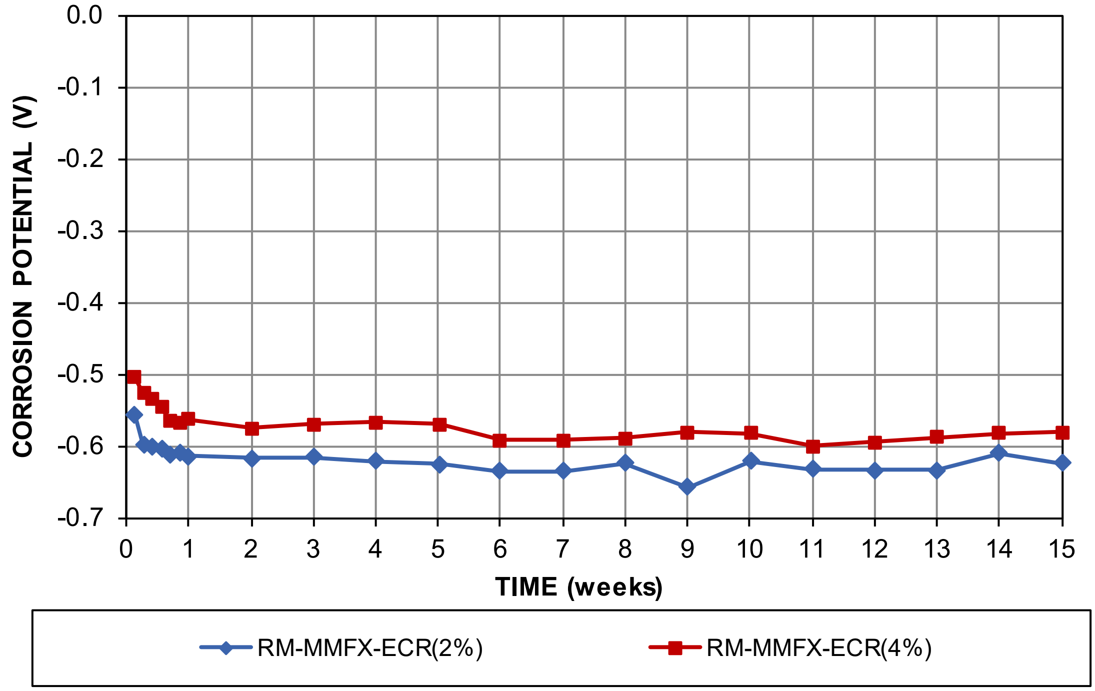

Figure 39— Average anode corrosion potentials (SCE) versus time for rapid macrocell tests containing MMFX bars

The average cathode corrosion potentials taken with respect to a saturated calomel electrode (SCE) are shown in Figure 40. After the first week of testing, the average potential for both coated bar types was –0.33 V and remained near that value through week 8. After week 8, the potential varied, and both the epoxy-coated MMFX-ECR(2%) and MMFX-ECR(4%) bars exhibited slightly increased potentials of –0.27 V at the end of 15 weeks of testing.

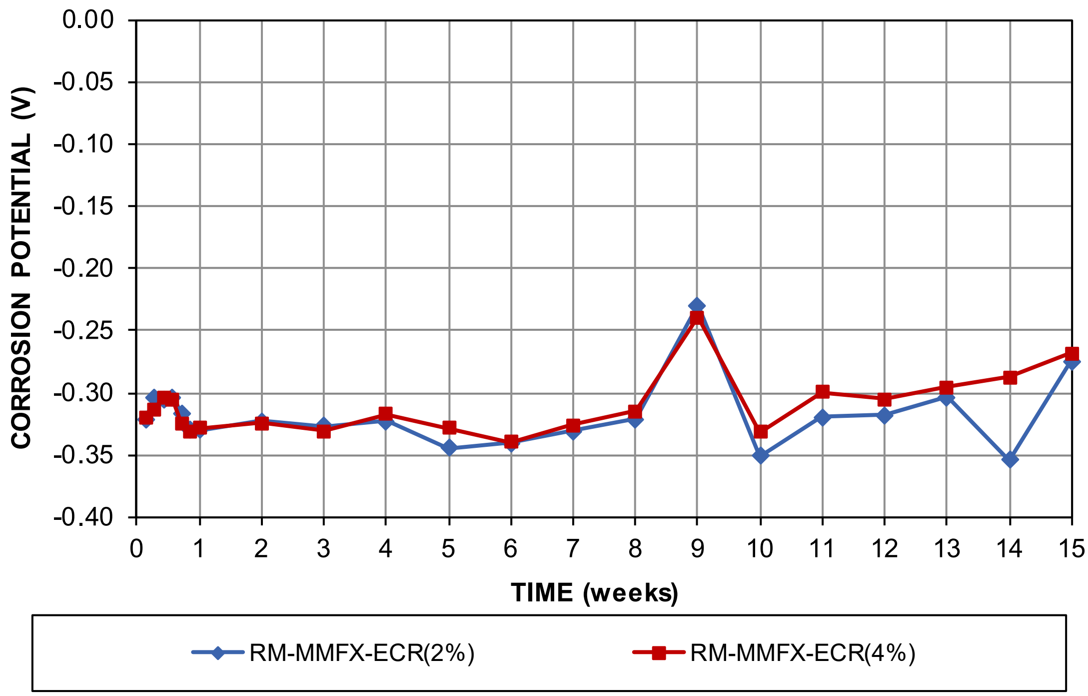

Figure 40— Average cathode corrosion potentials (SCE) versus time for rapid macrocell tests containing MMFX bars

Visual Observations

Upon completion of the rapid macrocell tests (15 weeks), all specimens were visually inspected and photographed. For the epoxy-coated bars, corrosion products were visible at the intentionally damaged sites. A disbondment test was performed at all four intentional damaged areas of the epoxy layer for each anode bar. If the tested site exhibited total disbondment, the disbonded area was recorded as 1.05 in^2 (677 mm^2). Bars with 4% and 2% chromium are shown in Figures 41 and 42, respectively. The disbonded area of anode bars of epoxy-coated MMFX bars containing 4% and 2% versus their total corrosion loss obtained from LPR test results are tabulated in Tables 14 and 15, respectively. The average corrosion loss (0.325 µm) and disbonded area (0.12 in^2 (78 mm^2)) of the epoxy-coated MMFX bars containing 4% chromium were approximately 30% and 50% of those in the epoxy-coated MMFX bars containing 2% chromium (1.07 µm as average corrosion loss and 0.23 in^2 (151 mm^2) as average disbonded area).

Figure 41— Rapid macrocell test, anode bar of MMFX-ECR(4%)-5 after disbondment test after 15 weeks

Figure 42— Rapid macrocell test, anode bar of MMFX-ECR(2%)-5 after disbondment test after 15 weeks

Table 14: Disbonded area and total corrosion loss for anode bars at week 15 for the MMFX-ECR(4%) in rapid macrocell test

Specimen	Total Corrosion Loss (µm)	Site 1 (in^2)	Site 2 (in^2)	Site 3 (in^2)	Site 4 (in^2)	Average (in^2)	Average (mm^2)
1	0.56	0.24	0.13	0.24	0.07	0.17	110
2	0.2	0.06	0.04	0.33	0.04	0.12	76
3	0.07	0.04	0.27	0	0.09	0.10	65
4	0.35	0.11	0.09	0.07	0.12	0.10	63
5	0.42	0.16	0.26	0.06	0.11	0.15	95
6	0.35	0.11	0.24	0.01	0.02	0.10	61
Average	0.325					0.12	78

Table 15: Disbonded area and total corrosion loss for anode bars at week 15 for the MMFX-ECR(2%) in rapid macrocell test

Specimen	Total Corrosion Loss (μm)	Site 1 (in^2)	Site 2 (in^2)	Site 3 (in^2)	Site 4 (in^2)	Average (in^2)	Average (mm^2)
1	1.01	0.06	0.25	0.13	0.26	0.18	113
2	1.03	0.25	0.09	0.25	0.22	0.20	131
3	1.51	0.25	0.14	0.26	0.33	0.25	158
4	0.97	0.36	0.45	0.13	0.10	0.26	168
5	0.85	0.37	0.27	0.19	0.19	0.26	165
6	1.03	0.42	0.23	0.29	0.12	0.27	171
Average	1.07					0.23	151

Critical Chloride Corrosion Threshold

For epoxy-coated MMFX bars containing 4% and 2% chromium, to obtain a more accurate determination of the critical chloride threshold, beam specimens were cast and sampled for measuring chloride content upon initiation. The macrocell corrosion rates, total corrosion rates (LPR test results), and corrosion potentials for the beam specimens containing epoxy-coated MMFX bars are shown in the Appendix A.

The critical chloride corrosion thresholds of the coated MMFX bars are shown in Table 16. The critical chloride threshold of beam specimens containing MMFX-ECR(2%) was 4.11 lb/yd^3 (2.44 kg/m^3) at 34 weeks, compared to MMFX-ECR(4%) with a chloride threshold of 5.16 lb/yd^3 (3.06 kg/m^3) at an average age of 45 weeks. The differences in chloride threshold and initiation age for the epoxy-coated bars were not statistically significant (p = 0.38 and 0.26, respectively). The chloride content for individual samples of each specimen is presented in Appendix A.

Table 16: Critical chloride corrosion threshold (lb/yd^3) of MMFX bars

Specimen	Water Soluble Chloride Content (lb/yd^3)*								Average	Std. Dev.
	1	2	3	4	5	6	7	8		
MMFX-ECR(2%)	4.44	5.41	3.93	4.26	3.69	2.96	-	-	4.11	0.63
MMFX-ECR(4%)	5.11	3.42	6.67	5.16	4.15	6.42	-	-	5.16	1.66

*1(lb/yd^3) = 0.593(kg/m^3)

DISCUSSION

Figures 43 and 44, respectively, compare the macrocell and total corrosion losses of epoxy-coated MMFX bars with conventional epoxy-coated steel based on total area of the bar. The intentionally damaged area of the epoxy layer was identical for all bars in a given test method (10 holes for bench-scale tests and 4 holes for the rapid macrocell test). The MMFX-ECR(4%) specimens had the least macrocell and total corrosion losses in the bench-scale tests. For the rapid macrocell test, the conventional epoxy-coated bars had the lowest average macrocell corrosion loss. (As discussed earlier, previous tests on conventional ECR exhibited greater losses than the ECR used for comparison in this study). The total corrosion loss for the conventional ECR (0.32 µm), however, was very close to that for MMFX-ECR(4%), 0.33 µm, but still one third of MMFX-ECR(2%) total corrosion loss (1.07 µm). The corrosion losses of the MMFX epoxy-coated bars containing 4% chromium were 12%, 30%, and 100% that of conventional epoxy-coated steel for, respectively, the Southern Exposure, cracked beam, and rapid macrocell tests, giving it the best corrosion resistance among the coated bars in this study.

Table 17: Average corrosion loss (µm) for epoxy-coated conventional (Darwin et al. 2013) and MMFX bars

Steel Designation	Macrocell Corrosion (µm)			Total (LPR) Corrosion (µm)		
	SE	CB	RM	SE	CB	RM
ECR	0.342	0.453	0.107	1.05	3.71	0.322
MMFX-ECR(2%)	0.076	0.506	0.450	0.25	1.93	1.07
MMFX-ECR(4%)	0.059	0.341	0.200	0.125	1.10	0.33

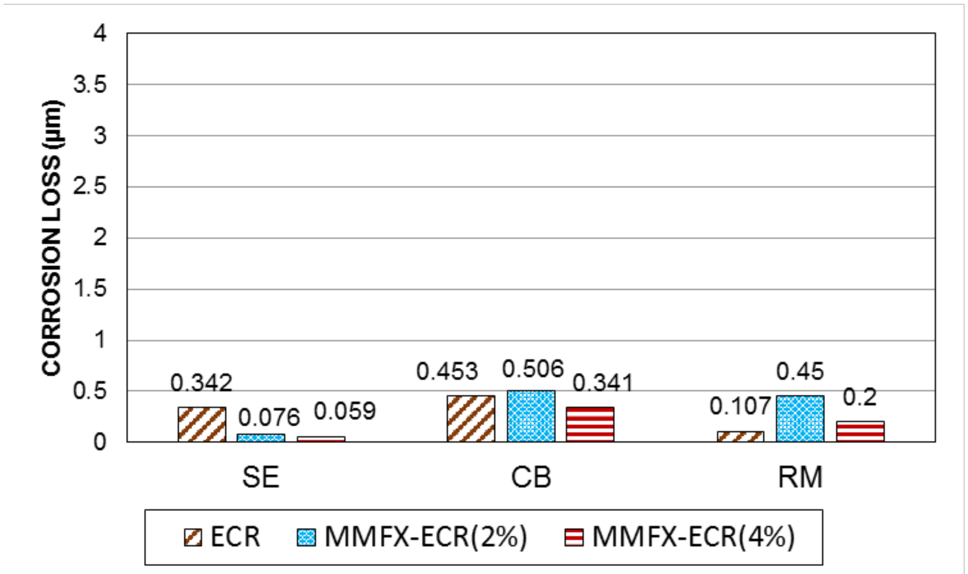

Figure 43— Corrosion loss (µm) for epoxy-coated conventional (Darwin et al. 2013) and MMFX bars in bench-scale and rapid macrocell tests obtained from macrocell corrosion rates

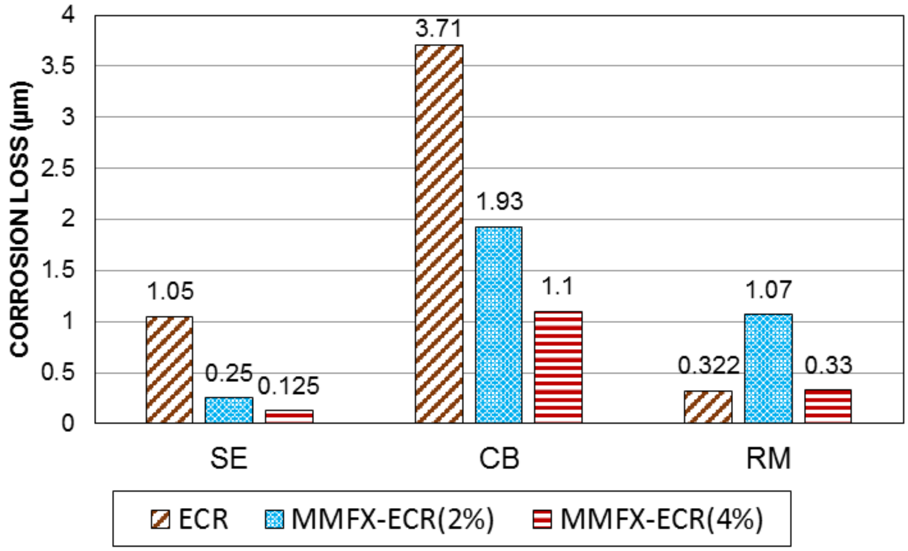

Figure 44— Corrosion loss (µm) for epoxy-coated conventional (Darwin et al. 2013) and MMFX bars in bench-scale and rapid macrocell tests obtained from LPR test corrosion rates.

To evaluate the statistical significance of the differences in mean values of corrosion loss for the different types of epoxy-coated bars, Student's t-test, a method of statistical analysis, was performed on the data sets. Student's t-test compares two data sets to determine the probability (p) of obtaining a difference in the mean values of two data sets at least as large as observed when in fact there is no difference. Differences are generally considered statistically significant if the probability is less than 5% ($p < 0.05$). The p values for the differences in total corrosion loss are tabulated in Table 18. Comparisons between the mean values for the MMFX-ECR(4%) and conventional epoxy-coated bars show that for the all specimens, the p values are less than 5%. Thus, the differences are statistically significant. The p values for comparisons between MMFX-ECR(2%) and conventional epoxy-coated bars in the bench-scale tests are more than 5% (7.4% for Southern Exposure and 9.4% for cracked beam), and thus, these difference are not statistically significant. For the rapid macrocell tests, the differences in the mean losses between the MMFX-ECR(2%) bars and the other two types of epoxy-coated reinforcement are statistically significant.

