

CORROSION PERFORMANCE OF PLAIN AND EPOXY-COATED MMFX BARS

By
Omid Farshadfar
Matthew O'Reilly
David Darwin

A Report on Research Sponsored by
MMFX Technologies, Inc.

Structural Engineering and Engineering Materials
SL Report 18-4
October 2018



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 ASTM A1035 Type CL (2% Cr), CM (4% Cr), and CS (9% Cr) steel bars produced by MMFX Technologies were evaluated in both cracked and uncracked concrete as well as in the rapid macrocell test. Uncoated bars with 4% and 9% chromium were tested both in the condition received and after pickling at the University of Kansas; coated bars with 2% and 4% chromium were also 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 conventional (ASTM A615) and epoxy-coated (ASTM A775) reinforcement from previous studies, and a life-cycle cost analysis over a 75-year design life was performed.

The uncoated MMFX bars with 4% and 9% chromium exhibited approximately three times the chloride threshold and between 30-66% of the corrosion rate of uncoated conventional reinforcement, with the 9% chromium bars exhibiting better performance than the 4% chromium bars. Pickling of 9% chromium bars significantly improved its corrosion resistance, while pickling the 4% chromium bars provided only mild benefit. 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

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INTRODUCTION

This report describes the results of corrosion resistance testing of ASTM A1035 Type CS (9% Cr), CM (4% Cr), and CL (2% Cr) bare and 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

Four types of bars were tested in this study: uncoated MMFX bars containing 9% and 4% chromium (ASTM A1035 type CS and CM, respectively) and 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(9%)	0.072	0.244	0.82	0.023	0.0028	9.46	0.129	0.078	0.019	0.02	110
MMFX(4%)	0.143	0.243	0.66	0.02	0.0028	4.05	0.073	0.081	0.011	0.0093	110
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.

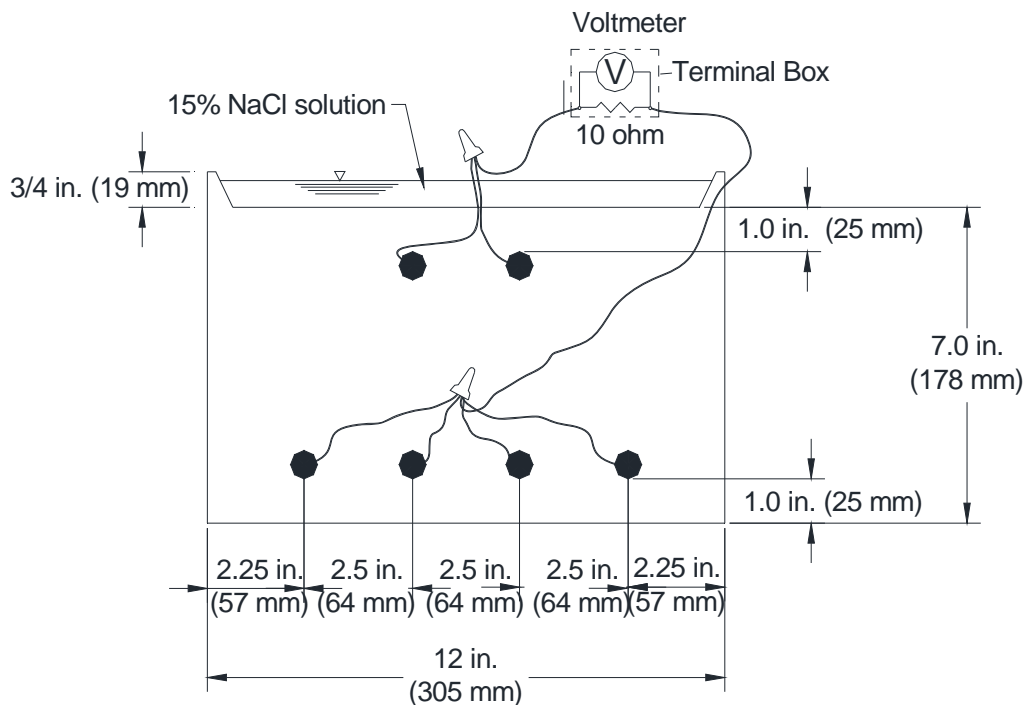


Figure 1– Southern Exposure (SE) specimen

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 was 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.

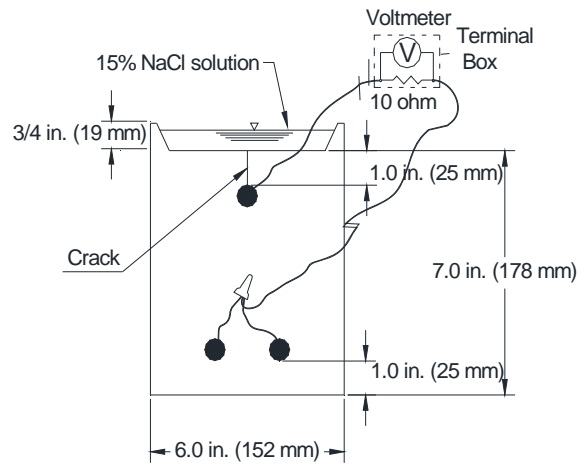


Figure 2— Cracked beam (CB) specimens

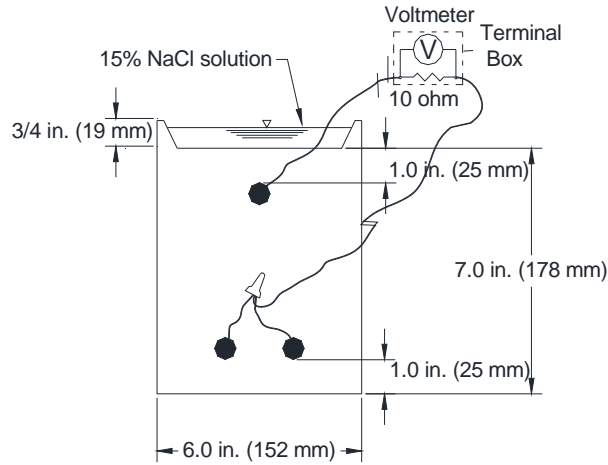


Figure 3— Beam (B) specimens

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.

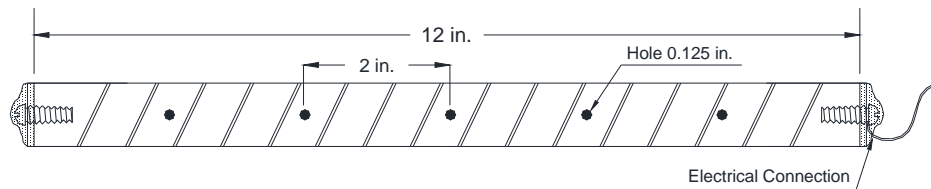


Figure 4— Damage pattern of epoxy-coated bar (plan view) in bench-scale tests

Epoxy-coated bars are rinsed with soapy water and uncoated bars are submerged in acetone for at least two hours 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 was 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 $0.3 \mu\text{m}/\text{yr}$ 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.”

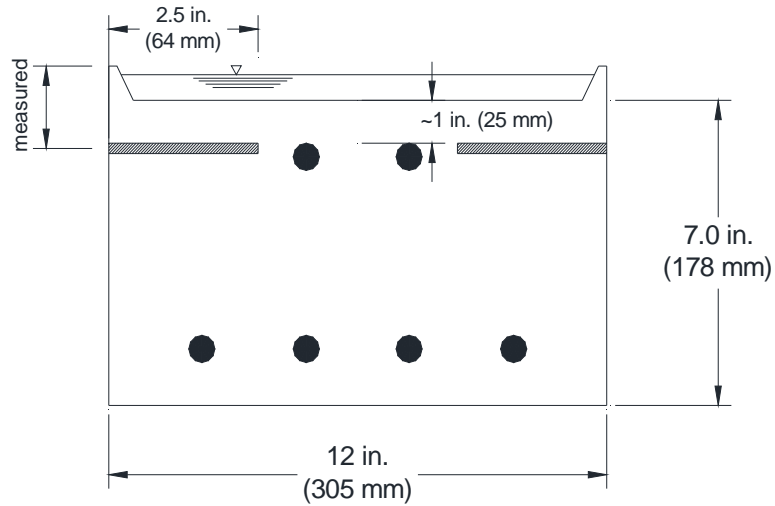


Figure 5— Southern Exposure specimen chloride sampling

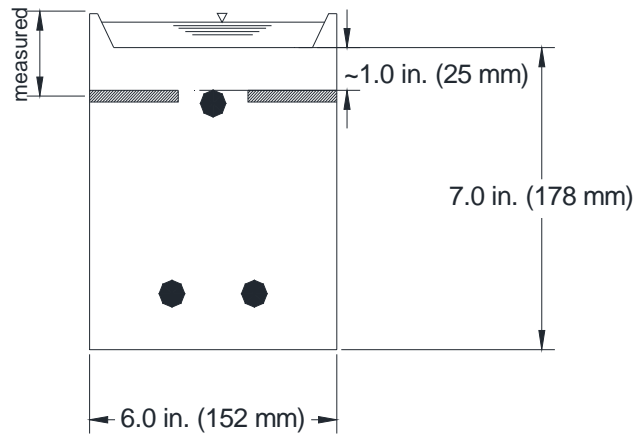


Figure 6— Beam specimen chloride sampling

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 mm²)) 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 CO₂, 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.

For this test method, one set of six specimens was tested for each uncoated bar type in both the as-received and pickled condition, as well as each coated bar type.

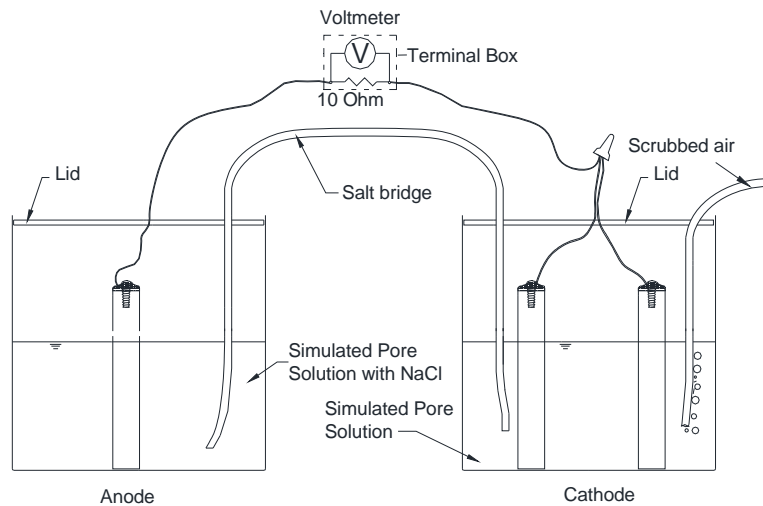


Figure 7— Rapid Macrocell Specimen

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 and bare bar soaked in acetone for at least two hours 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™ 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.

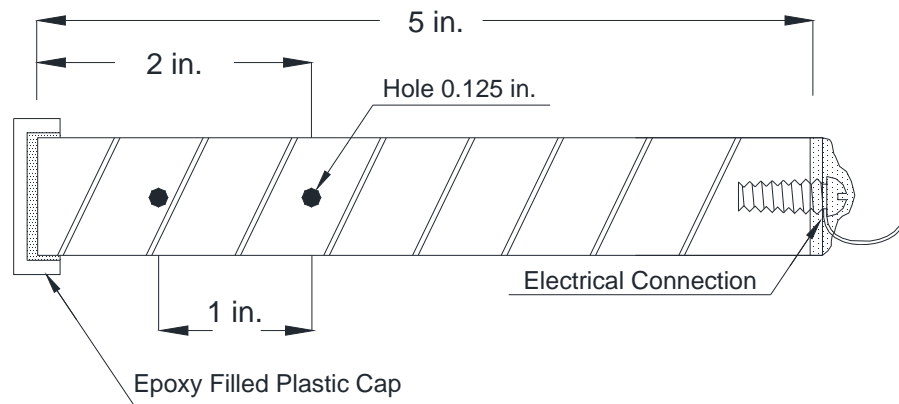


Figure 8— Damage pattern of epoxy-coated bar in rapid macrocell test

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:

$$i_{\text{corr}} = 10^6 \times \frac{V}{RA} \quad (1)$$

where i_{corr} is current density ($\mu\text{A}/\text{cm}^2$); 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:

$$r = k \frac{ia}{nF\rho} \quad (2)$$

where r is the corrosion rate ($\mu\text{m}/\text{year}$); k is a conversion factor ($315360 \text{ (A}\cdot\mu\text{m}\cdot\text{s)} / (\mu\text{A}\cdot\text{cm}\cdot\text{yr})$); 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 ($96485 \text{ Coulombs/equivalent}$); 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 $\mu\text{m}/\text{yr}$ ($0.457i$ 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 are 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 four types of reinforcement (MMFX bare bars containing 4% and 9% chromium and MMFX epoxy-coated bars containing 2% and 4% chromium), six Southern Exposure specimens, six cracked beam specimens, and six rapid macrocell tests were prepared. (For the Southern Exposure test, an additional two specimens of each type of uncoated MMFX bare bar were cast). 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. To investigate the effect of pickling on MMFX bars, uncoated bars containing 4% and 9% chromium (one set of six bars from each) were also pickled and evaluated using the rapid macrocell test. The bars were pickled in a solution containing 2.5% nitric acid (HNO₃) and 0.5% hydrofluoric acid (HF) at room temperature (72 °F) for 15 minutes. 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(4%)	8	6	-	6	20
MMFX(9%)	8	6	-	6	20
PMMFX(4%)	-	-	-	6	6
PMMFX(9%)	-	-	-	6	6
MMFX-ECR(2%)	6	6	6	6	24
MMFX-ECR(4%)	6	6	6	6	24
Total	28	24	12	36	100

^aMMFX(4%) = MMFX steel containing 4% chromium

MMFX(9%) = MMFX steel containing 9% chromium

PMMFX(4%) = Pickled MMFX steel containing 4% chromium

PMMFX(9%) = Pickled MMFX steel containing 9% chromium

MMFX-ECR(2%) = Epoxy-coated MMFX steel containing 2% chromium

MMFX-ECR(4%) = Epoxy-coated MMFX steel containing 4% chromium

^bSE = Southern Exposure specimen

^cCB = Cracked beam specimen

^dB = Beam specimen

^eRM = 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. One cracked beam specimen was cast in batch 4 to replace one of cracked beams since the inserted shim had not been removed properly from one specimen. Batch 5 consisted of four Southern Exposure specimens-two of each uncoated 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 $6 \pm 1\%$, 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/yd³ (kg/m³)	Cement lb/yd³ (kg/m³)	Coarse Agg. lb/yd³ (kg/m³)	Fine Agg. lb/yd³ (kg/m³)	Air- entraining Agent oz/yd³ (mL/m³)
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 MMFX uncoated bars containing 9% chromium (SE-MMFX(9%)) and 4% chromium (SE-MMFX(4%)) are shown in Figures 9 and 10, respectively. For the SE-MMFX(9%) bars,

Specimens 1 and 2 initiated corrosion at weeks 11 and 8, respectively. Specimens 3, 5, and 6 initiated at week 13 and Specimen 4 at week 31. Specimen 8 initiated corrosion at week 36 and specimen 7 initiated corrosion at week 46. The average time to corrosion initiation for SE-MMFX(9%) specimens was 21.4 weeks. The maximum corrosion rates for specimens SE-MMFX(9%) through week 96 ranged from 9.2 to 16.9 $\mu\text{m}/\text{yr}$.

For bars containing 4% chromium, Specimen SE-MMFX-4%-3 initiated corrosion at week 4 and had a maximum corrosion rate of 13.9 $\mu\text{m}/\text{yr}$ at week 32. The early initiation was likely due to corrosion at an electrical connection; thus, this specimen was excluded from the average initiation age. Specimens 1, 2, 4, 5 and 6 exhibited corrosion initiation at weeks 19, 20, 24, 29 and 14, respectively. Specimens 7 and 8 exhibited corrosion initiation at weeks 31 and 51, respectively. The average time to corrosion initiation for the SE-MMFX(4%) specimens was 27 weeks. The maximum corrosion rates for the SE-MMFX(4%) specimens through week 96 ranged from 8.0 to 22.5 $\mu\text{m}/\text{yr}$.

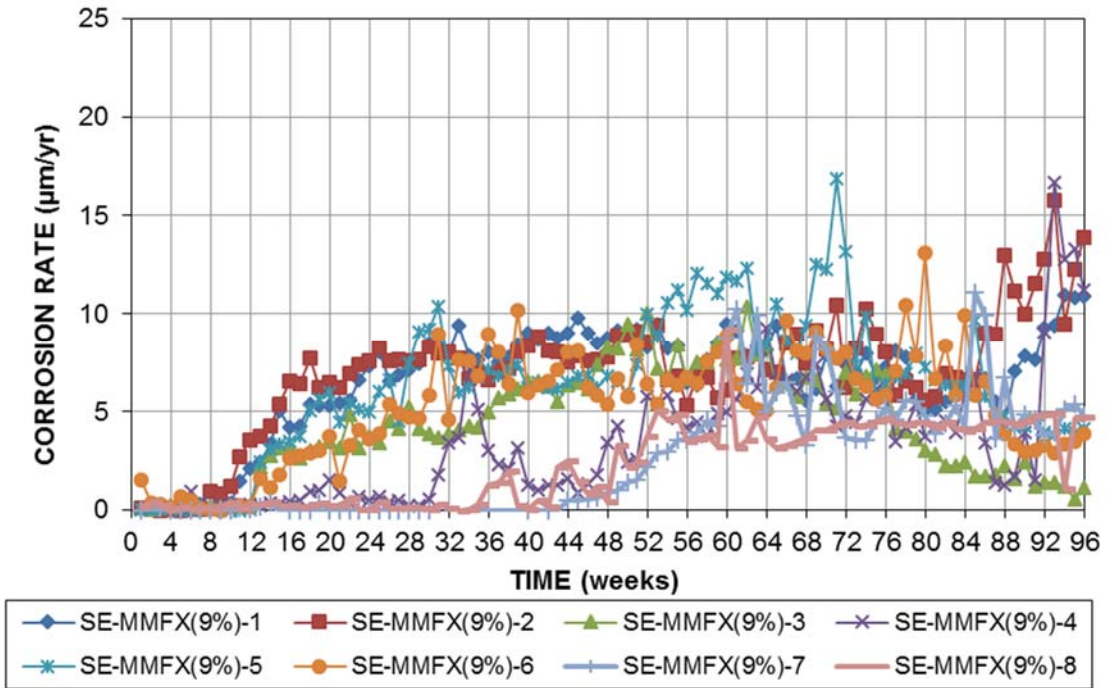


Figure 9— Macrocell corrosion rates ($\mu\text{m}/\text{yr}$) for Southern Exposure specimens containing MMFX(9%) bars

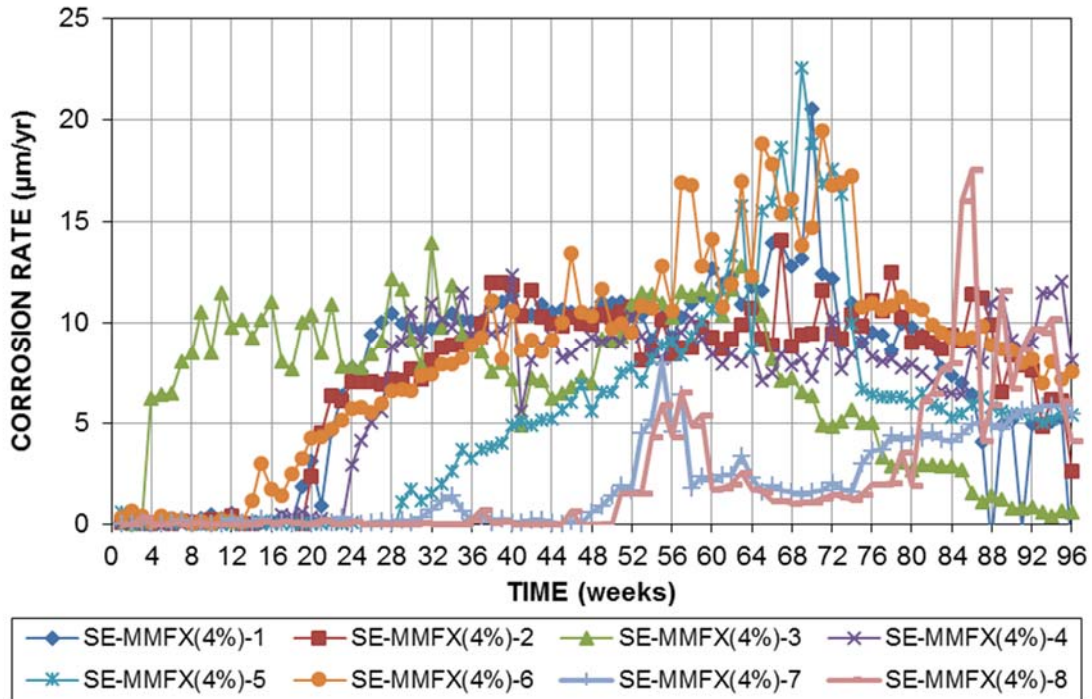


Figure 10— Macrocell corrosion rates ($\mu\text{m}/\text{yr}$) for Southern Exposure specimens containing MMFX(4%) bars

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 11 and 12, 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 $\mu\text{m}/\text{yr}$ and 0.187 to 0.918 $\mu\text{m}/\text{yr}$, respectively.

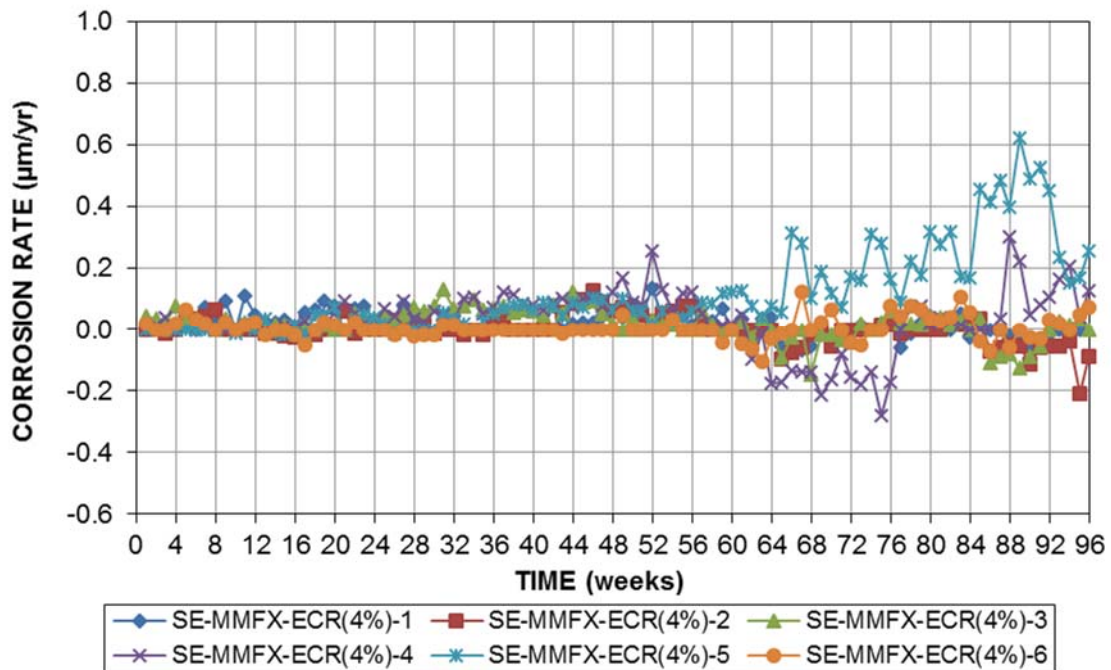


Figure 11— Macrocell corrosion rates ($\mu\text{m}/\text{yr}$) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

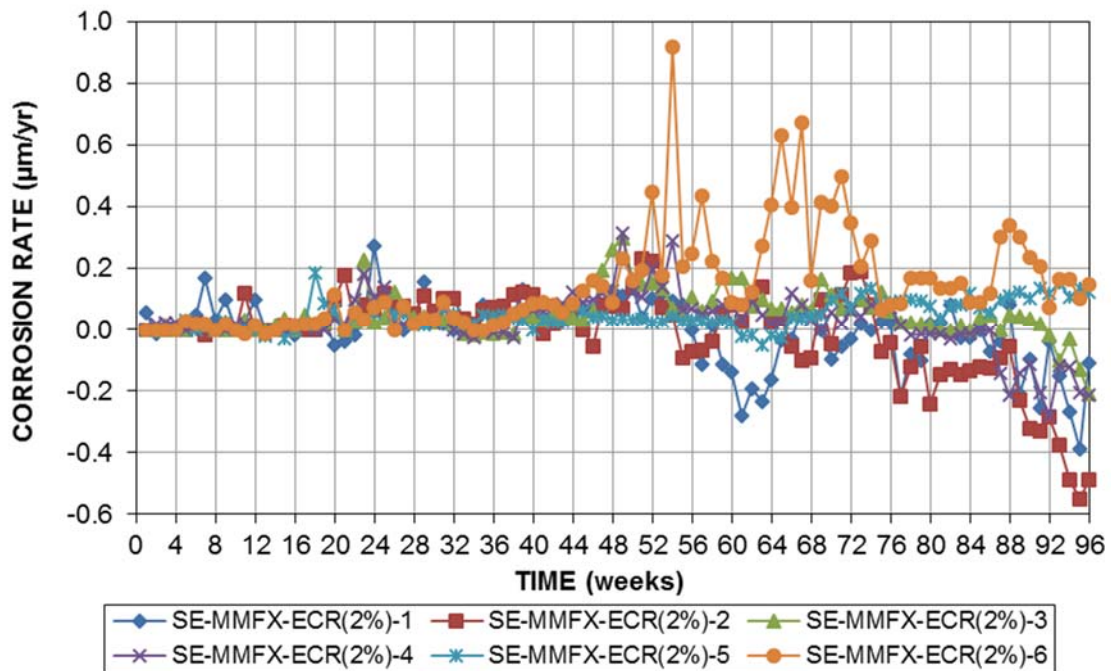


Figure 12— Macrocell corrosion rates ($\mu\text{m}/\text{yr}$) based on total area of the reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

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 13 and 14 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 $\mu\text{m}/\text{yr}$ and 35.8 to 176.3 $\mu\text{m}/\text{yr}$, respectively.

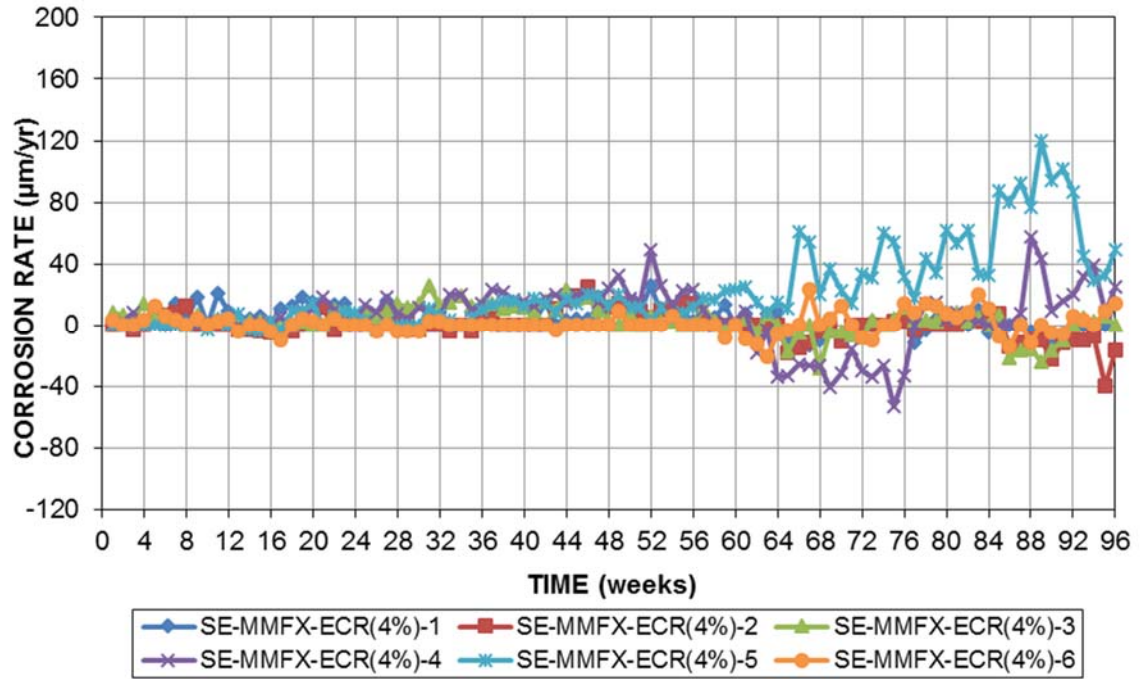


Figure 13— Macrocell corrosion rates ($\mu\text{m/yr}$) based on exposed area of the reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

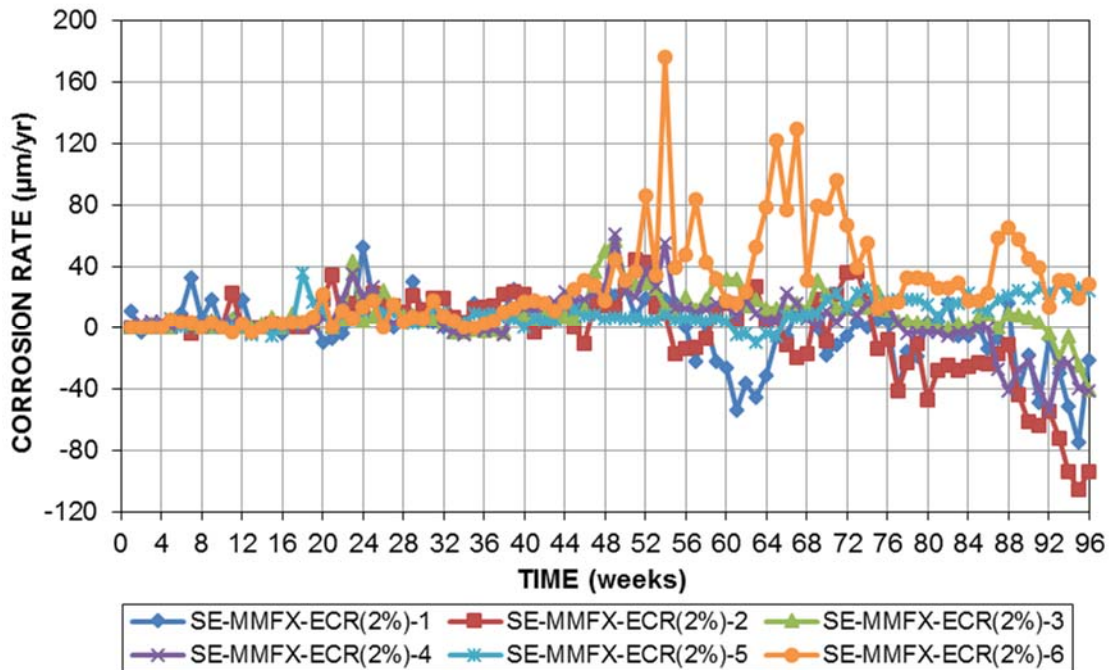


Figure 14— Macrocell corrosion rates ($\mu\text{m/yr}$) based on exposed area of the reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

Figure 15 shows the average corrosion rate for the Southern Exposure specimens based on total area. The epoxy-coated specimens exhibited very low corrosion rates based on total area; less than 0.1 $\mu\text{m}/\text{yr}$ for bars containing 4% chromium and less than 0.25 $\mu\text{m}/\text{yr}$ for bars containing 2% chromium. The SE-MMFX(4%) and SE-MMFX(9%) specimens exhibited average corrosion rates of less than 1 $\mu\text{m}/\text{yr}$ through week 6 and 12 respectively. Average corrosion rates for SE-MMFX(4%) reached a maximum of 10 $\mu\text{m}/\text{yr}$ at week 67, and then decreased to 4 $\mu\text{m}/\text{yr}$ at week 96. SE-MMFX(9%) reached a maximum corrosion rate of 8.35 $\mu\text{m}/\text{yr}$ at week 60, decreasing to 4.4 $\mu\text{m}/\text{yr}$ at week 87 before increasing to about 7 $\mu\text{m}/\text{yr}$ for the final five weeks of testing.

Figure 16 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 $\mu\text{m}/\text{yr}$ or less through week 23. Between weeks 23 and 96, the corrosion rates on these specimens fluctuated between -33.0 and 46.9 $\mu\text{m}/\text{yr}$. The epoxy-coated bars with 4% nominal chromium content exhibited a maximum average corrosion rate of 20.1 $\mu\text{m}/\text{yr}$ at week 89.