Table 18: Student's t-test results (p values) for total corrosion loss of epoxy-coated bars

Steel Designation	Southern Exposure			Cracked beam			Rapid macrocell		
	ECR	MMFX-ECR(2%)	MMFX-ECR(4%)	ECR	MMFX-ECR(2%)	MMFX-ECR(4%)	ECR	MMFX-ECR(2%)	MMFX-ECR(4%)
ECR	-	0.074	**0.041**	-	0.094	**0.019**	-	**0.00003**	0.97
MMFX-ECR(2%)	0.074	-	**0.042**	0.094	-	0.22	**0.00003**	-	**0.00008**
MMFX-ECR(4%)	**0.041**	**0.042**	-	**0.019**	0.22		0.97	**0.00008**	**-**

The disbondment test results for the top and bottom bars of Southern Exposure and cracked beam specimens and anode bars of rapid macrocell test of MMFX epoxy-coated reinforcement obtained from this study are compared with similar results for conventional epoxy-coated bars obtained from Darwin et al. (2013) in Figures 45, 46 and 47, respectively. For the top and anode bars, the MMFX bars containing 4% chromium had the least disbonded area in all three tests. The MMFX bars containing 4% chromium had disbonded areas equal to 52%, 67%, and 67% of the values for the conventional epoxy-coated reinforcement and 80%, 70%, and 50% of the values for the MMFX-ECR(2%) bars in Southern Exposure, cracked beam and rapid macrocell tests, respectively. MMFX bars containing 2% chromium had less disbonded area than the conventional epoxy-coated bars in the Southern Exposure specimens, but the disbonded area was comparable to that of the conventional ECR bars in cracked beam specimens and greater than that of the conventional ECR bars in rapid macrocell specimens.

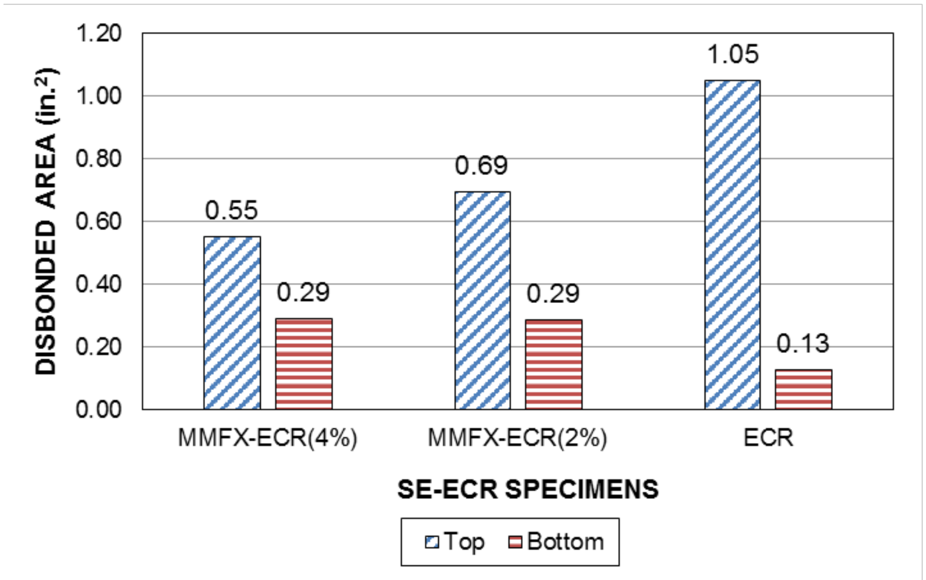

Figure 45— Comparison of disbondment test results of top and bottom bars in Southern Exposure specimens containing epoxy-coated conventional (Darwin et al. 2013) and MMFX bars

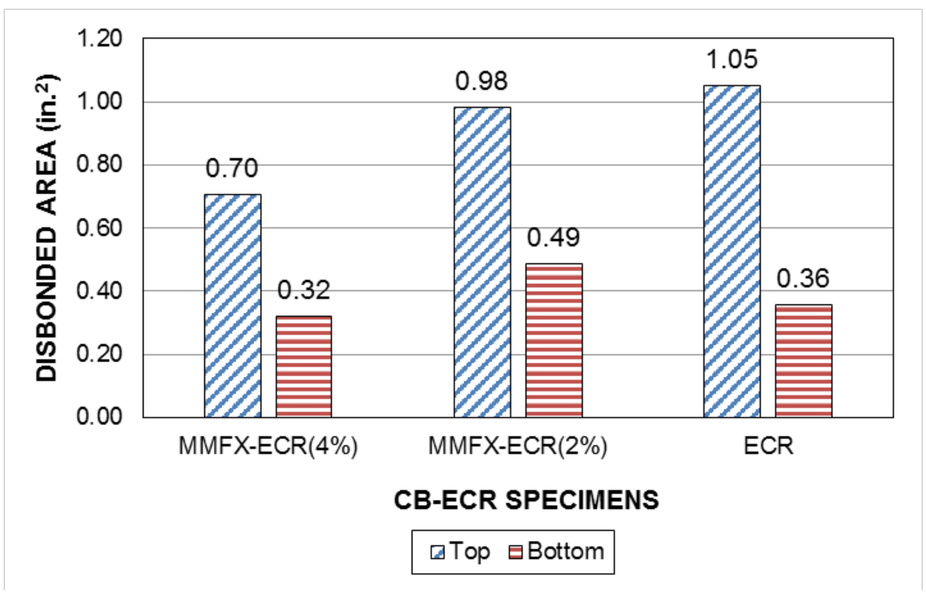

Figure 46— Comparison of disbondment test results of top and bottom bars in cracked beam specimens containing epoxy-coated conventional (Darwin et al. 2013) and MMFX bars

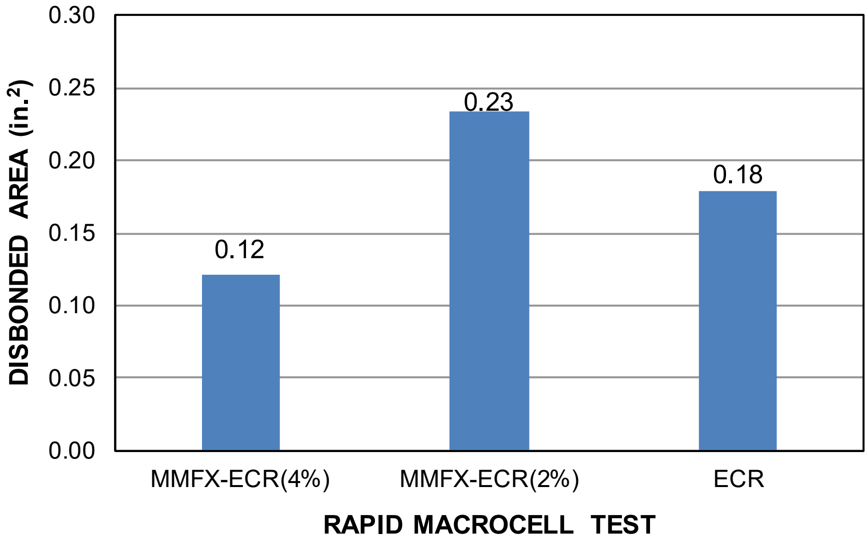

Figure 47— Comparison of disbondment test results of anode bars in rapid macrocell tests containing epoxy-coated conventional (Darwin et al. 2013) and MMFX bars

The critical chloride corrosion threshold of the epoxy-coated MMFX bars containing 4% chromium obtained in this study was 5.16 lb/yd^3 (3.06 kg/m^3), with an average initiation age of 45 weeks; for epoxy-coated MMFX bars containing 2% chromium, the critical chloride corrosion threshold was 4.11 lb/yd^3 (2.44 kg/m^3) with an average initiation age of 31 weeks. The chloride thresholds for these bars are comparable to the chloride threshold for epoxy-coated conventional reinforcement, 4.59 lb/yd^3 (2.72 kg/m^3) reported by Darwin et al. (2013). This finding is not surprising; chlorides do not penetrate evenly through concrete, but rather migrate rapidly through microcracks and high porosity regions while moving more slowly around aggregate and through denser regions. With coated reinforcement, the chloride threshold is controlled more by the probability of a high-chloride region hitting a damaged portion of the coating than by the corrosion resistance of the metal under the coating.

LIFE EXPECTANCY

In this section, the life expectancy of bridge decks with the corrosion protection systems evaluated in this study is estimated. Conventional bare and epoxy-coated reinforcement are compared with epoxy-coated MMFX steel containing 4% and 2% chromium (epoxy-coated ASTM A1035 Type CM and CL steel).

The time to first repair of a concrete bridge deck (expected life) can be represented as two phases–the time to corrosion initiation of reinforcement and the time for a corroding bar to crack the concrete cover. Estimations of each of these phases are presented in the following sections.

Time to Corrosion Initiation

The onset of corrosion occurs when the chloride content amount at the surface of embedded bar reaches its critical chloride corrosion threshold (CCCT). The time to corrosion initiation is determined by comparing the CCCT value for each corrosion protection system with the chloride concentration at the depth of the reinforcement in concrete bridge decks. Lindquist et al. (2006) measured the chloride content of 57 bridge decks with an average annual daily traffic (AADT) greater than 7500. Concrete was sampled in 0.75 in. (19 mm) increments up to 3.75 in. (95 mm) from the surface. Results are then interpolated to a depth of 3 in. (76.2 mm) (the cover to the top mat of steel in bridge decks) and reported at crack locations as well as away from cracks. Since existence of cracks over and parallel to the bars is common in bridge decks and can accelerate corrosion, chloride contents at crack locations are used. Figure 48 shows the average chloride concentration with respect to the age of the structure at crack locations at a depth of 3 in. (76.2 mm).

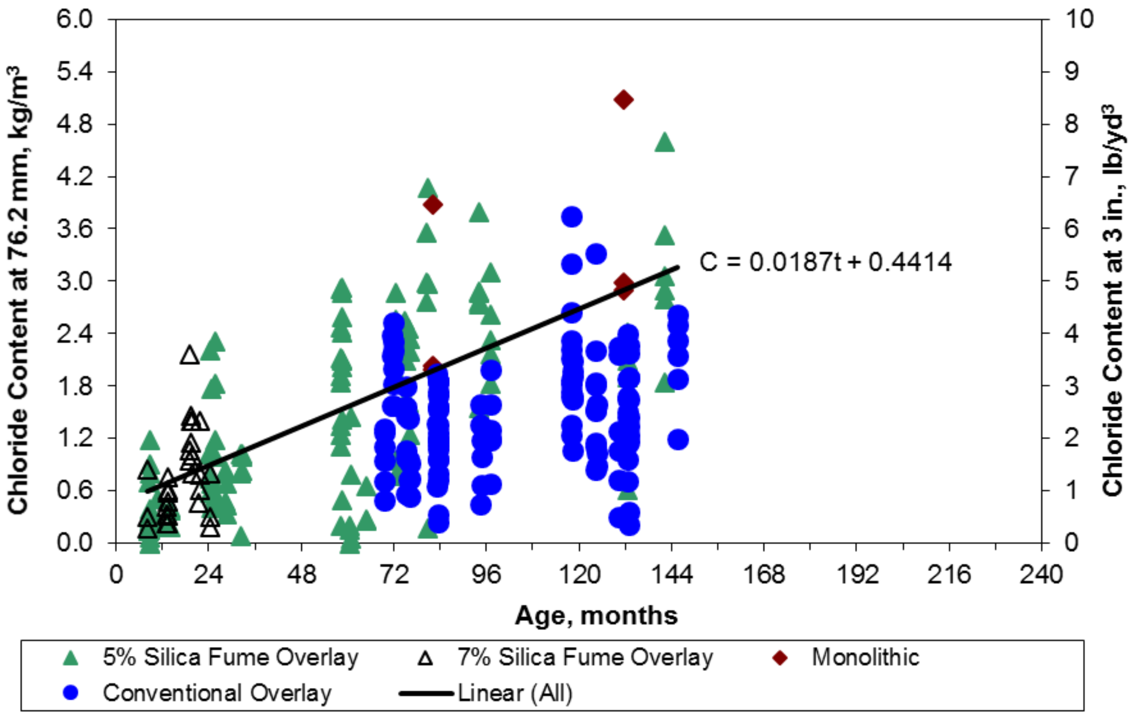

Figure 48— Chloride content taken on cracks interpolated at depth of 3 in. vs. placement age for bridges with an AADT > 7500 (Lindquist et al. 2006)

The trend line equation obtained from the data shows a linear relationship between chloride concentration and time at the crack locations and is independent of permeability of concrete; thus, it can be used for all specimens including specimens containing supplementary cementitious materials. The average time to reach a specific critical chloride threshold at crack locations on the bridge decks can be expressed as:

$$t_1 = (C_{crit} - 0.4414) / 0.0187 \tag{1}$$

where

C_{crit} = critical chloride corrosion threshold, kg/m^3

t_1 = time to reach the critical chloride corrosion threshold, months

The critical chloride corrosion threshold (CCCT) and calculated average time to initiation based on Eq. 1 for each corrosion protection system in this study are tabulated in

Table 19. MMFX reinforcement had a time to initiation of almost 10 years, about five times greater than bridge decks with conventional bars. ECR also had a time to initiation of approximately 10 years.

Table 19: Critical chloride threshold and time to initiation for bridge decks with different corrosion protection systems

System[a]	Critical chloride corrosion threshold		Initiation time
	lb/yd^3	kg/m^3	years
Conv.	1.53	0.91	1.9
ECR	4.59	2.72	10.1
MMFX steel			
MMFX-ECR(2%)	4.11	2.43	8.9
MMFX-ECR(4%)	5.16	3.06	11.6

Corrosion Propagation Time to Crack Concrete Cover

To calculate the time to crack concrete after corrosion initiation of steel, the total corrosion loss required to crack concrete (critical corrosion loss) and the average corrosion rate of steel after initiation are necessary. By dividing the critical corrosion loss by the average corrosion rate, the time that is taken for corroded bar to crack concrete can be determined for each system.

Critical Corrosion Loss

A sufficient amount of buildup corrosion products (the critical corrosion loss) is needed to crack the concrete cover. Critical corrosion loss is estimated using an equation developed by O'Reilly et al. (2011) which represents a relationship between corrosion loss of steel at crack initiation, concrete cover, and bar diameter for localized corrosion as well as general corrosion:

$$x_{crit} = 45\left(\frac{\left[C/25.4\right]^{2-A_f}}{D^{0.38} \times L_f^{\ 0.1} \times A_f^{\ 0.6}} + 0.2\right) \times 3^{A_f - 1} \tag{2}$$

where

x_{crit} = corrosion loss at crack initiation, µm

C = cover, mm.

D = bar diameter, mm.

L_f = fractional length of bar corroding, $L_{\text{corroding}}/L_{\text{bar}}$

A_f = fractional area of bar corroding, $A_{\text{corroding}}/A_{\text{bar}}$

Epoxy-coated reinforcement in this report was intentionally damaged with ten holes, five on the each side of bar, with a diameter of 0.125 in. (3 mm), to simulate the damage that occurs on coated reinforcement in practice. The exposed fractional area of a bar, A_f, can be obtained by dividing the exposed area of a bar by its total embedded area in concrete:

$$A_f = \frac{A_{corroding}}{A_{bar}} = \frac{10 \times \pi \left(d_h/2\right)^2}{\pi d_b l} = \frac{10 \times \pi \left(3\text{mm}/2\right)^2}{\pi \times 16\ \text{mm} \times 304.8\ \text{mm}} = 0.0046$$

Exposed fractional length of a bar, L_f, is obtained as a quotient of dividing the exposed length of a bar by its total length:

$$L_f = \frac{L_{corroding}}{L_{bar}} = \frac{d_h}{l} = \frac{5 \times 3\ \text{mm}}{304.8\ \text{mm}} = 0.049$$

By substituting the calculated A_f and L_f values in Eq. 2, the critical corrosion loss required to crack a 3 in. (76.2 mm) concrete cover by corrosion of a No. 5 (No. 16) epoxy-coated bar is:

$$x_{crit} = 45\left(\frac{\left[{}^{76.2}\!/_{25.4}\right]^{2-0.0046}}{16^{0.38}\times 0.049^{0.1}\times 0.0046^{0.6}}+0.2\right)\times 3^{0.0046-1}$$

$$x_{crit} = 1610\ \mu\text{m}$$

MMFX bars are assumed to behave in a manner similar to conventional steel in terms of the corrosion losses required to crack concrete; thus, the calculated values of conventional steel were used for epoxy-coated MMFX reinforcement.

Average Corrosion Rate

The average corrosion rate after initiation for each system is determined from its total corrosion loss plots obtained from LPR test results, and is described in detail by Farshadfar et al. (2017). The average corrosion rates based on LPR test results for each system in this study are tabulated in Table 20. Conventional epoxy-coated reinforcement in specimens with 100% portland cement showed the highest total corrosion rate based on exposed area (50.0 μm/yr) among specimens with coated bars. While the average corrosion rate of MMFX-ECR(2%) specimens (40.2 μm/yr) was comparable to that of epoxy-coated conventional reinforcement (42.8 μm/yr), MMFX-ECR(4%) specimens exhibited approximately half the average corrosion rate of epoxy-coated conventional reinforcement (21.7 μm/yr).

Table 20: Average corrosion rate (μm/yr) after corrosion initiation based on LPR test corrosion losses

System[a]	Specimen								Avg.	Std. Dev.	COV
	1	2	3	4	5	6	7	8			
Conv.	10.9	16.3	15.9	15.1	14.8	13.8	-	-	14.5	1.94	0.13
ECR	39.7	59.3	38.0	42.4	86.4	34.2	-	-	50.0	19.8	0.40
MMFX steel											
MMFX-ECR(2%)	27.6	45.5	49.0	24.1	51.2	43.9	-	-	40.2	11.5	0.29
MMFX-ECR(4%)	19.2	16.9	13.4	16.1	40.9	23.7	-	-	21.7	10.0	0.46

[a] For epoxy-coated reinforcement corrosion losses are obtained based on exposed area of bars

To establish the average corrosion rates for each system in bridge decks, some modification factors that represent the relationship between the tested specimens in laboratory and real bridge decks should be used. Two major differences between conditions experienced by a bridge deck and those experienced by the laboratory specimens are the severity of environment and presence of cracks on the concrete surface. Bench-scale specimens are exposed to chlorides more frequently than a real bridge deck and kept saturated for over three quarters of the time, whereas a bridge deck is saturated for a much lower percentage of time. This would result in a lower corrosion rate on bridge decks than in the lab. However, the existence of cracks on bridge decks may increase the corrosion rate compared to uncracked specimens in the lab. O'Reilly (2011), developed a coefficient relating the corrosion rate of uncracked laboratory specimens to that of field specimens under the same exposure conditions as bridge decks in Kansas. O'Reilly found that corrosion rates from laboratory tests on bare bars could be converted to equivalent field corrosion rates in uncracked and cracked concrete by multiplying by 0.155 and 0.241, respectively. For coated bars, the conversion factors for uncracked and cracked concrete were 0.476 and 0.847. O'Reilly also noted that uncoated bars in field specimens tended to exhibit localized corrosion-only 40% of the bar area exhibited corrosion in uncracked concrete, with 33% of the bar area exhibiting corrosion in cracked concrete. This led to an additional conversion to "effective corroding area", accounting only for the percentage of bar corroding.

Using O'Reilly's coefficients, the total equivalent corrosion rate for bridge decks with and without cracks for each corrosion protection system based on exposed area of epoxy-coated reinforcement as well as total area and effective area of bare bars are calculated and tabulated in Table 21. Equivalent corrosion rate based on effective area of corroded bare bars in uncracked field specimens are less than but close to cracked field specimens. This can be explained by the fact that the higher corrosion rates based on total area for cracked specimens is due to their higher effective corroded area; however, the corrosion rate of an actual corroded area of a bar is very close in cracked and uncracked concrete. A coefficient of 1.8 was introduced by O'Reilly (2011) to convert corrosion rates of uncracked specimens to cracked specimens in laboratory tests. By applying this factor, equivalent corrosion rates of laboratory cracked beam specimens are calculated and shown in Table 23 for comparison.

Table 21: Equivalent total corrosion rates for bridge decks with and without cracks, and different corrosion protection systems

System[a]	Laboratory specimen corrosion rate (µm/yr)		Equivalent total corrosion rate (µm/yr)			
			Exposed area		Effective area	
	Uncracked	Cracked	Uncracked	Cracked	Uncracked	Cracked
Conv.	14.5	26.1	2.25	3.50	6.74	8.74
ECR	50.0	89.0	23.8	42.4	-	-
MMFX steel						
MMFX-ECR(2%)	40.2	71.6	19.1	34.1	-	-
MMFX-ECR(4%)	21.7	38.6	10.3	18.4	-	-

The time from corrosion initiation to cracking of the concrete cover for each system can be obtained by taking the critical corrosion loss to crack concrete and dividing by the equivalent total corrosion rates in Table 22 based on effective area for bare bars and exposed area for epoxy-coated reinforcement. Since it is more likely that bridge decks develop cracks over the reinforcement, corrosion rates for cracked specimens are used for comparison. The estimated times to first cracking after corrosion initiation are listed in Table 23. The lowest estimated time from initiation to first cracking is observed in concrete decks that contain conventional bare steel (6.4 years). For epoxy-coated bars, conventional ECR exhibits the lowest time to cracking, 38 years, followed by MMFX-ECR(2%) and MMFX-ECR(4%), at 47.3 and 87.6 years, respectively.

Table 22: Estimated times to first cracking after corrosion initiation based on corrosion rate in cracked concrete

System	Corrosion rate (µm/yr)	Critical corrosion loss (µm)	Cracking time (yr)
Conv.	8.74	56	6.4
ECR	42.4	1610	38.0
MMFX steel			
MMFX-ECR(2%)	34.1	1610	47.3
MMFX-ECR(4%)	18.4	1610	87.6

Time to First Repair

The expected life of a bridge deck is the elapsed time between the construction of a bridge and the time replacement or repair of the deck is required. The time to first repair is different from the time to first crack since a bridge deck is not fully repaired at the development of the first crack, but only after significant degradation of the deck has occurred. Based on discussions with the Kansas Department of Transportation, a ten-year period is assumed between first cracking and first repair of bridge decks for all systems. The time to first cracking is the summation of the time to corrosion initiation and the time to cracking after initiation. Table 23 shows the initiation time, the time to first cracking after initiation, the time to first repair after cracking concrete, and the expected life of a bridge deck for each system. Conventional reinforcement in concrete without any supplementary cementitious material has the lowest expected time to first repair of 18 years, which is within the range of 10 to 25 years predicted by the Kansas and South Dakota Departments of Transportation, KDOT and SDDOT, (Darwin et al. 2002). Decks containing ECR have an expected time to first repair of 58 years, compared to the 35 to 40 years estimated by KDOT and SDDOT (Darwin et al. 2002). In systems containing epoxy-coated MMFX bars, MMFX bars with 2% chromium had an expected life of 66 years, similar to that of conventional ECR; however, epoxy-coated MMFX bars with 4% chromium show an estimated life of 109 years–50% more than that for ECR.

Table 23: Time to first repair for corrosion protection systems based on corrosion rate in cracked concrete

System[a]	Time to initiation (yr)	Time from initiation to cracking (yr)	Time from cracking to repair (yr)	Expected time to first repair (yr)
Conv.	1.9	6.4	10	18
ECR	10.1	38.0	10	58
MMFX-ECR(2%)	8.9	47.3	10	66
MMFX-ECR(4%)	11.6	87.6	10	109

Cost Effectiveness

Based on the time to first repair shown in Table 23 and the costs of new construction and repair work in Kansas, Farshadfar et al. (2017) estimated the total cost over a 75-year design life for conventional and MMFX reinforcement, using a 150 ft (46 m) long, 36 ft (11 m) wide, 8.5 in. (216 mm) thick bridge deck. These results are summarized in Table 24. MMFX-ECR(4%), with an estimated time to first repair of 109 years, did not require repair over a 75-year design life. For all other systems, repairs were assumed to last 25 years, and a present value of 2% was assumed in calculating equivalent life cycle costs.

Conventional reinforcement had the highest life cycle cost, \$597.58/yd^2 of bridge deck. Of the coated bar systems, MMFX-ECR(4%) hade a life cycle cost of \$215.28, making it the most cost-effective system in this study. ECR and MMFX-ECR(2%) hade life-cycle costs of \$281.27 and \$289.11, respectively.

Table 24: Total costs over 75-year design life of a bridge deck for different corrosion protection systems

System	Initial cost $/yd^2 ($/m^2)	Repair cost with i = 2% $/yd^2 ($/m^2)	Total cost $/yd^2 ($/m^2)
Conv.	192.56 (229.86)	405.02 (484.08)	597.58 (713.94)
ECR	199.05 (238.31)	82.22 (98.26)	281.27 (336.58)
MMFX(4%)	209.44 (250.04)	254.38 (304.03)	463.81 (554.07)
MMFX(9%)	233.45 (278.76)	235.00 (280.87)	468.4 (559.64)
MMFX-ECR(2%)	210.09 (250.82)	79.03 (94.45)	289.11 (345.27)
MMFX-ECR(4%)	215.28 (257.02)	0	215.28 (257.02)

SUMMARY AND CONCLUSIONS

The corrosion resistance of coated ASTM A1035 Type CL (2% Cr) and CM (4% Cr) steel bars produced by MMFX Technologies was evaluated in both cracked and uncracked concrete as well as in the rapid macrocell test. Coated bars were evaluated after simulating damage typical to that which would occur during normal handling and placement at a construction site. A 75-year life-cycle cost analysis was also performed on the systems in this study.

The following conclusions are based on the results presented in this report:

1- The critical chloride corrosion threshold of epoxy-coated MMFX bars containing 2% and 4% chromium were 4.11 lb/yd^3 (2.44 kg/m^3) and 5.16 lb/yd^3 (3.06 kg/m^3), respectively, comparable to that of conventional epoxy-coated reinforcement [4.59 lb/yd^3 (2.72 kg/m^3)].

2- Epoxy-coated MMFX bars containing 4% chromium had greater corrosion resistance than MMFX-ECR(2%) and conventional epoxy-coated bars. The average total corrosion rate of MMFX-ECR(4%) reinforcement ranged from 30% to 60% of that for MMFX reinforcement with 2% chromium, and from 15% to 30% of that for epoxy-coated conventional steel. The disbonded area of the epoxy layer for MMFX bars containing 4% chromium was half to two-thirds of that for conventional epoxy-coated bars and 50% to 80% of that for MMFX bars containing 2% chromium.

3- Epoxy-coated MMFX bars containing 2% chromium did not show significantly better performance against corrosion compared to conventional epoxy-coated bars.

4- Over a 75-year design life, epoxy-coated MMFX bars containing 4% chromium have a greater corrosion resistance and are more cost effective than MMFX-ECR(2%) and conventional epoxy-coated bars.

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APPENDIX A

SUPPLEMENTARY DATA

Table A.1: Critical chloride threshold for beam specimens with MMFX epoxy-coated bars containing 2% chromium

Specimen	Chloride Content (lb/yd^3)[a]								Avg.	Std. Dev.
	1	2	3	4	5	6	7	8		
MMFX-ECR(2%)-1	8.24	3.48	3.52	2.63	4.00	4.75	-	-	4.44	1.99
MMFX-ECR(2%)-2	2.72	2.18	5.72	8.09	9.96	5.37	3.83	-	5.41	2.83
MMFX-ECR(2%)-3	2.33	4.49	7.27	3.15	3.99	2.39	-	-	3.93	2.06
MMFX-ECR(2%)-4	2.43	4.01	2.68	4.31	4.83	4.04	7.41	4.34	4.26	1.52
MMFX-ECR(2%)-5	9.14	2.07	1.76	6.00	1.59	1.59	-	-	3.69	3.17
MMFX-ECR(2%)-6	2.57	2.94	1.69	6.33	1.04	3.20	-	-	2.96	1.84
									4.11	**1.94**

[a] 1 (lb/yd^3) = 0.592 (kg/m^3)

Table A.2: Critical chloride threshold for beam specimens with MMFX epoxy-coated bars containing 4% chromium

Specimen	Chloride Content (lb/yd^3)[a]						Avg.	Std. Dev.
	1	2	3	4	5	6		
MMFX-ECR(4%)-1	5.33	5.12	9.05	5.23	3.18	2.76	5.11	2.23
MMFX-ECR(4%)-2	2.42	2.05	3.56	2.28	5.14	5.10	3.42	1.41
MMFX-ECR(4%)-3	8.92	5.65	5.30	7.00	7.79	5.34	6.67	1.49
MMFX-ECR(4%)-4	6.72	6.92	6.42	2.13	4.25	4.52	5.16	1.88
MMFX-ECR(4%)-5	6.42	3.69	4.54	2.77	3.12	4.37	4.15	1.31
MMFX-ECR(4%)-6	8.52	7.15	6.12	7.17	4.00	5.56	6.42	1.56
							5.16	**1.66**

[a] 1 (lb/yd^3) = 0.592 (kg/m^3)

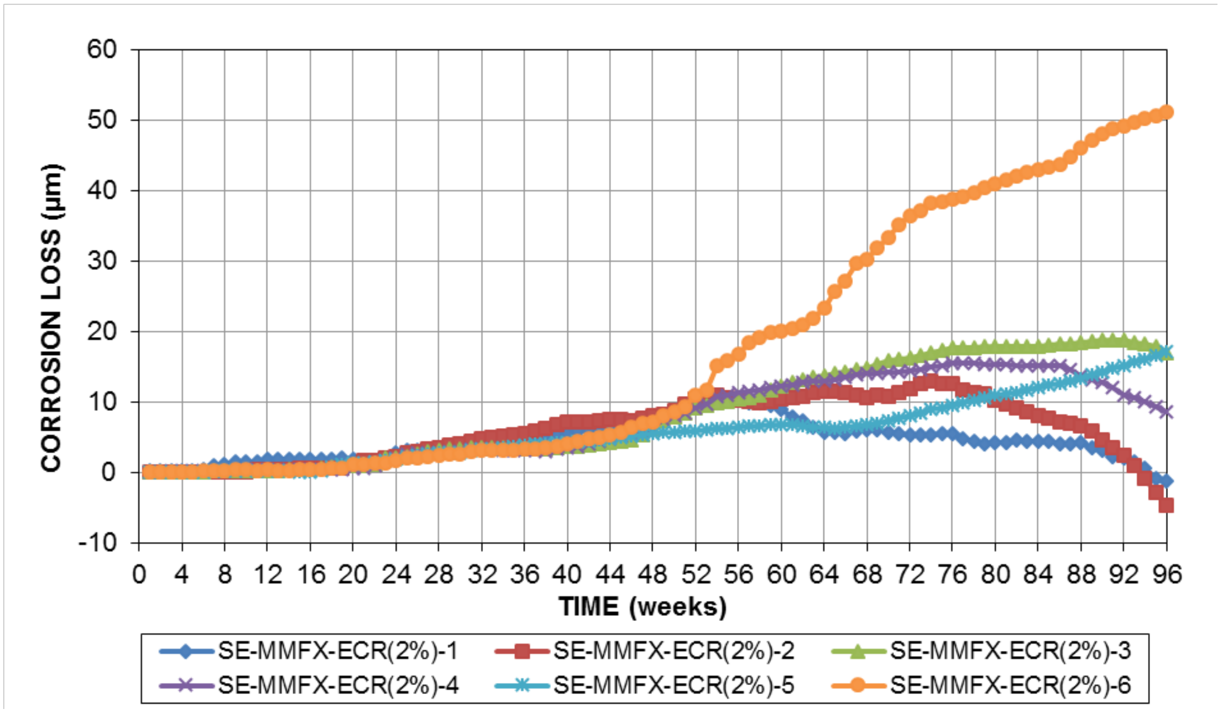

Figure A.1— Macrocell corrosion losses (µm) based on exposed area of reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