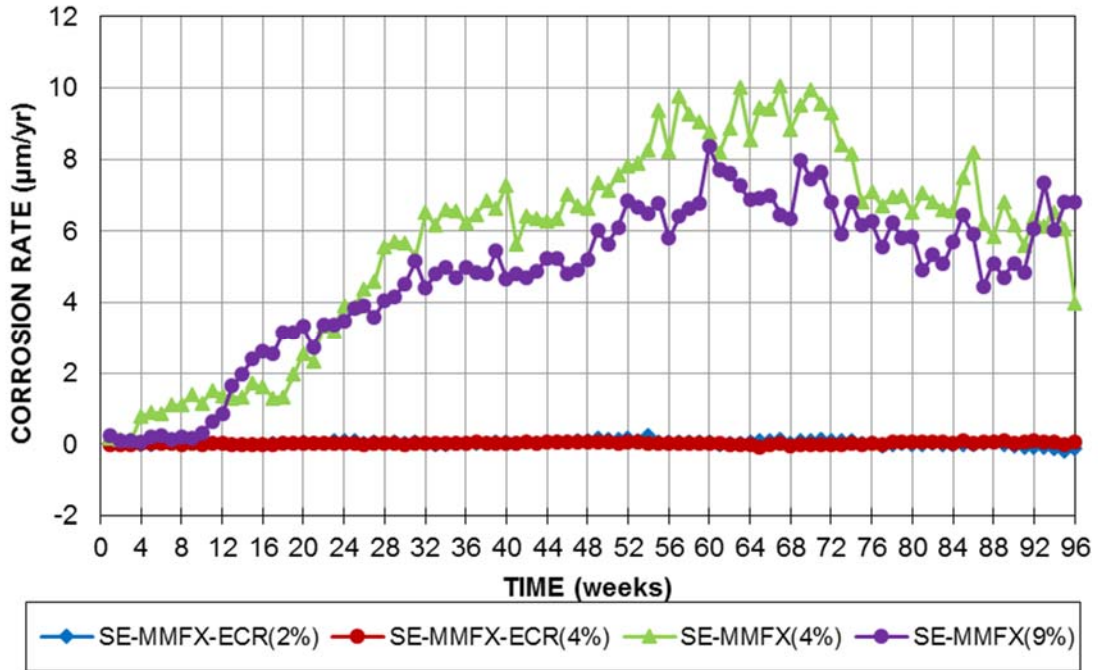


Figure 15— Average corrosion rate ($\mu\text{m}/\text{yr}$) based on total area versus time for Southern Exposure specimens containing bare and epoxy-coated MMFX bars

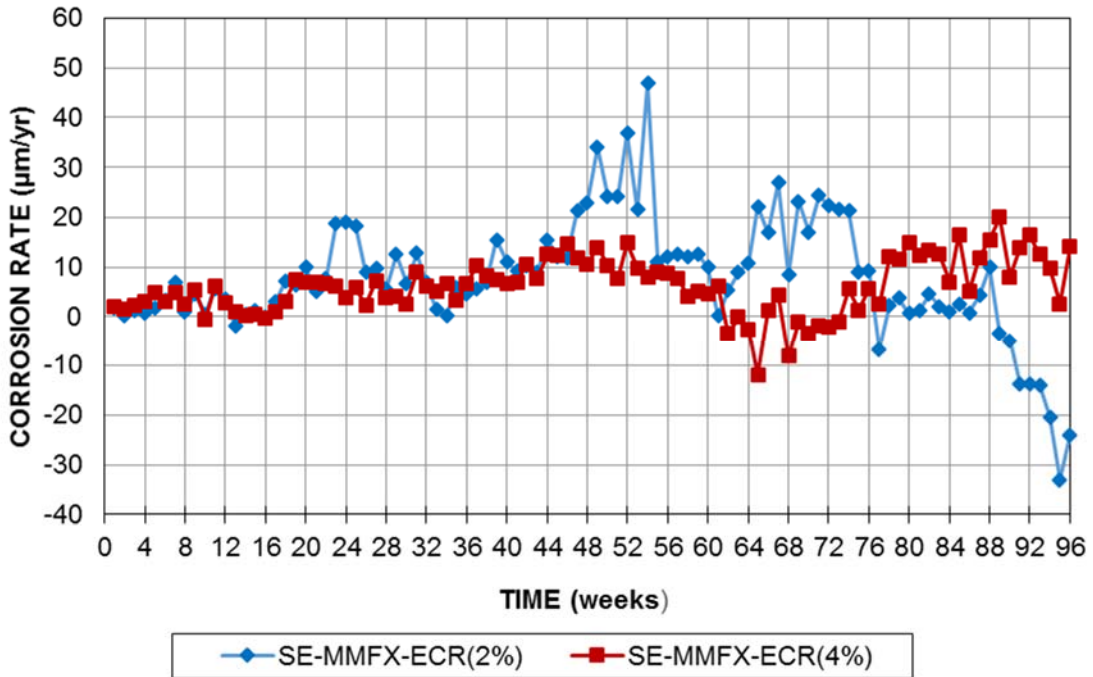


Figure 16— Average corrosion rate ($\mu\text{m}/\text{yr}$) based on exposed area versus time for Southern Exposure specimens containing epoxy-coated MMFX bars

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. Average corrosion losses for MMFX(4%) and MMFX(9%) specimens at week 96 were 10.3 and 8.73 μm , respectively. Based on total area, the greatest individual loss, 15.6 μm , was observed on specimen MMFX(4%)-6. The maximum corrosion loss for the MMFX-9% specimens was 13.0 μm for MMFX(9%)-2. 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		Week 96			
	1	2	3	4	5	6	7	8		
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
MMFX(4%)	13.7	13.3	13.1	12.2	10.0	15.6	3.45	4.08	10.7	4.54
MMFX(9%)	12.1	13.0	8.05	6.34	11.7	9.73	4.73	4.23	8.73	3.41
	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 obtained from LPR test on Southern Exposure specimens with uncoated MMFX bars containing 9% and 4% chromium are shown in Figures 17 and 18, respectively. The maximum corrosion rates for specimens SE-MMFX(9%) and SE-MMFX(4%) through week 96 ranged from 3.7 to 21.6 $\mu\text{m}/\text{yr}$ and 3.6 to 34.2 $\mu\text{m}/\text{yr}$, respectively.

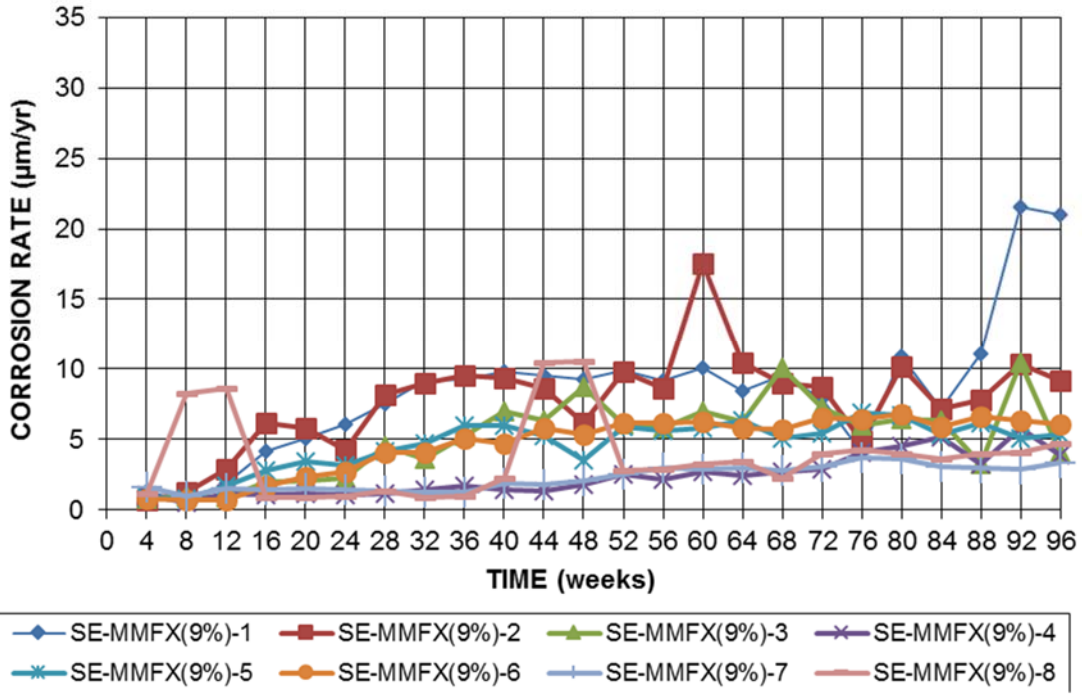


Figure 17— LPR test corrosion rates (µm/yr) for Southern Exposure specimens containing MMFX(9%) bars

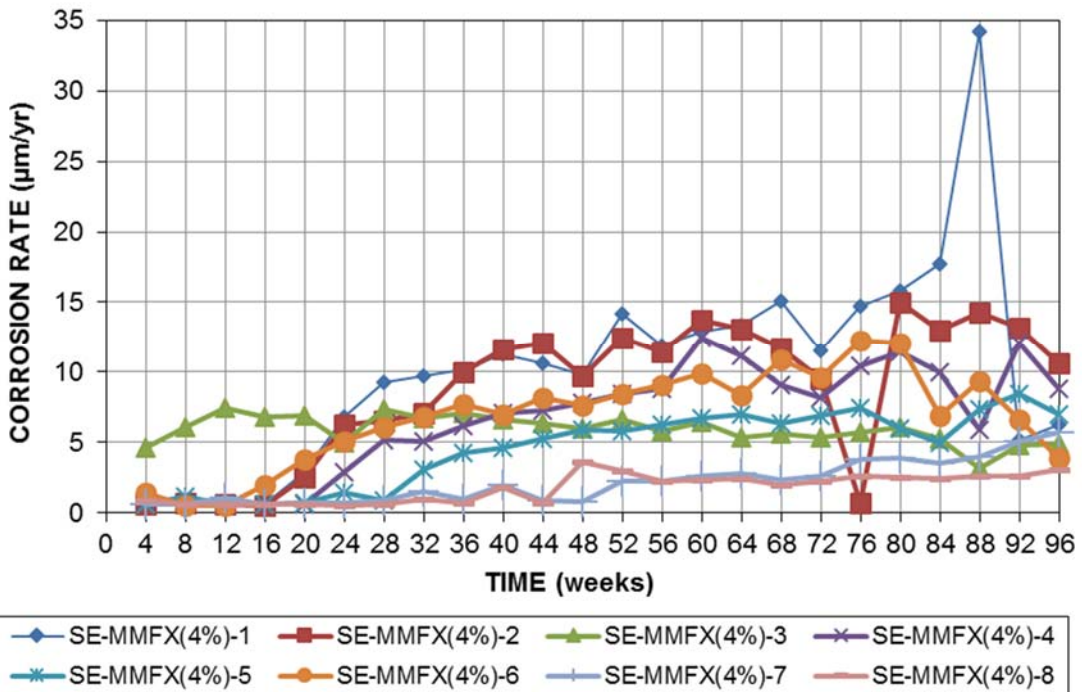


Figure 18— LPR test corrosion rates (µm/yr) for Southern Exposure specimens containing MMFX(4%) bars

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 19 and 20, 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 $\mu\text{m}/\text{yr}$ and 0.22 to 0.72 $\mu\text{m}/\text{yr}$, respectively.

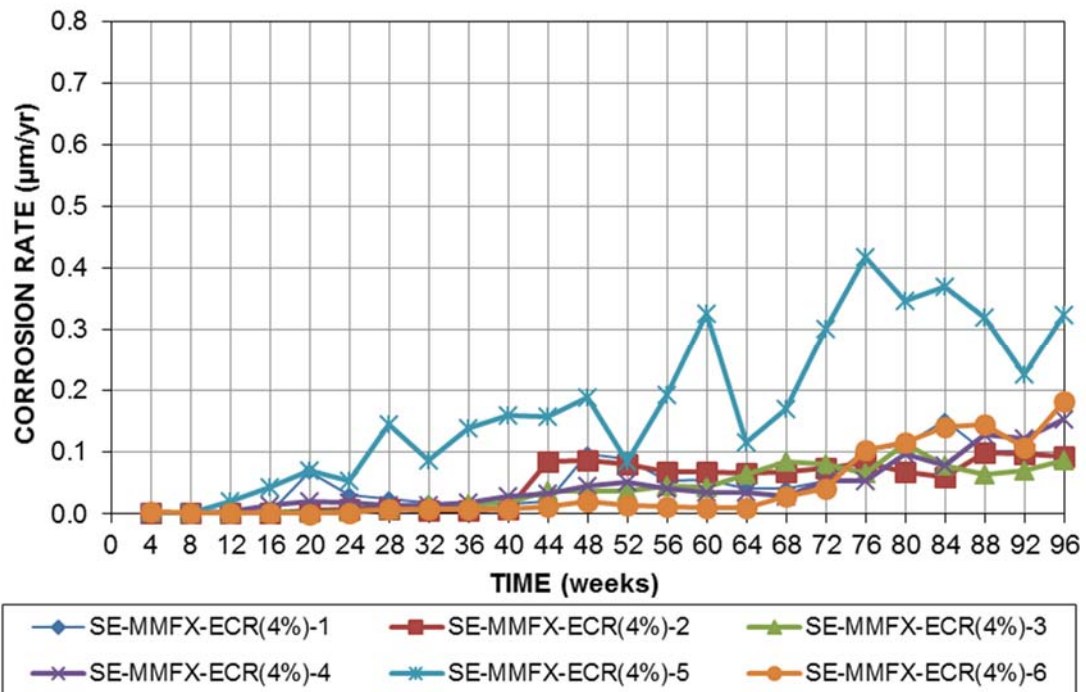


Figure 19— LPR test corrosion rates ($\mu\text{m}/\text{yr}$) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

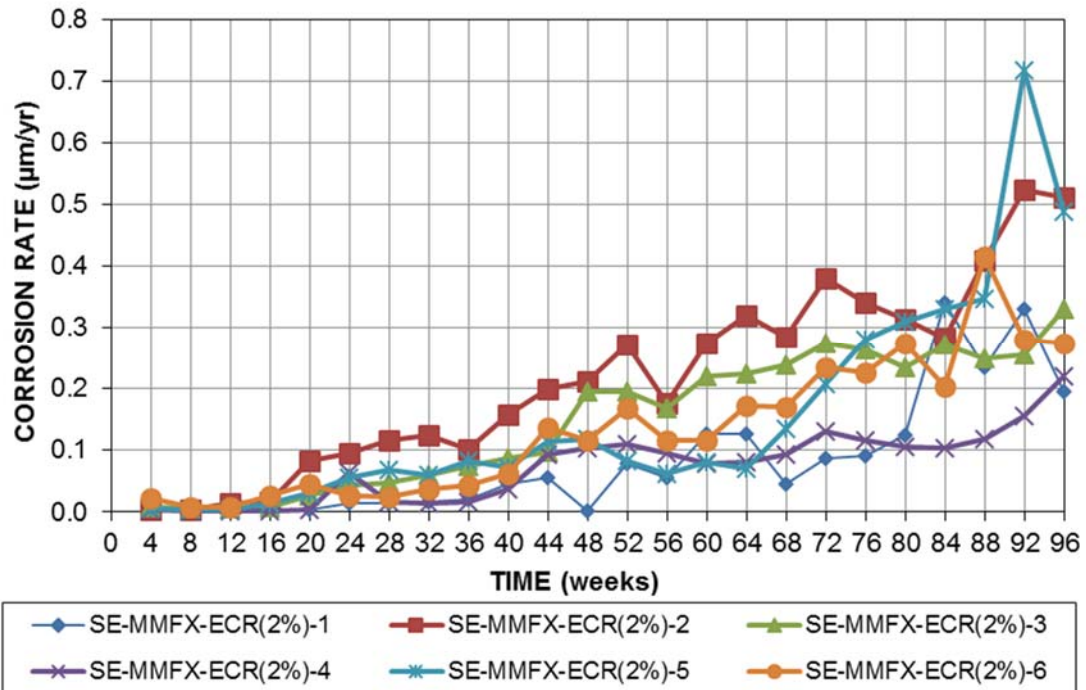


Figure 20— LPR test corrosion rates ($\mu\text{m}/\text{yr}$) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

Figure 21 shows the average corrosion rate for the Southern Exposure specimens based on total area obtained from LPR test results. For all specimens, average corrosion rates generally increased through the end life of the test (96 weeks). Compared to the uncoated bars, the epoxy-coated specimens exhibited very low corrosion rates based on total area. The maximum average corrosion rates for epoxy-coated bars containing 4% and 2% chromium were 0.15 and 0.38 $\mu\text{m}/\text{yr}$, compared to 8.35 and 10 $\mu\text{m}/\text{yr}$ for uncoated bars containing 9% and 4% chromium, respectively.

Figure 22 shows the average corrosion rate for the Southern Exposure specimens containing epoxy-coated bars based on exposed area obtained from the LPR test results. As observed for the uncoated bars, 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 $\mu\text{m}/\text{yr}$ at week 88. The epoxy-coated

bars with 4% nominal chromium content exhibited a maximum average corrosion rate of 29.7 $\mu\text{m}/\text{yr}$ at week 96.

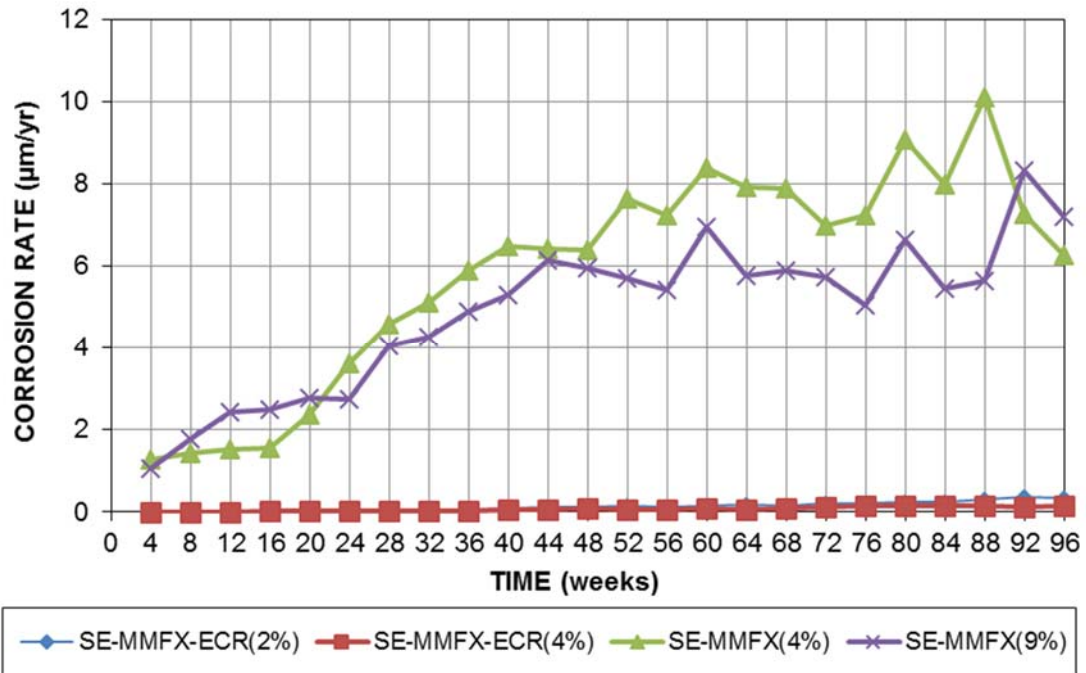


Figure 21— Average LPR test corrosion rate ($\mu\text{m}/\text{yr}$) based on total area versus time for Southern Exposure specimens containing bare and epoxy-coated MMFX bars

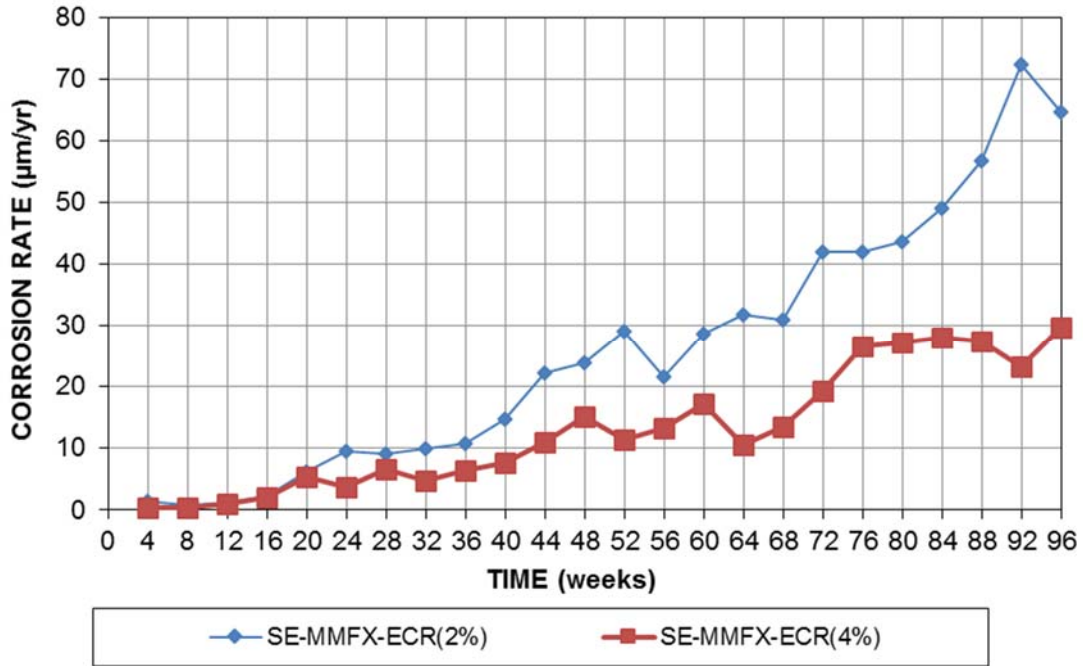


Figure 22— Average LPR test corrosion rate ($\mu\text{m}/\text{yr}$) based on exposed area versus time for Southern Exposure specimens containing epoxy-coated MMFX bars

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. Average corrosion losses for MMFX(4%) and MMFX(9%) specimens at week 96 were 10.8 and 9.05 μm , respectively, about 1% more than that obtained from macrocell corrosion rates. Based on total area, the greatest individual loss, 18.9 μm , was observed on Specimen MMFX(4%)-1. The maximum corrosion loss for the MMFX(9%) specimens was 15.7 μm for MMFX(9%)-1. 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		Week 96			
	1	2	3	4	5	6	7	8		
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
MMFX(4%)	18.9	15.9	10.9	12.4	8.42	12.6	4.03	3.27	10.8	5.43
MMFX(9%)	15.7	14.2	9.49	4.38	8.62	8.68	4.23	6.96	9.05	4.17
	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 23. The average bottom mat corrosion potentials are exhibited in the Appendix A. The average top mat potential for all specimens was between -0.23 V and -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 MMFX(4%) specimens exhibited corrosion potentials near -0.25 V through week 13, after which the potential dropped to -0.62 V by week 96. The potential of the MMFX(9%) specimens gradually increased to -0.21 V by week 7, after which the potential decreased to -0.58 V by week 96. The drops in potential correspond to the initiation of corrosion for a specimen in the series.

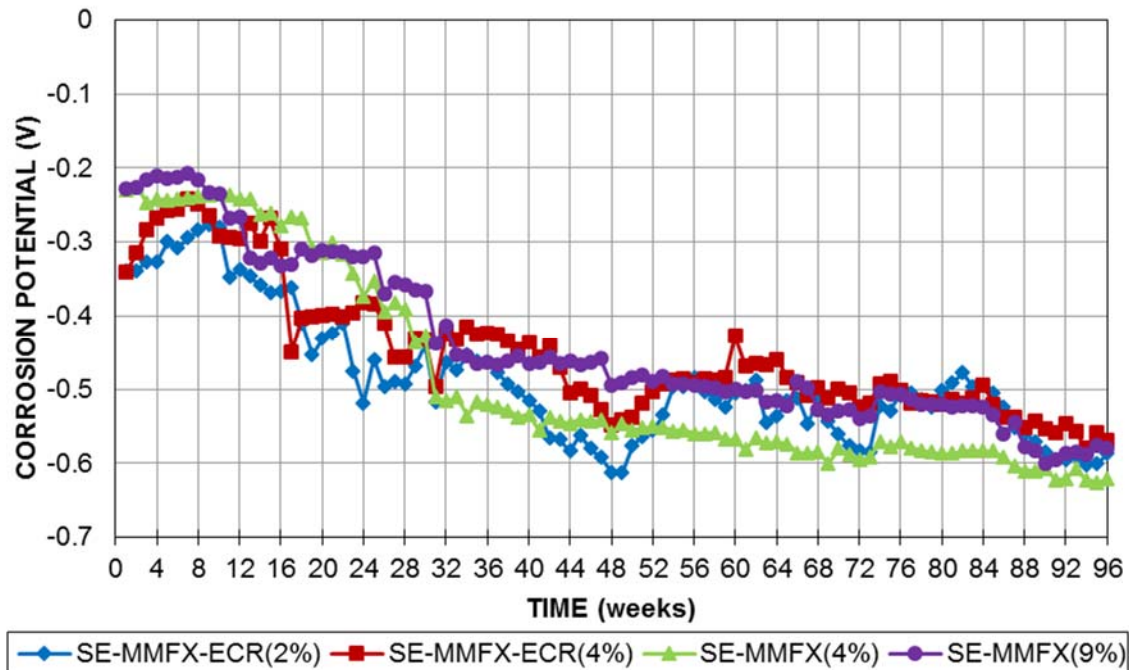


Figure 23—Top mat (anode) corrosion potential (CSE) versus time for Southern Exposure specimens containing bare and epoxy-coated MMFX bars

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. Figures 24 and 25 show the top and bottom mats, respectively, of a Southern Exposure specimen containing bars with 4% chromium (Specimen SE-MMFX(4%)-6) after autopsy. Figures 26 and 27 show the top and bottom mat of a representative specimen with MMFX reinforcement containing 9% chromium (SE-MMFX(9%)-5). Signs of corrosion can be observed on both top and bottom mat bars of specimens. On the top bars, corrosion was concentrated on the upper face of the bars, with as much as 50% of the surface area corroded. Corroded regions on the bottom mat bars were significantly less than the top mat (about 10% of one side of one or two bars). This indicates that the duration of the bench-scale tests (96 weeks) were long enough for chlorides to penetrate through much of the

concrete, reach the bottom bar surface, and initiate corrosion there. The corrosion initiation of bottom bars can be determined by the drop in corrosion potentials of bottom mat bars; this data is presented in Appendix A. The corroded area on the surface of bars with 9% chromium was generally lower than that on bars with 4% chromium.



Figure 24— Southern Exposure MMFX(4%)-6 top bars after 96 weeks



Figure 25— Southern Exposure MMFX(4%)-6 bottom bars after 96 weeks



Figure 26— Southern Exposure MMFX(9%)-5 top bars after 96 weeks



Figure 27— Southern Exposure MMFX(9%)-5 bottom bars after 96 weeks

Figure 28 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 29 and 30, respectively. Figures 31 and 32 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 29 and 31 are indicated by ovals.



Figure 28— Southern Exposure MMFX-ECR(4%)-5 top bars before disbondment test after 96 weeks



Figure 29— Southern Exposure MMFX-ECR(4%)-5 top bars after disbondment test after 96 weeks



Figure 30— Southern Exposure MMFX-ECR(4%)-5 bottom bar after disbondment test after 96 weeks



Figure 31— Southern Exposure MMFX-ECR(2%)-5 top bars after disbondment test after 96 weeks



Figure 32— 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 in² (358 mm²), was 20% less than the disbondment for MMFX-ECR(2%), 0.69 in² (447 mm²), however, a wide variation between 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 MMFX uncoated bars containing 9% chromium (CB-MMFX(9%)) and 4% chromium (CB-MMFX(4%)) are shown in Figures 33 and 34, respectively. The maximum corrosion rates for the CB-MMFX(9%) and CB-MMFX(4%) specimens through week 96 ranged from 16.6 to 24.6 $\mu\text{m}/\text{yr}$ and 23.5 to 29.1 $\mu\text{m}/\text{yr}$, respectively.

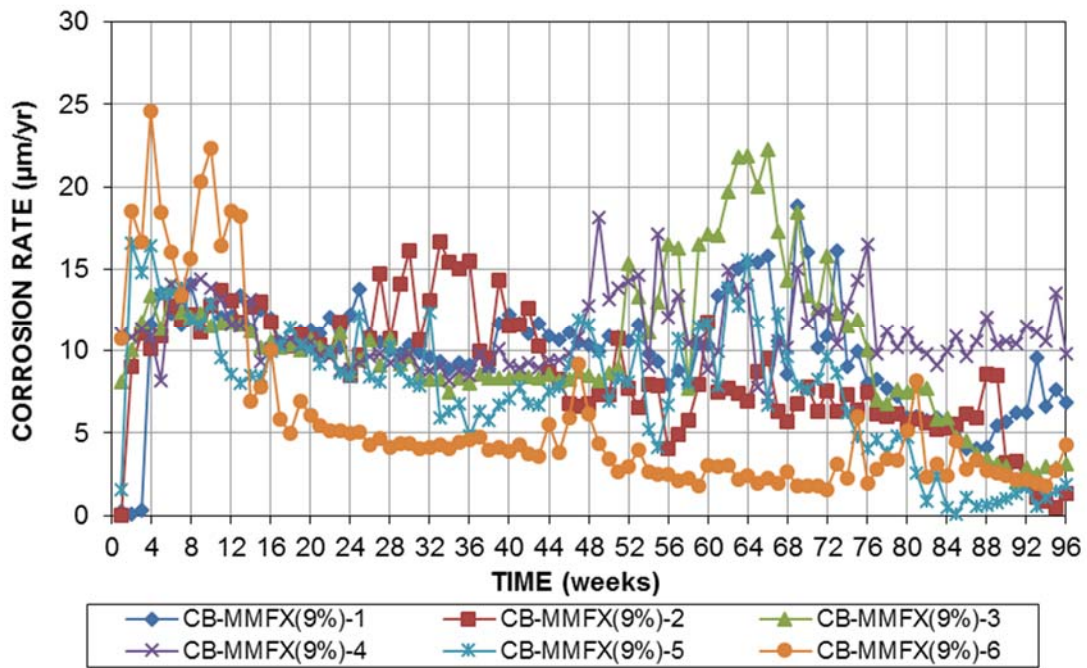


Figure 33— Macrocell corrosion rates ($\mu\text{m}/\text{yr}$) for cracked beam specimens containing MMFX(9%) bars

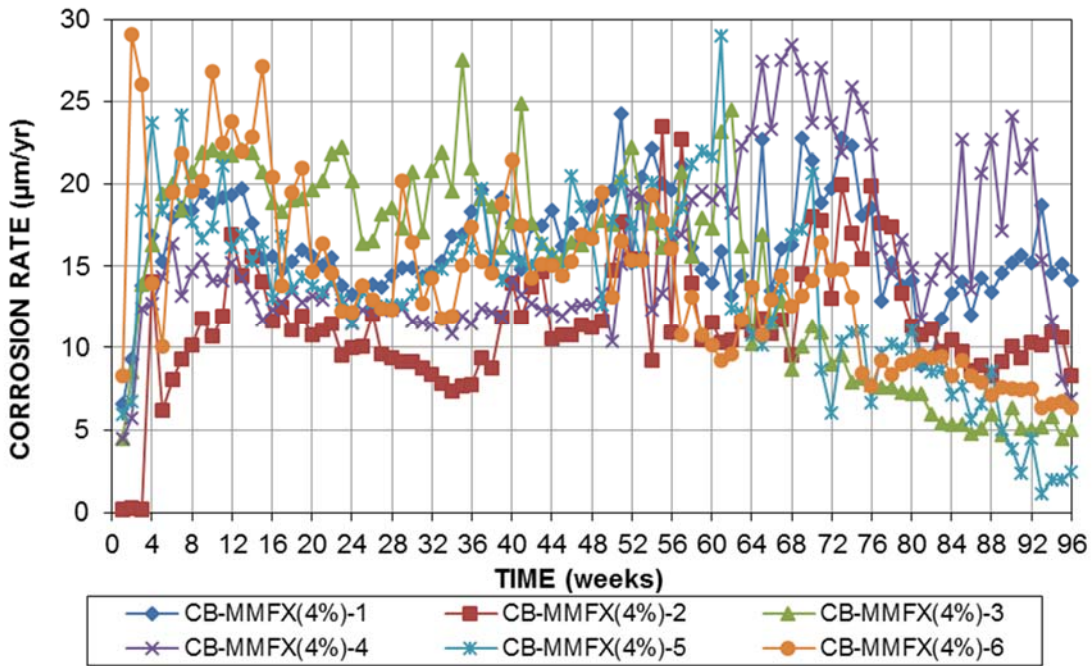


Figure 34— Macrocell corrosion rates ($\mu\text{m}/\text{yr}$) for cracked beam specimens containing MMFX(4%) bars

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 35 and 36, 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 $\mu\text{m}/\text{yr}$ and 0.602 to 2.08 $\mu\text{m}/\text{yr}$, respectively.

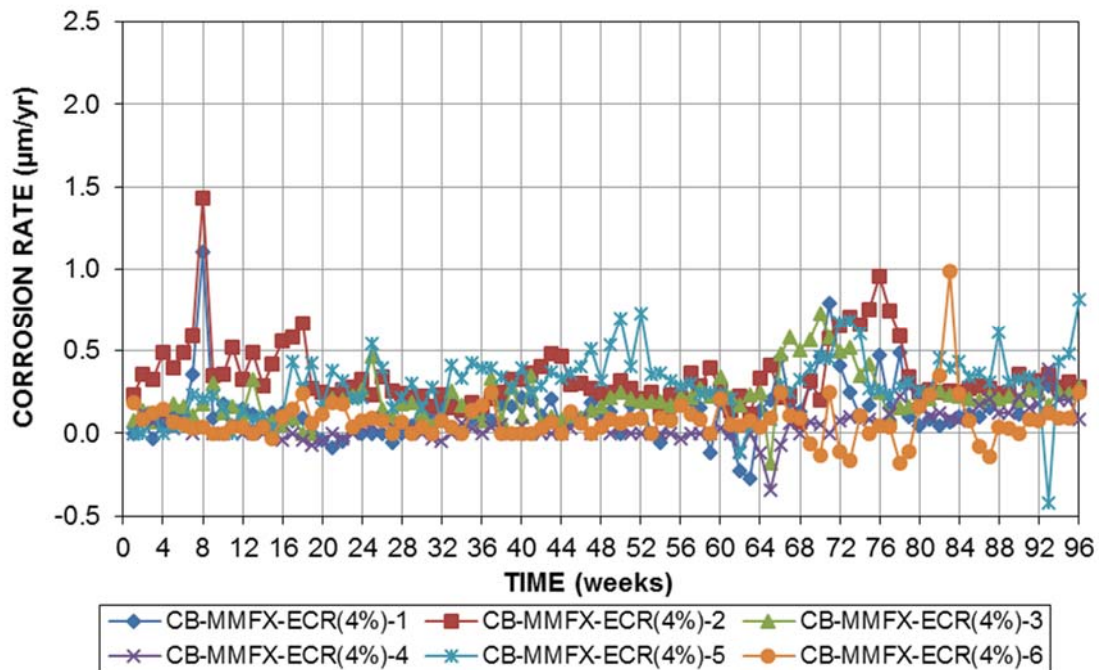


Figure 35— Macrocell corrosion rates based on total area ($\mu\text{m}/\text{yr}$) for cracked beam specimens containing MMFX-ECR(4%) bars

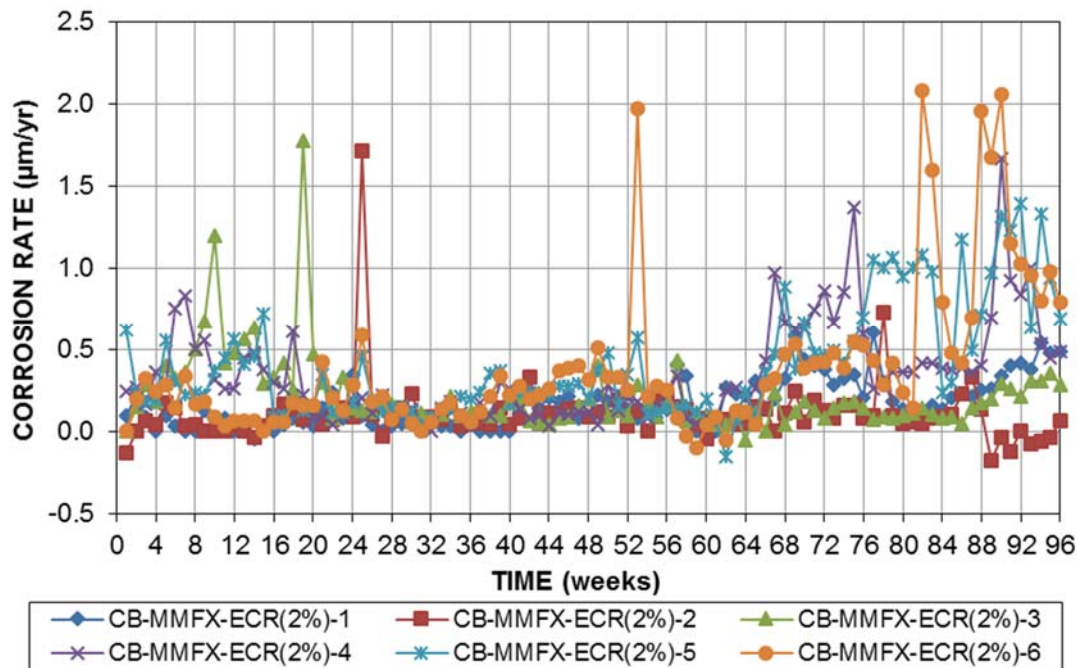


Figure 36— Macrocell corrosion rates based on total area ($\mu\text{m}/\text{yr}$) for cracked beam specimens containing MMFX-ECR(2%) bars

Figures 37 and 38 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 $\mu\text{m}/\text{yr}$ and 116 to 399 $\mu\text{m}/\text{yr}$, respectively.