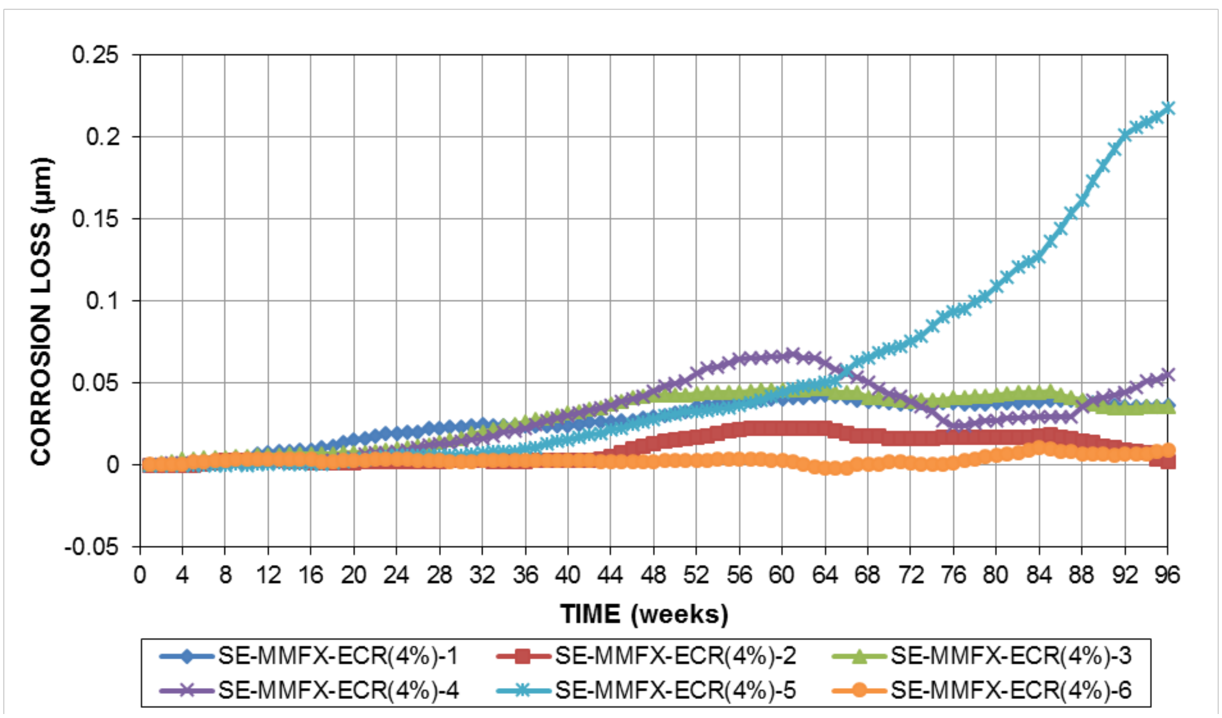

Figure A.2— Macrocell corrosion losses (µm) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

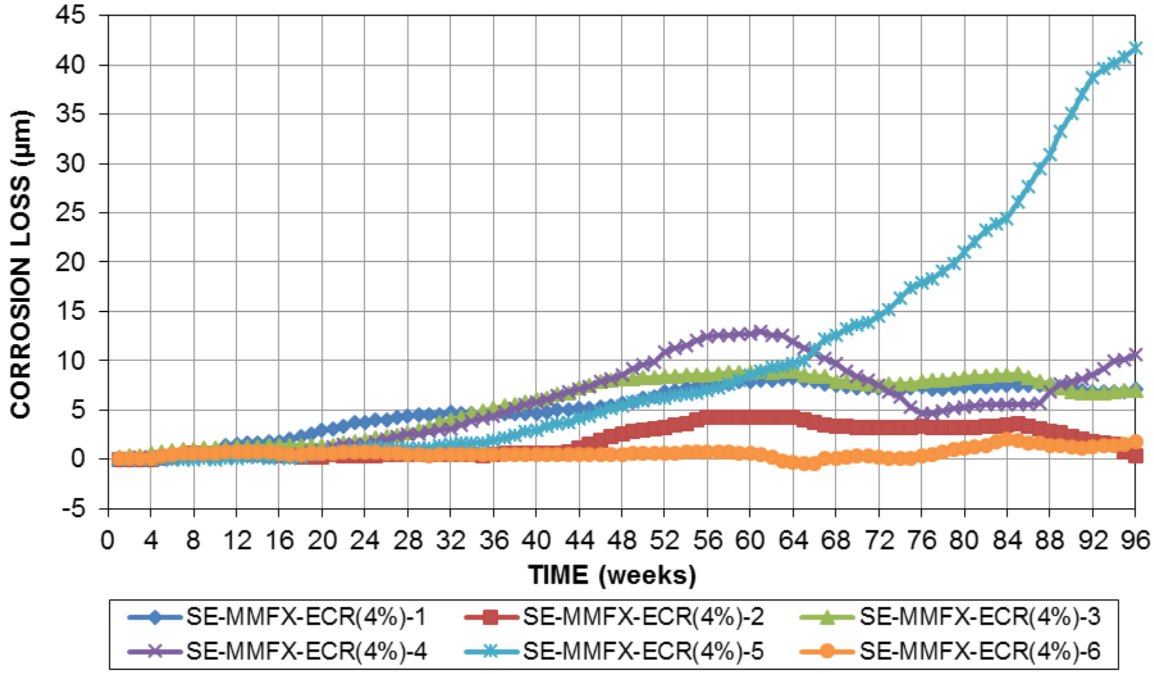

Figure A.3— Macrocell corrosion losses (µm) based on exposed area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

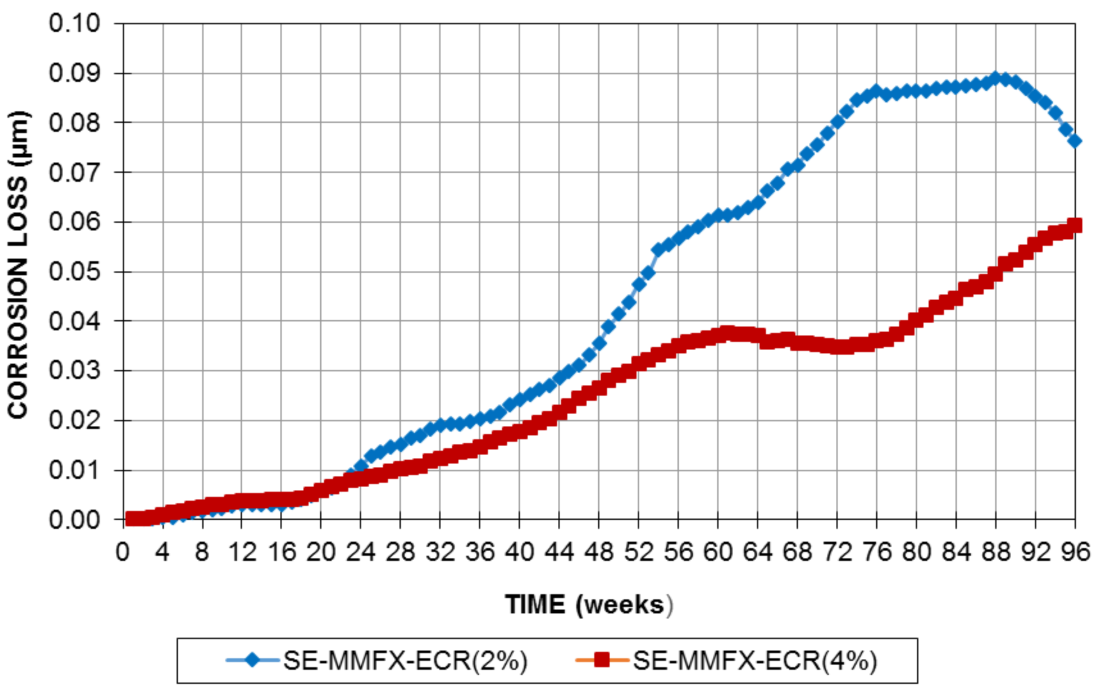

Figure A.4— Average corrosion loss (µm) based on total area versus time for Southern Exposure specimens with epoxy-coated reinforcement

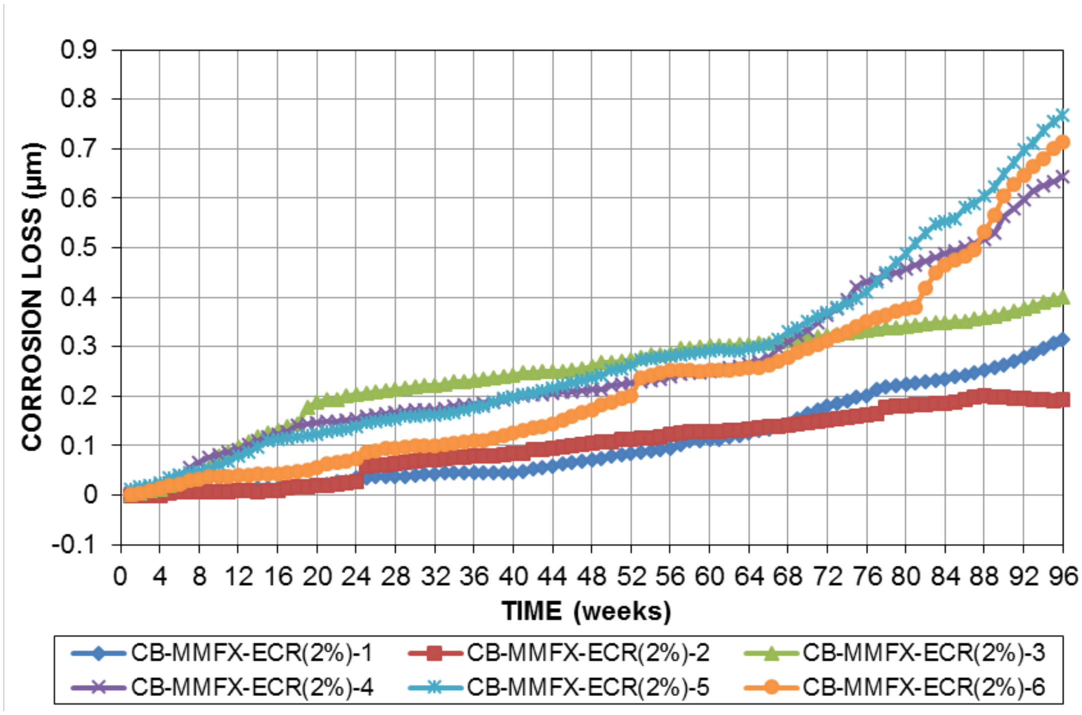

Figure A.5— Macrocell corrosion losses (µm) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

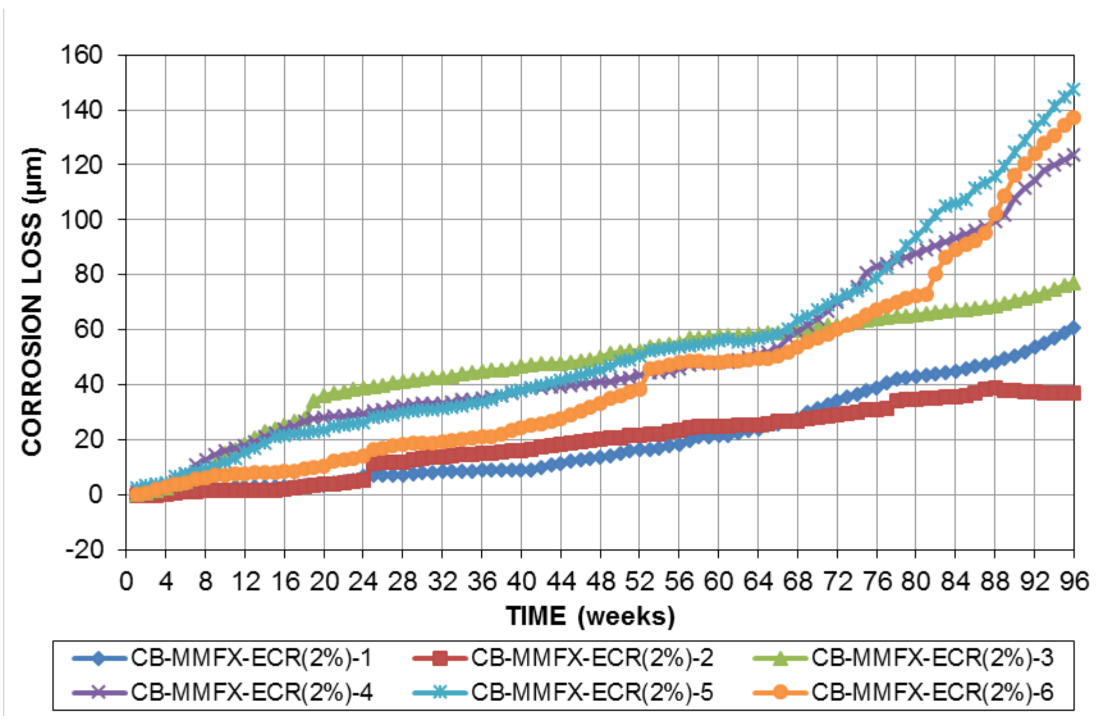

Figure A.6— Macrocell corrosion losses (µm) based on exposed area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

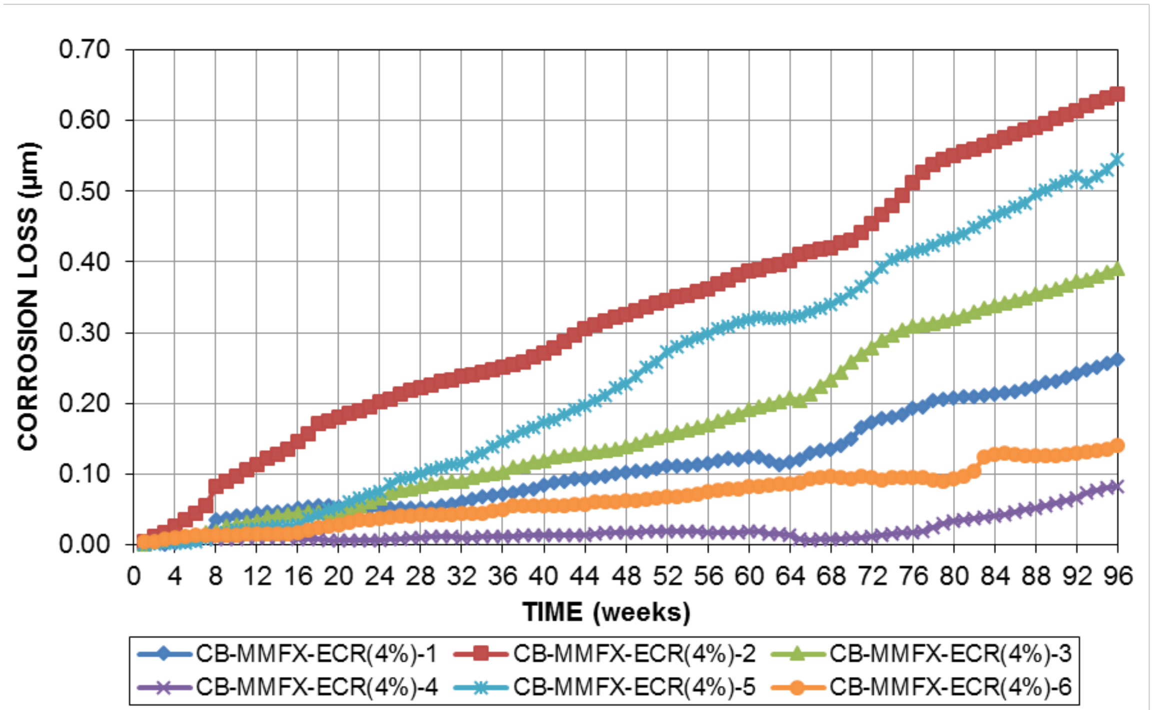

Figure A.7— Macrocell corrosion losses (μm) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(4%) bars