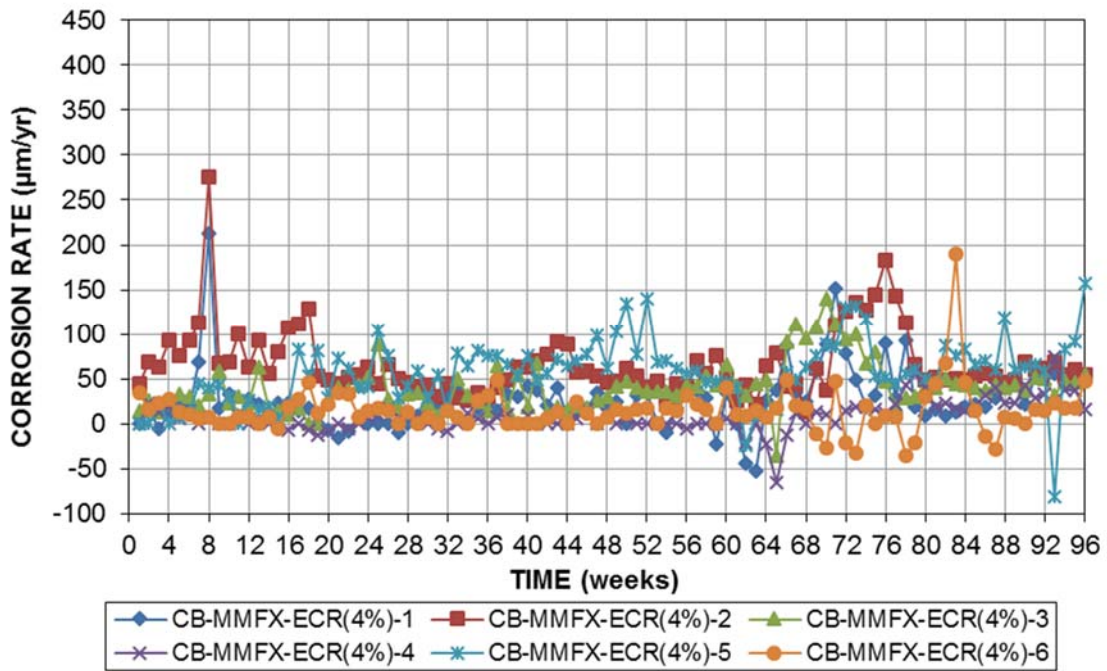


Figure 37— Macrocell corrosion rates based on exposed area ($\mu\text{m}/\text{yr}$) for cracked beam specimens containing MMFX-ECR(4%) bars

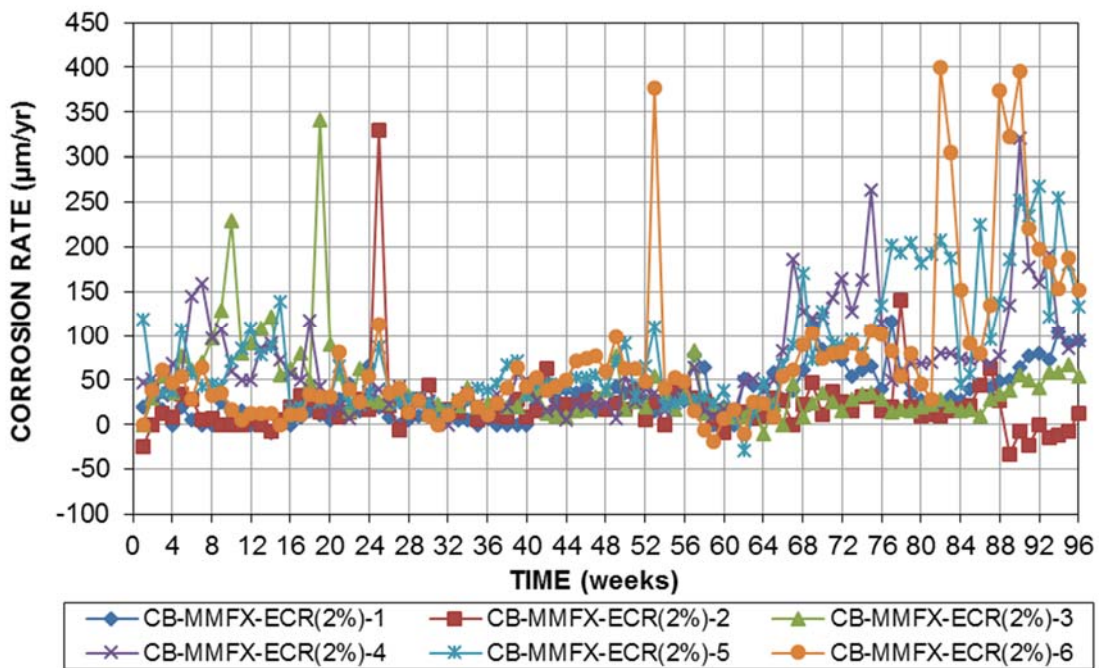


Figure 38— Macrocell corrosion rates based on exposed area ($\mu\text{m}/\text{yr}$) for cracked beam specimens containing MMFX-ECR(2%) bars

Figure 39 shows the average corrosion rates for the cracked beam specimens. The highest corrosion rates through week 96 were observed on the CB-MMFX(4%) specimens, with the peak average corrosion rate of 19.1 $\mu\text{m}/\text{yr}$ occurring at week 51. The CB-MMFX(9%) specimens exhibited a maximum average corrosion rate of 14.5 $\mu\text{m}/\text{yr}$ at week 4. Based on total area, the epoxy-coated bars with the 2% and 4% nominal chromium contents had corrosion rates less than 1 $\mu\text{m}/\text{yr}$ over 96 weeks of testing. The epoxy-coated CB-MMFX-ECR(2%) and CB-MMFX-ECR(4%) specimens exhibited maximum corrosion rates of 0.94 $\mu\text{m}/\text{yr}$ and 0.50 $\mu\text{m}/\text{yr}$ at weeks 90 and 8, respectively. Based on exposed area (Figure 40), the corrosion rate of epoxy-coated bars with 2% nominal chromium content fluctuated between 0 and 180 $\mu\text{m}/\text{yr}$; bars with 4% chromium content had rates between 0 and 95 $\mu\text{m}/\text{yr}$.

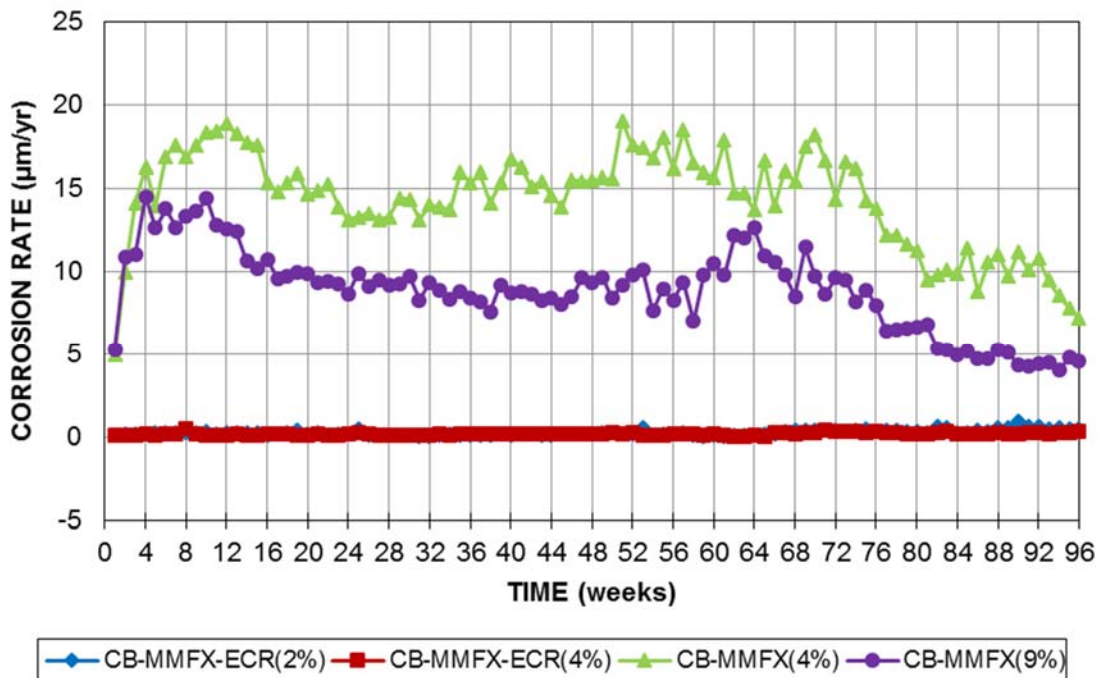


Figure 39— Average corrosion rate ($\mu\text{m}/\text{yr}$) based on total area versus time for cracked beam specimens containing bare and epoxy-coated MMFX bars

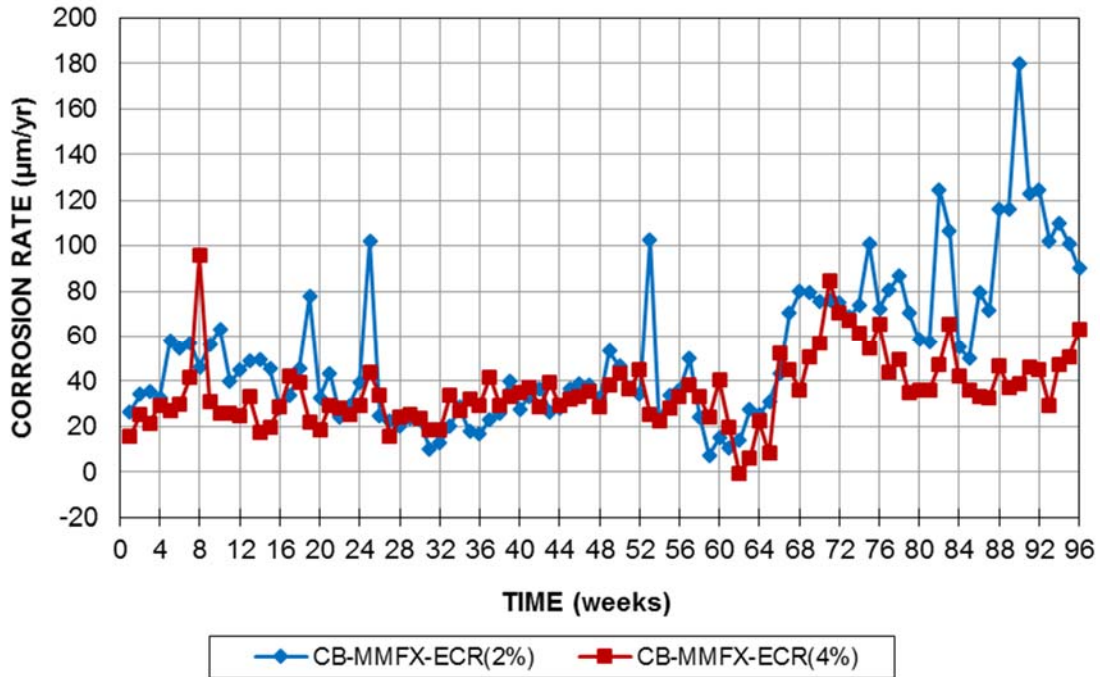


Figure 40— Average corrosion rate ($\mu\text{m}/\text{yr}$) based on exposed area versus time for cracked beam specimens containing epoxy-coated MMFX bars

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 total area, the greatest individual loss, $30.1 \mu\text{m}$ was observed for Specimen MMFX(4%)-1. The average corrosion loss of the MMFX(4%) specimens was $26.5 \mu\text{m}$. The corrosion losses for the MMFX-9% specimens ranged from 10.6 to $20.4 \mu\text{m}$, with an average of $16.4 \mu\text{m}$. Based on total area, the epoxy-coated bars exhibited losses approximately two orders of magnitude less than the uncoated bars. Based on exposed area, losses for the MMFX-ECR(2%) and MMFX-ECR(4%) specimens ranged from 37.0 to $147 \mu\text{m}$, with an average of $97.1 \mu\text{m}$, and 15.8 to $123 \mu\text{m}$, with an average loss of $65.4 \mu\text{m}$, 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
MMFX(4%)	30.1	21.3	27.6	29.0	25.0	26.2	26.5	3.16
MMFX(9%)	18.3	16.1	18.9	20.4	14.2	10.6	16.4	3.59
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)

Corrosion rates obtained from LPR test results for cracked beam specimens with uncoated MMFX bars containing 9% and 4% chromium are shown in Figures 41 and 42, respectively. The maximum corrosion rates for specimens CB-MMFX(9%) and CB-MMFX(4%) through week 96 ranged from 10.2 to 45.9 $\mu\text{m}/\text{yr}$ and 19.3 to 79.2 $\mu\text{m}/\text{yr}$, respectively.

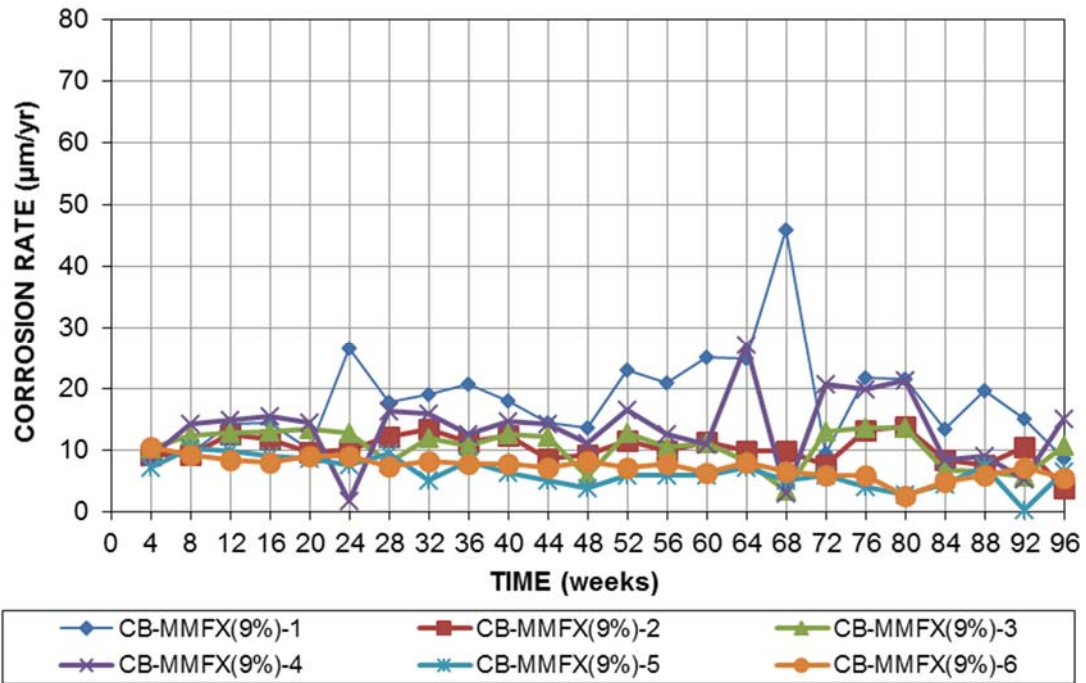


Figure 41— LPR test corrosion rates ($\mu\text{m}/\text{yr}$) for cracked beam specimens containing MMFX(9%) bars

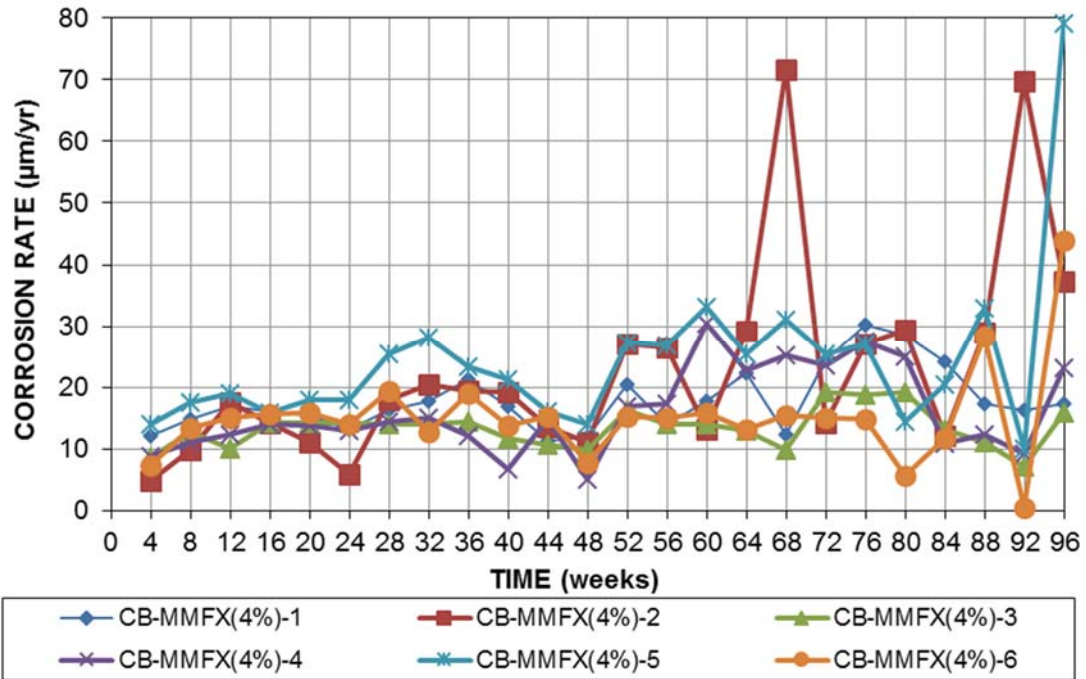


Figure 42— LPR test corrosion rates ($\mu\text{m}/\text{yr}$) for cracked beam specimens containing MMFX(4%) bars

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 43 and 44, 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 $\mu\text{m}/\text{yr}$ and 0.66 to 9.95 $\mu\text{m}/\text{yr}$, respectively.

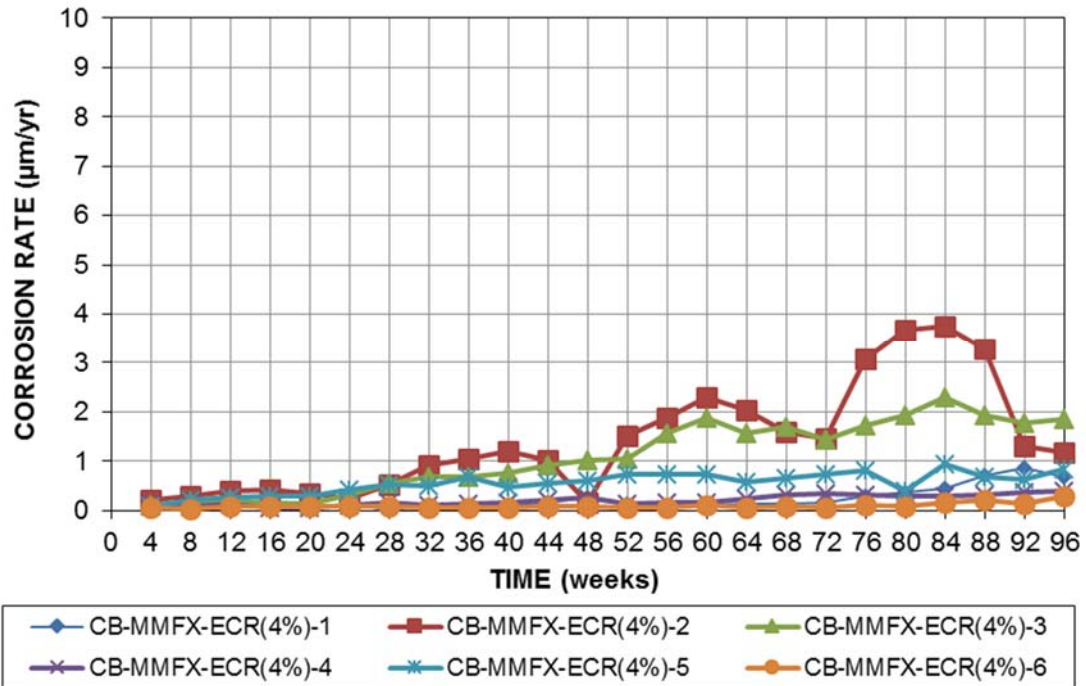


Figure 43— LPR test corrosion rates ($\mu\text{m}/\text{yr}$) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(4%) bars

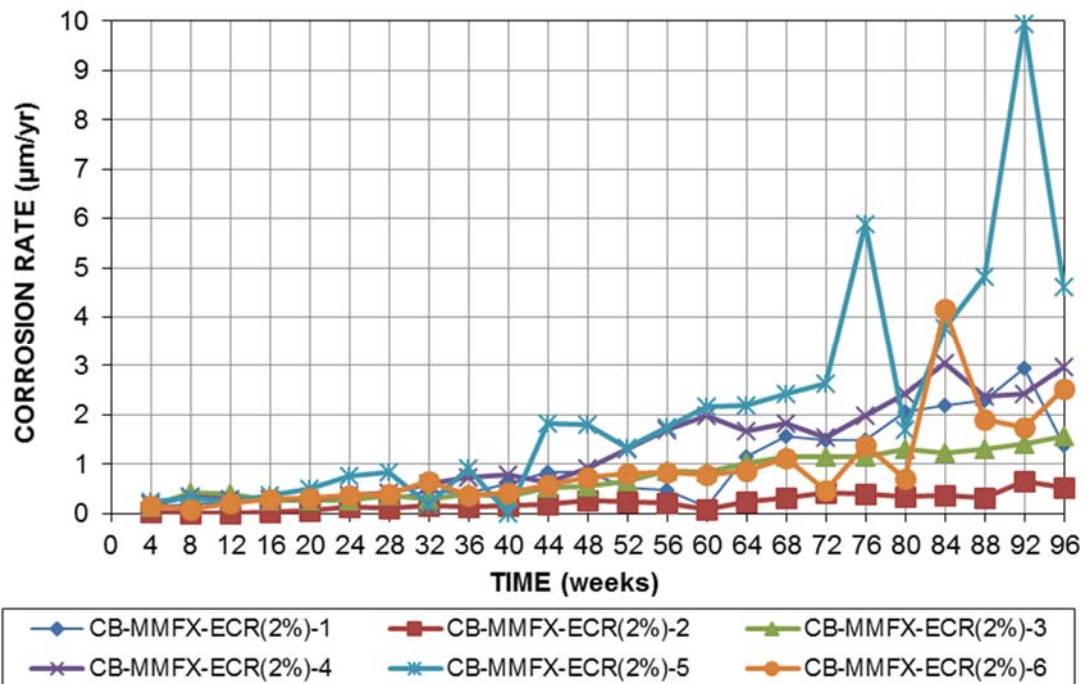


Figure 44— LPR test corrosion rates ($\mu\text{m}/\text{yr}$) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

Figure 45 shows the average corrosion rate for the cracked beam specimens based on total area obtained from LPR test results. For the CB-MMFX(4%) specimens, the average corrosion rate generally increased throughout the test and reached the peak value (44 $\mu\text{m}/\text{yr}$) at the end of test, while the average corrosion rate for the CB-MMFX(9%) specimens remained relatively constant during the test and ranged from 7.3 to 14.2 $\mu\text{m}/\text{yr}$. The epoxy-coated bar specimens had lower corrosion rates than the uncoated bar specimens based on total area, with average corrosion rates for epoxy-coated bars containing 4% and 2% chromium of 1.31 and 3.19 $\mu\text{m}/\text{yr}$, respectively.

Figure 46 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 $\mu\text{m}/\text{yr}$ and 253 $\mu\text{m}/\text{yr}$ at weeks 92 and 84, respectively.

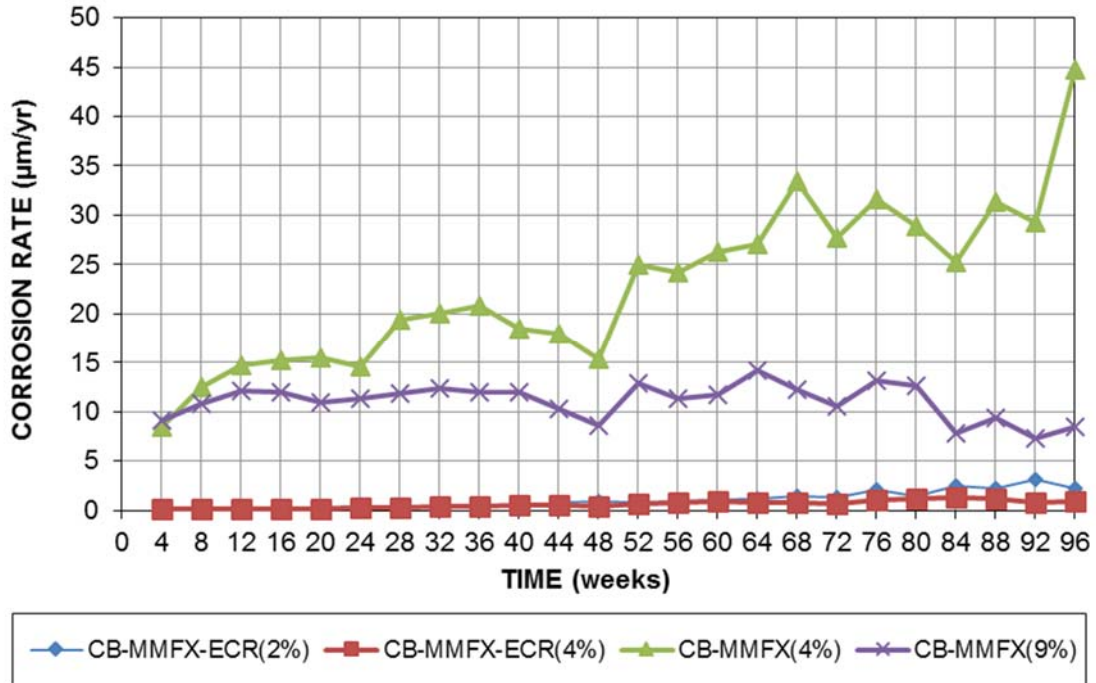


Figure 45— Average LPR test corrosion rate ($\mu\text{m}/\text{yr}$) based on total area versus time for cracked beam specimens containing bare and epoxy-coated MMFX bars

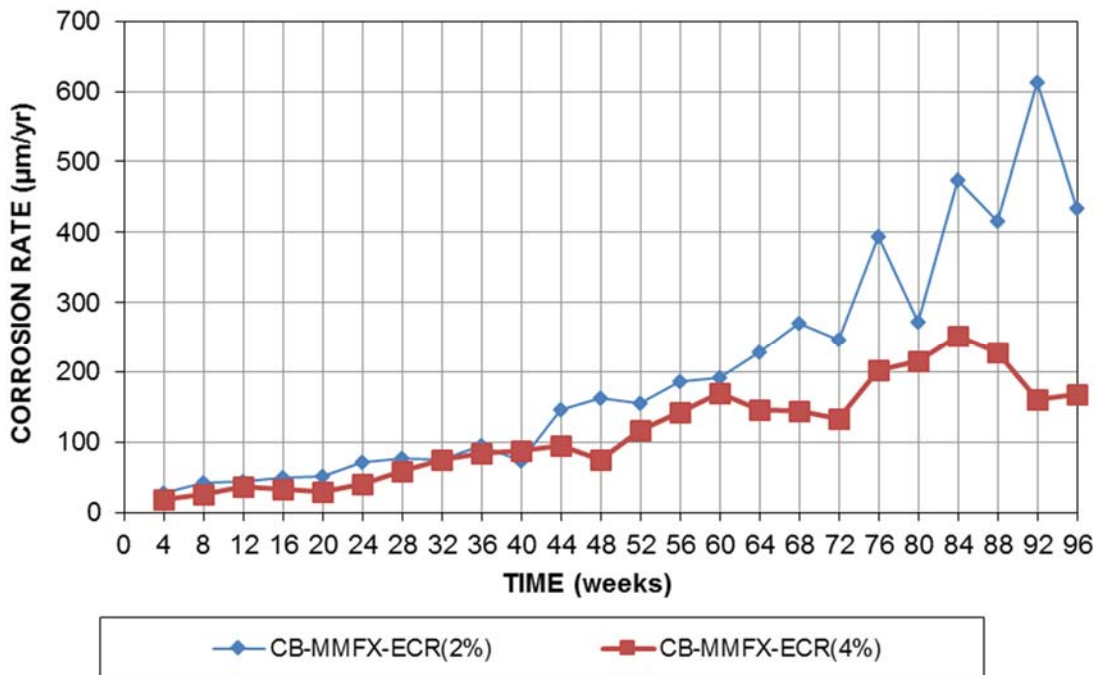


Figure 46— Average LPR test corrosion rate ($\mu\text{m}/\text{yr}$) based on exposed area versus time for cracked beam specimens containing epoxy-coated MMFX bars

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 total area, the greatest individual loss, 44.9 μm was observed for Specimen MMFX(4%)-5. The average corrosion loss of the MMFX(4%) specimens was 33.8 μm , about 28% higher than that obtained from macrocell corrosion rates. The corrosion losses for the MMFX(9%) specimens ranged from 11.7 to 33.6 μm , with an average of 20.4 μm , about 24% higher than that obtained from macrocell corrosion rates. Based on total area, the epoxy-coated bars exhibited losses approximately one order of magnitude less than the uncoated bars. 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
MMFX(4%)	33.1	42.4	24.6	29.7	44.9	27.9	33.8	8.2
MMFX(9%)	33.6	19.0	19.4	24.97	11.7	13.5	20.4	8.0
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 47. The specimens with all four bar types exhibited potentials between -0.40 V and -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%), MMFX(4%), and MMFX(9%) specimens dropped from the values at the start of testing to near -0.58 V, -0.53 V, and -0.52 V at weeks 2, 4, and 5, respectively, and exhibited potentials between -0.60 V and -0.70 V through week 96. The potentials indicate that the specimens initiated corrosion in the first week of testing.

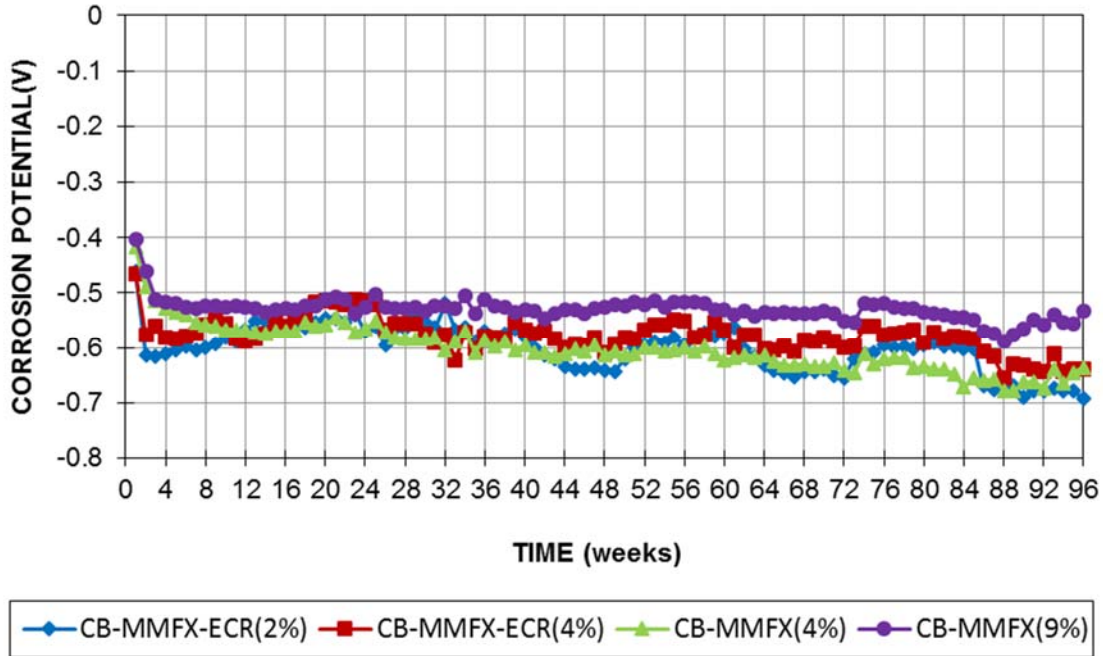


Figure 47— Top mat (anode) corrosion potential (CSE) versus time for cracked beam specimens containing bare and epoxy-coated MMFX bars

Autopsy Results

Upon completion of the test (96 weeks), the cracked beam specimens were autopsied and photographed. Top and bottom bars from a cracked beam specimen with uncoated bars containing 4% chromium (Specimen CB-MMFX(4%)-5) are shown in

Figures 48 and 49; a top bar from a specimen containing a bar with 9% chromium (Specimen MMFX(9%)-5) is shown in Figure 50. Corrosion products can be observed on the both top and bottom mat bars of the specimens with bars containing 4% chromium. However, the corroded area on the top bar was significantly greater (70% of the top face and 30% of the bottom face) than the corroded area of the bottom bar (35% of the top face and 30% of the bottom face). As shown in Figure 52, corrosion products were also visible on the top bars of specimens containing 9% chromium (20% of the top face and 5% of the bottom face), but with a significantly lower corroded area than that on bars with 4% chromium.



Figure 48— Cracked beam MMFX(4%)-5 top bar after 96 weeks



Figure 49— Cracked beam MMFX(4%)-5 bottom bars after 96 weeks



Figure 50— Cracked beam MMFX(9%)-5 top bar after 96 weeks

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 51 through 54. 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 51— Cracked beam MMFX-ECR(2%)-2 top bar after disbondment test after 96 weeks



Figure 52— Cracked beam MMFX-ECR(2%)-2 bottom bar after disbondment test after 96 weeks



Figure 53— Cracked beam MMFX-ECR(4%)-5 top bar after disbondment test after 96 weeks



Figure 54— 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 mm²), the maximum area measured at each disbondment site. The average disbondment of MMFX-ECR(4%) top bars was 0.71 in.² (454 mm²). 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 mm²).

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

For all four types of reinforcement (MMFX bare bars containing 4% and 9% chromium and MMFX epoxy-coated bars containing 2% and 4% chromium), six rapid macrocell tests were prepared. In addition, to investigate the effect of pickling on MMFX bars, uncoated bars containing 4% and 9% chromium (one set of six bars each) were also pickled and evaluated using the rapid macrocell test. Macrocell corrosion, corrosion potential, LPR test, autopsy, and (for epoxy-coated bars) disbondment test results for these specimens are discussed in the following sections.