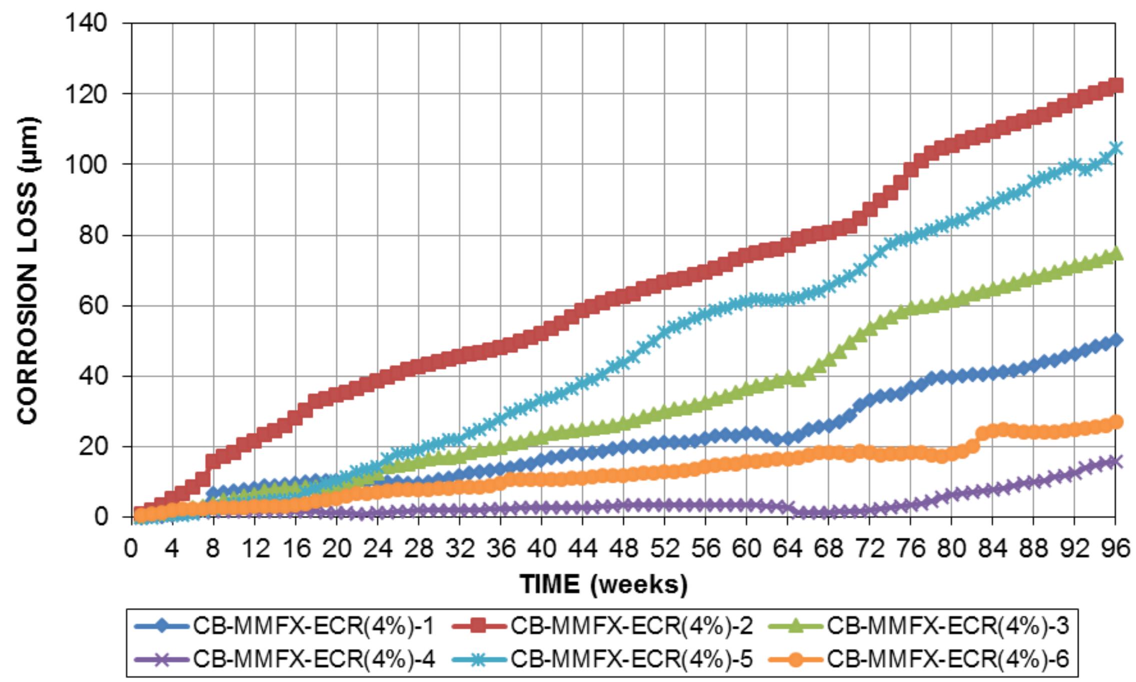

Figure A.8— Macrocell corrosion losses (μm) based on exposed area of reinforcement for cracked beam specimens containing MMFX-ECR(4%) bars

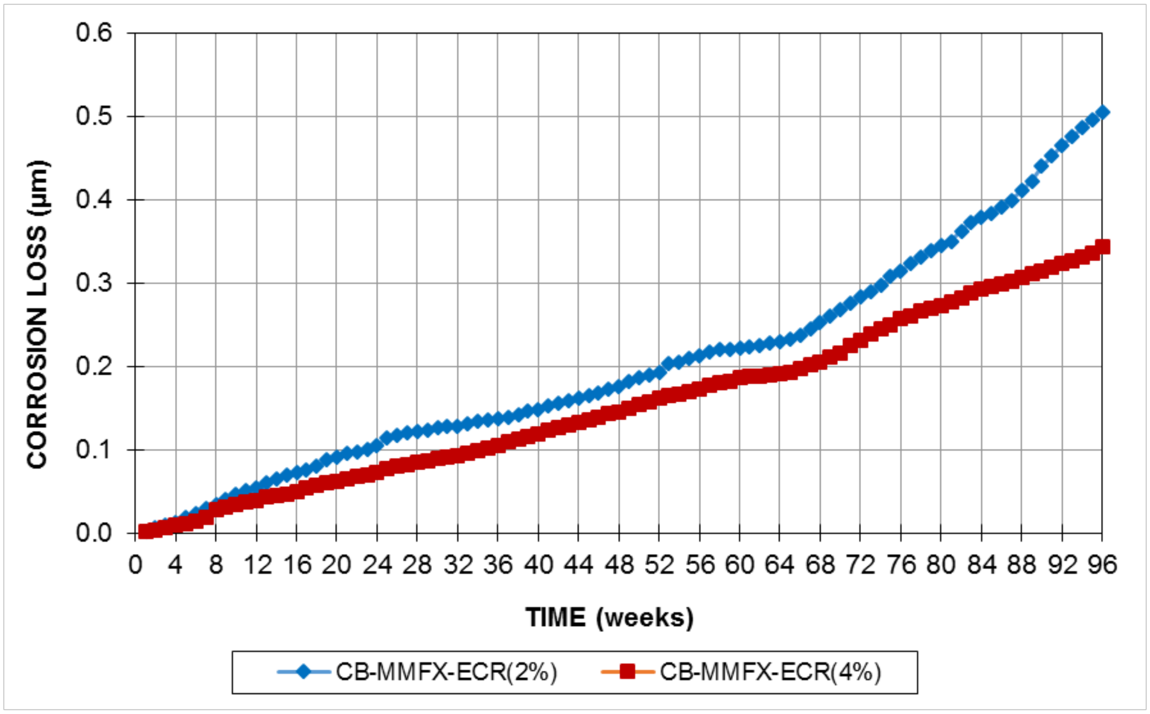

Figure A.9— Average corrosion loss (µm) based on total area versus time for cracked beam specimens with epoxy-coated reinforcement

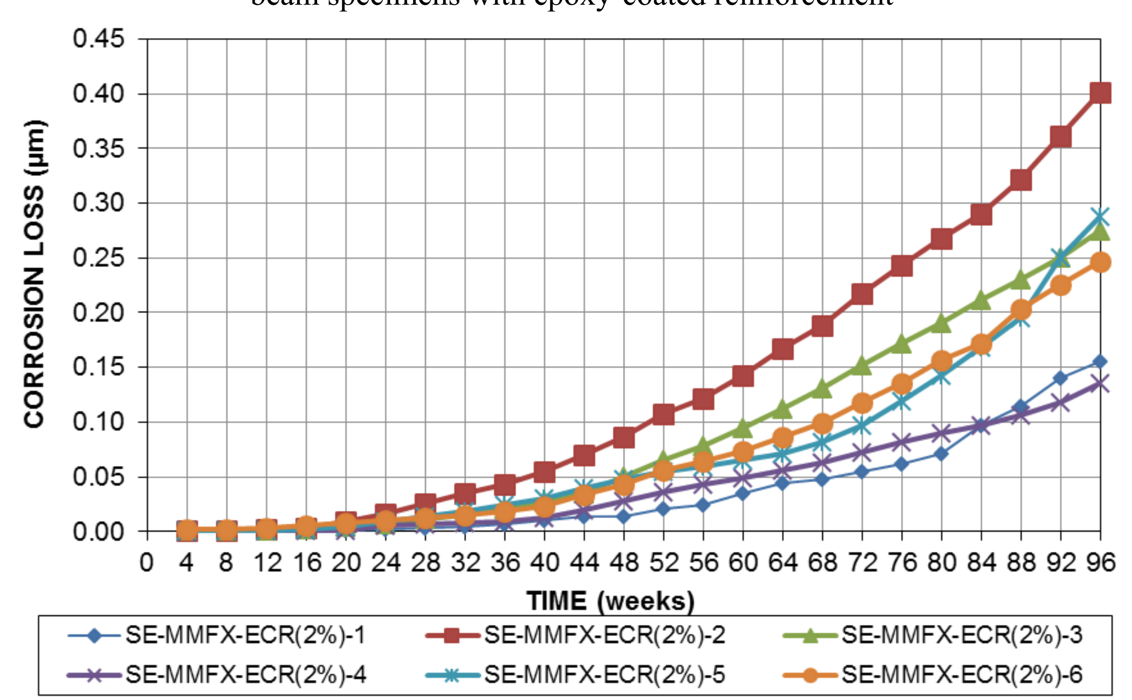

Figure A.10— LPR test corrosion losses (µm) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

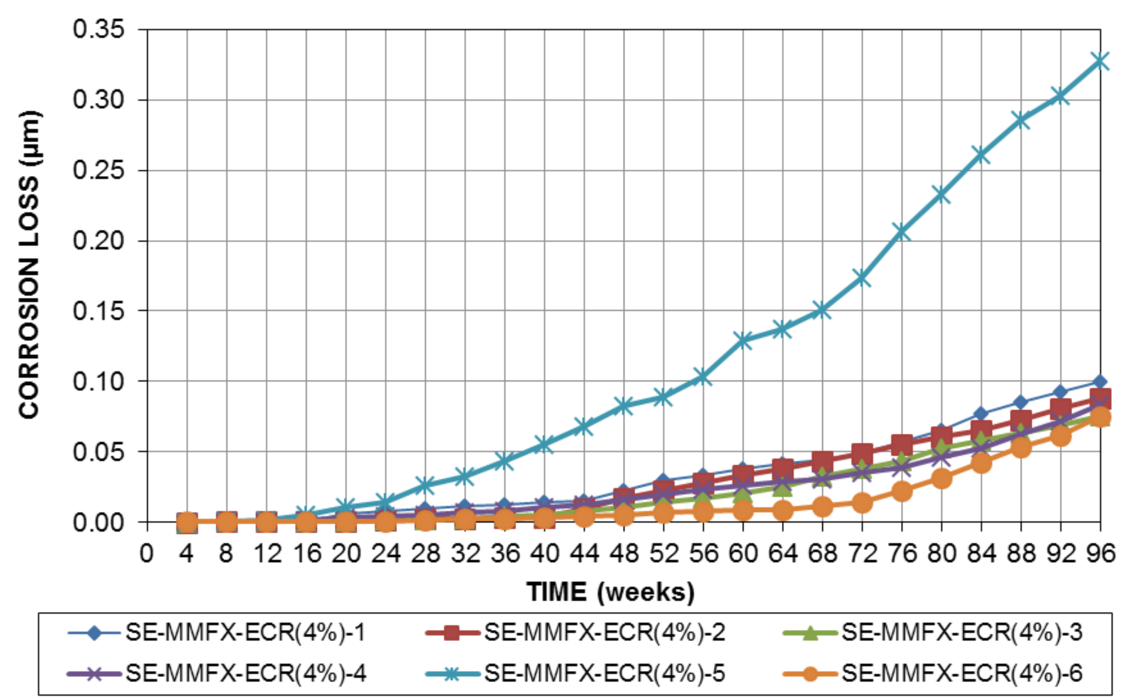

Figure A.11— LPR test corrosion losses (µm) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

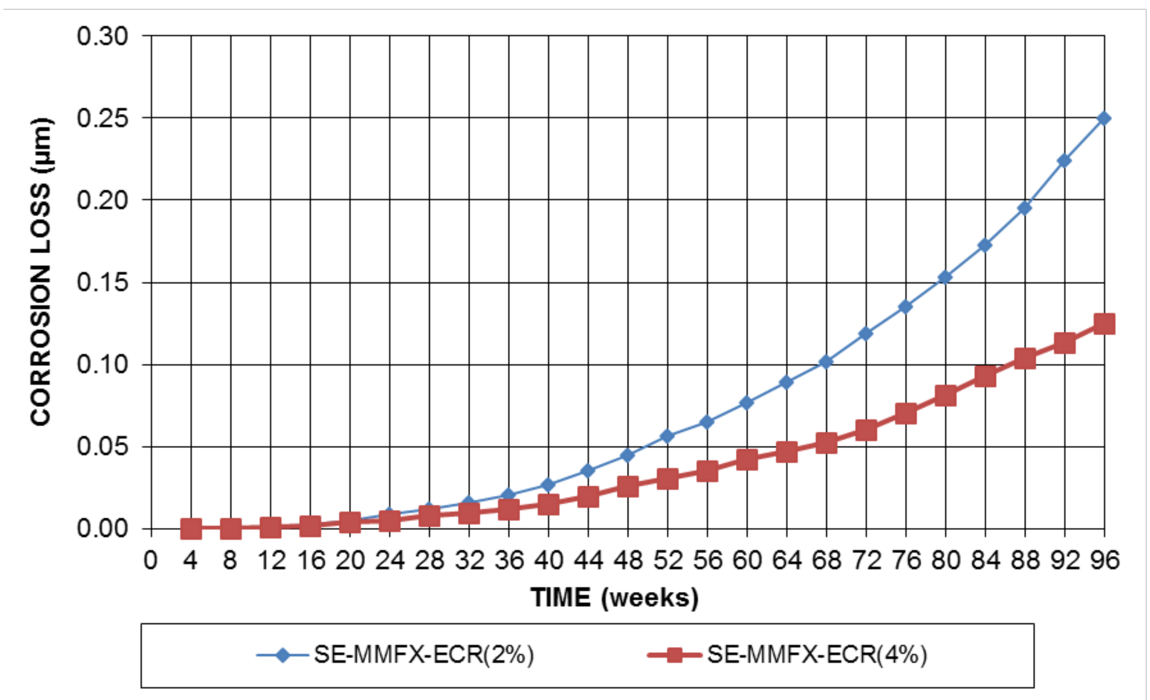

Figure A.12— Average LPR test corrosion loss (µm/yr) based on total area versus time for Southern Exposure specimens containing epoxy-coated reinforcement

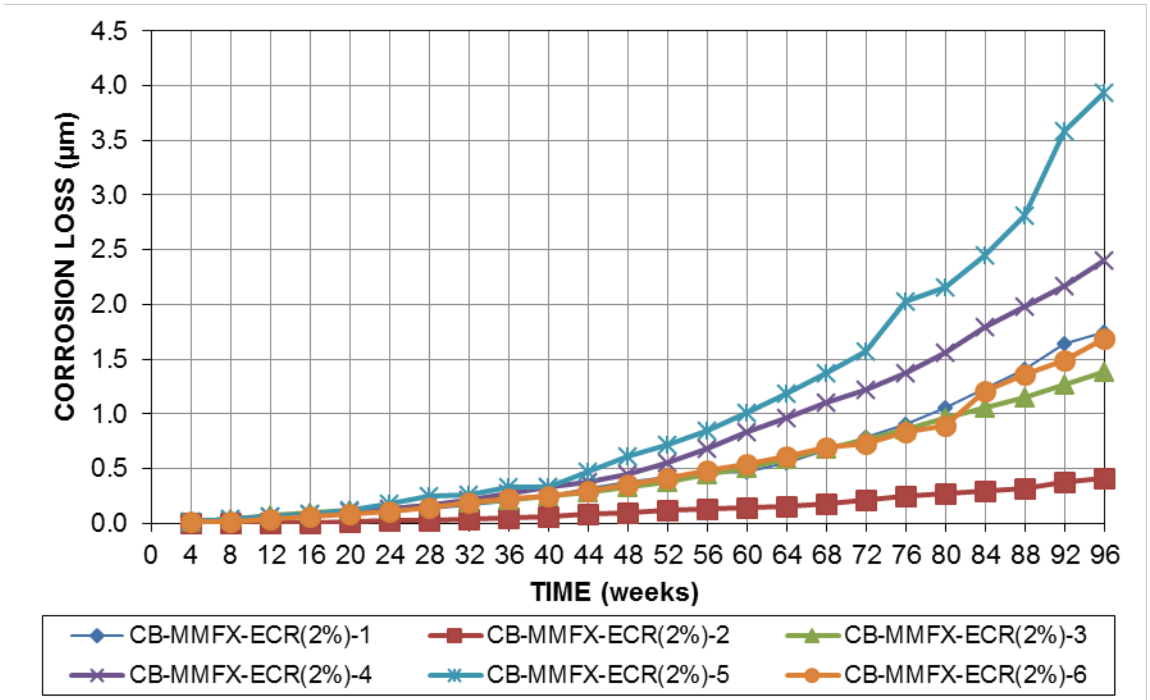

Figure A.13— LPR test corrosion losses (µm) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