Macrocell Corrosion

The average corrosion rates of the bare MMFX bar specimens with 4% and 9% nominal chromium content in the as-received and pickled conditions are shown in Figure 55. Over the 15 weeks of testing, the as-received MMFX(4%) specimens exhibited the greatest corrosion rate (42.34 $\mu\text{m}/\text{yr}$ during first week of testing), whereas the pickled MMFX(9%) specimens exhibited the lowest corrosion rate (below 12.20 $\mu\text{m}/\text{yr}$). After the first week, the corrosion rates of the as-received MMFX(4%) specimens decreased gradually, to 35.20 $\mu\text{m}/\text{yr}$ at week 15. The corrosion rates of as-received MMFX(9%) specimens was 20.25 $\mu\text{m}/\text{yr}$ or less, except for the peak at week 4. The corrosion rate of

the pickled MMFX(4%) specimens fluctuated between 33.77 $\mu\text{m}/\text{yr}$ at week 2 and 8.07 $\mu\text{m}/\text{yr}$ at week 11, but generally decreased over time. For bars with both chromium contents, pickling resulted in reductions in the average corrosion rate relative to unpickled bars.

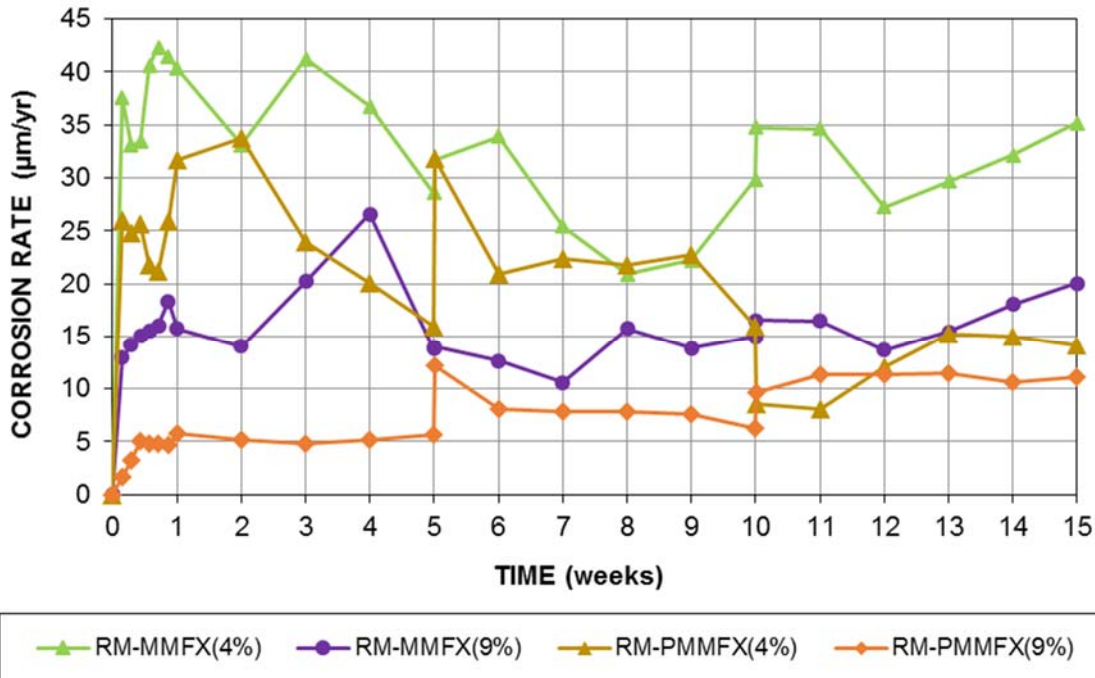


Figure 55—Average corrosion rates ($\mu\text{m}/\text{yr}$) versus time for rapid macrocell tests containing bare MMFX bars in as-received and pickled condition

The average corrosion rates of the epoxy-coated MMFX bars with 2% and 4% nominal chromium content are shown in Figure 56. Over 15 weeks of testing, the average corrosion rate of MMFX-ECR(4%) specimens was lower than that of MMFX-ECR(2%); however, all of the coated bar specimens exhibited average corrosion rates below 2.00 $\mu\text{m}/\text{yr}$, with the exception of the epoxy-coated MMFX-ECR(2%) specimens at week 5, which had an average corrosion rate of 2.33 $\mu\text{m}/\text{yr}$.

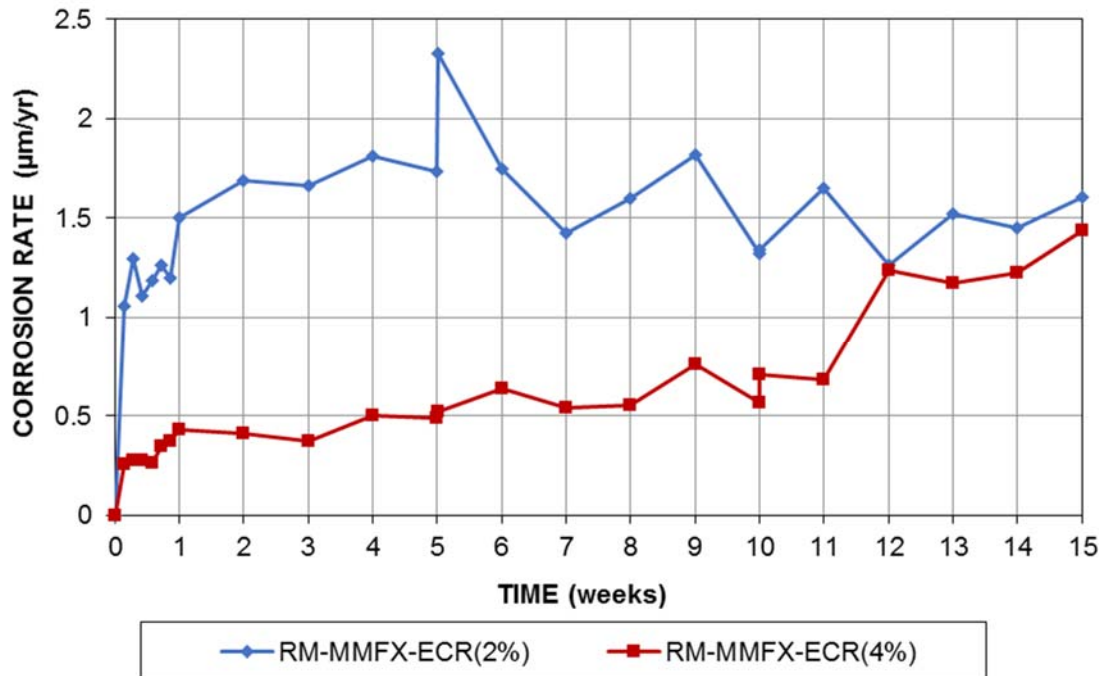


Figure 56— Average corrosion rates ($\mu\text{m}/\text{yr}$) versus time for rapid macrocell tests containing epoxy-coated MMFX bars based on total area

The individual corrosion losses at the end of the test (week 15) of the uncoated MMFX bar specimens with 4% and 9% nominal chromium content in the as-received and pickled conditions, and epoxy-coated bars containing 2% and 4% chromium are tabulated in Table 12. The average corrosion loss during the test for bare bars in the as-received and pickled condition and for the epoxy-coated bars (based on the total area) are shown in Figures 57 and 58, respectively. Corrosion losses were obtained by integrating the macrocell corrosion rates with respect to time. The corrosion losses of the as-received bars with 4% and 9% chromium after 15 weeks were $9 \mu\text{m}$ and $4.63 \mu\text{m}$, respectively; whereas the pickled bars with 4% and 9% chromium exhibited lower corrosion losses ($5.51 \mu\text{m}$ and $2.27 \mu\text{m}$ respectively). After 15 weeks, corrosion loss of MMFX-ECR(4%) was $0.21 \mu\text{m}$, less than half of corrosion loss of MMFX-ECR(2%), $0.45 \mu\text{m}$.

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
MMFX(4%)	4.36	4.30	10.2	13.2	11.8	10.2	9.00	3.79
MMFX(9%)	4.90	2.44	4.03	5.99	6.53	3.90	4.63	1.50
PMMFX(4%)	5.78	4.96	6.39	4.56	5.21	6.15	5.51	0.72
PMMFX(9%)	2.54	3.10	1.74	2.27	2.16	1.83	2.27	0.50

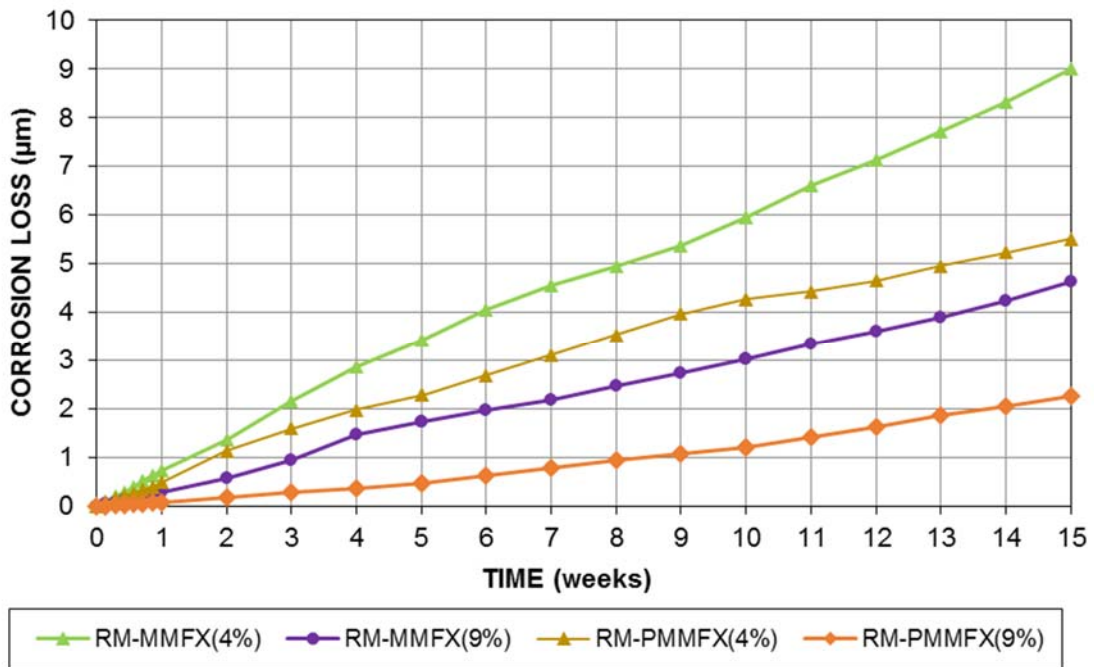


Figure 57—Average corrosion loss (μm) versus time for rapid macrocell tests containing bare MMFX bars in as-received and pickled condition

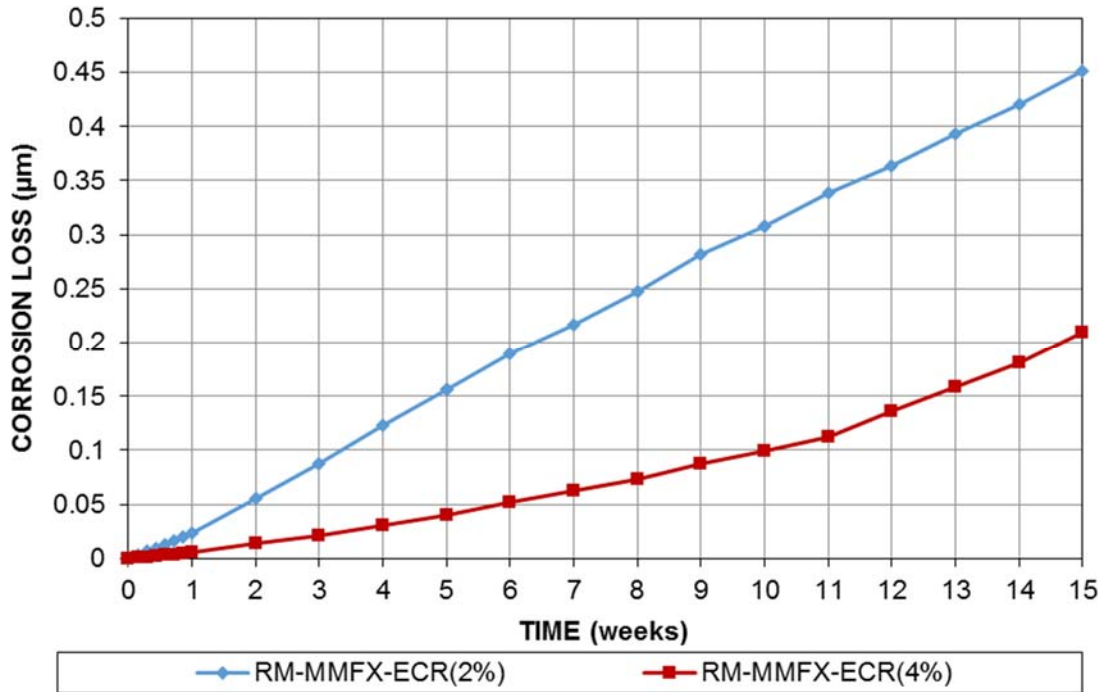


Figure 58— Average corrosion loss (μm) versus time for rapid macrocell tests containing epoxy-coated MMFX bars based on total area.

Linear Polarization Resistance (LPR)

Figures 59 and 60 show the average corrosion rate and loss, respectively, from LPR test results for the rapid macrocell specimens based on total area. Similar to results obtained from macrocell corrosion data, for bare bars, corrosion rate and loss decreased as chromium content increased. Although pickling reduced the corrosion rate and loss of MMFX bars containing 9% chromium, it was not effective on the MMFX bars with 4% chromium.

The individual corrosion loss at the end of the test (week 15) of the uncoated MMFX bar specimens with 4% and 9% nominal chromium content in the as-received and pickled conditions, and epoxy-coated bars containing 2% and 4% chromium based on the LPR test results are tabulated in Table 13. Pickling MMFX bars containing 9% chromium approximately halved the corrosion loss ($1.92 \mu\text{m}$ for PMMFX(9%) and $4.08 \mu\text{m}$ for MMFX(9%)) after 15 weeks. Pickling, however was not effective on reducing corrosion

loss of MMFX bars containing 4% chromium (8.28 μm for PMMFX(4%) and 8.73 μm for MMFX(4%)). 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. For bare bars the difference between LPR and macrocell corrosion losses was not significant.

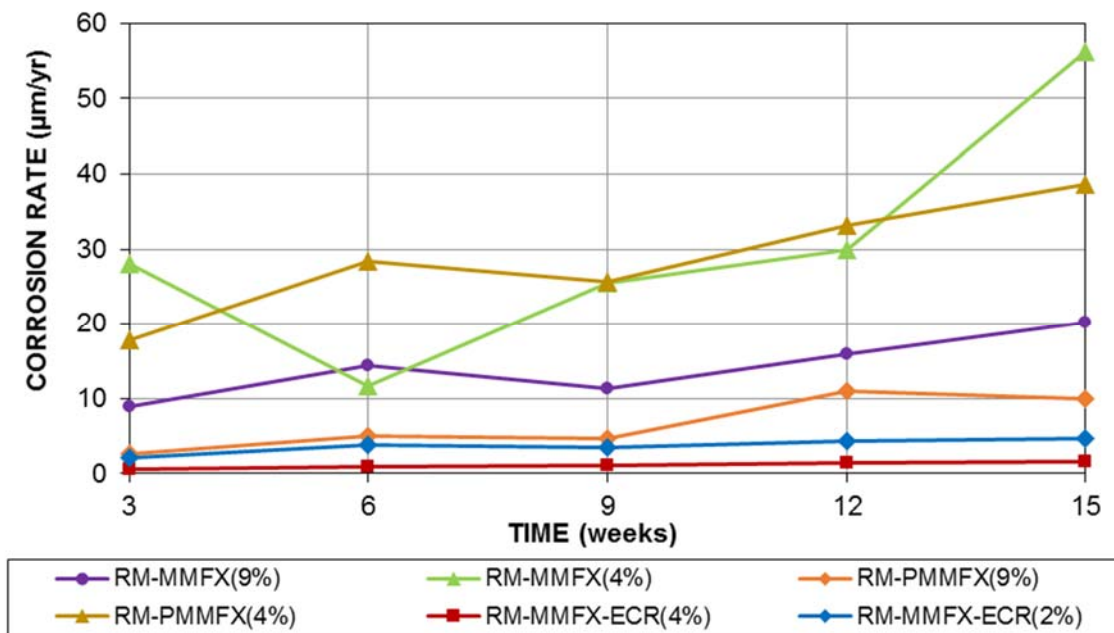


Figure 59— Average corrosion rates ($\mu\text{m}/\text{yr}$) versus time for rapid macrocell tests containing MMFX bars based on total area from LPR test results

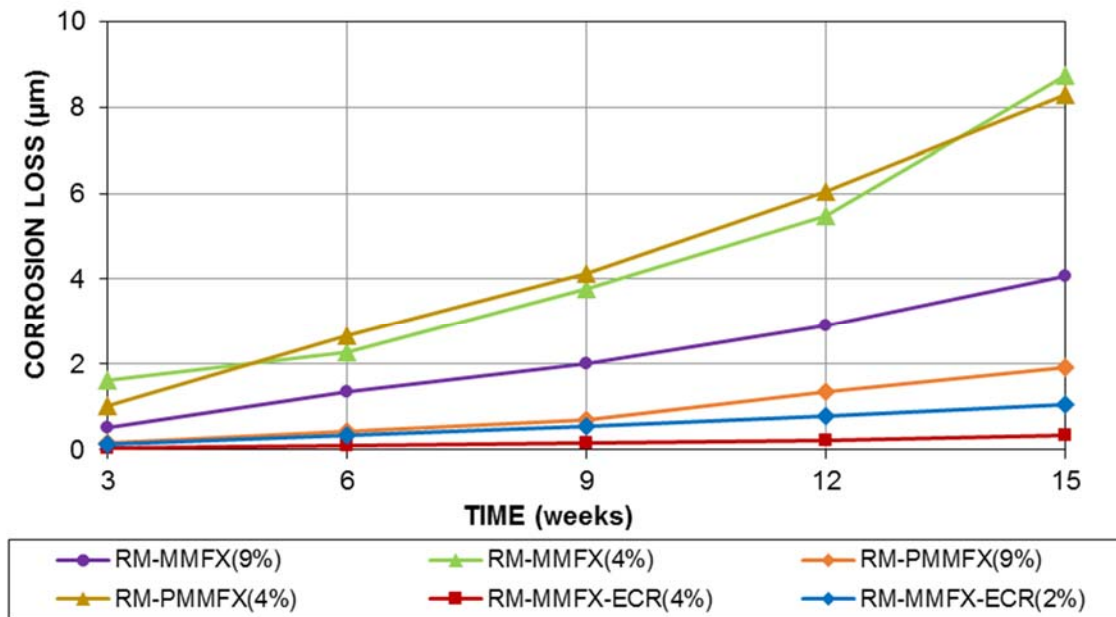


Figure 60— Average corrosion loss (μm) versus time for rapid macrocell tests containing MMFX bars based on total area from LPR test results

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
MMFX(4%)	8.27	3.75	8.41	14.3	7.95	9.74	8.73	3.39
MMFX(9%)	2.48	3.62	4.46	3.32	5.95	4.64	4.08	1.21
PMMFX(4%)	7.01	6.92	10.8	6.00	7.96	11.1	8.28	2.13
PMMFX(9%)	1.64	2.52	1.81	1.55	2.50	1.50	1.92	0.47

Corrosion Potential

The average anode corrosion potentials taken with respect to a saturated calomel electrode (SCE) are shown in Figure 61. The anode potentials for the as-received and pickled MMFX(9%) specimens, ranged from -0.40 V to -0.46 V and -0.31 V to -0.51 V , respectively. Similarly, potentials ranged from -0.46 V to -0.55 V for the as-received and pickled MMFX(4%) specimens. As shown, the pickling process did not significantly affect

the corrosion potential of bars with 9% or 4% chromium. 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.

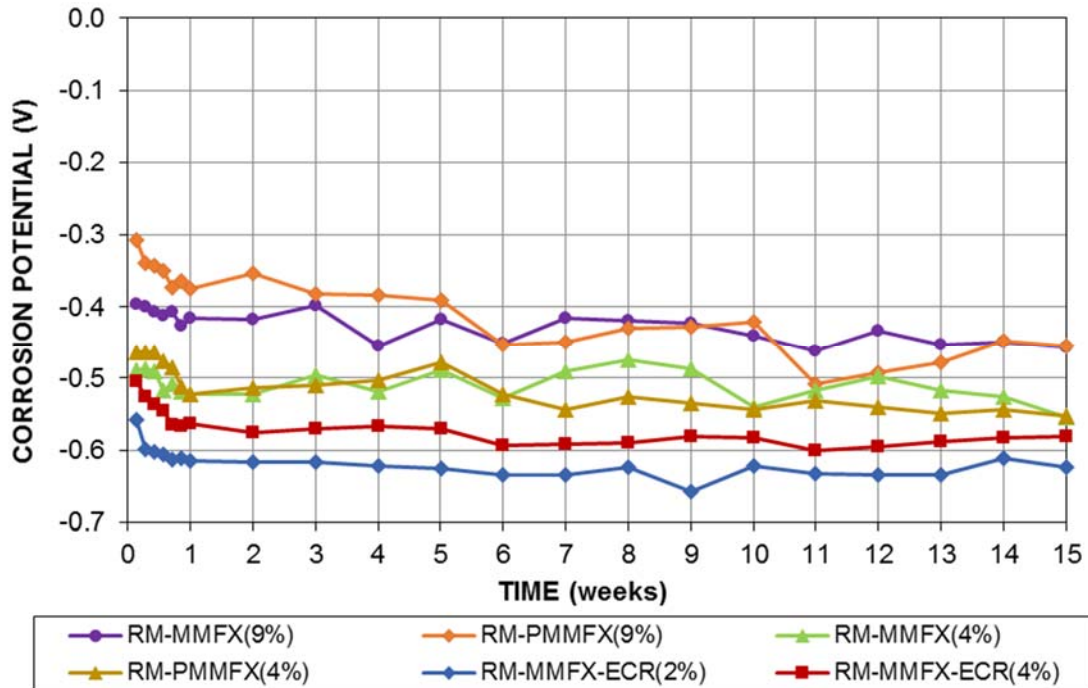


Figure 61— Average anode corrosion potentials (SCE) versus time for rapid macrocell tests containing MMFX bars

The average cathode corrosion potentials taken with respect to a saturated calomel electrode (SCE) are shown in Figure 62. The cathode potential of the bare MMFX bar specimens ranged from -0.17 V to -0.28 V at the first week of testing. The potentials of all, as-received and pickled, bare bars became more positive after the first week and ranged between -0.15 V and -0.17 V at week 5. After week 5, the potentials showed greater variation, with potentials between -0.15 V and -0.19 V at the end of 15 week testing.

The epoxy-coated bars showed more negative potentials compared to the uncoated bars, likely due to the oxygen-blocking effect of the coating. 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.

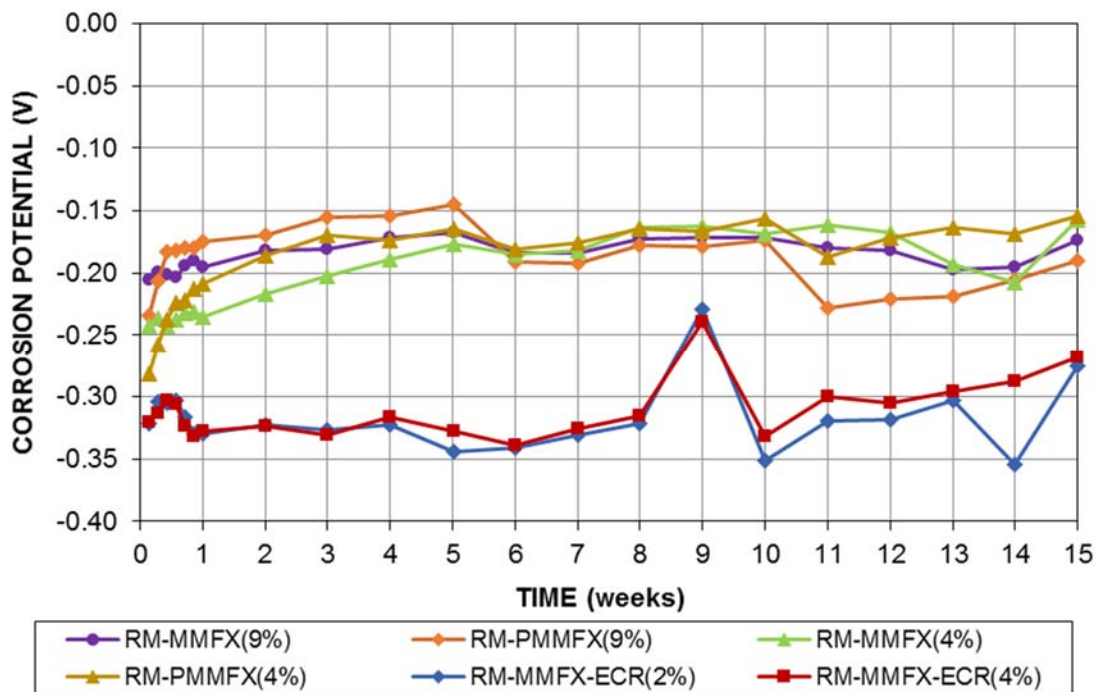


Figure 62— Average cathode corrosion potentials (SCE) versus time for rapid macrocell tests containing MMFX bars

Visual Observations

Upon completion of the rapid macrocell tests (15 weeks), all specimens were visually inspected and photographed. As shown in Figures 63 through 66, corrosion products were observed on the bars for all as-received and pickled uncoated MMFX steel, predominantly at and above the surface level of the solution.



Figure 63— Rapid macrocell test, anode bar of as-received MMFX(9%)-6 after 15 weeks



Figure 64 — Rapid macrocell test, anode bar of as-received MMFX(4%)-6 after 15 weeks



Figure 65— Rapid macrocell test, anode bar of pickled PMMFX(9%)-3 after 15 weeks



Figure 66— Rapid macrocell test, anode bar of pickled PMMFX(4%)-4 after 15 weeks

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 in² (677 mm²). Bars with 4% and 2% chromium are shown in Figures 67 and 68, 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 in² (78 mm²)) 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 in² (151 mm²) as average disbonded area).



Figure 67— Rapid macrocell test, anode bar of MMFX-ECR(4%)-5 after disbondment test after 15 weeks



Figure 68— 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 specimens with MMFX bare bars containing 9% and 4% chromium, Southern Exposure specimens were sampled for measuring critical chloride corrosion threshold at corrosion initiation. 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 and uncoated MMFX bars are shown in Table 16. Southern Exposure specimens with uncoated MMFX reinforcement containing 9% chromium had a similar critical chloride threshold (4.54 lb/yd³ (2.69 kg/m³)) to the MMFX bars containing 4% chromium (4.25 lb/yd³ (2.52 kg/m³)). The average time to corrosion initiation for MMFX(9%) and MMFX(4%) specimens was 21.4 and 27 weeks, respectively. The differences in chloride threshold and initiation age were analyzed using a Student's T-test and not found to be statistically significant ($p = 0.81$ and 0.94 , respectively). The critical chloride threshold of beam specimens containing MMFX-ECR(2%) was 4.11 lb/yd³ (2.44 kg/m³) at 34 weeks, compared to MMFX-ECR(4%) with a chloride threshold of 5.16 lb/yd³ (3.06 kg/m³) at an average age of 45 weeks. The differences in chloride threshold and initiation age for the epoxy-coated bars were also not statistically significant ($p = 0.38$ and 0.26 , respectively). The chloride content for individual samples of each specimen is presented in the Appendix A.

Table 16: Critical chloride corrosion threshold (lb/yd³) 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
MMFX(4%)	3.05	3.46	5.51	3.03	3.78	2.34	5.35	7.46	4.25	1.81
MMFX(9%)	4.24	5.59	2.76	4.12	1.87	1.59	5.45	10.7	4.54	1.47

*1(lb/yd³) = 0.593(kg/m³)

DISCUSSION

By comparing the average corrosion rate of Southern Exposure specimens (Figures 15 and 21) and cracked beam specimens (Figures 39 and 45) containing MMFX bars with 4% and 9% chromium for both macrocell corrosion and LPR test results, it can be seen that

MMFX bars containing 9% chromium exhibit greater corrosion resistance than MMFX bars containing 4% chromium.

The corrosion loss of conventional and MMFX steel for bench-scale tests and rapid macrocell tests are shown in Tables 17 and 18 for bare bars and epoxy-coated bars, respectively. The corrosion losses presented in the tables for conventional (coated and uncoated) steel were obtained from research by Darwin et al. (2013) with all the test procedures and specifications identical to the ones used for this study. Tabulated corrosion losses were obtained by integrating macrocell corrosion and LPR test corrosion rates with respect to time to express the macrocell and total corrosion losses, respectively.

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

Steel Designation	Macrocell Corrosion (μm)			Total (LPR) Corrosion (μm)		
	SE	CB	RM	SE	CB	RM
Conv.	16.4	30.1	10.9	16.6	56.4	13.6
MMFX(4%)	10.7	26.5	9.00	10.8	33.8	8.73
MMFX(9%)	8.70	16.4	4.63	9.05	20.4	4.08

Macrocell and total corrosion losses tabulated in Table 17 are compared in Figures 69 and 70, respectively. For uncoated reinforcement, the corrosion loss decreases as chromium content increases. The corrosion losses of MMFX(9%) were 55%, 36%, and 30% of those for conventional bars for Southern Exposure, cracked beam, and rapid macrocell tests, respectively. These findings agree with the results of study by Gong et al. (2003), which showed that the macrocell corrosion rate of MMFX bars was between one-third and two-thirds of that for conventional steel. Total corrosion losses of MMFX(4%) obtained from Southern Exposure, cracked beam and rapid macrocell tests were 65%, 60%,

and 64% of the ones for conventional bars, respectively, greater than that observed for MMFX(9%) but still about two-thirds of the losses for conventional steel.

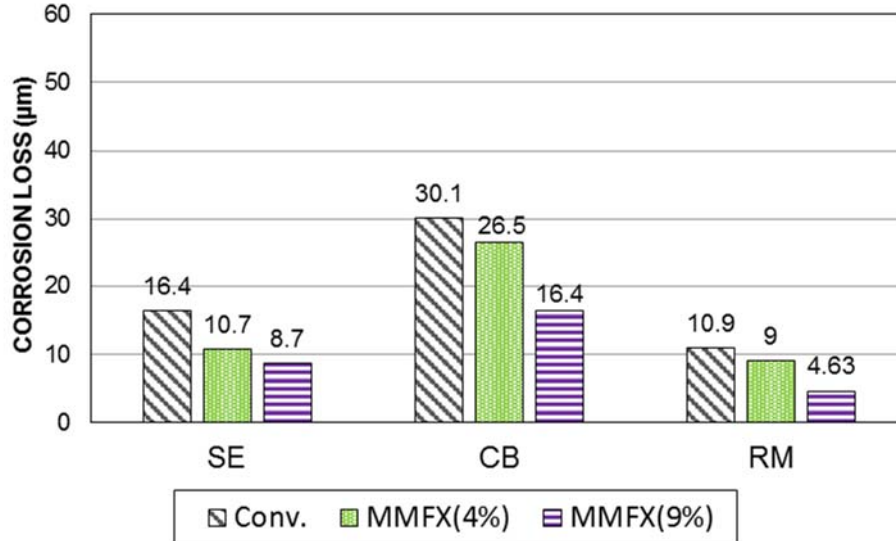


Figure 69— Corrosion loss (μm) for uncoated conventional (Darwin et al. 2013) and MMFX bars in bench-scale and rapid macrocell tests obtained from macrocell corrosion rates

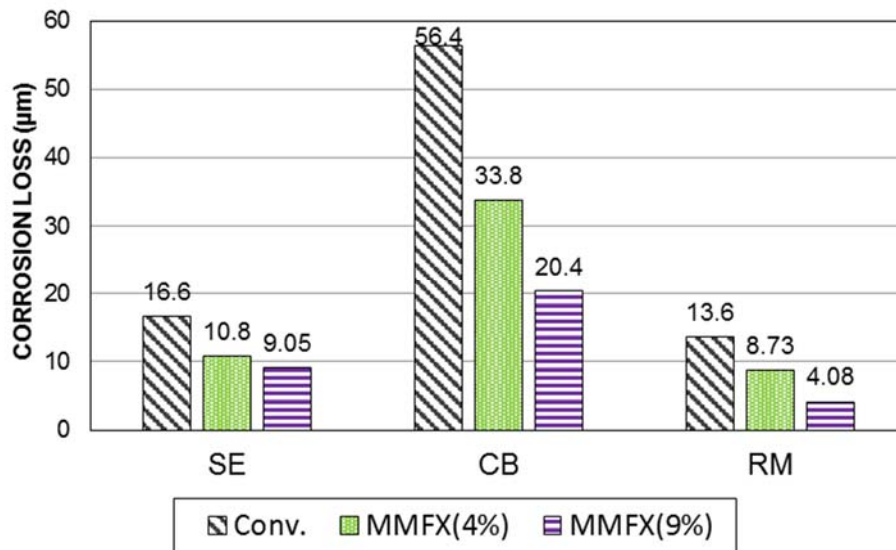


Figure 70— Corrosion loss (μm) for uncoated conventional (Darwin et al. 2013) and MMFX bars in bench-scale and rapid macrocell tests obtained from LPR test corrosion rates

Figures 71 and 72, 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 18: 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

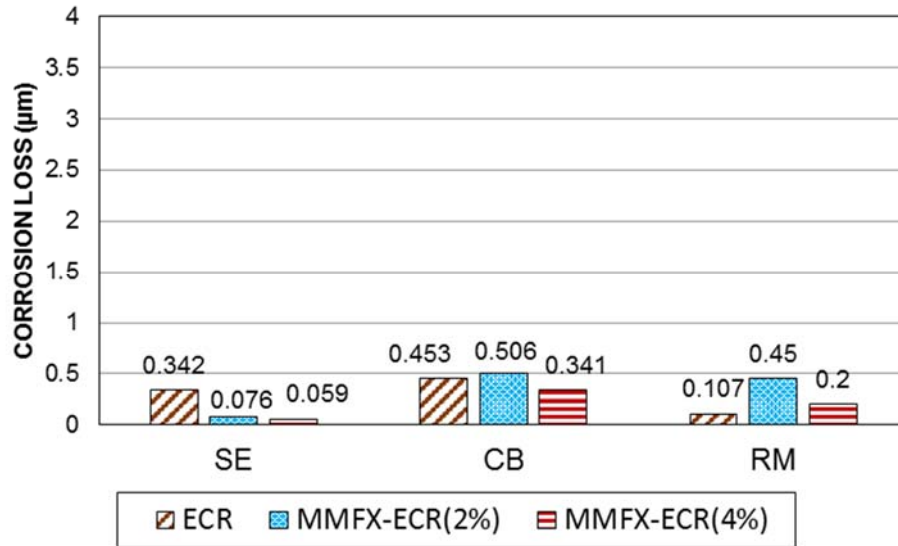


Figure 71— Corrosion loss (μm) for epoxy-coated conventional (Darwin et al. 2013) and MMFX bars in bench-scale and rapid macrocell tests obtained from macrocell corrosion rates

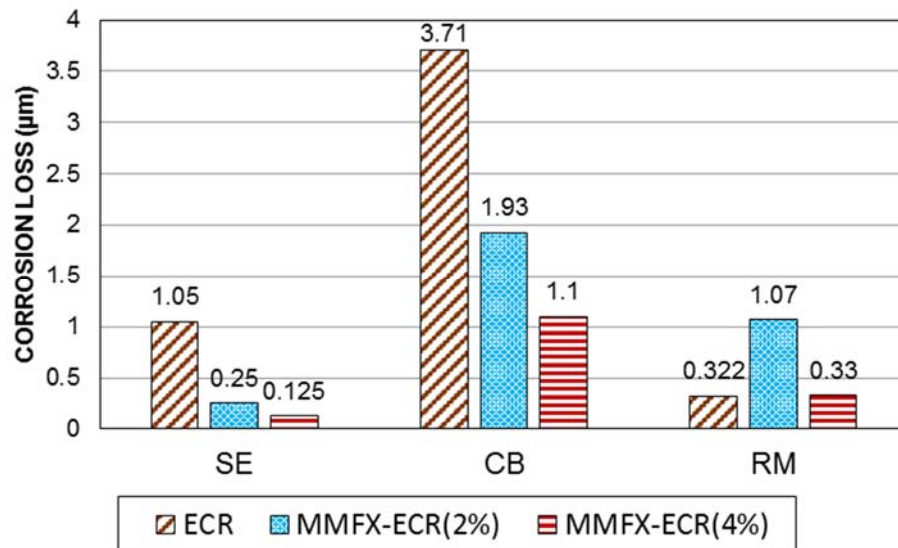


Figure 72— Corrosion loss (μm) for epoxy-coated conventional (Darwin et al. 2013) and MMFX bars in bench-scale and rapid macrocell tests obtained from LPR test corrosion rates.

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 19. 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 19: 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 73, 74 and 75, 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.

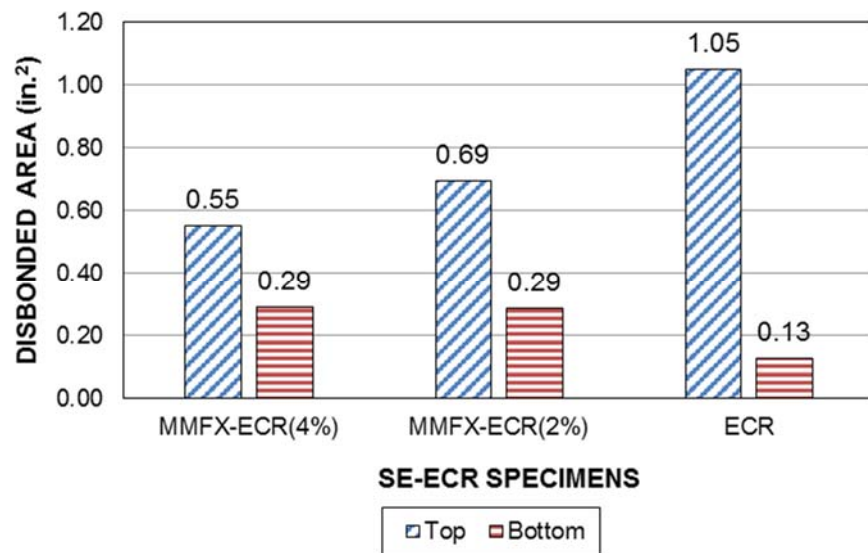


Figure 73— Comparison of disbondment test results of top and bottom bars in Southern Exposure specimens containing epoxy-coated conventional (Darwin et al. 2013) and MMFX bars

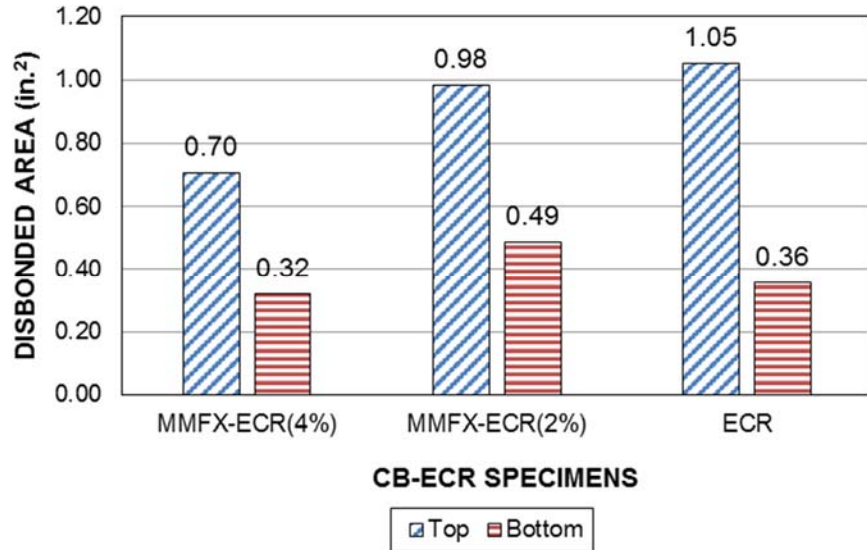


Figure 74— Comparison of disbondment test results of top and bottom bars in cracked beam specimens containing epoxy-coated conventional (Darwin et al. 2013) and MMFX bars

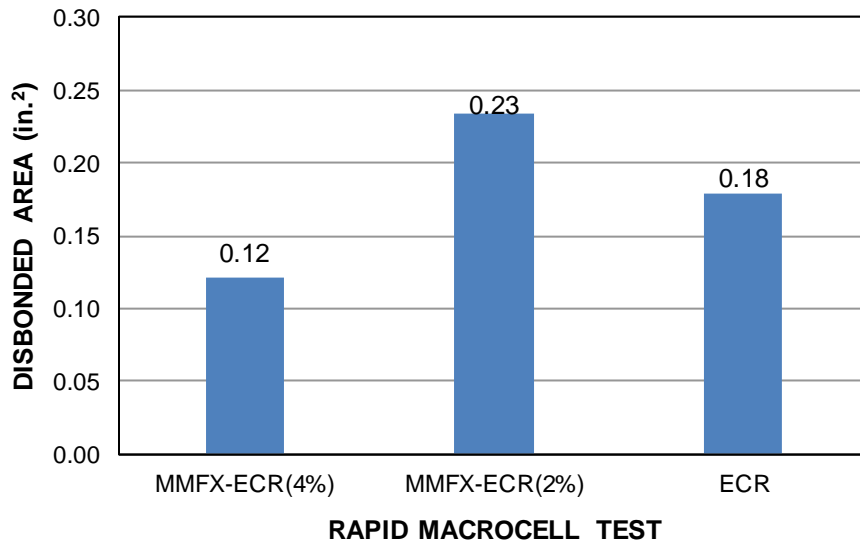


Figure 75— Comparison of disbondment test results of anode bars in rapid macrocell tests containing epoxy-coated conventional (Darwin et al. 2013) and MMFX bars

The critical chloride corrosion threshold of the MMFX bars containing 9% chromium obtained in this study was 4.54 lb/yd³ (2.69 kg/m³), which is in agreement with the results of a study carried out by Darwin et al. (2009) that showed the critical chloride

threshold of the reinforcement ranged from 4.72 to 6.86 lb/yd³ (2.8 to 4.07 kg/m³). The critical chloride threshold of the MMFX bars containing 4% chromium (4.25 lb/yd³ (2.52 kg/m³)) was close to that for MMFX(9%) bars (4.54 lb/yd³ (2.69 kg/m³)); as was the time to corrosion initiation (21.4 weeks for MMFX(9%) and 27 weeks for MMFX(4%)). These critical chloride thresholds were almost three times that of reported for uncoated conventional steel (1.53 to 2.05 lb/yd³ (0.91 to 1.22 kg/m³)) in prior research (Ji et al. 2005).

The critical chloride corrosion threshold of the epoxy-coated MMFX bars containing 4% chromium obtained in this study was 5.16 lb/yd³ (3.06 kg/m³), 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/yd³ (2.44 kg/m³) 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/yd³ (2.72 kg/m³) 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.

A comparison between total corrosion rates and losses of pickled and as-received MMFX bars in Figure 59 and Table 13 shows that pickling reduced total corrosion loss of MMFX(9%) bars by almost half and, thus, was effective in improving the corrosion resistance of MMFX bars containing 9% chromium. Pickling, however, was not as

effective on corrosion performance of MMFX bars containing 4% chromium, with only a 5% reduction in corrosion loss.

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 MMFX steel containing 9% and 4% chromium (ASTM A1035 Type CS and CM steel), and 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 76 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).

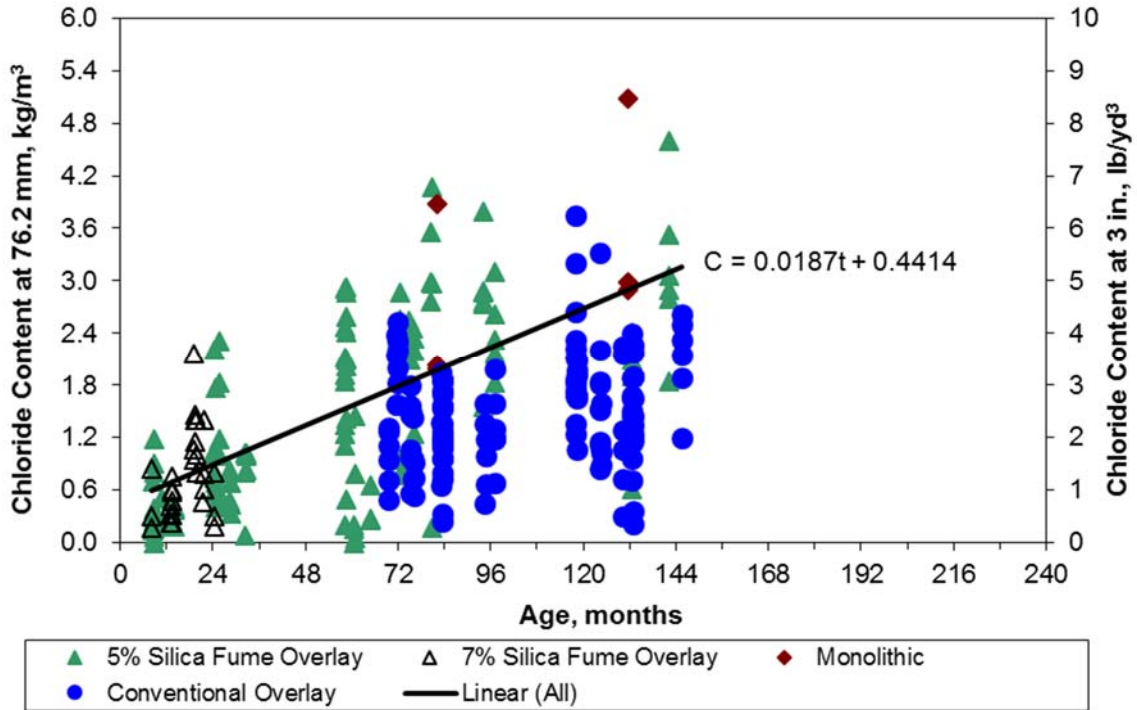


Figure 76— Chloride content taken on cracks interpolated at depth of 3 in. vs. placement age for bridges with an AADT > 7500 (Lindquist et al. 2006)

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:

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

where

C_{crit} = critical chloride corrosion threshold, kg/m³

t_i = 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 20. 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 20: 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(4%)	4.25	2.52	9.2
MMFX(9%)	4.54	2.69	10.0
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:

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

where

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

C = cover, mm.

D = bar diameter, mm.

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

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

For conventional reinforcement, assuming uniform corrosion, fractional length (L_f) and fractional area (A_f) of corroding bar are set to 1. Thus, in a bridge deck with 3 in. (76.2 mm) clear concrete cover containing No. 5 (No. 16) uncoated steel, critical corrosion loss would be:

$$x_{crit} = 45 \left(\frac{[76.2/25.4]^{2-1}}{16^{0.38} \times 1^{0.1} \times 1^{0.6}} + 0.2 \right) \times 3^{1-1}$$
$$x_{crit} = 56 \mu\text{m}$$

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:

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

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:

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

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

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 bare and 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 21. For systems with bare bars, specimens with MMFX reinforcement containing 4% and 9% chromium showed approximately half the average corrosion rate (7.55 and 6.17 $\mu\text{m}/\text{yr}$, respectively) as specimens with conventional steel (14.5 $\mu\text{m}/\text{yr}$). Conventional epoxy-coated reinforcement in specimens with 100% portland cement showed the highest total corrosion rate based on exposed area (50.0 $\mu\text{m}/\text{yr}$) among specimens with coated bars. While the average corrosion rate of MMFX-ECR(2%) specimens (40.2 $\mu\text{m}/\text{yr}$) was comparable to that of epoxy-coated conventional reinforcement (42.8 $\mu\text{m}/\text{yr}$), MMFX-ECR(4%) specimens exhibited approximately half the average corrosion rate of epoxy-coated conventional reinforcement (21.7 $\mu\text{m}/\text{yr}$).

Table 21: Average corrosion rate ($\mu\text{m}/\text{yr}$) 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(4%)	13.0	10.9	6.18	8.97	6.44	8.21	3.74	3.03	7.55	3.40	0.45
MMFX(9%)	10.2	8.84	6.49	3.00	5.60	6.27	2.89	6.03	6.17	2.53	0.41
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 22. 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 22: Equivalent total corrosion rates for bridge decks with and without cracks, and different corrosion protection systems

System ^a	Laboratory specimen corrosion rate ($\mu\text{m}/\text{yr}$)		Equivalent total corrosion rate ($\mu\text{m}/\text{yr}$)			
	Uncracked	Cracked	Exposed area		Effective area	
			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(4%)	7.55	13.59	1.17	1.82	3.51	4.55
MMFX(9%)	6.17	11.1	0.96	1.49	2.87	3.72
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 23 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 24. The lowest estimated time from initiation to first cracking is observed in concrete decks that contain conventional bare steel (6.4 years). Bridge decks with MMFX bars containing 4% chromium have almost twice the estimated time from initiation to cracking (12.3 years) compared to conventional bare bars. Estimated time from initiation to first cracking for concrete containing MMFX bars with 9% chromium, 15.1 years, is almost triple of that for conventional reinforcement. 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 23: Estimated times to first cracking after corrosion initiation based on corrosion rate in cracked concrete

System	Corrosion rate ($\mu\text{m}/\text{yr}$)	Critical corrosion loss (μm)	Cracking time (yr)
Conv.	8.74	56	6.4
ECR	42.4	1610	38.0
MMFX steel			
MMFX(4%)	4.55	56	12.3
MMFX(9%)	3.72	56	15.1
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 24 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). Uncoated MMFX bars containing 4% and 9% chromium, respectively, show an expected life of 31 and 35 years in bridges, approximately twice as much as conventional reinforcement. 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 24: 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(4%)	9.2	12.3	10	31
MMFX(9%)	10	15.1	10	35
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 24 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 25. 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/yd² of bridge deck. MMFX(4%) and MMFX(9%) had life cycle costs of \$463.81 and \$468.40, respectively. Of the coated bar systems, MMFX-ECR(4%) had a life cycle cost of

\$215.28, making it the most cost-effective system in this study. ECR and MMFX-ECR(2%) had life-cycle costs of \$281.27 and \$289.11, respectively.

Table 25: 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 ASTM A1035 Type CL (2% Cr), CM (4% Cr), and CS (9% Cr) steel bars produced by MMFX Technologies was evaluated in both cracked and uncracked concrete as well as in the rapid macrocell test. Uncoated bars with 4% and 9% chromium were tested both in the condition received and after pickling at the University of Kansas; coated bars with 2% and 4% chromium were also 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 MMFX bars containing 4% and 9% chromium were similar and about three times greater than the critical chloride

threshold of conventional steel (4.25 lb/yd³ (2.52 kg/m³) and 4.54 lb/yd³ (2.69 kg/m³), respectively).

- 2- The critical chloride corrosion threshold of epoxy-coated MMFX bars containing 2% and 4% chromium were 4.11 lb/yd³ (2.44 kg/m³) and 5.16 lb/yd³ (3.06 kg/m³), respectively, comparable to that of conventional epoxy-coated reinforcement [4.59 lb/yd³ (2.72 kg/m³)].
- 3- The average corrosion loss of MMFX bars containing 9% chromium ranged from 30% to 55% that of conventional steel, while for MMFX bars containing 4% chromium the average corrosion loss was approximately two-thirds of that for conventional steel.
- 4- Pickling was effective in improving corrosion resistance of MMFX bars containing 9% chromium but less so on MMFX bars containing 4% chromium.
- 5- 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. This represents a significant improvement in performance relative to uncoated MMFX containing 4% chromium, which exhibited an average corrosion rate of approximately two-thirds that of uncoated conventional steel. The disbanded 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.

- 6- Epoxy-coated MMFX bars containing 2% chromium did not show significantly better performance against corrosion compared to conventional epoxy-coated bars.
- 7- 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 Southern Exposure specimens with MMFX uncoated bars containing 9% chromium

Specimen	Chloride Content (lb/yd ³) ^a						Avg.	Std. Dev.
	1	2	3	4	5	6		
MMFX(9%)-1	4.16	4.84	4.48	2.61	4.35	5.00	4.24	0.85
MMFX(9%)-2	5.74	6.18	5.22	6.04	6.08	4.28	5.59	0.73
MMFX(9%)-3	2.56	2.21	1.74	1.87	3.00	5.17	2.76	1.27
MMFX(9%)-4	6.67	4.50	2.99	3.50	4.04	3.01	4.12	1.38
MMFX(9%)-5	2.01	1.48	2.16	1.96	1.90	1.73	1.87	0.24
MMFX(9%)-6	1.45	1.57	1.57	1.56	1.50	1.90	1.59	0.16
MMFX(9%)-7	4.75	4.88	10.23	4.52	4.62	3.71	5.45	2.38
MMFX(9%)-8	5.74	7.82	8.55	16.5	8.78	16.8	10.7	4.73
							4.54	1.47

^a1 (lb/yd³) = 0.592 (kg/m³)

Table A.2: Critical chloride threshold for Southern Exposure specimens with MMFX uncoated bars containing 4% chromium

Specimen	Chloride Content (lb/yd ³) ^a						Avg.	Std. Dev.
	1	2	3	4	5	6		
MMFX(4%)-1	1.75	3.45	2.73	3.28	4.71	2.38	3.05	1.02
MMFX(4%)-2	3.17	2.74	2.28	2.65	4.80	5.14	3.46	1.21
MMFX(4%)-3	0.44	2.65	3.97	11.92	8.83	5.24	5.51	4.21
MMFX(4%)-4	0.45	2.18	4.02	2.57	3.80	5.17	3.03	1.66
MMFX(4%)-5	5.77	5.03	3.94	2.14	2.66	3.11	3.78	1.41
MMFX(4%)-6	-	3.53	2.39	1.67	1.96	2.12	2.34	0.72
MMFX(4%)-7	7.55	5.66	5.03	4.43	5.63	3.79	5.35	1.30
MMFX(4%)-8	7.59	5.18	5.62	12.67	5.00	8.70	7.46	2.94
							4.25	1.81

^a1 (lb/yd³) = 0.592 (kg/m³)

Table A.3: 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

^a1 (lb/yd³) = 0.592 (kg/m³)

Table A.4: 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

^a1 (lb/yd³) = 0.592 (kg/m³)

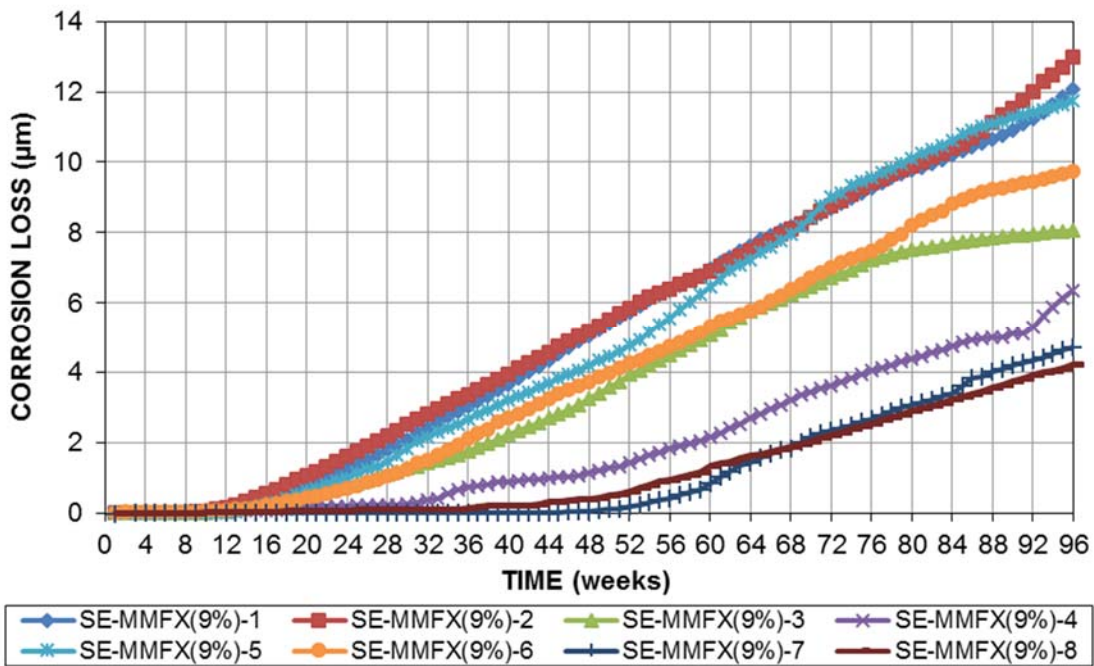


Figure A.17— Macrocell corrosion losses (μm) for Southern Exposure specimens containing MMFX(9%) bars

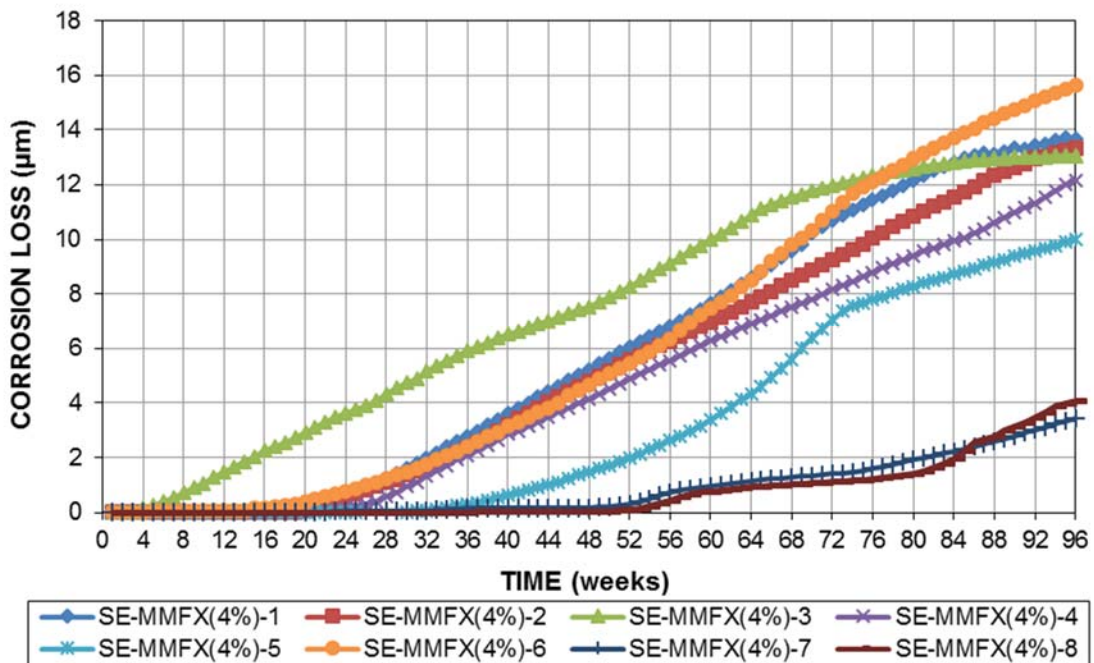


Figure A.18— Macrocell corrosion losses (μm) for Southern Exposure specimens containing MMFX(4%) bars

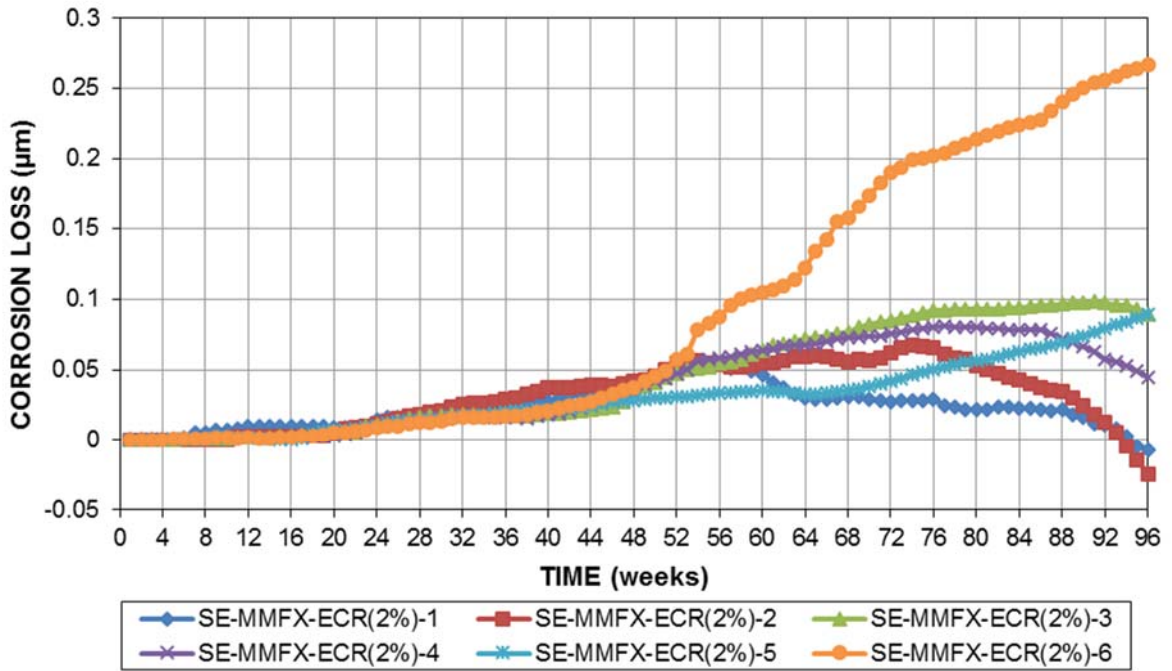


Figure A.19— Macrocell corrosion losses (μm) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

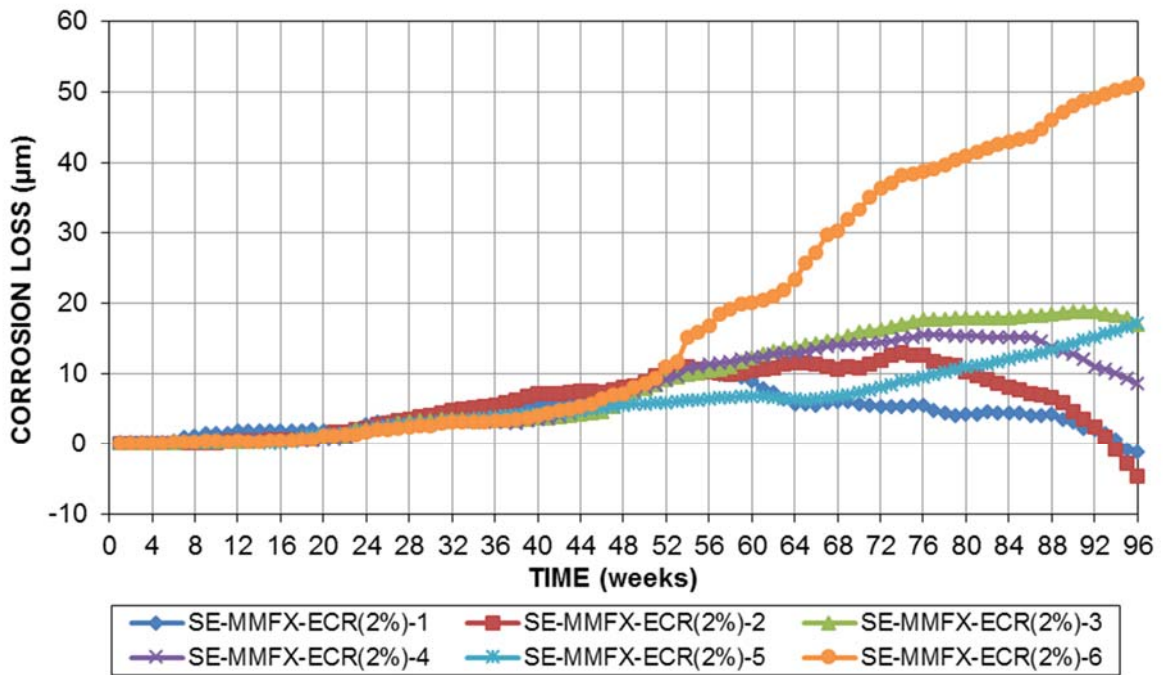


Figure A.20— Macrocell corrosion losses (μm) based on exposed area of reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

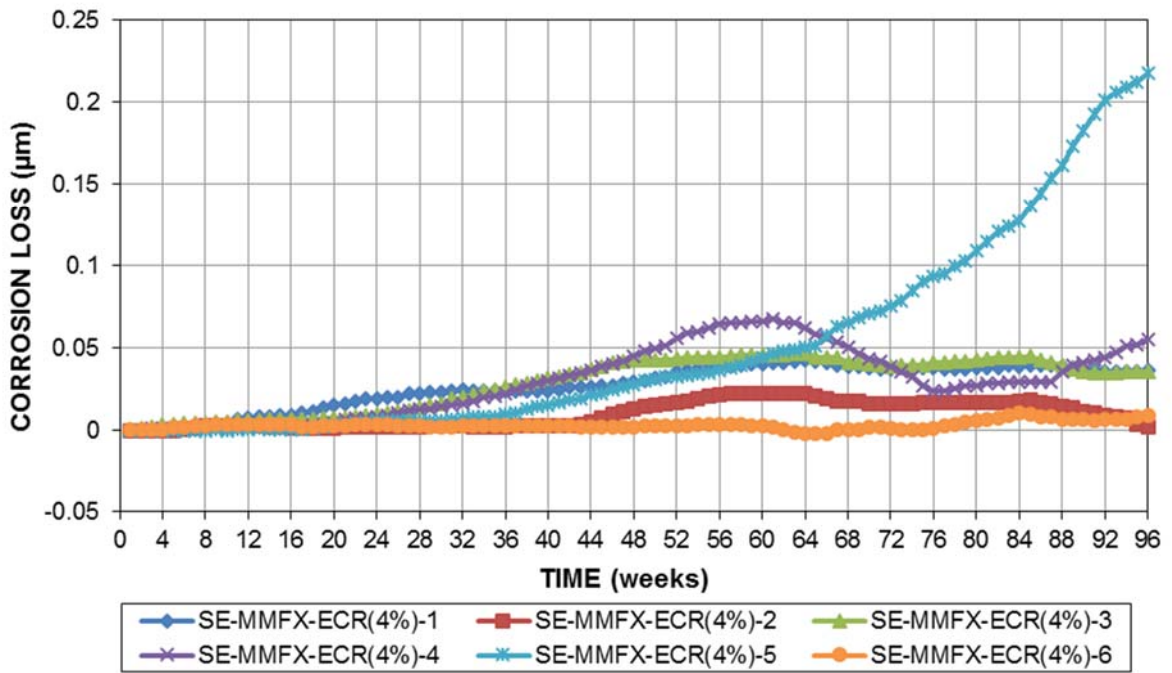


Figure A.21— Macrocell corrosion losses (μm) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

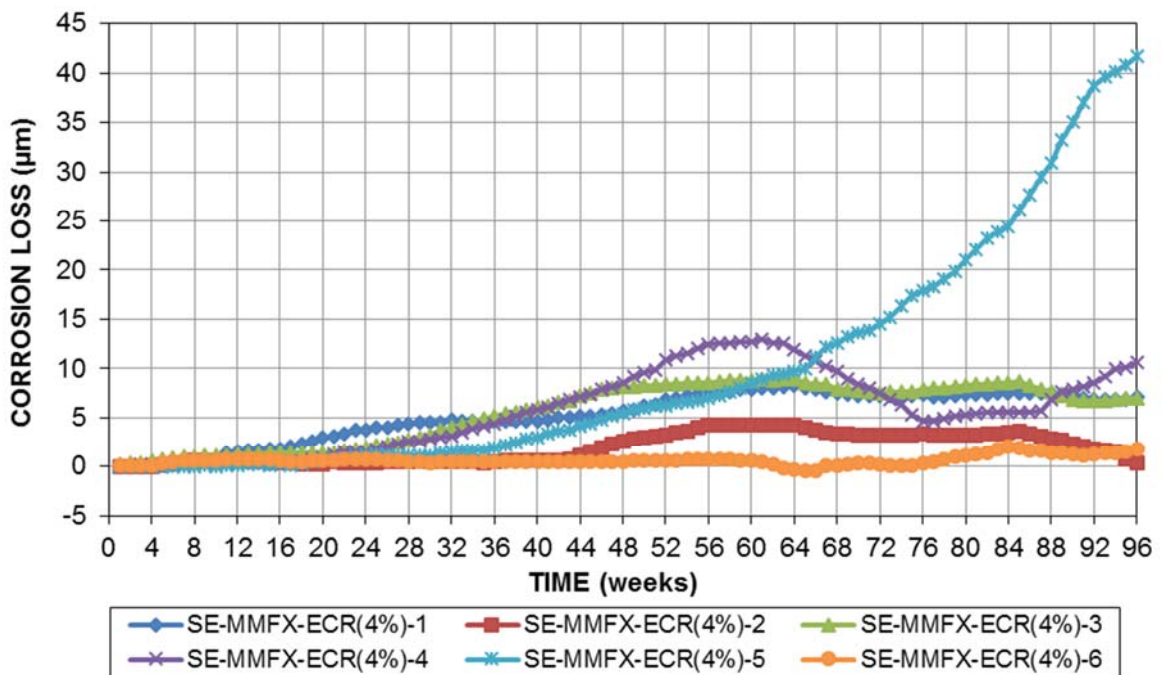


Figure A.22— Macrocell corrosion losses (μm) based on exposed area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