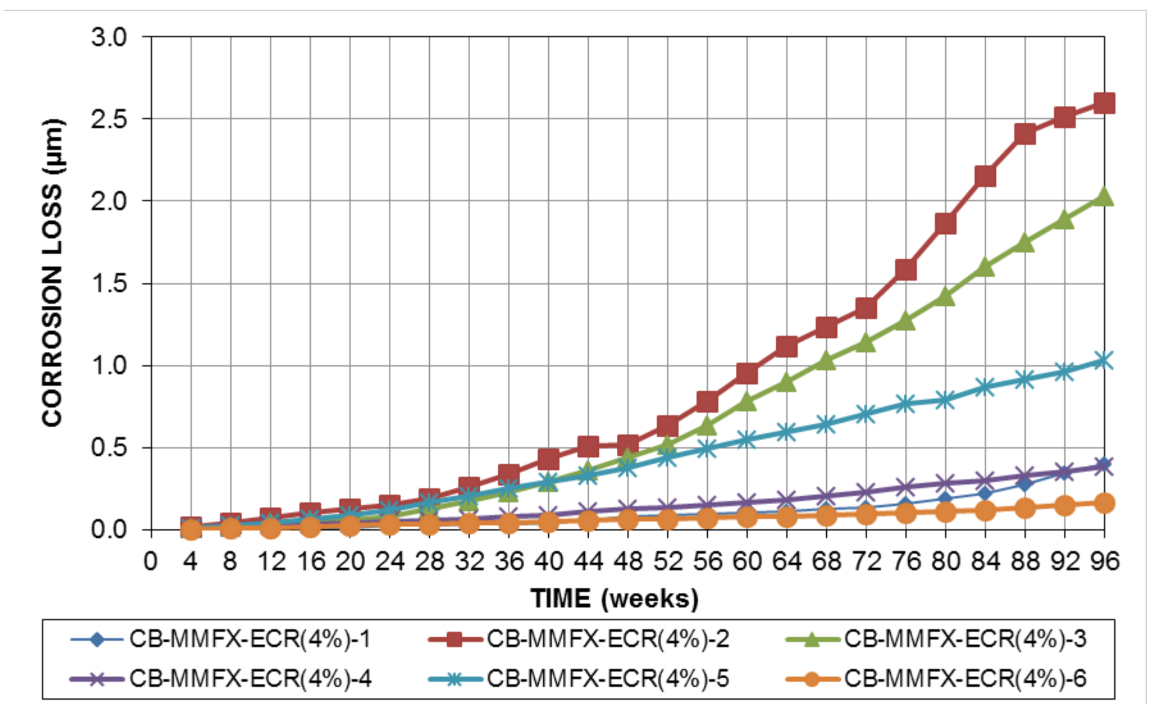

Figure A.14— LPR test corrosion losses (µm) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

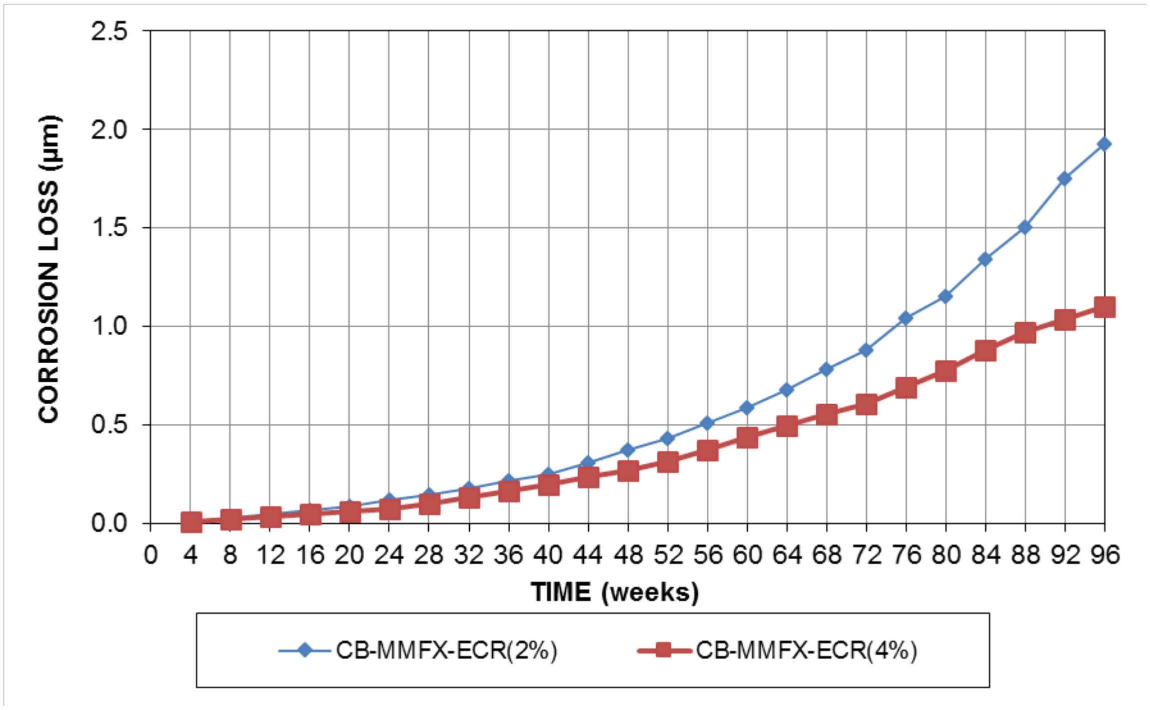

Figure A.15— Average LPR test corrosion loss (µm/yr) based on total area versus time for cracked beam specimens containing epoxy-coated reinforcement

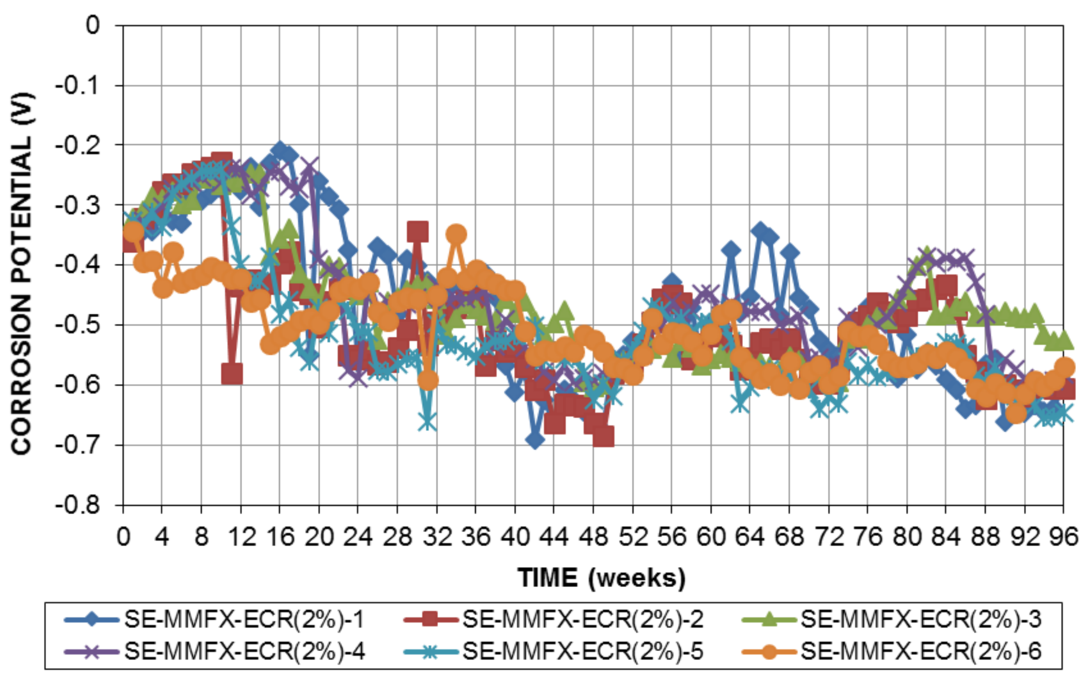

Figure A.16—Top mat (anode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX-ECR(2%) bars

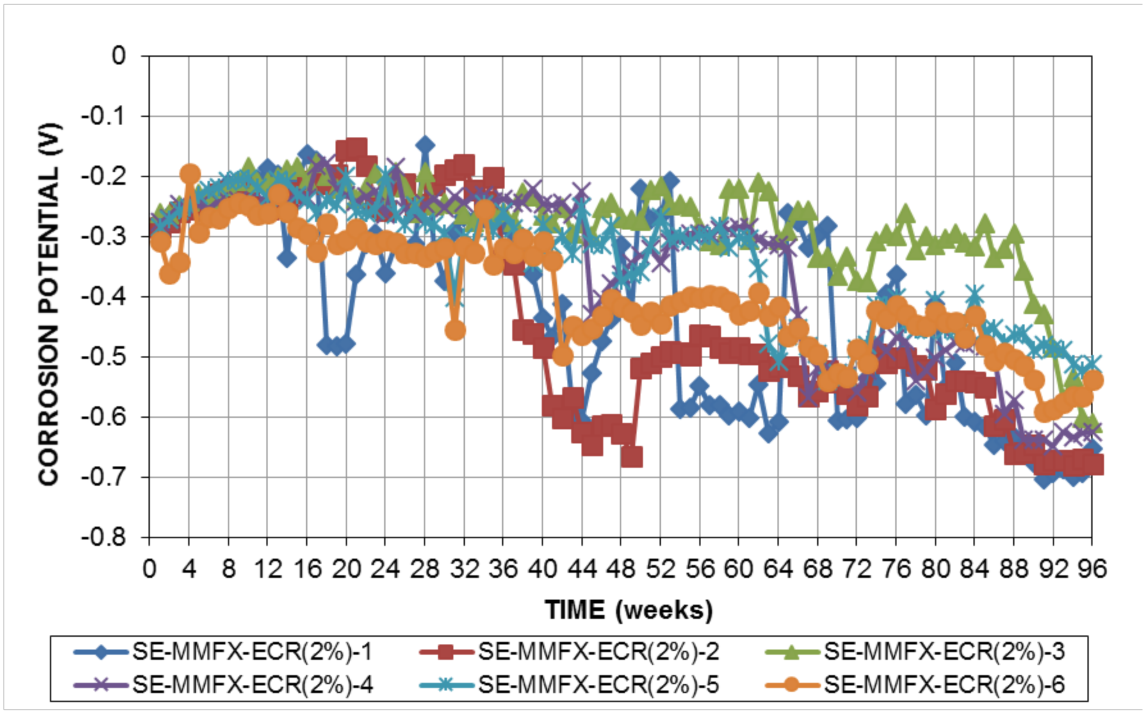

Figure A.17—Bottom mat (cathode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX-ECR(2%) bars

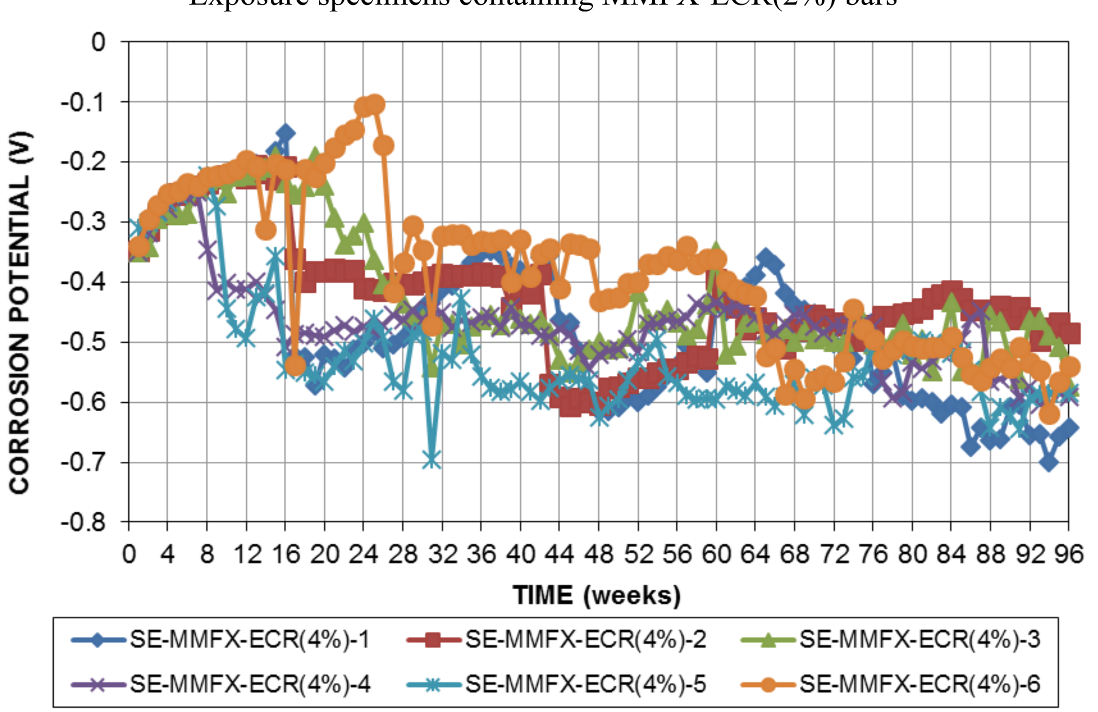

Figure A.18—Top mat (anode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX-ECR(4%) bars

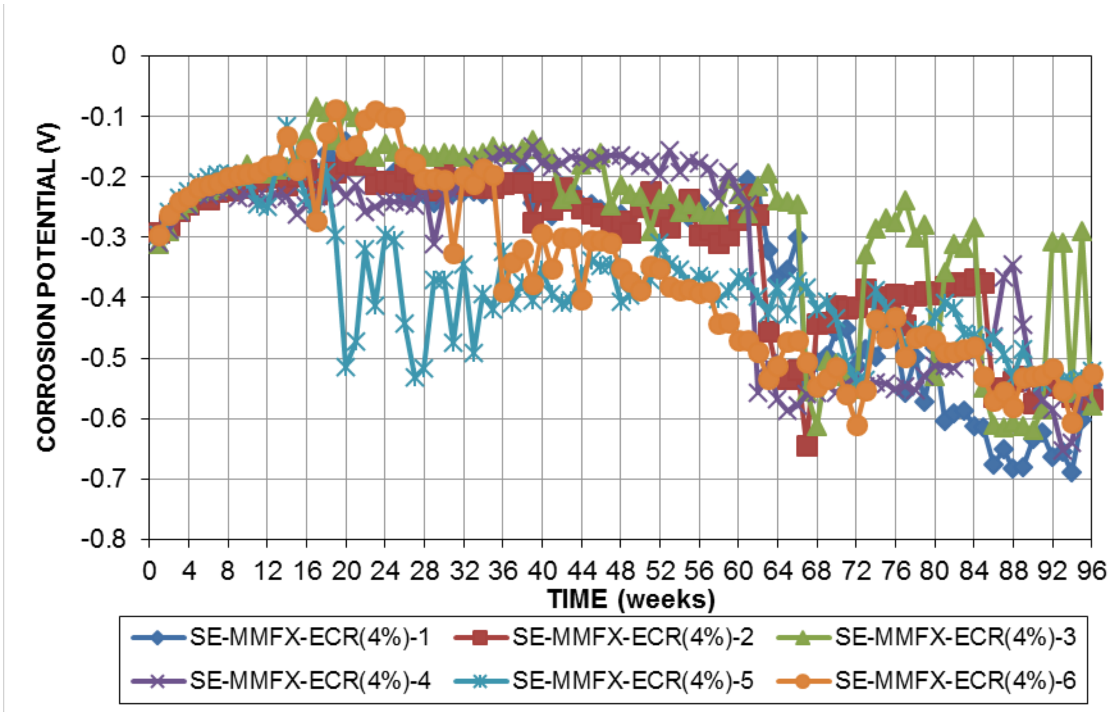

Figure A.19—Bottom mat (cathode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX-ECR(4%) bars