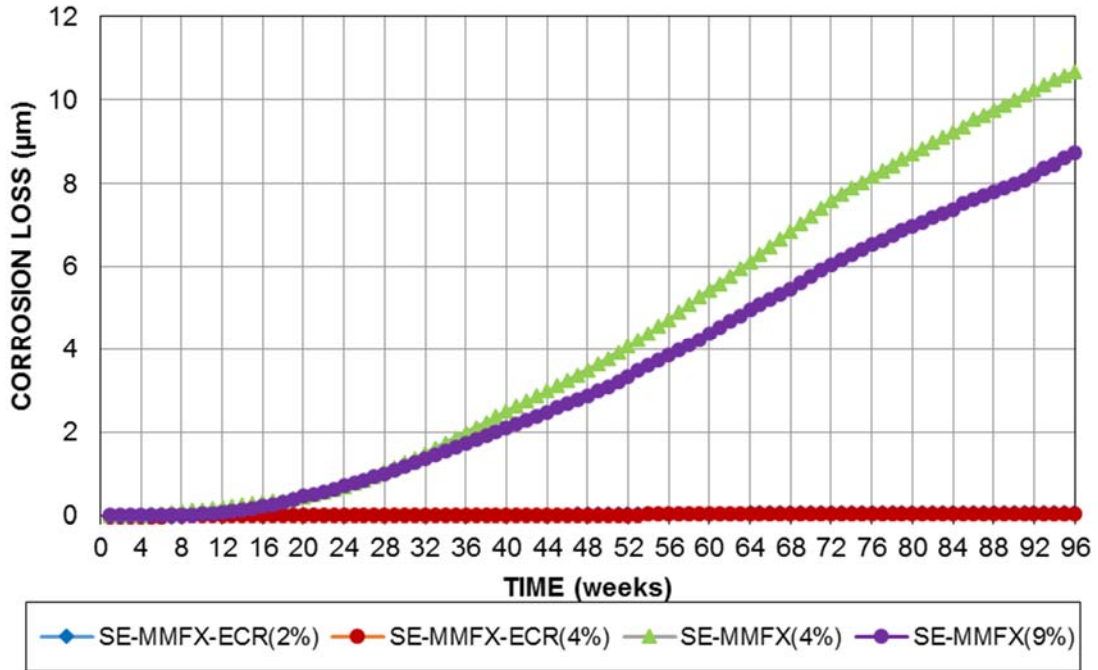


Figure A.23— Average corrosion loss (µm) based on total area versus time for Southern Exposure specimens

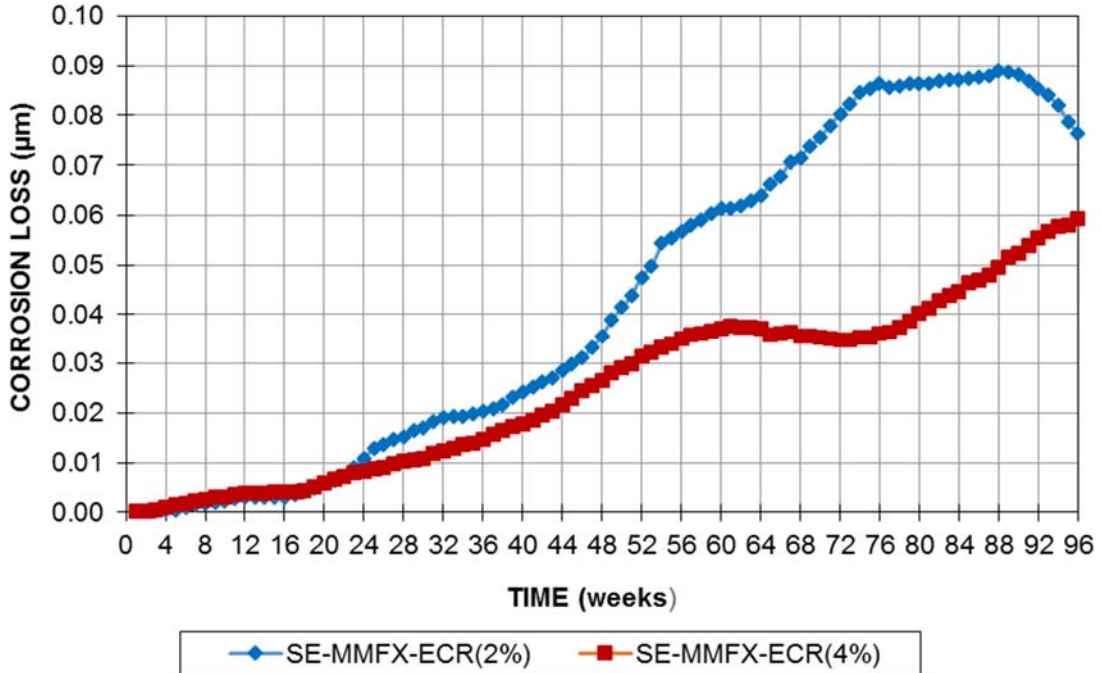


Figure A.24— Average corrosion loss (µm) based on total area versus time for Southern Exposure specimens with epoxy-coated reinforcement

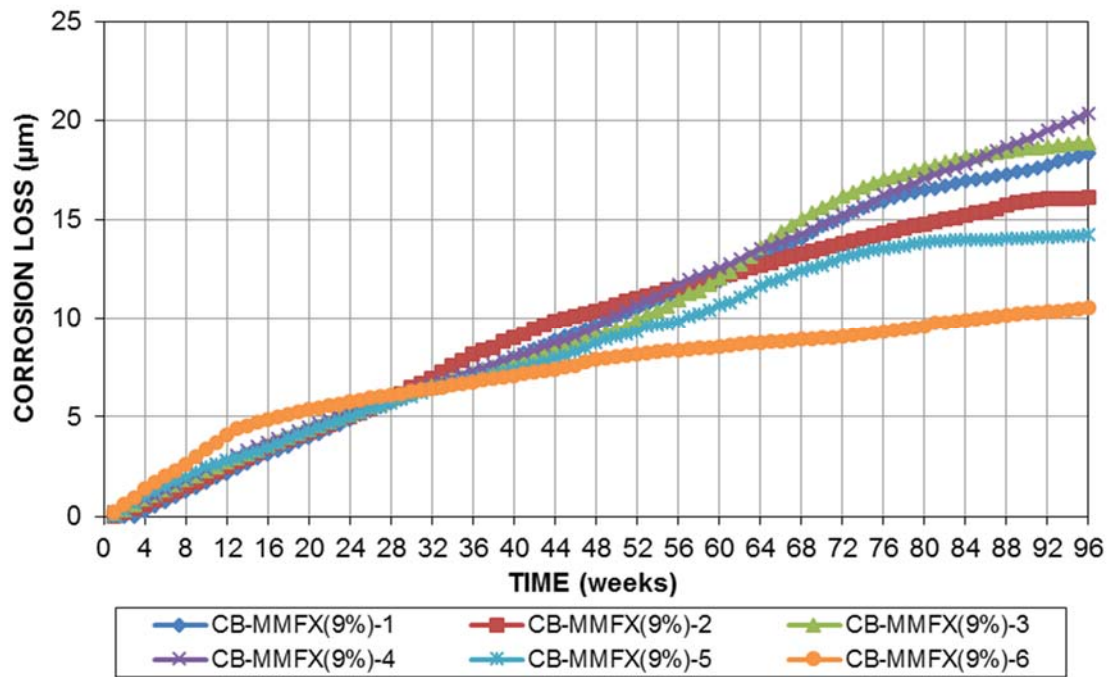


Figure A.25— Macrocell corrosion losses (μm) for cracked beam specimens containing MMFX(9%) bars

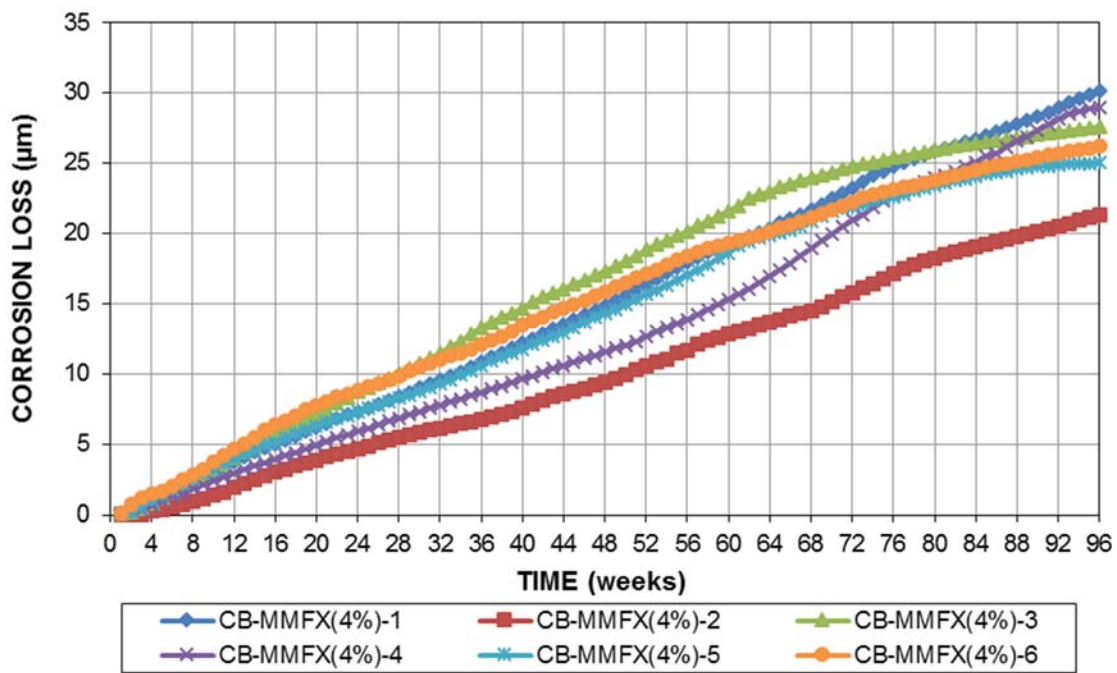


Figure A.26— Macrocell corrosion losses (μm) for cracked beam specimens containing MMFX(4%) bars

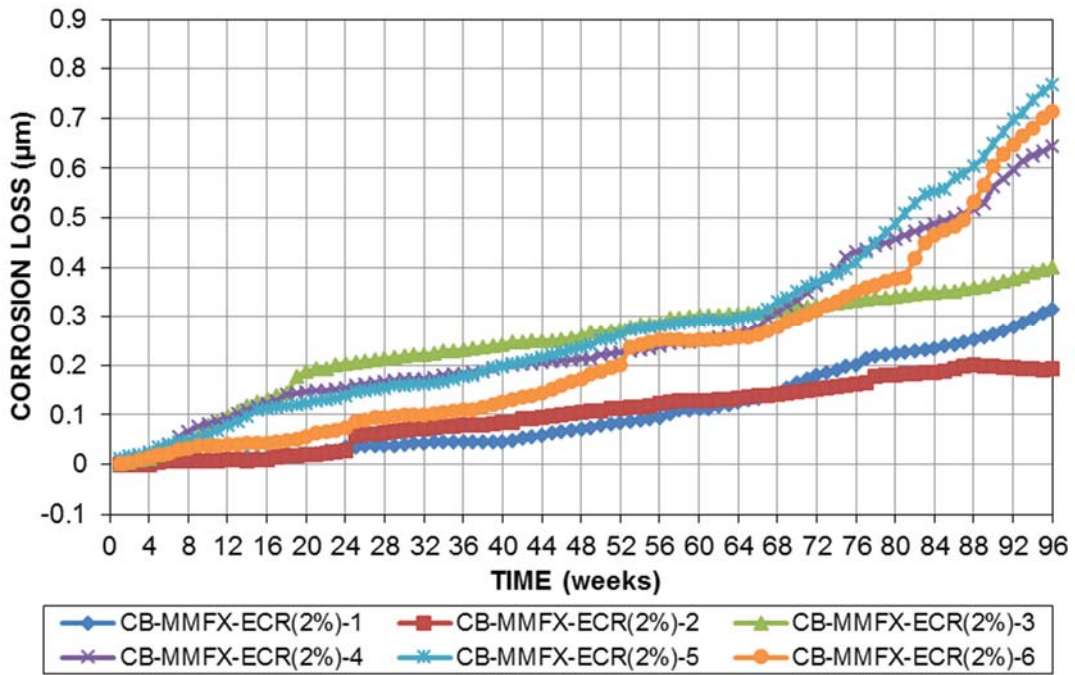


Figure A.27— Macrocell corrosion losses (μm) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

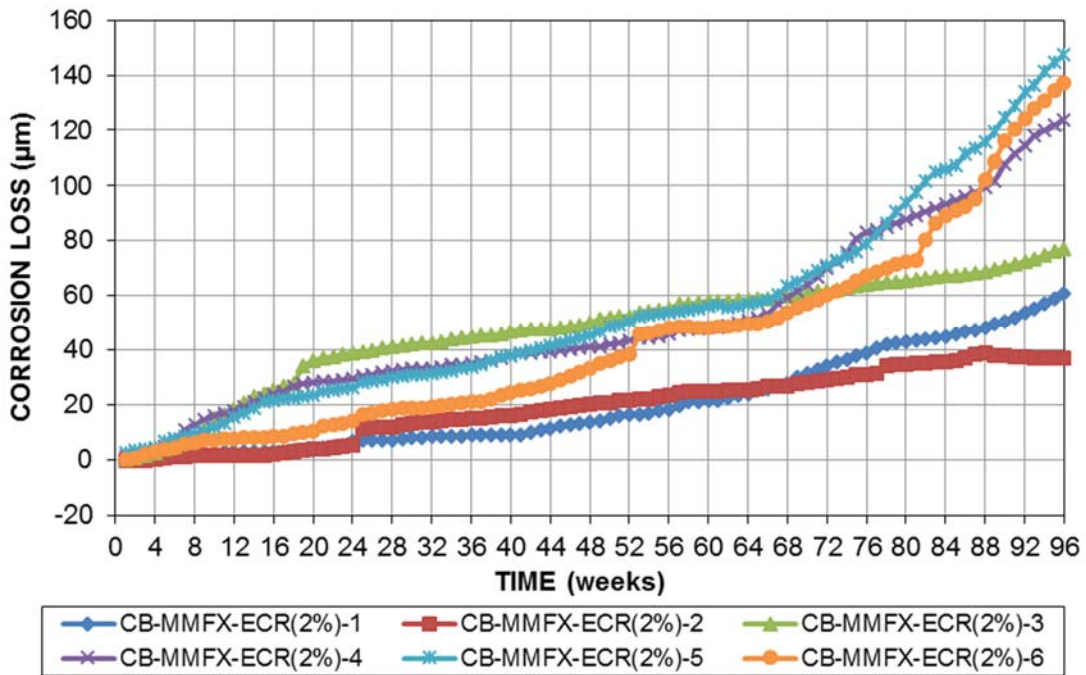


Figure A.28— Macrocell corrosion losses (μm) based on exposed area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

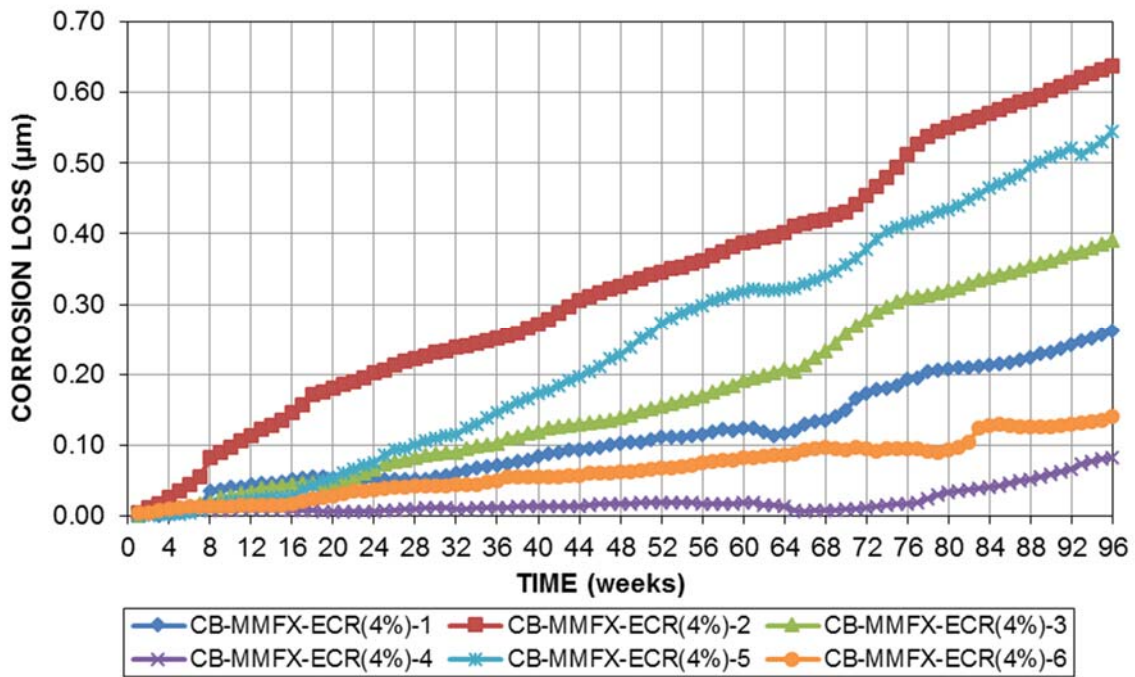


Figure A.29— Macrocell corrosion losses (μm) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(4%) bars

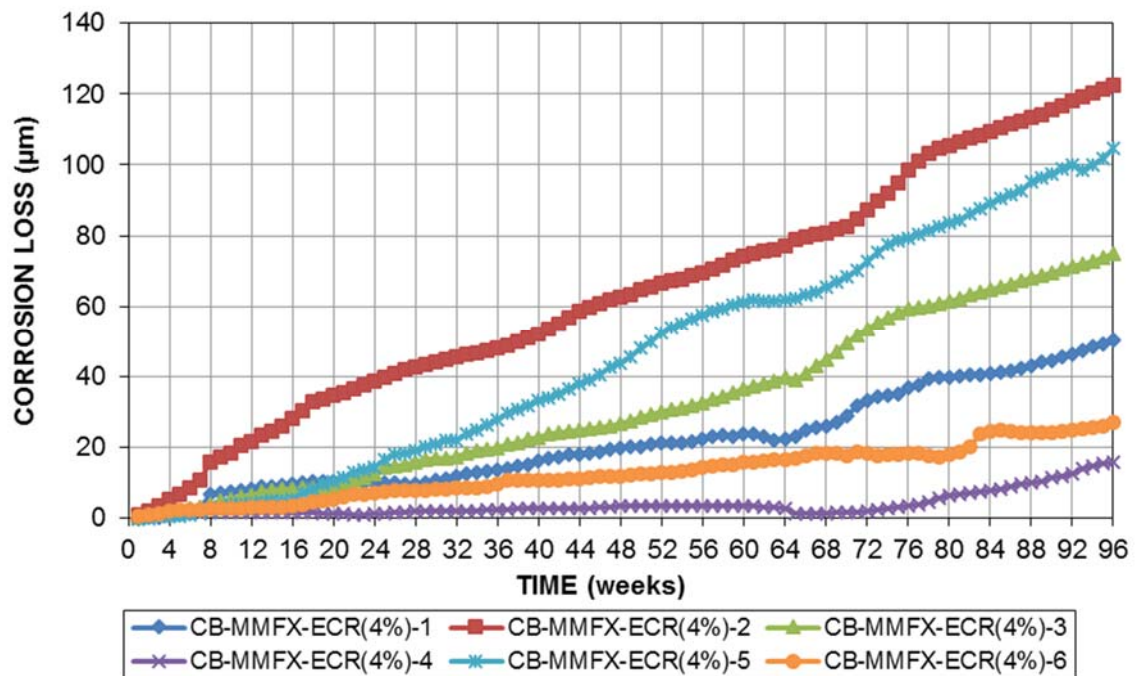


Figure A.30— Macrocell corrosion losses (μm) based on exposed area of reinforcement for cracked beam specimens containing MMFX-ECR(4%) bars

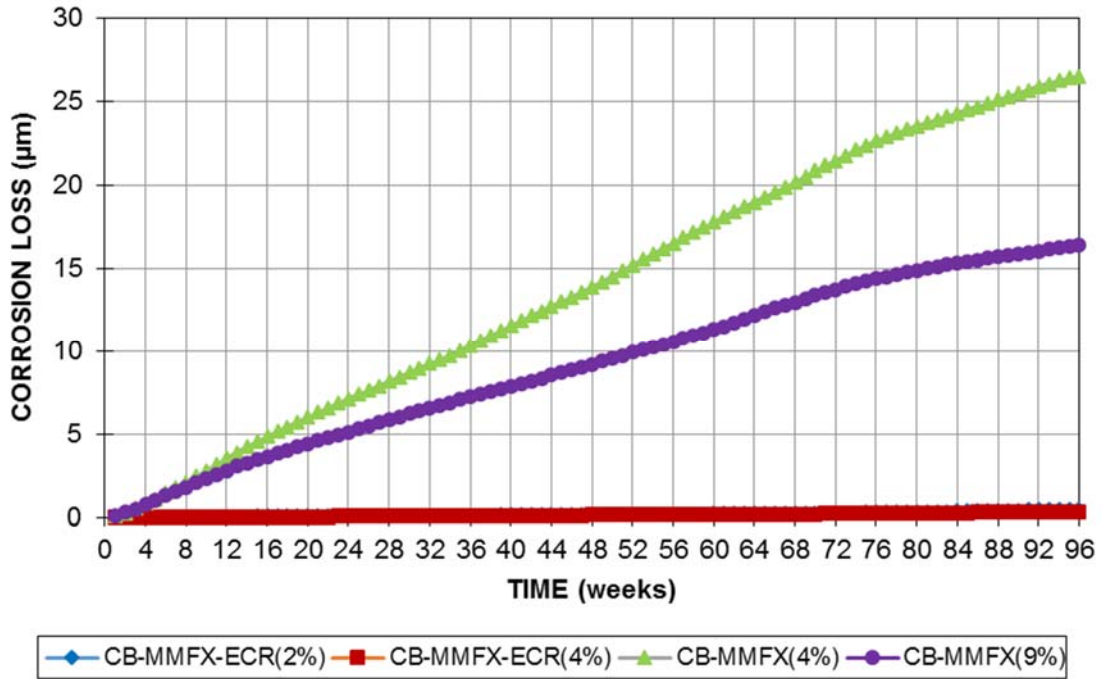


Figure A.31— Average corrosion loss (μm) based on total area versus time for cracked beam specimens

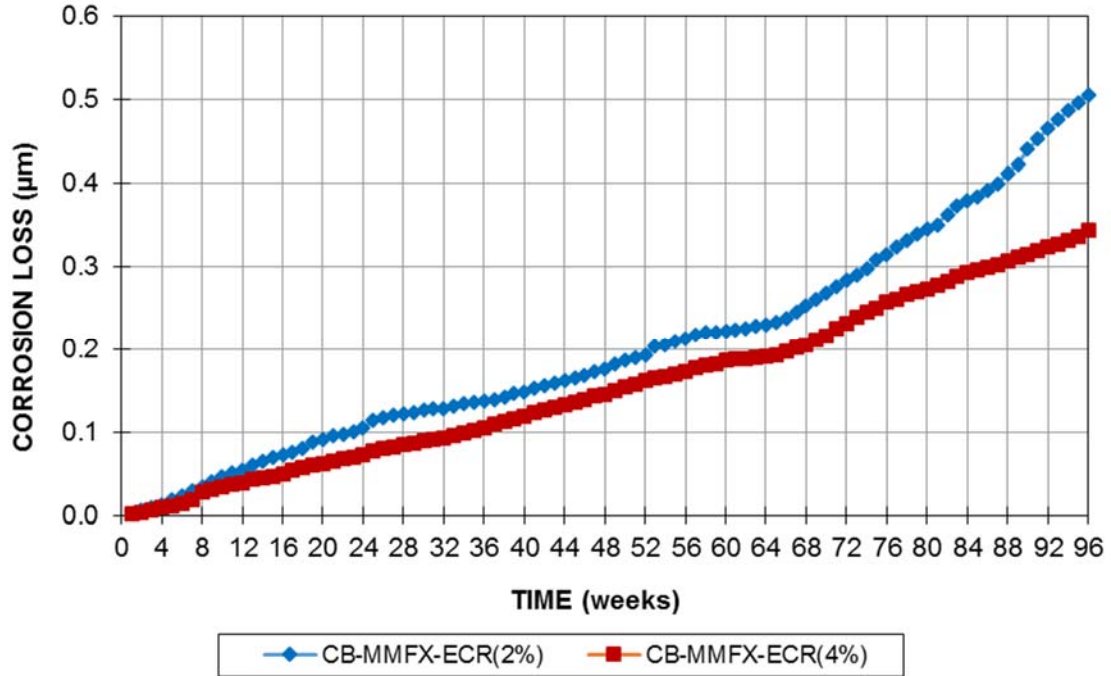


Figure A.32— Average corrosion loss (μm) based on total area versus time for cracked beam specimens with epoxy-coated reinforcement

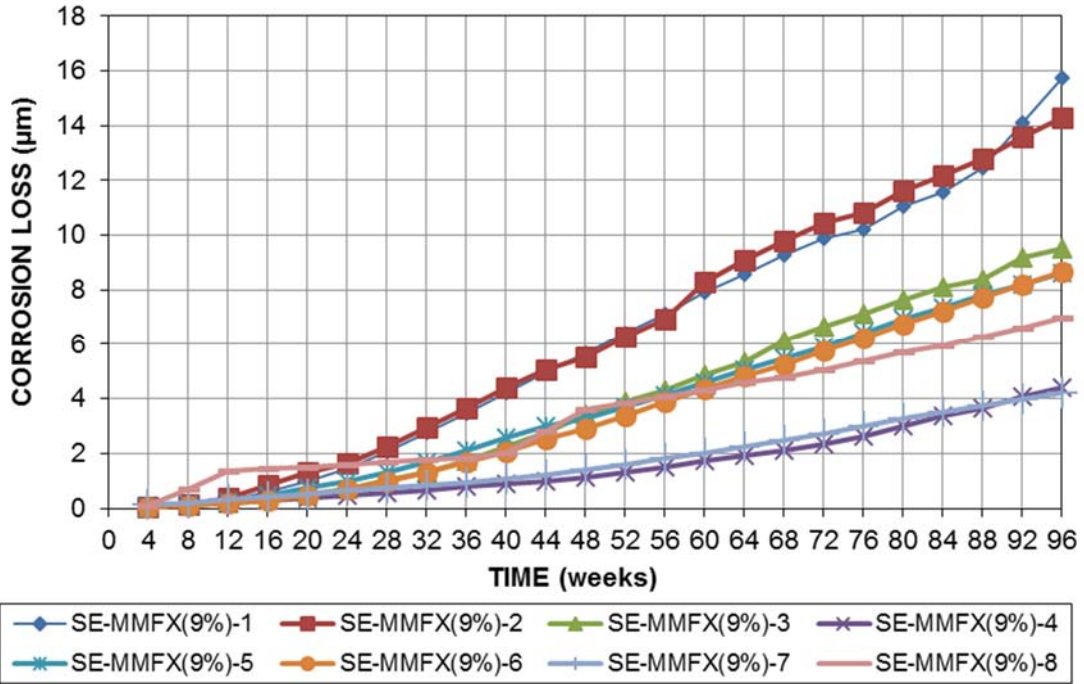


Figure A.27— LPR test corrosion losses (μm) for Southern Exposure specimens containing MMFX(9%) bars

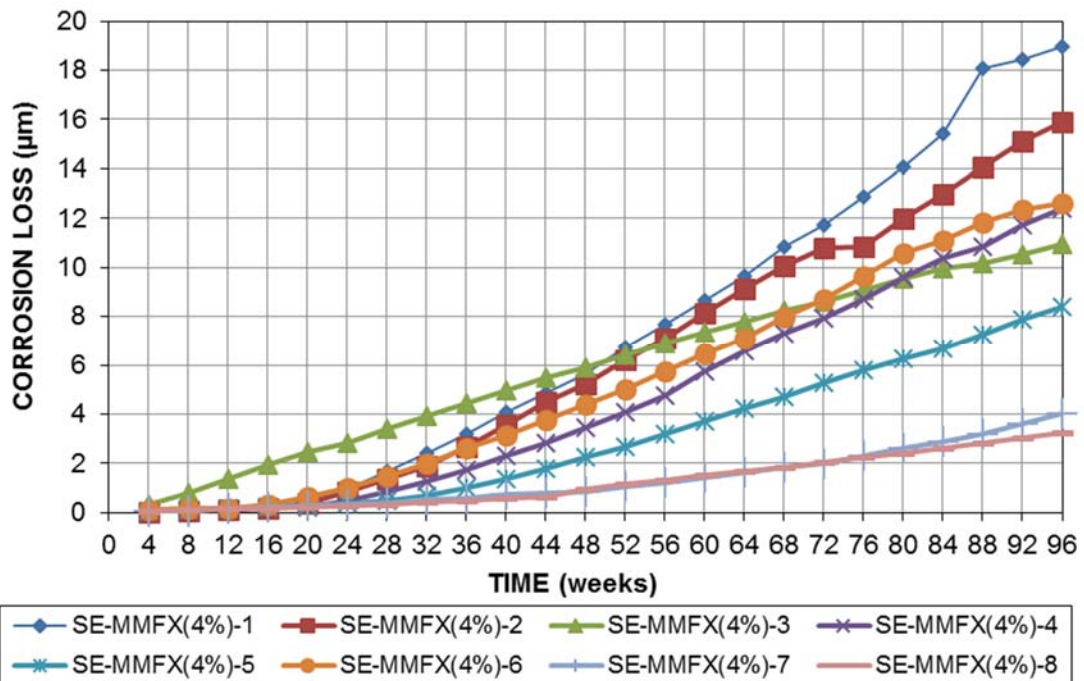


Figure A.18— LPR test corrosion losses (μm) for Southern Exposure specimens containing MMFX(4%) bars

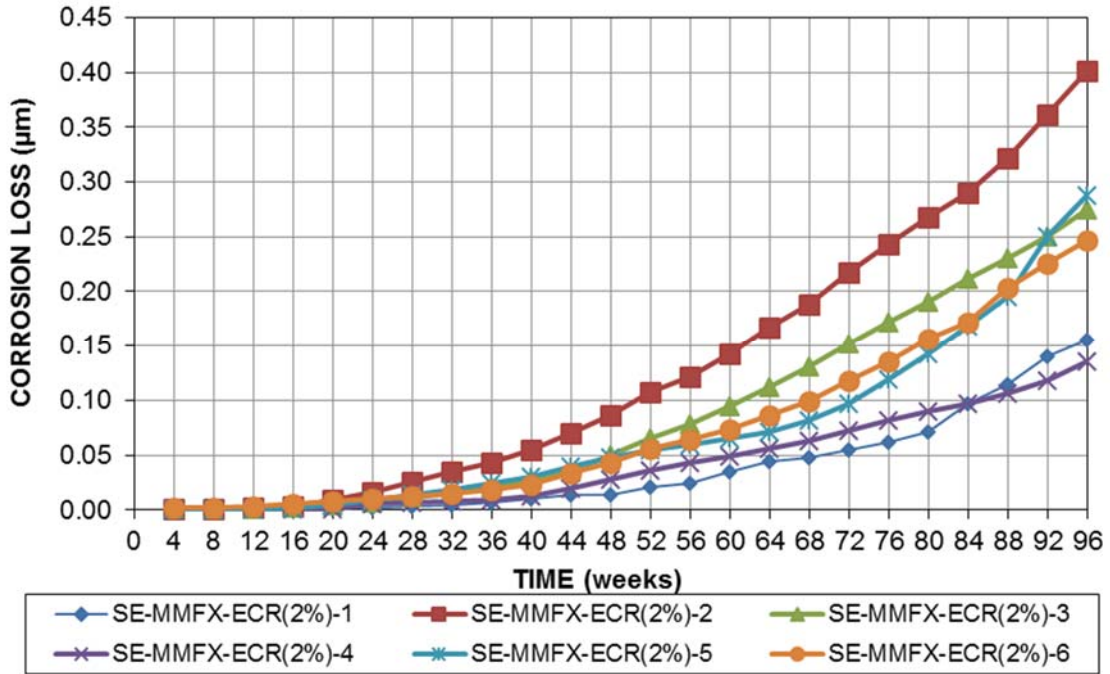


Figure A.19— LPR test corrosion losses (μm) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(2%) bars

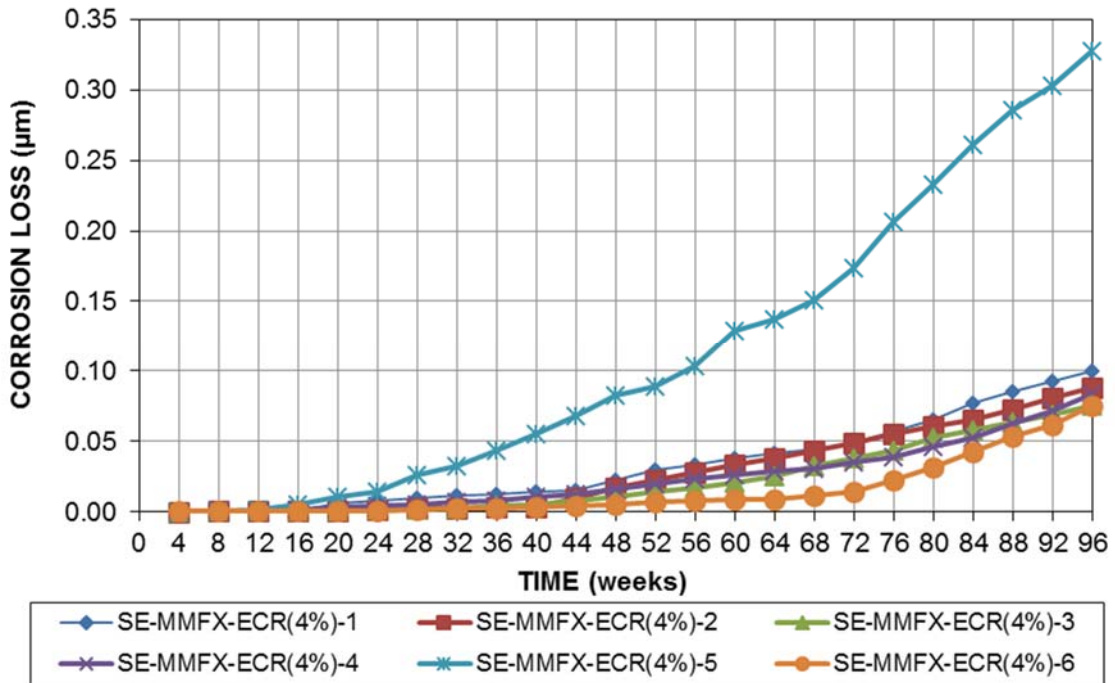


Figure A.20— LPR test corrosion losses (μm) based on total area of reinforcement for Southern Exposure specimens containing MMFX-ECR(4%) bars