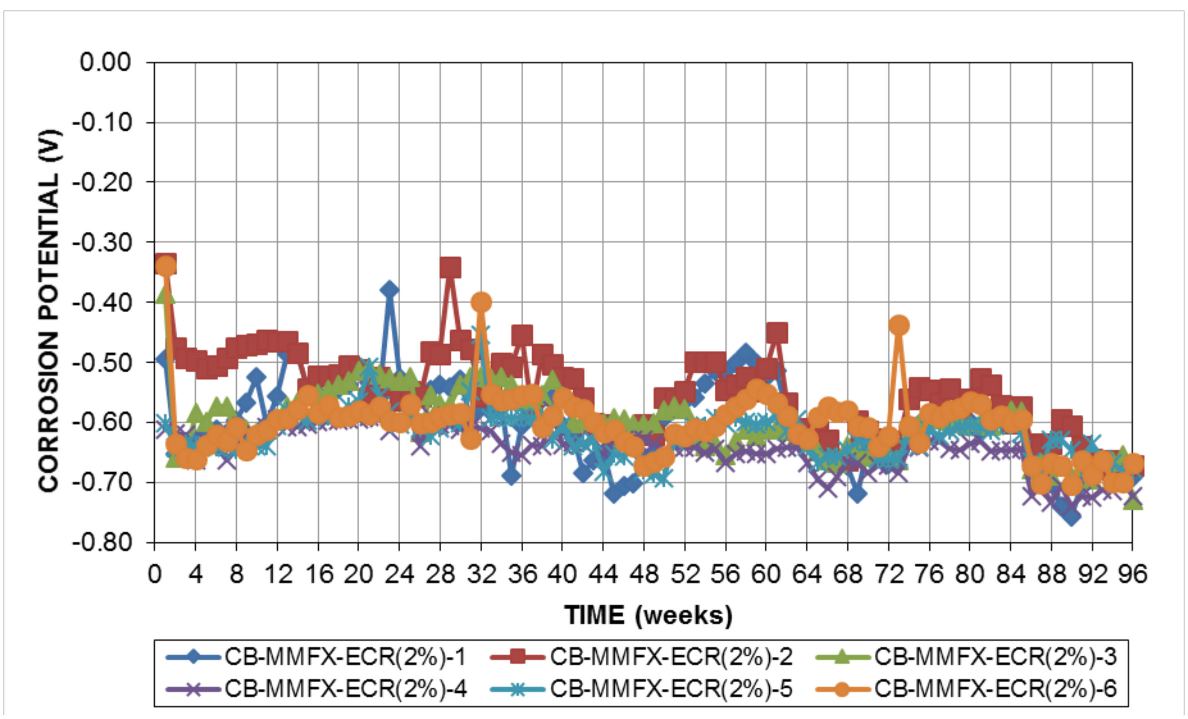

Figure A.20—Top mat (anode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX-ECR(2%) bars

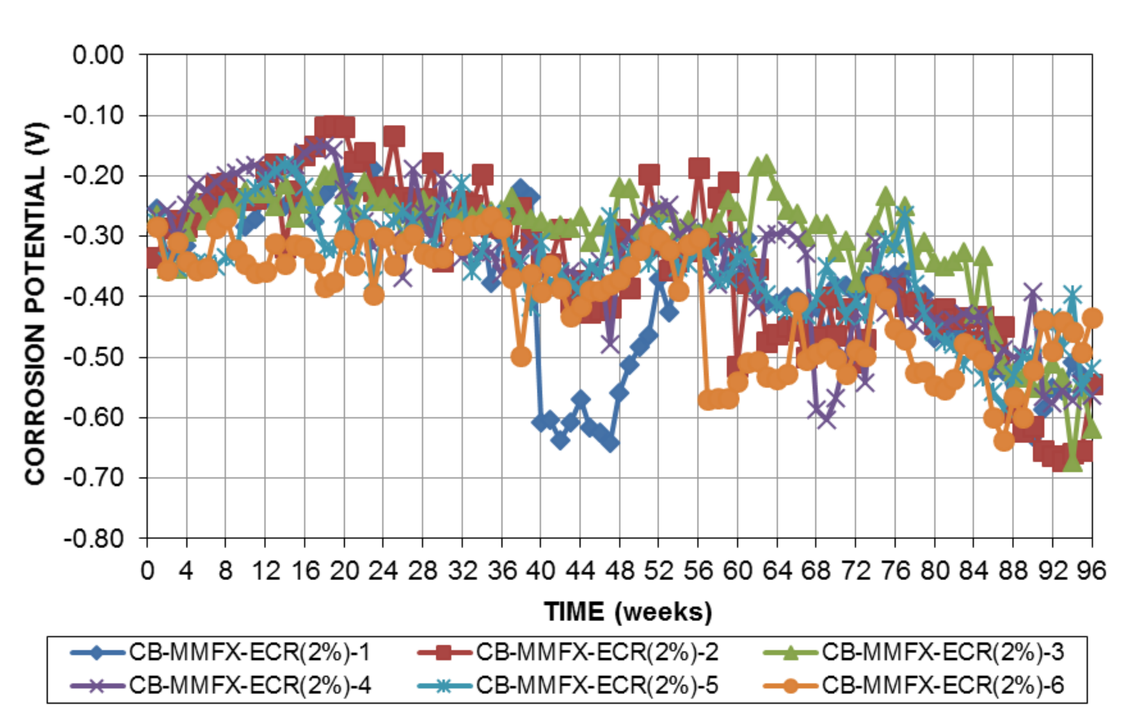

Figure A.21—Bottom mat (cathode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX-ECR(2%) bars

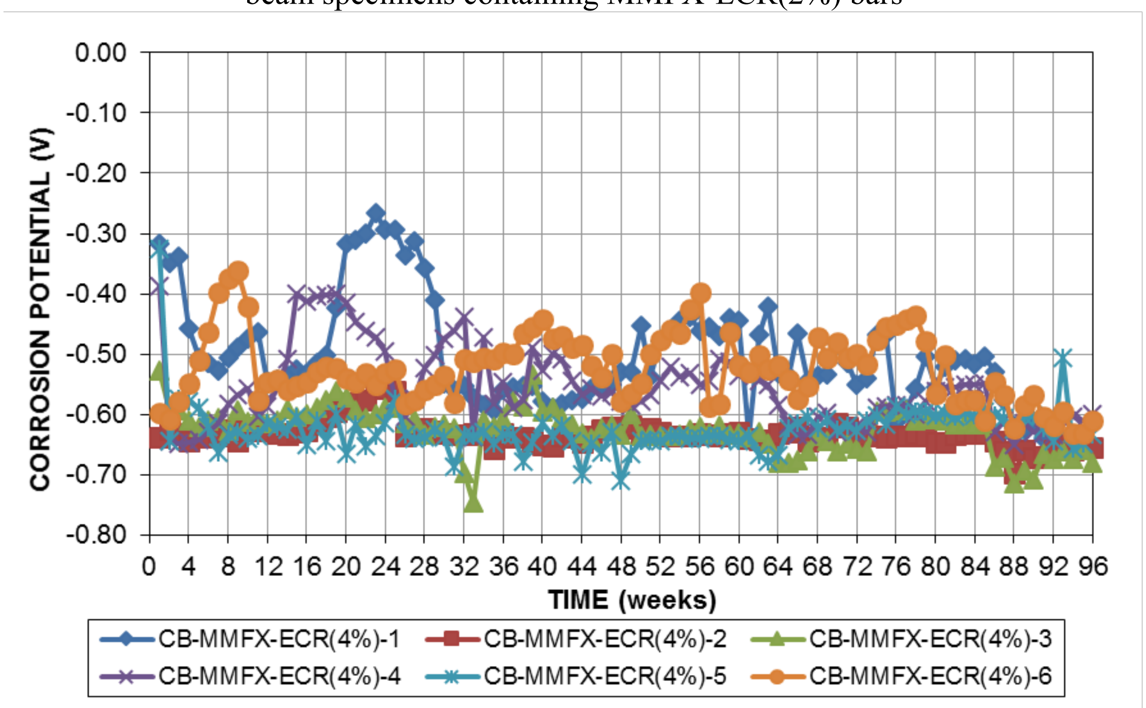

Figure A.22—Top mat (anode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX-ECR(4%) bars

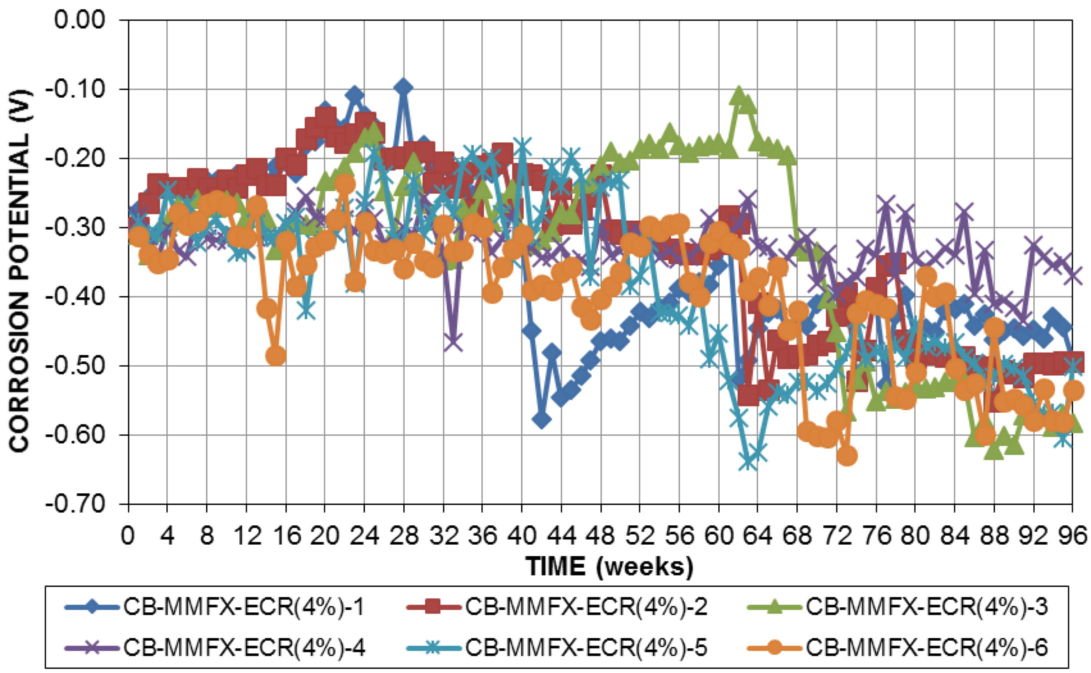

Figure A.23—Bottom mat (cathode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX-ECR(4%) bars

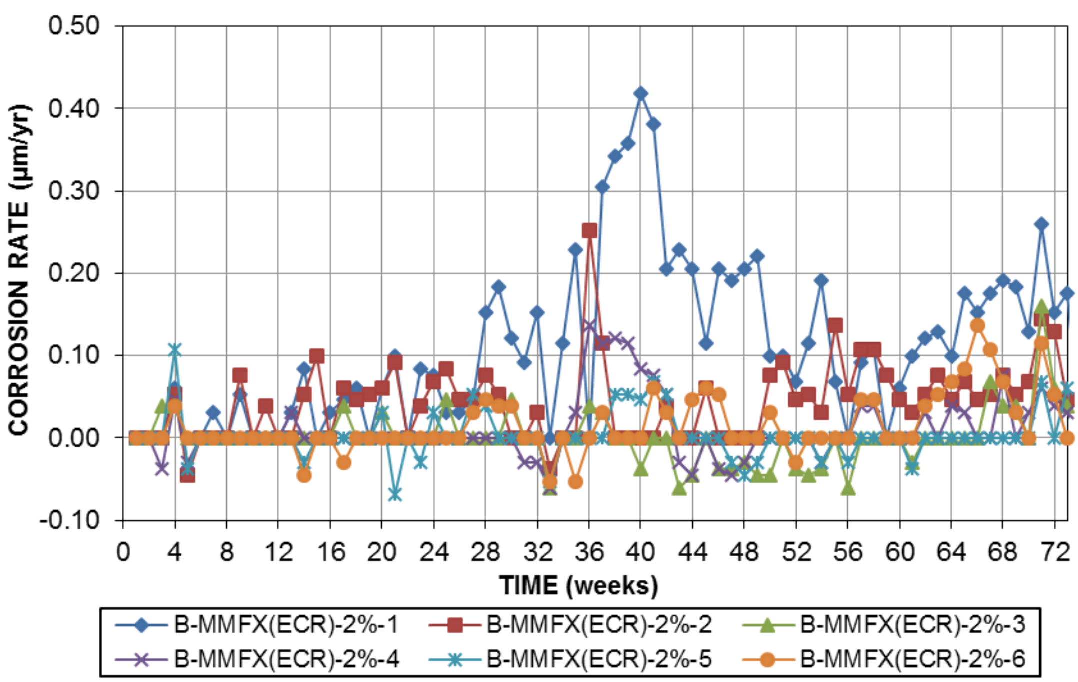

Figure A.24— Macrocell corrosion rates (µm) based on total area of reinforcement for beam specimens containing MMFX-ECR(2%) bars

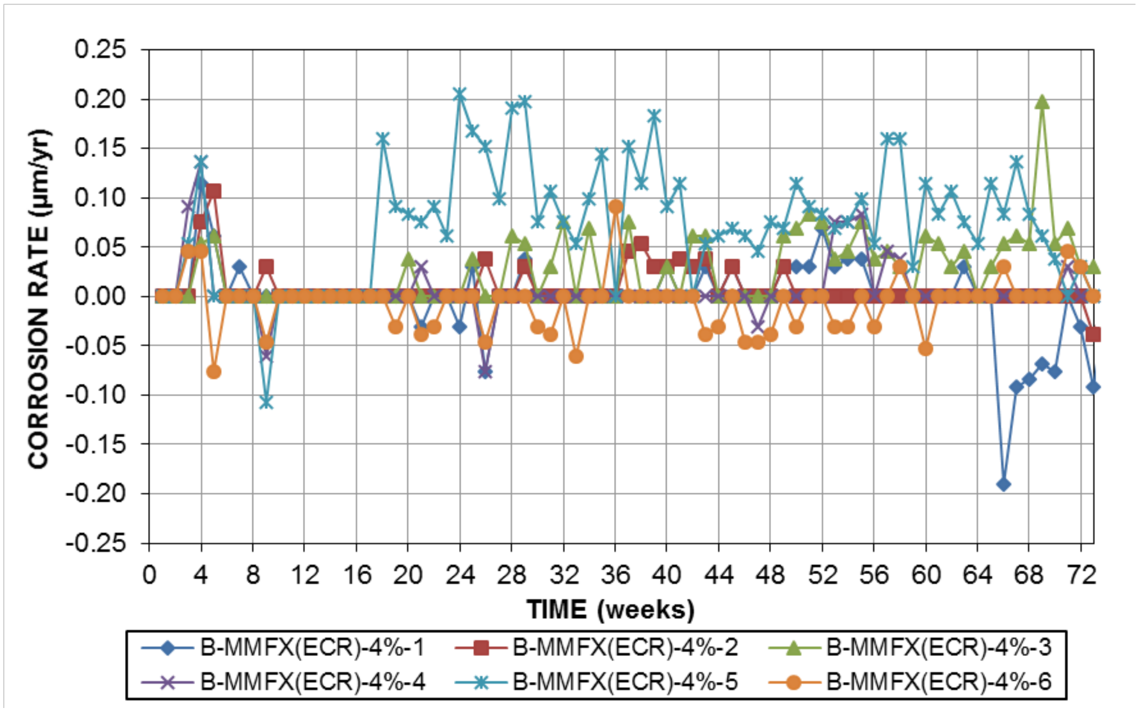

Figure A.25— Macrocell corrosion rates (µm) based on total area of reinforcement for beam specimens containing MMFX-ECR(4%) bars