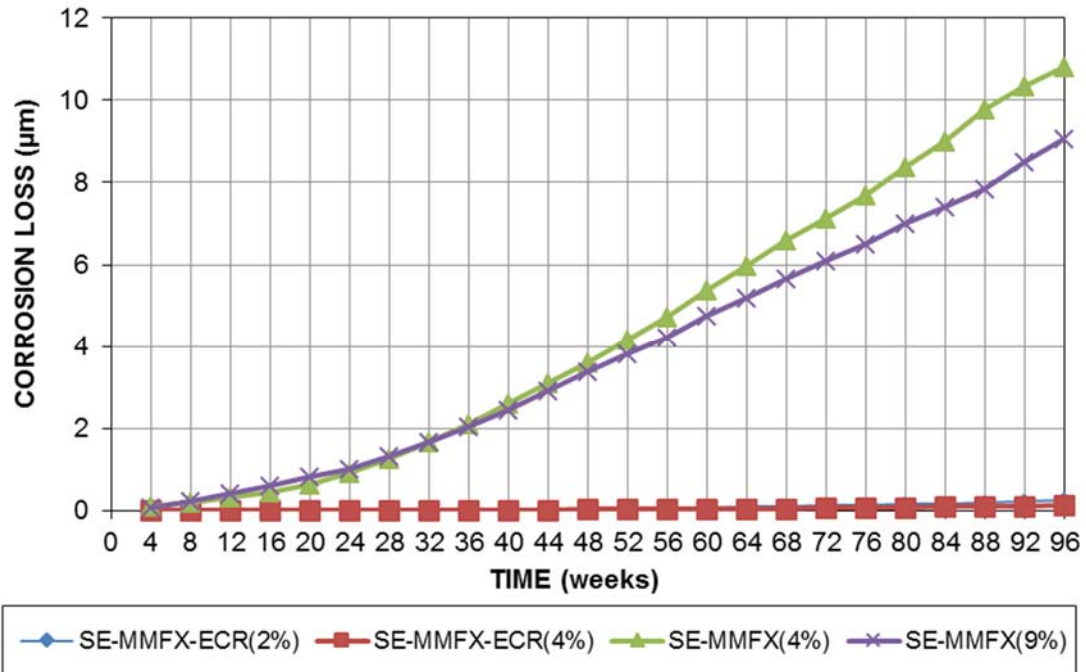


Figure A.21— Average LPR test corrosion loss ($\mu\text{m}/\text{yr}$) based on total area versus time for Southern Exposure specimens

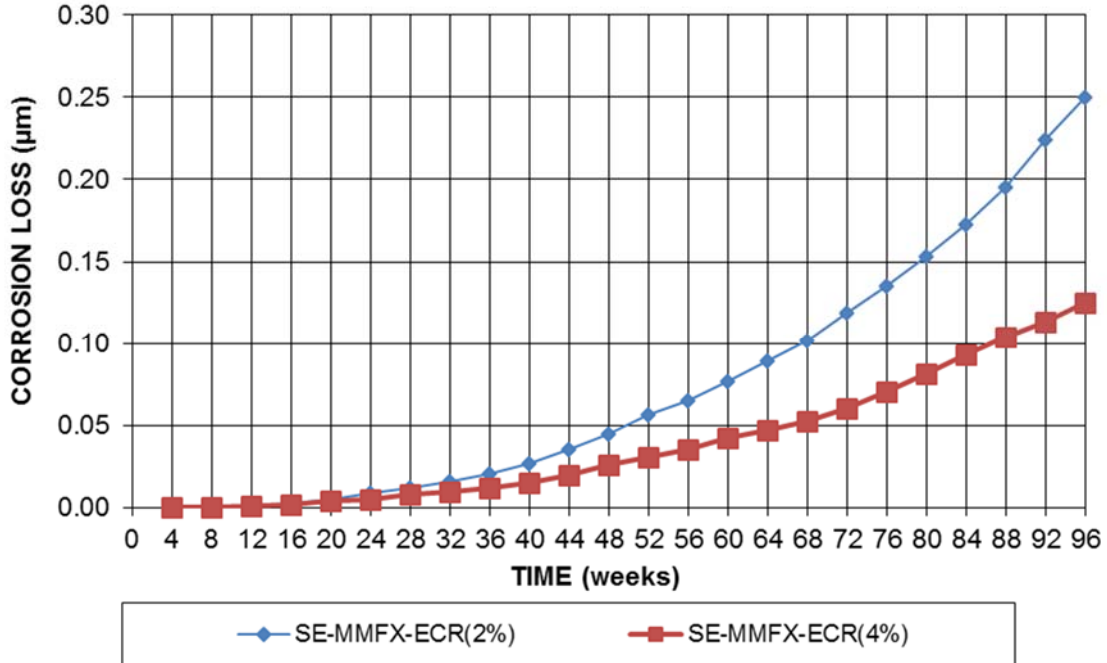


Figure A.22— Average LPR test corrosion loss ($\mu\text{m}/\text{yr}$) based on total area versus time for Southern Exposure specimens containing epoxy-coated reinforcement

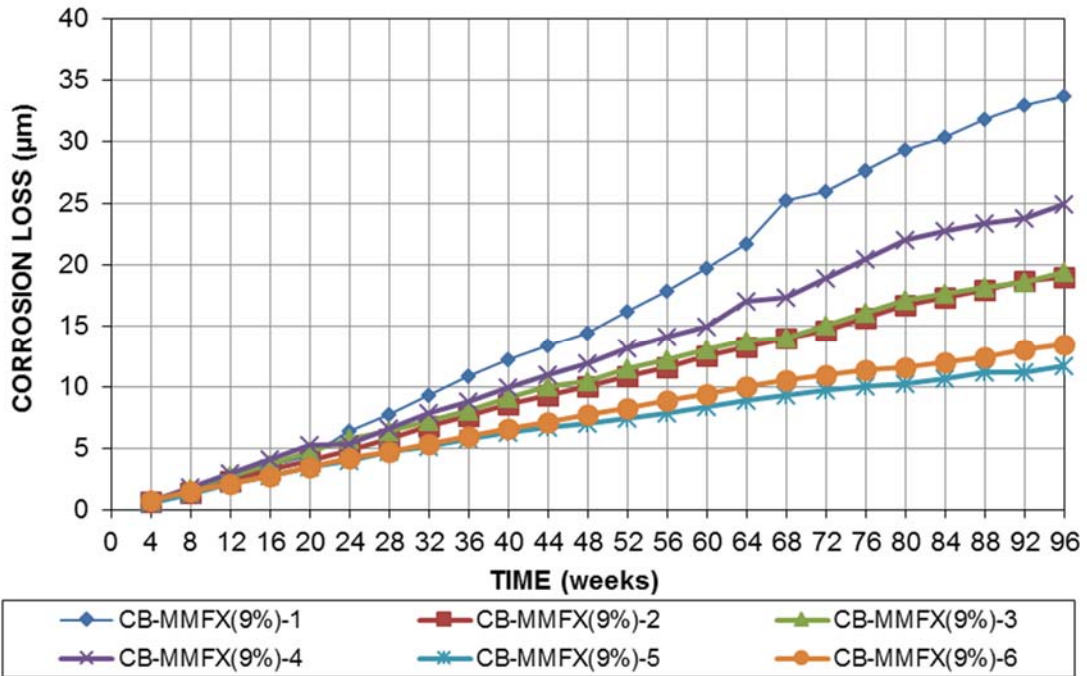


Figure A.23— LPR test corrosion losses (μm) for cracked beam specimens containing MMFX(9%) bars

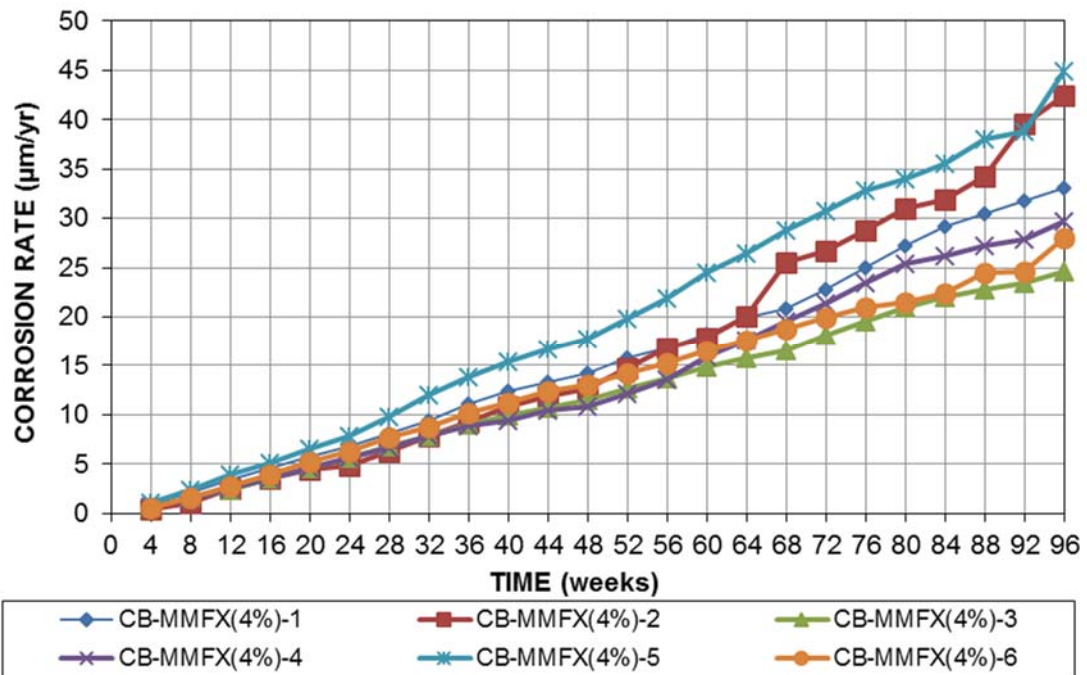


Figure A.24— LPR test corrosion losses (μm) for cracked beam specimens containing MMFX(4%) bars

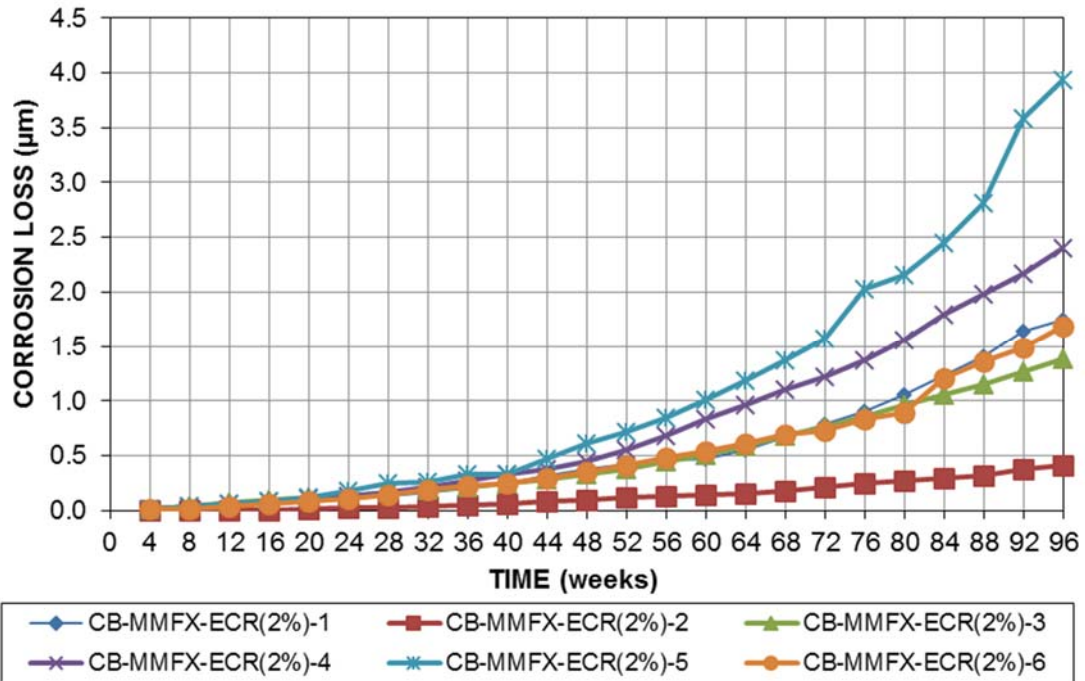


Figure A.25— LPR test corrosion losses (μm) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(2%) bars

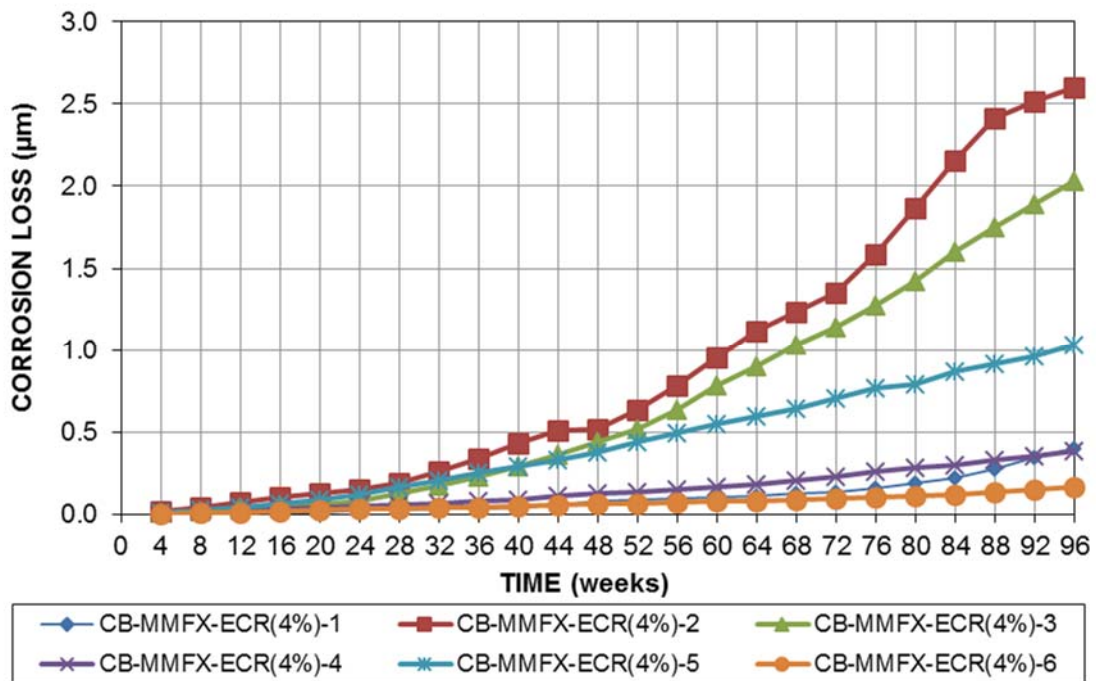


Figure A.26— LPR test corrosion losses (μm) based on total area of reinforcement for cracked beam specimens containing MMFX-ECR(4%) bars

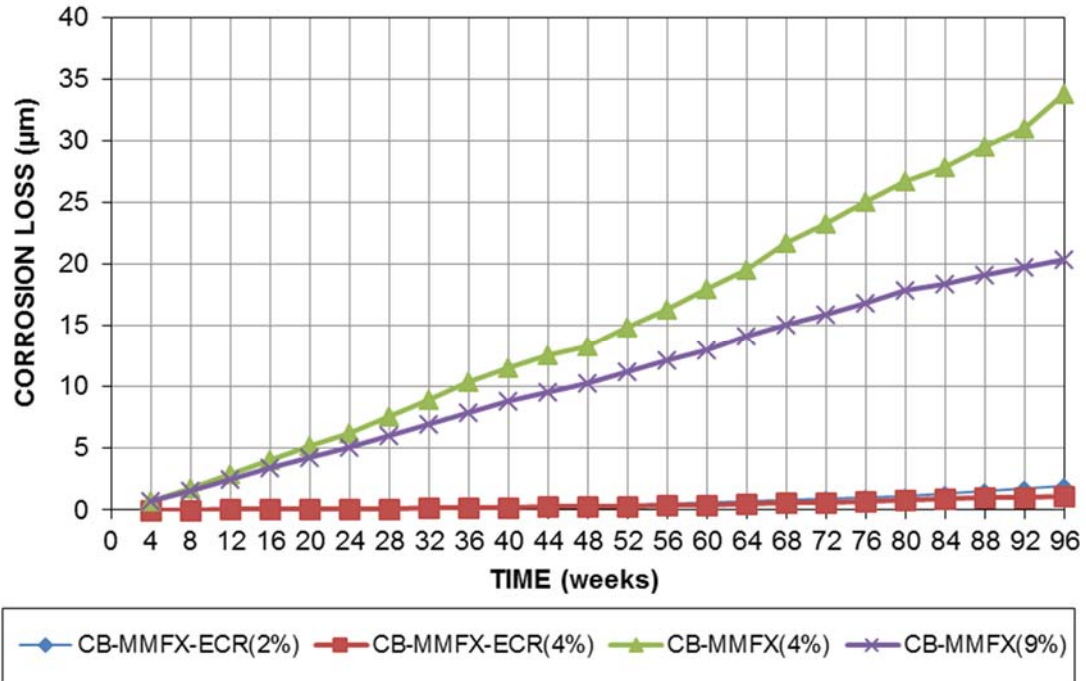


Figure A.27— Average LPR test corrosion loss (µm/yr) based on total area versus time for cracked beam specimens

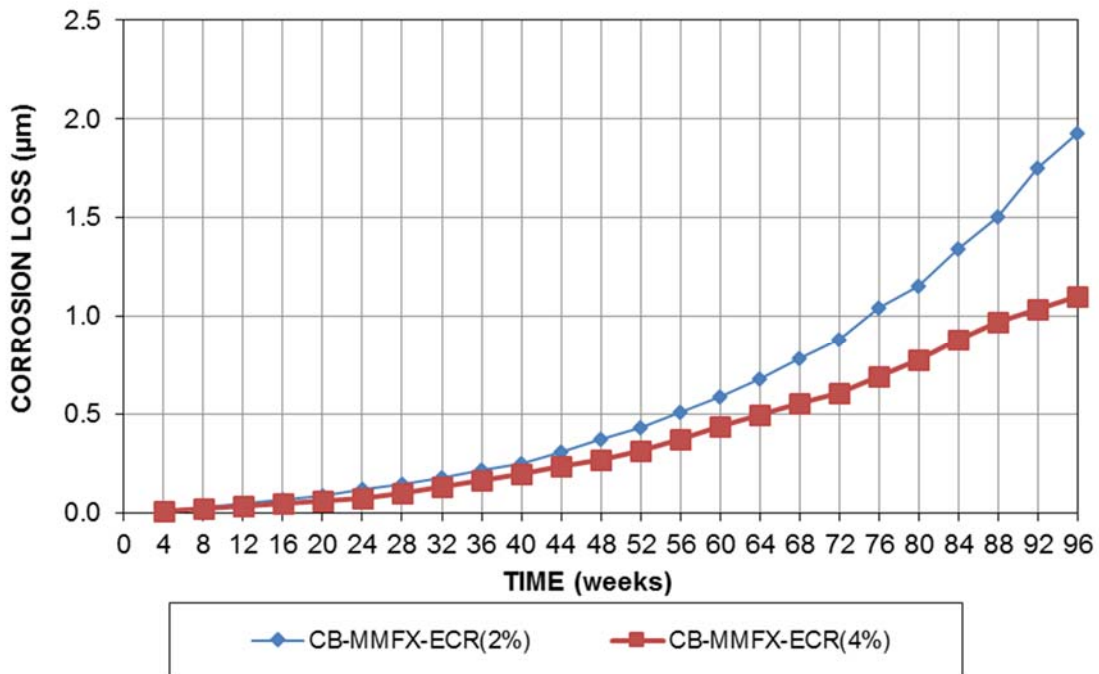


Figure A.28— Average LPR test corrosion loss (µm/yr) based on total area versus time for cracked beam specimens containing epoxy-coated reinforcement

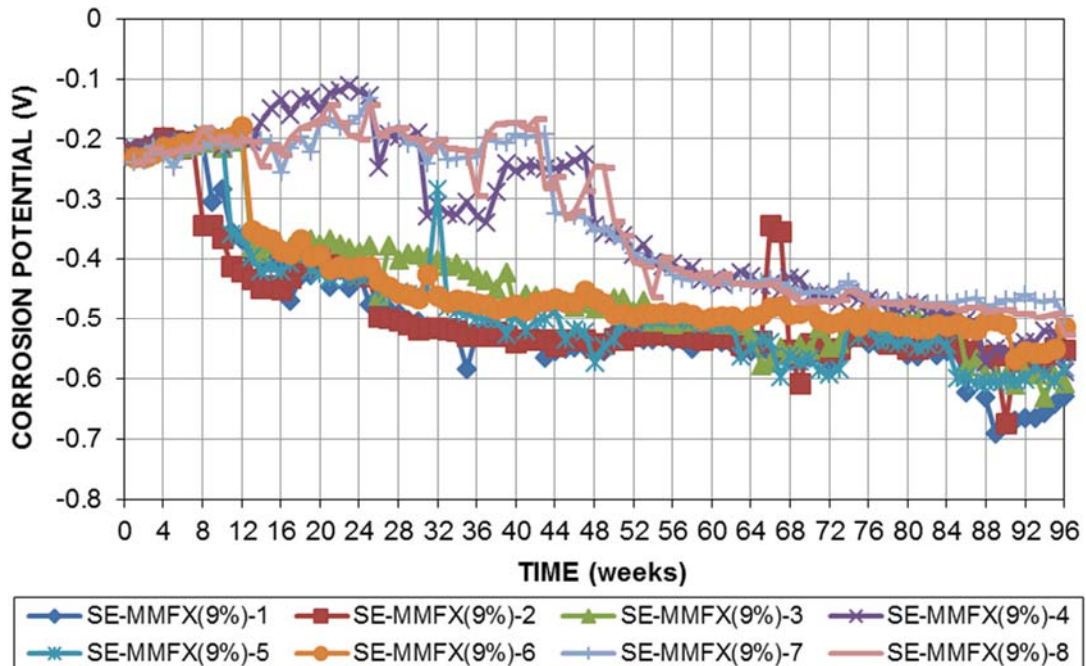


Figure A.29—Top mat (anode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX(9%) bars

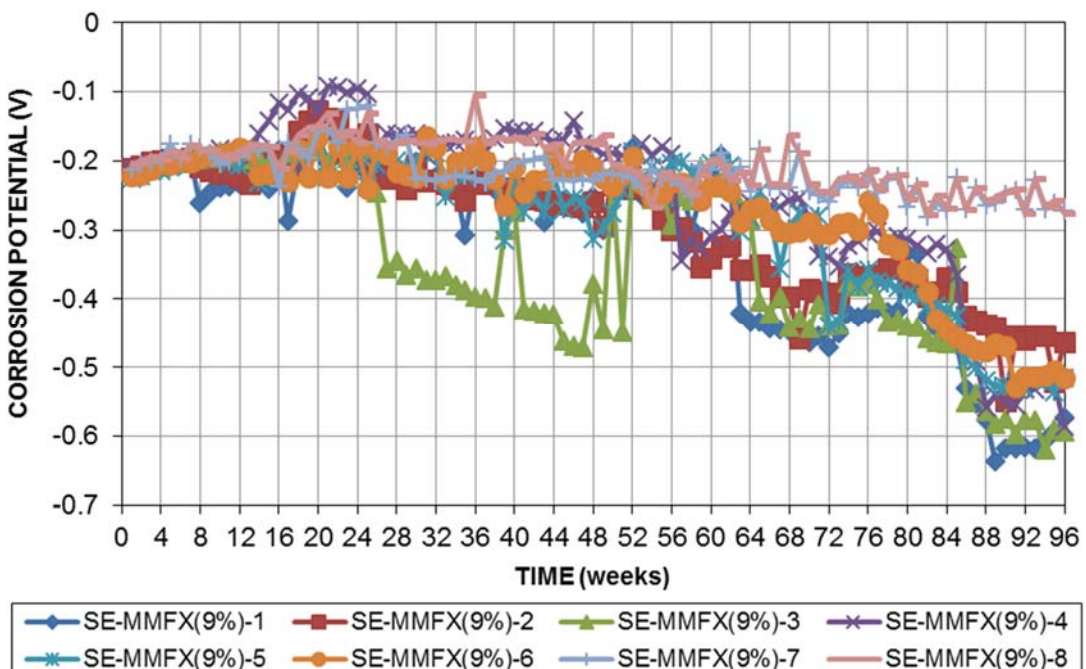


Figure A.30—Bottom mat (cathode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX(9%) bars

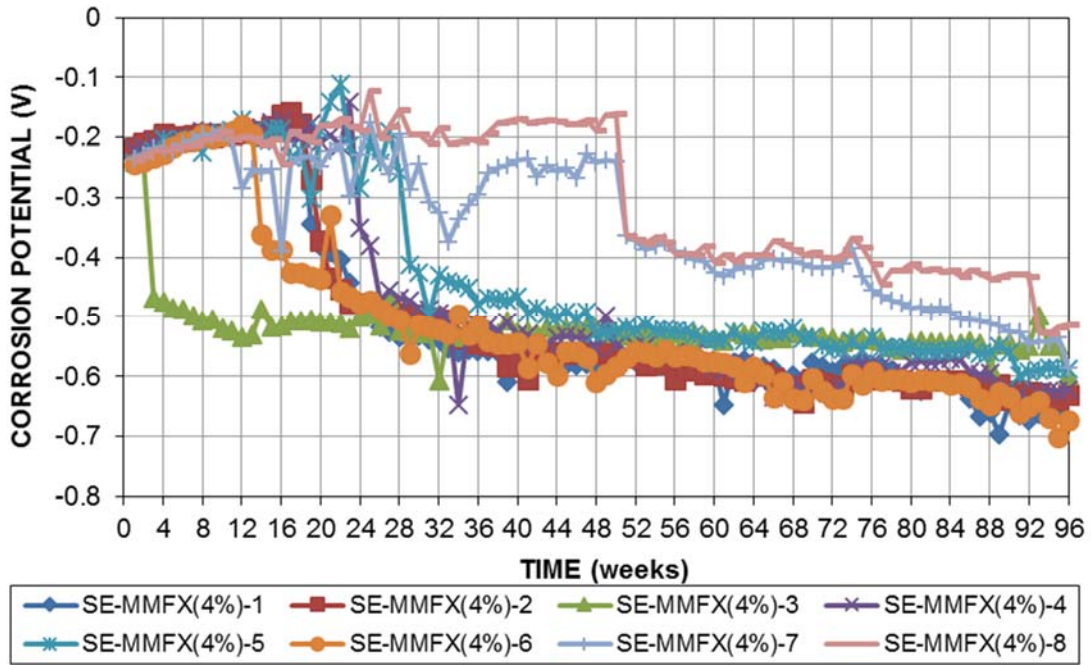


Figure A.31—Top mat (anode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX(4%) bars

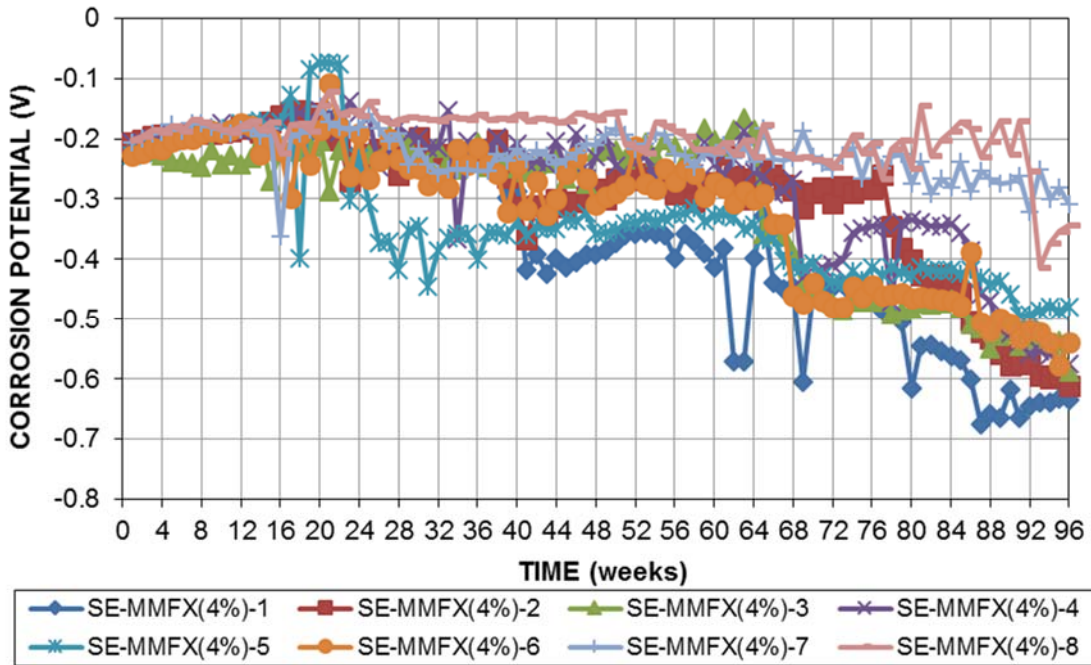


Figure A.32—Bottom mat (cathode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX(4%) bars

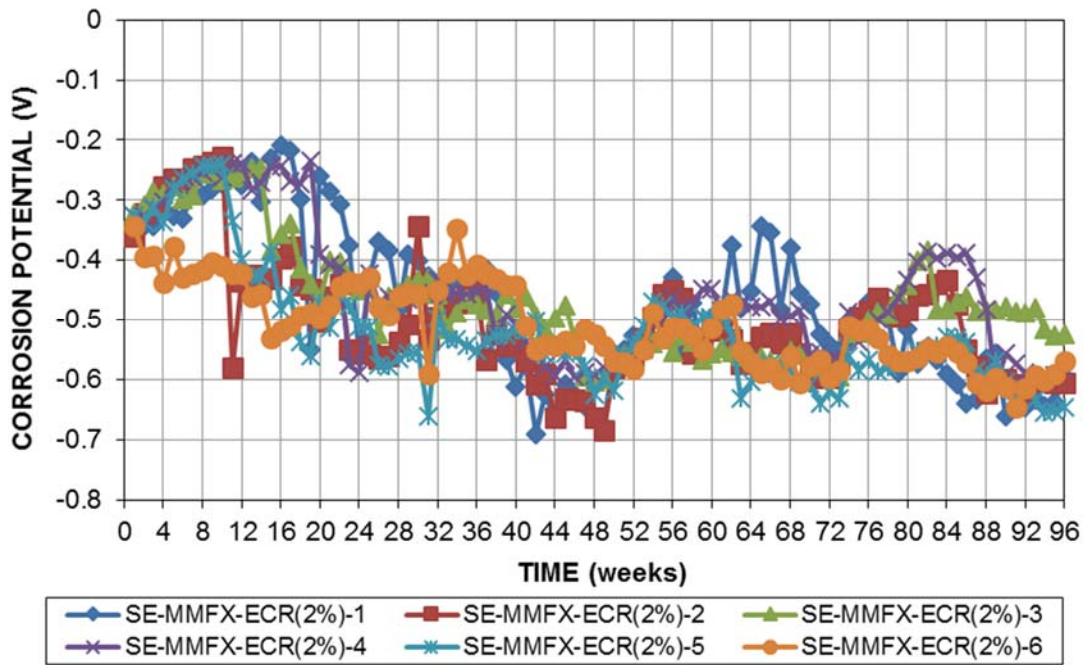


Figure A.33—Top mat (anode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX-ECR(2%) bars

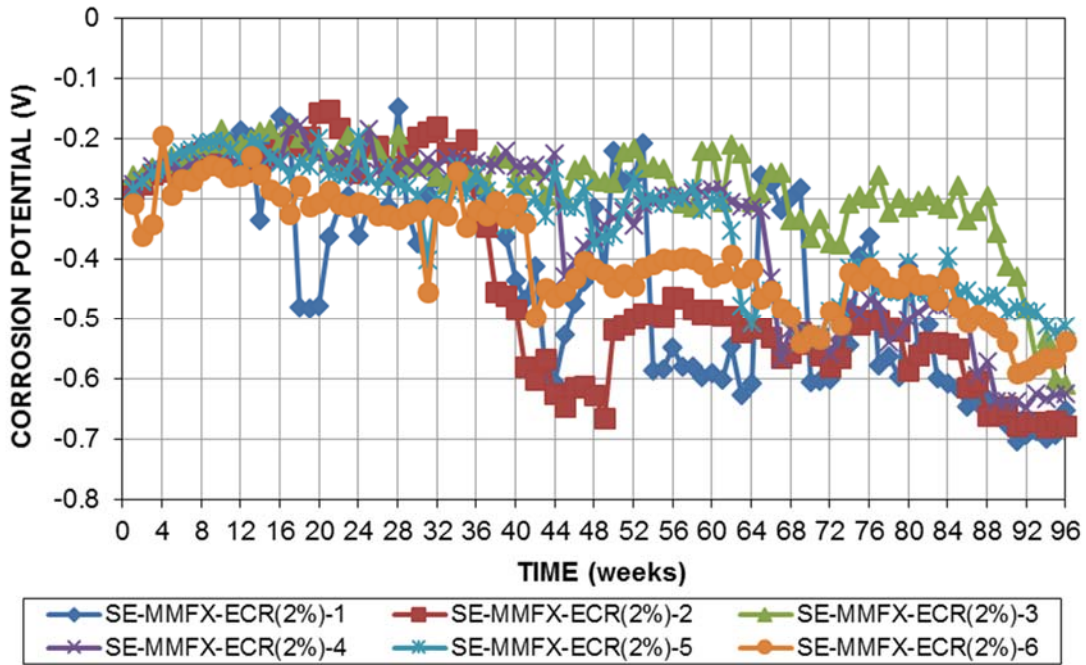


Figure A.34—Bottom mat (cathode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX-ECR(2%) bars

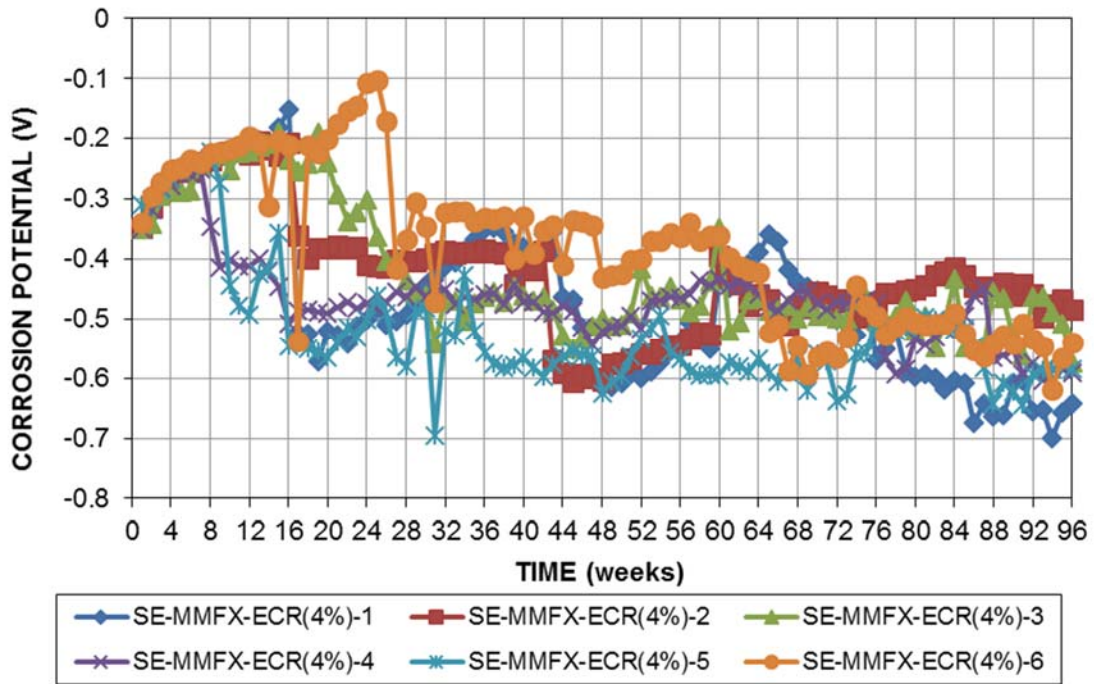


Figure A.35—Top mat (anode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX-ECR(4%) bars