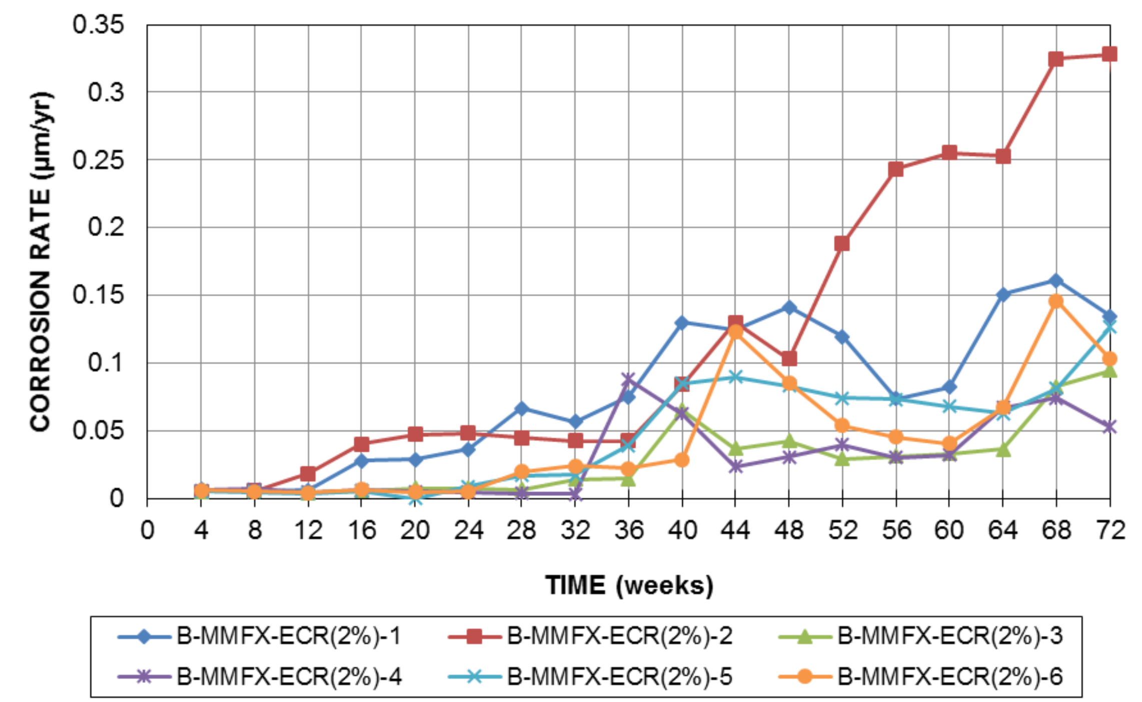

Figure A.26— LPR test corrosion rates (µm) based on total area of reinforcement for beam specimens containing MMFX-ECR(2%) bars

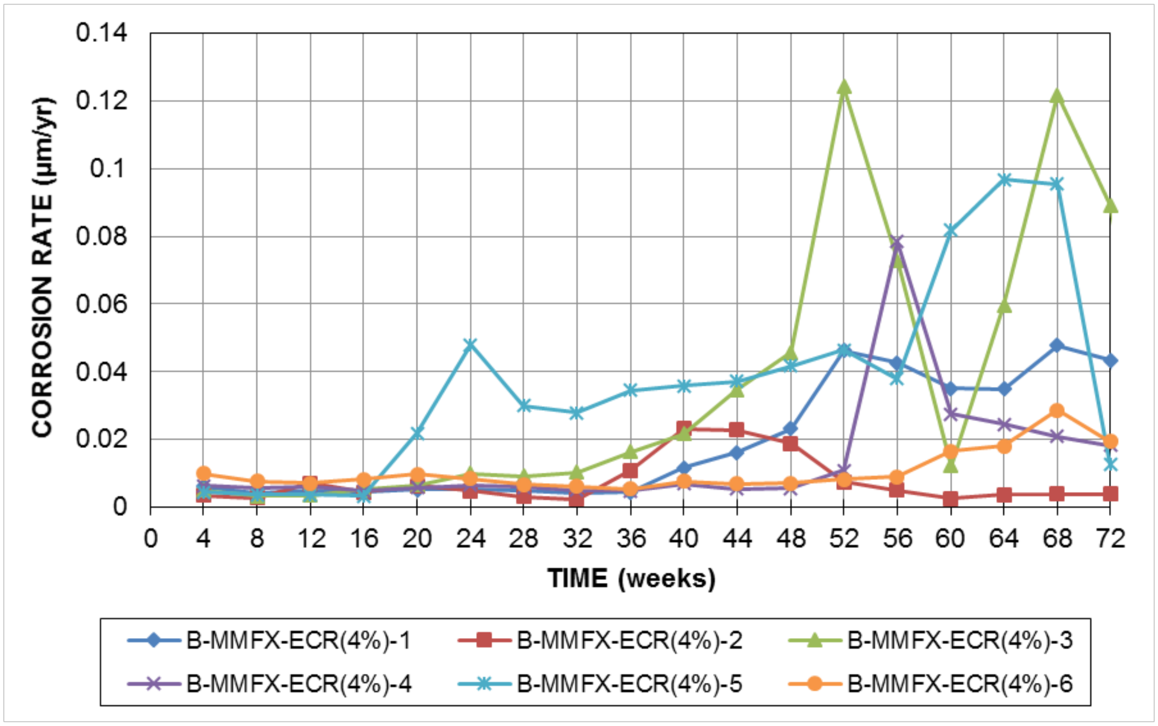

Figure A.27— LPR test corrosion rates (µm) based on total area of reinforcement for beam specimens containing MMFX-ECR(4%) bars

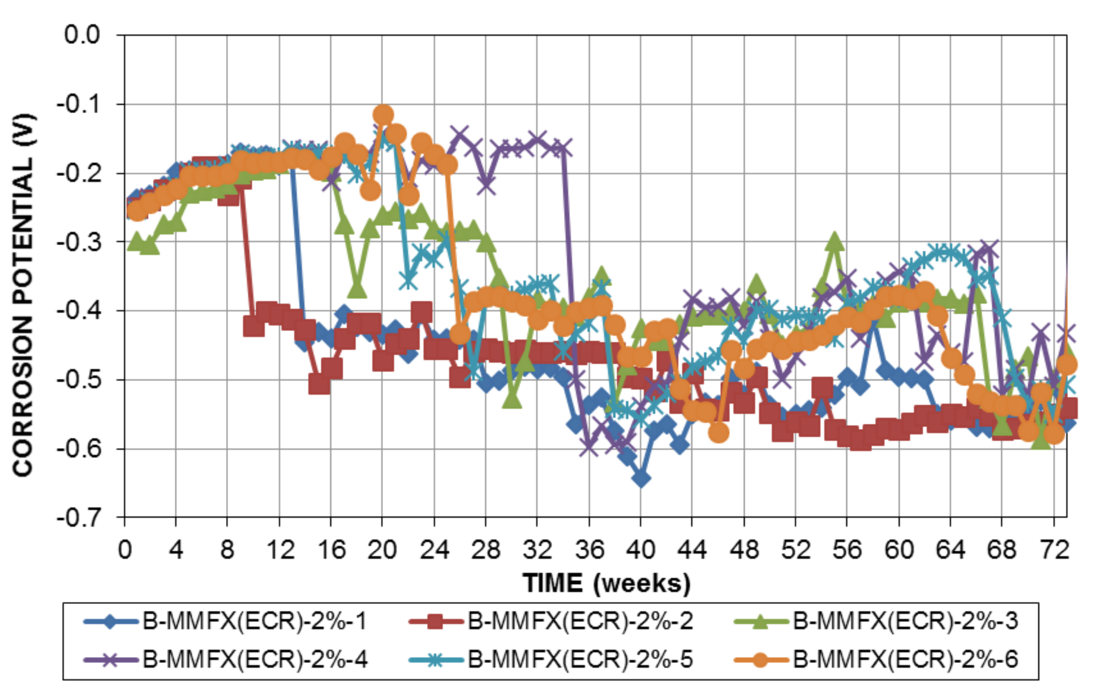

Figure A.28—Top mat (anode) corrosion potential (CSE) versus time for beam specimens containing MMFX-ECR(2%) bars

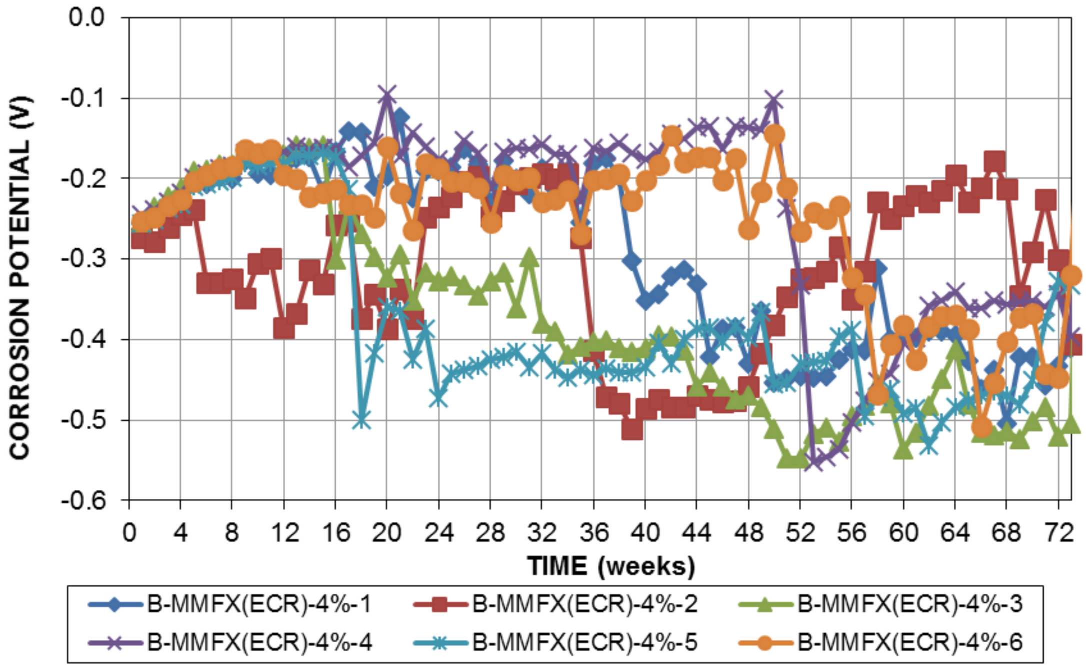

Figure A.29—Top mat (anode) corrosion potential (CSE) versus time for beam specimens containing MMFX-ECR(4%) bars

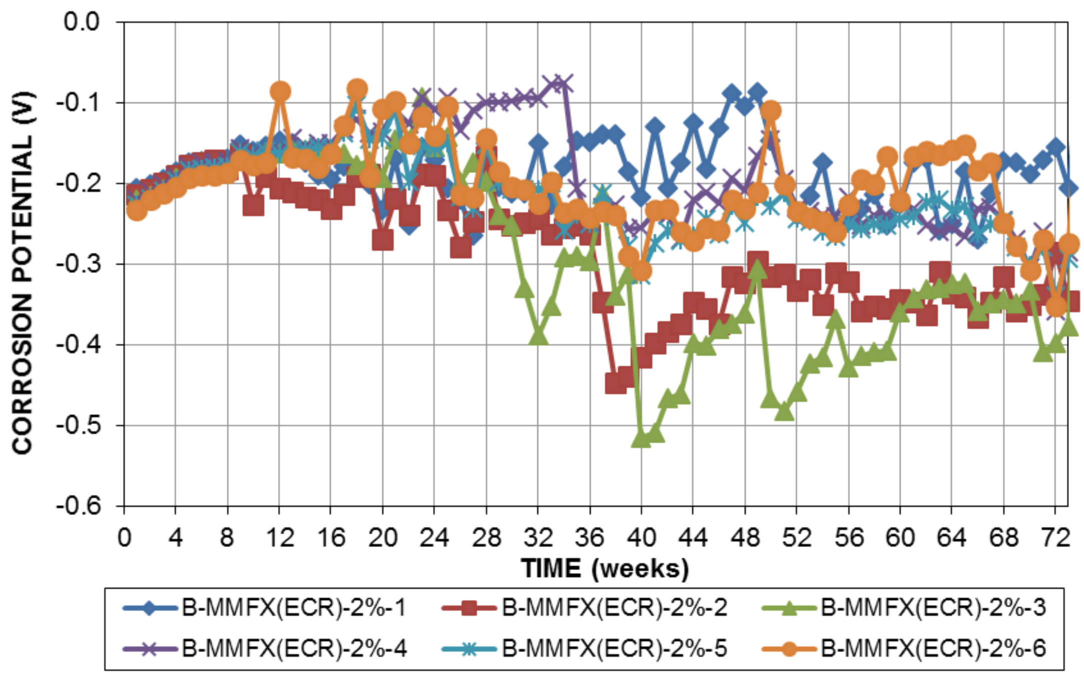

Figure A.30—Bottom mat (cathode) corrosion potential (CSE) versus time for beam specimens containing MMFX-ECR(2%) bars

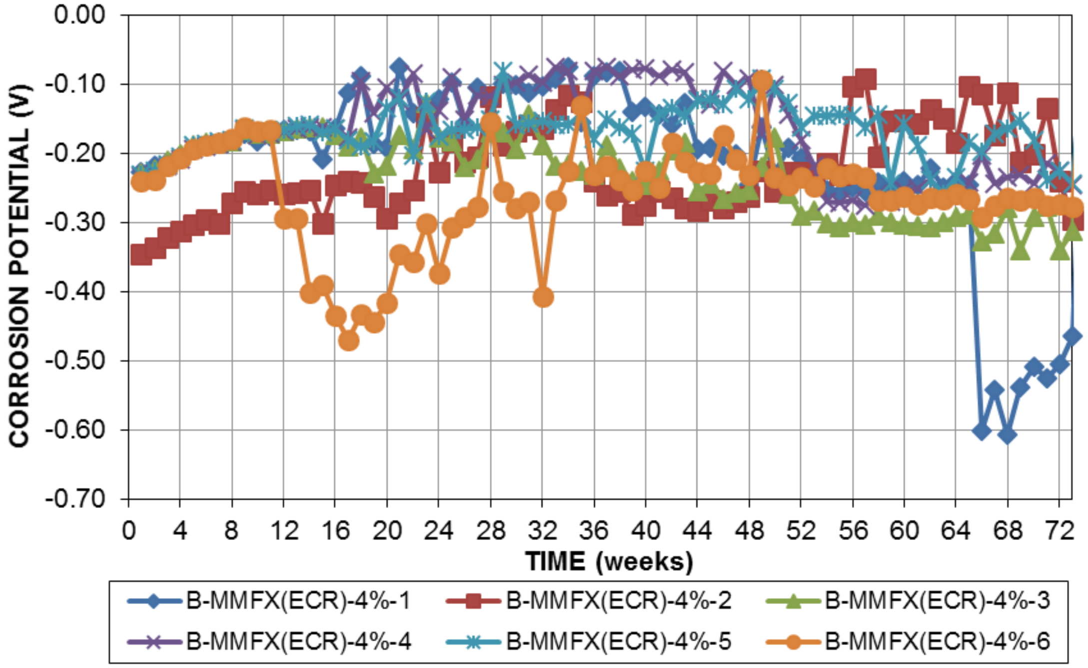

Figure A.31—Bottom mat (cathode) corrosion potential (CSE) versus time for beam specimens containing MMFX-ECR(4%) bars