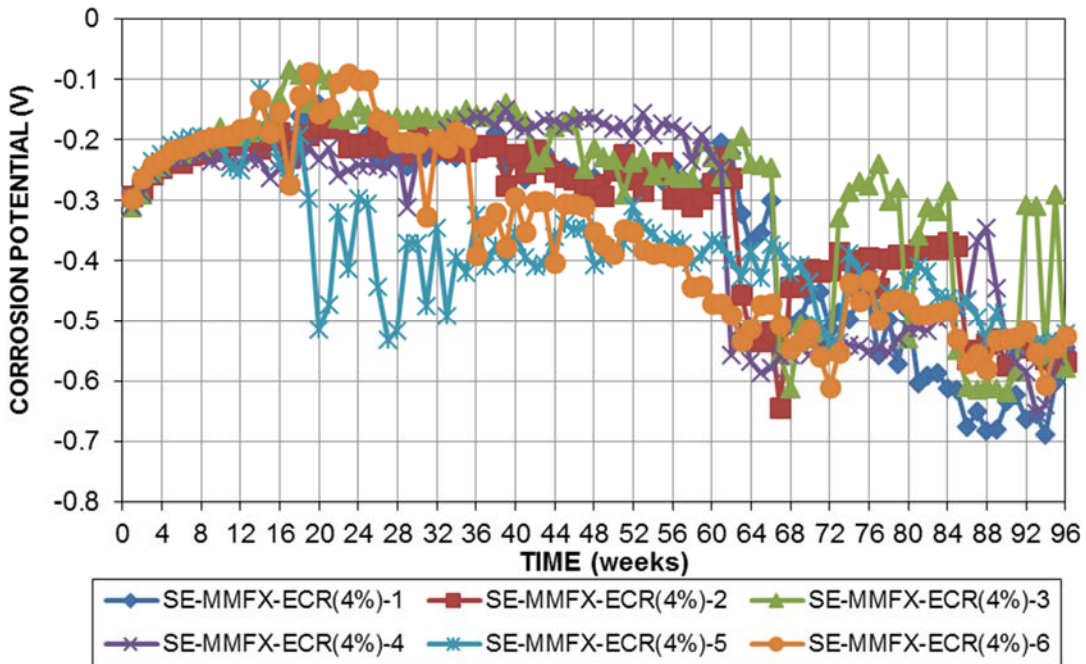


Figure A.36—Bottom mat (cathode) corrosion potential (CSE) versus time for Southern Exposure specimens containing MMFX-ECR(4%) bars

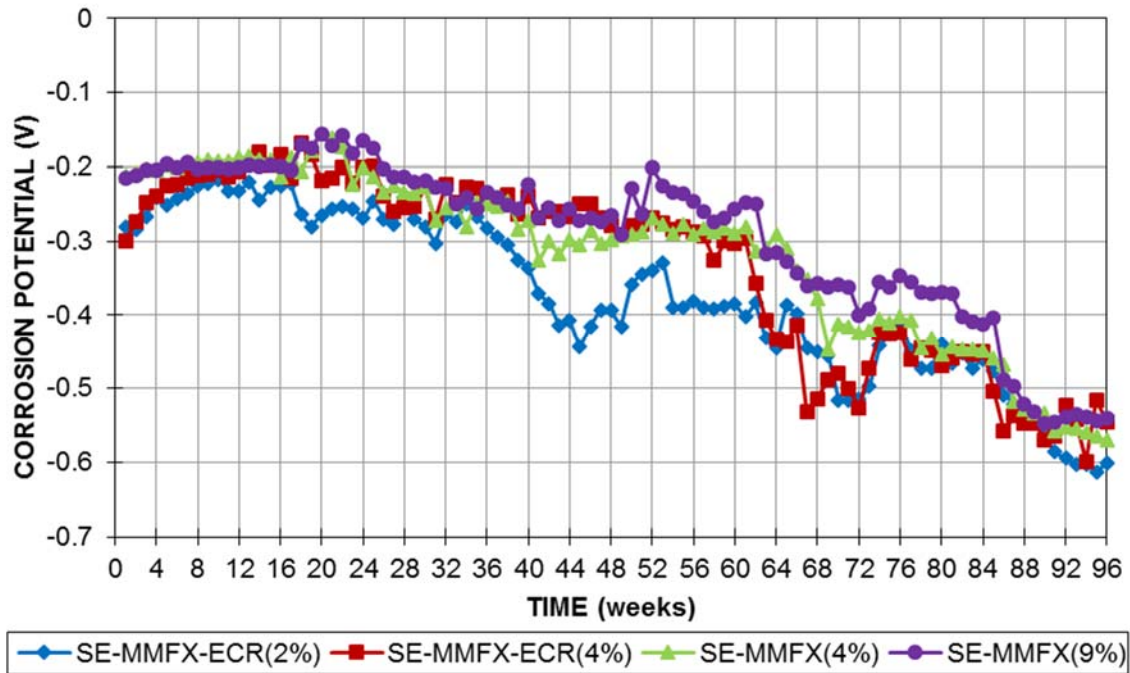


Figure A.37—Bottom mat (cathode) corrosion potential (CSE) versus time for Southern Exposure specimens

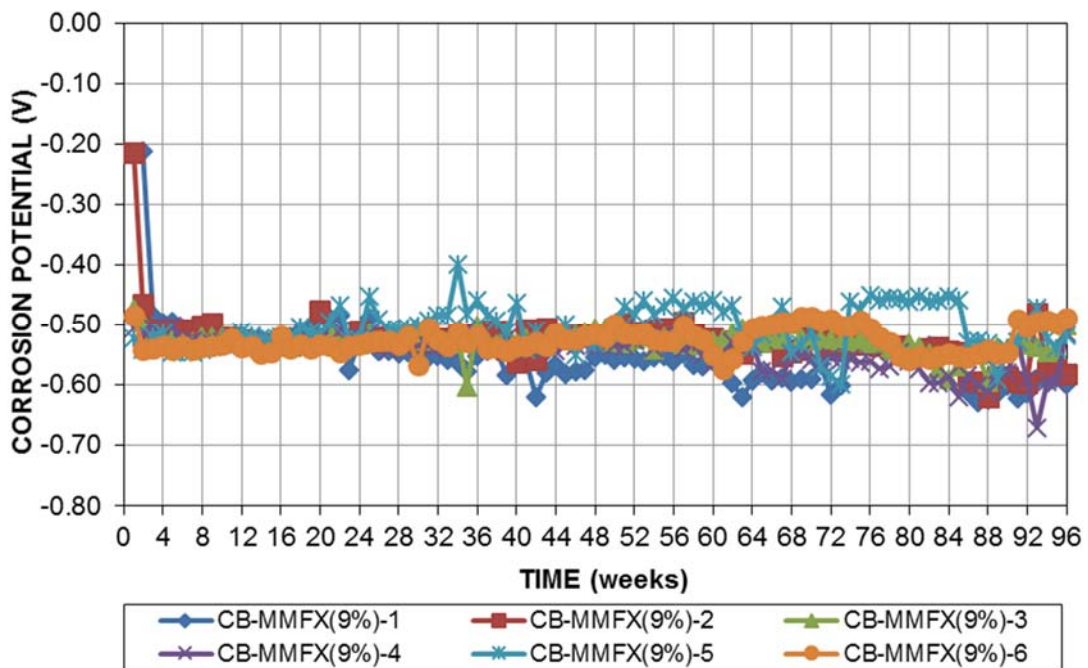


Figure A.38—Top mat (anode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX(9%) bars

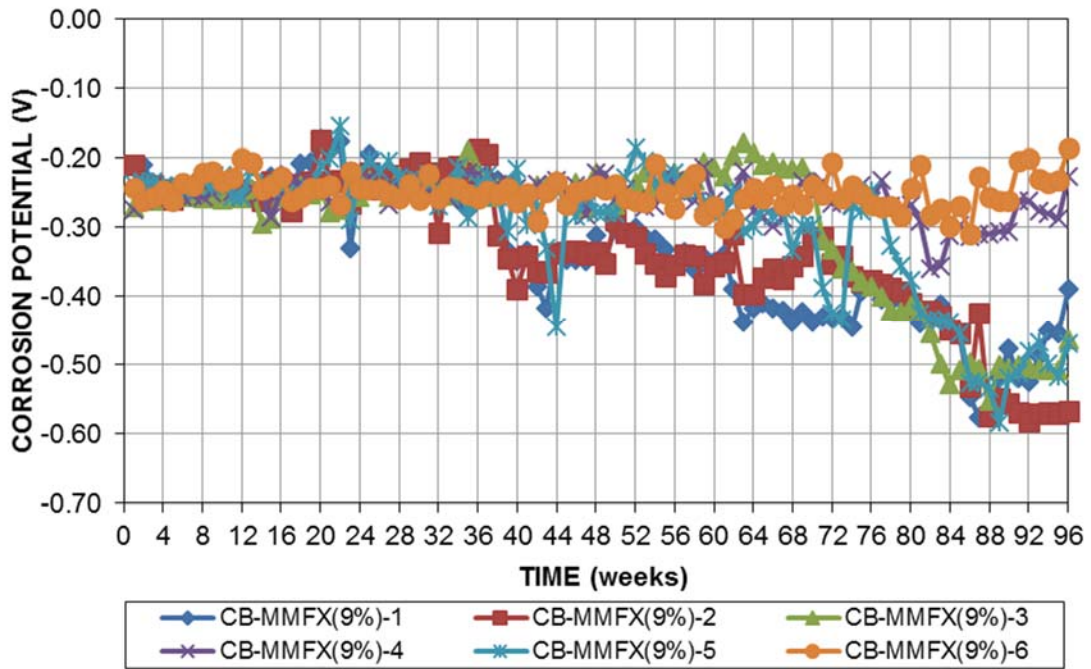


Figure A.39—Bottom mat (cathode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX(9%) bars

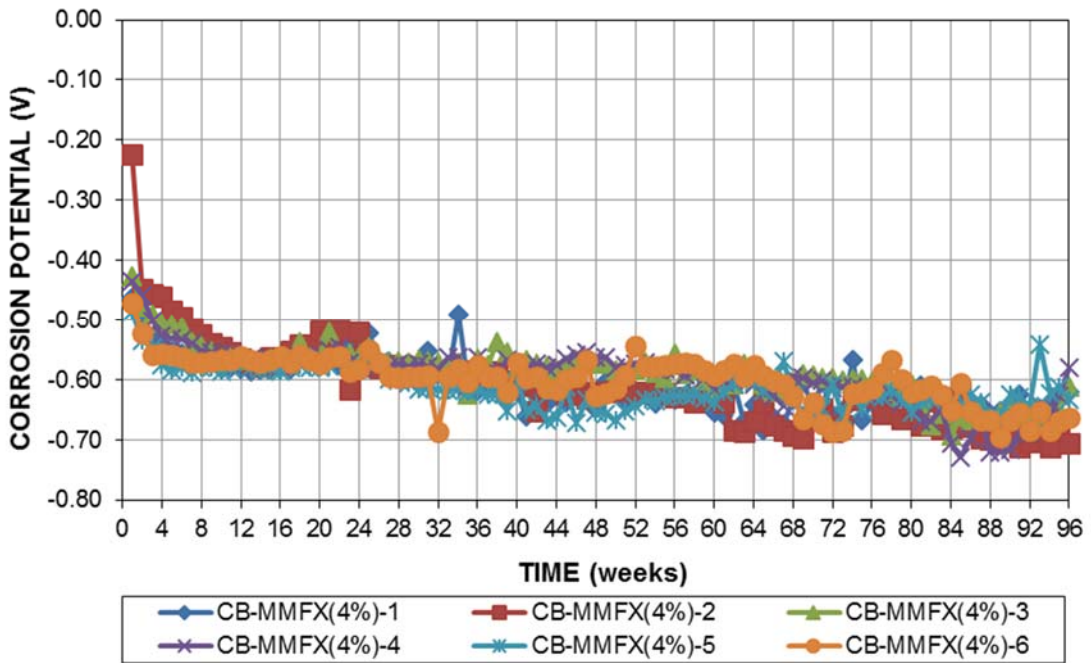


Figure A.40—Top mat (anode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX(4%) bars

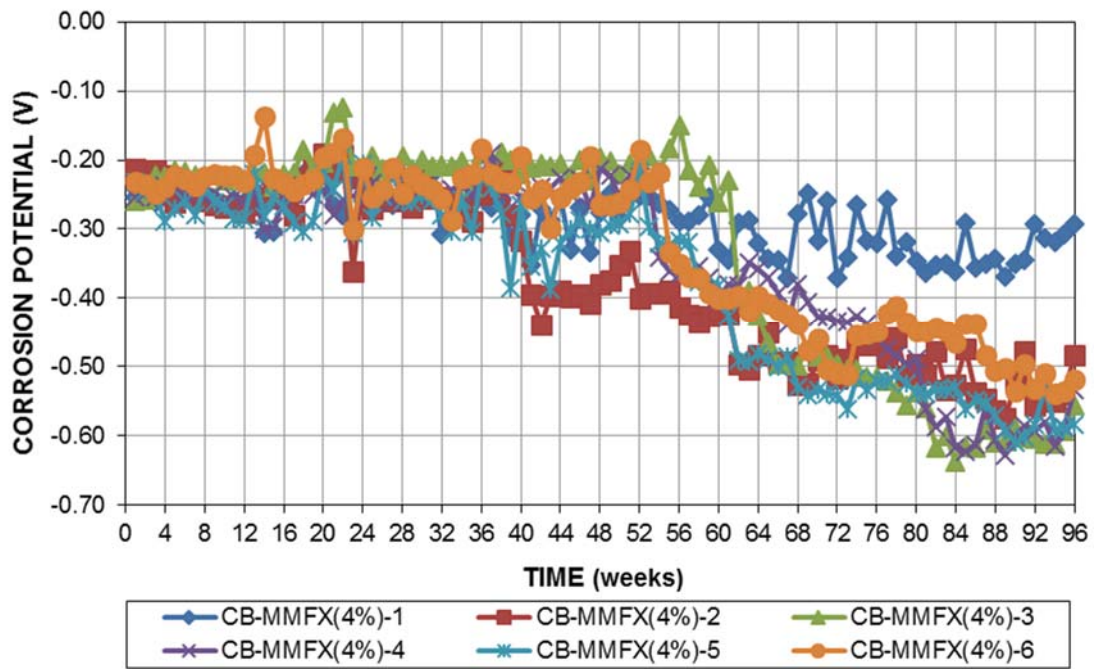


Figure A.41—Bottom mat (cathode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX(4%) bars

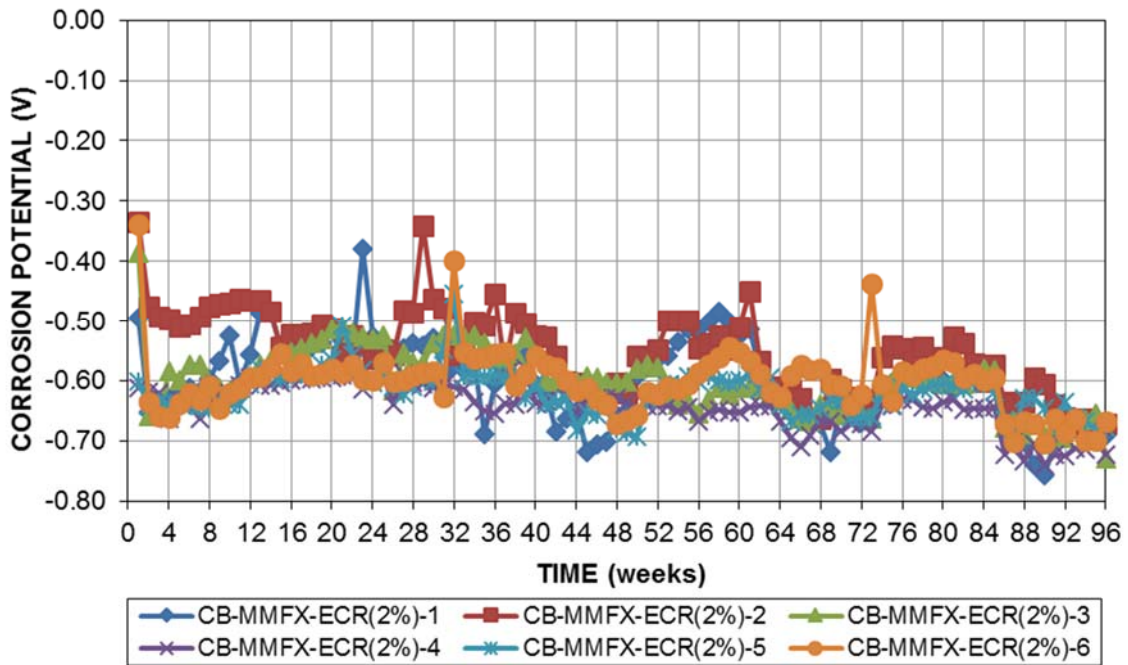


Figure A.42—Top mat (anode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX-ECR(2%) bars

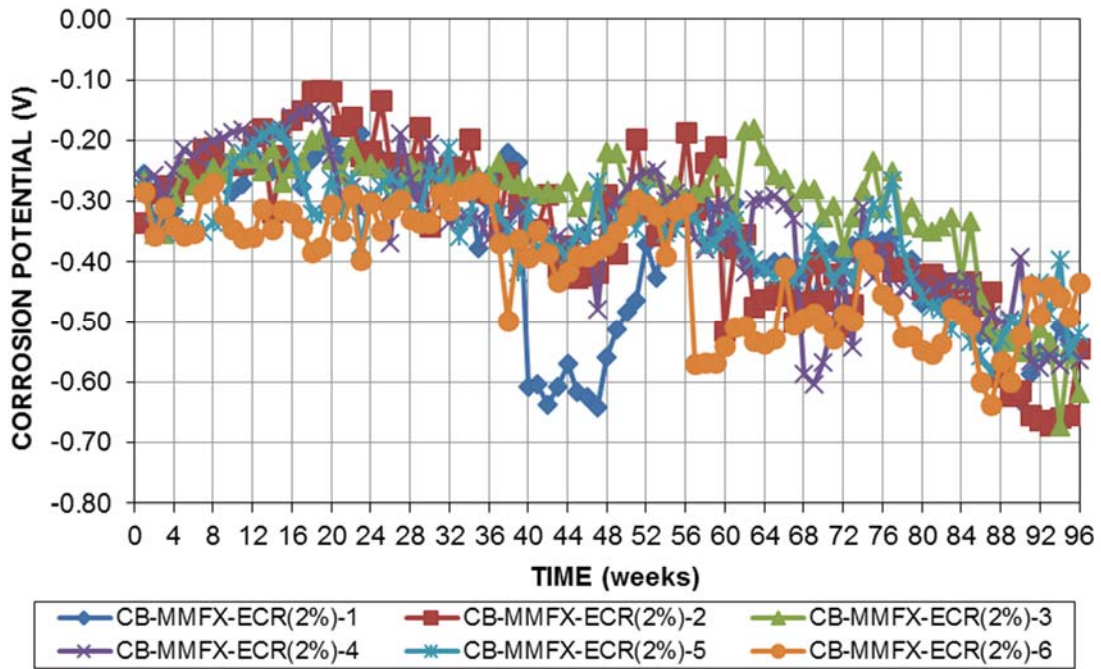


Figure A.43—Bottom mat (cathode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX-ECR(2%) bars

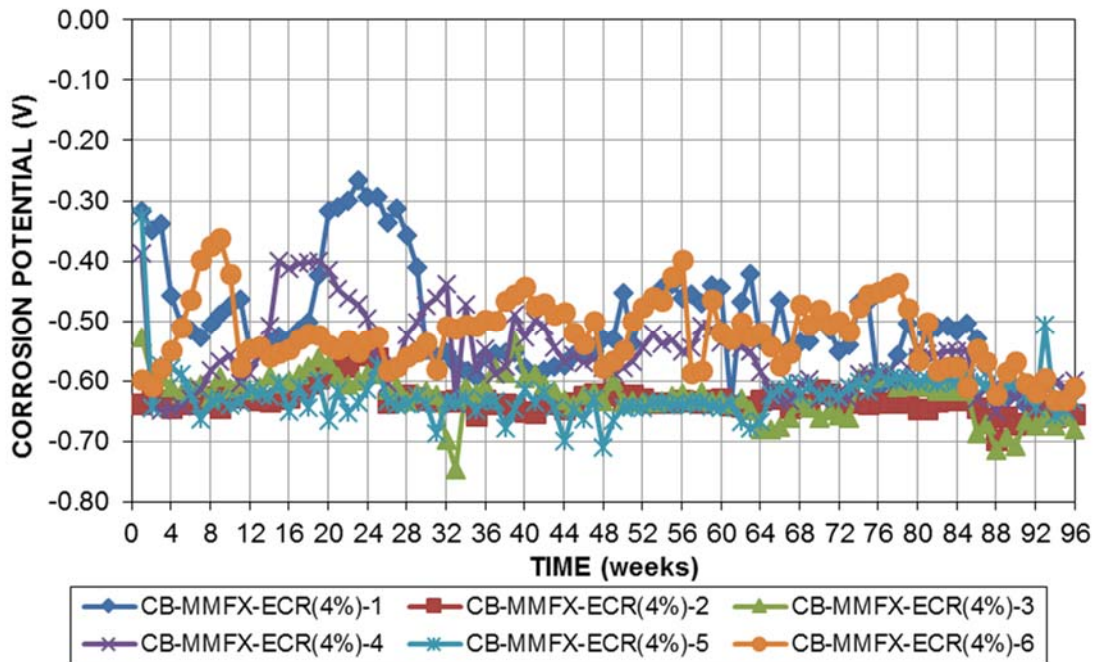


Figure A.44—Top mat (anode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX-ECR(4%) bars

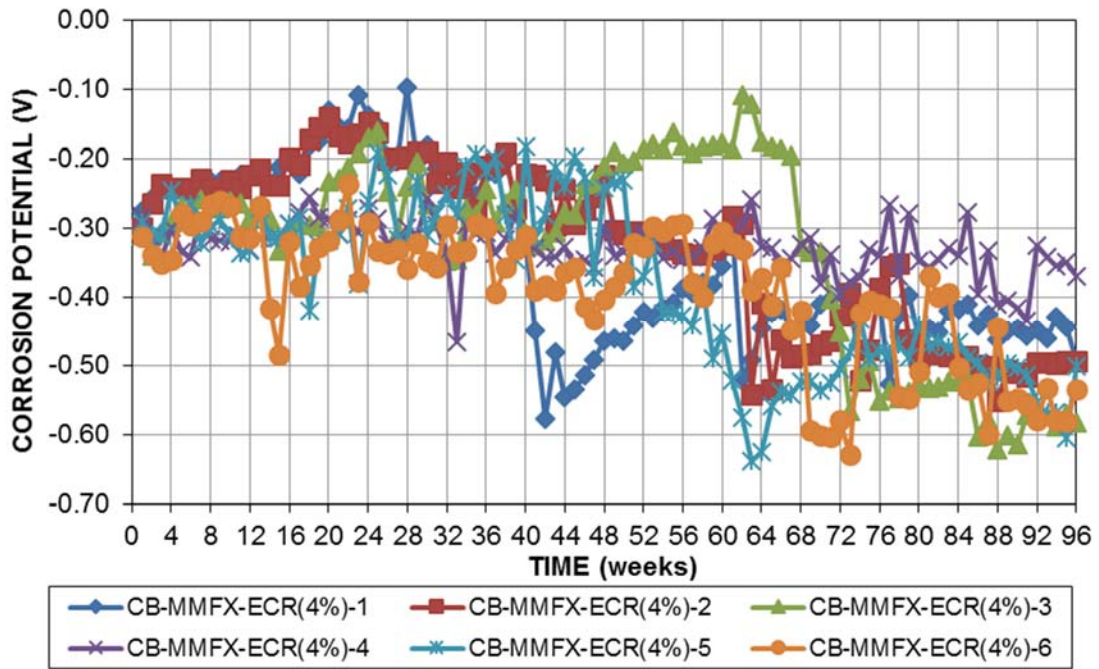


Figure A.45—Bottom mat (cathode) corrosion potential (CSE) versus time for cracked beam specimens containing MMFX-ECR(4%) bars

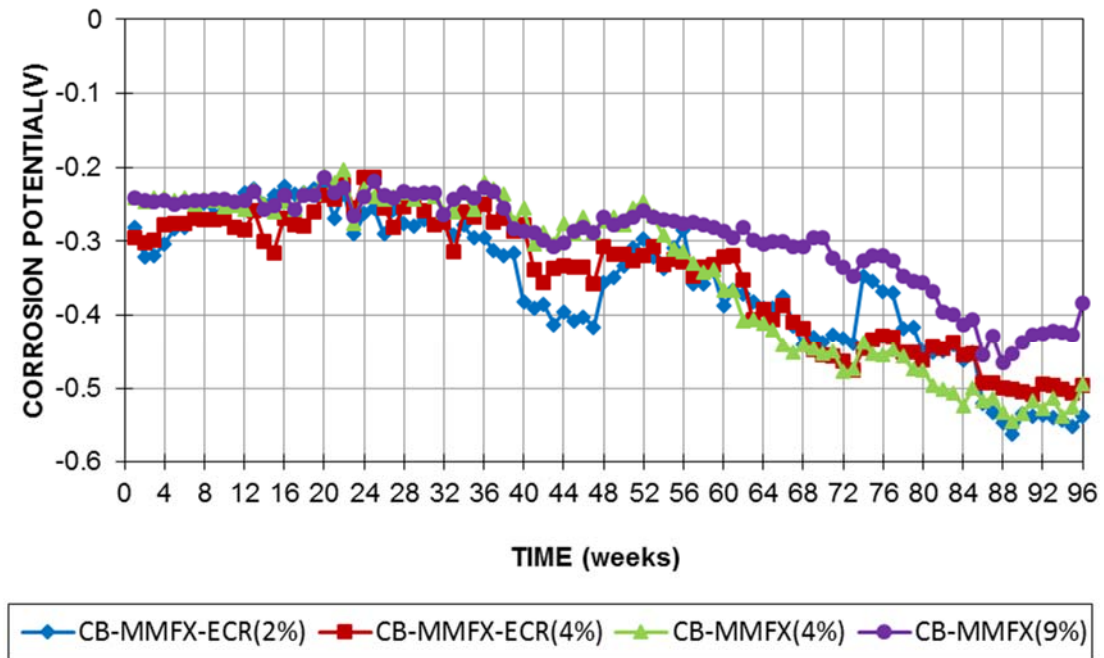


Figure A.46—Bottom mat (cathode) corrosion potential (CSE) versus time for cracked beam specimens

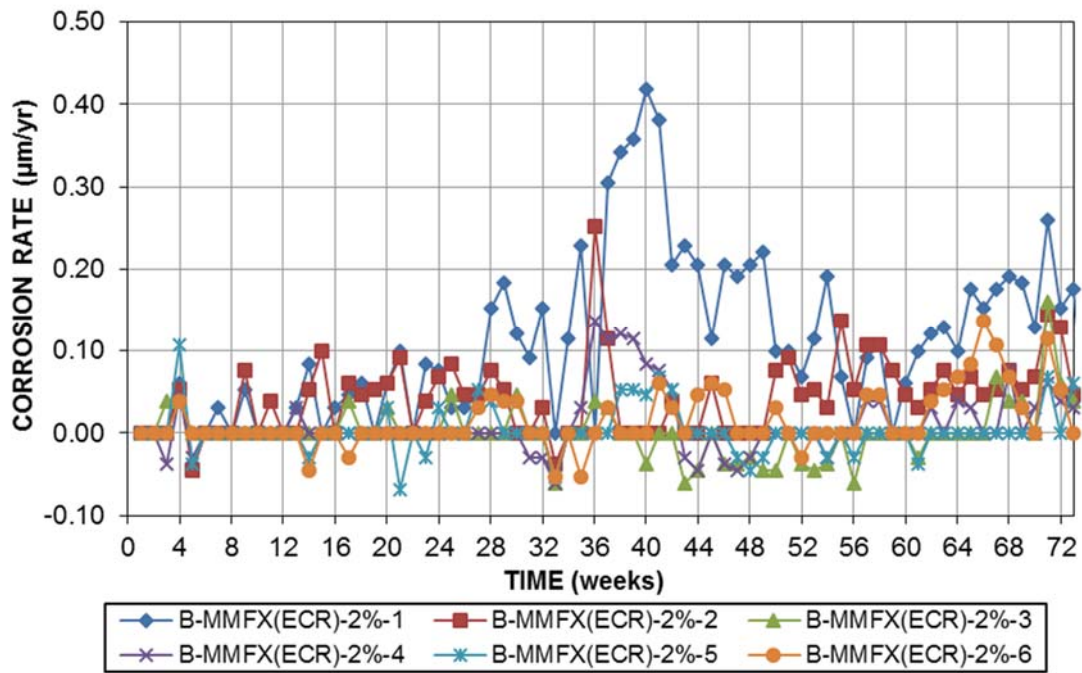


Figure A.47— Macrocell corrosion rates (μm) based on total area of reinforcement for beam specimens containing MMFX-ECR(2%) bars

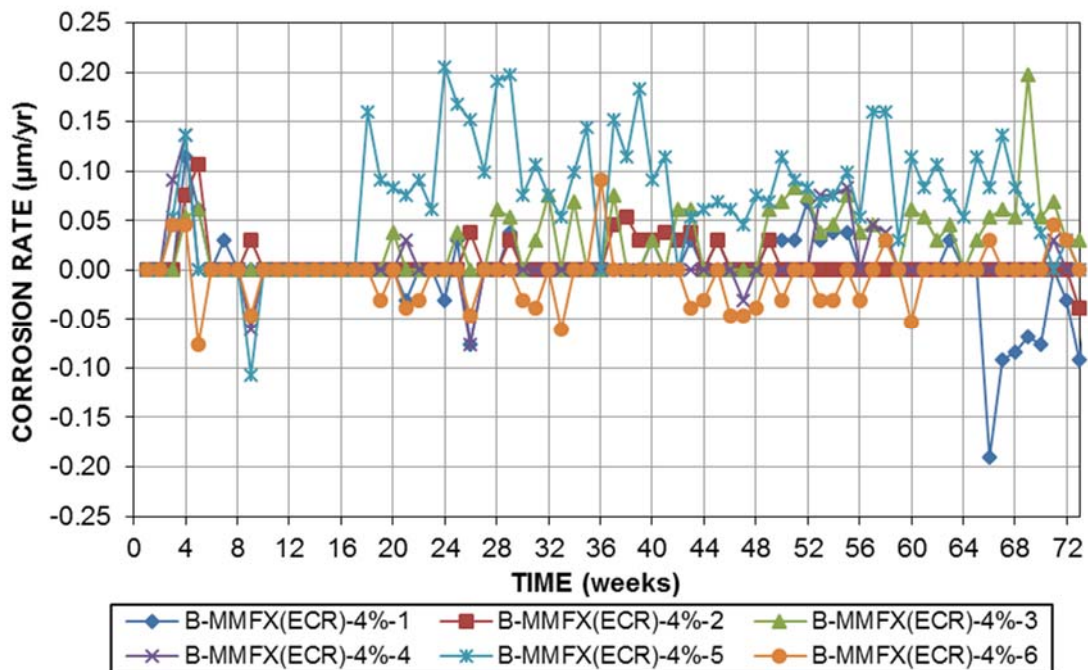


Figure A.48— Macrocell corrosion rates (μm) based on total area of reinforcement for beam specimens containing MMFX-ECR(4%) bars

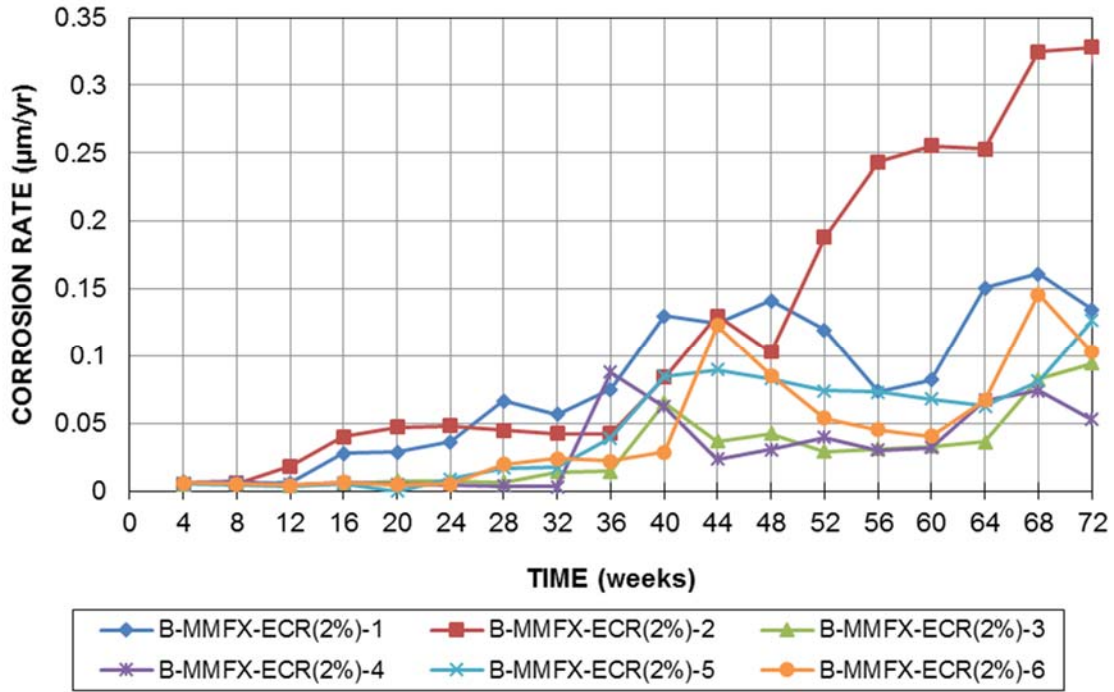


Figure A.49— LPR test corrosion rates (μm) based on total area of reinforcement for beam specimens containing MMFX-ECR(2%) bars

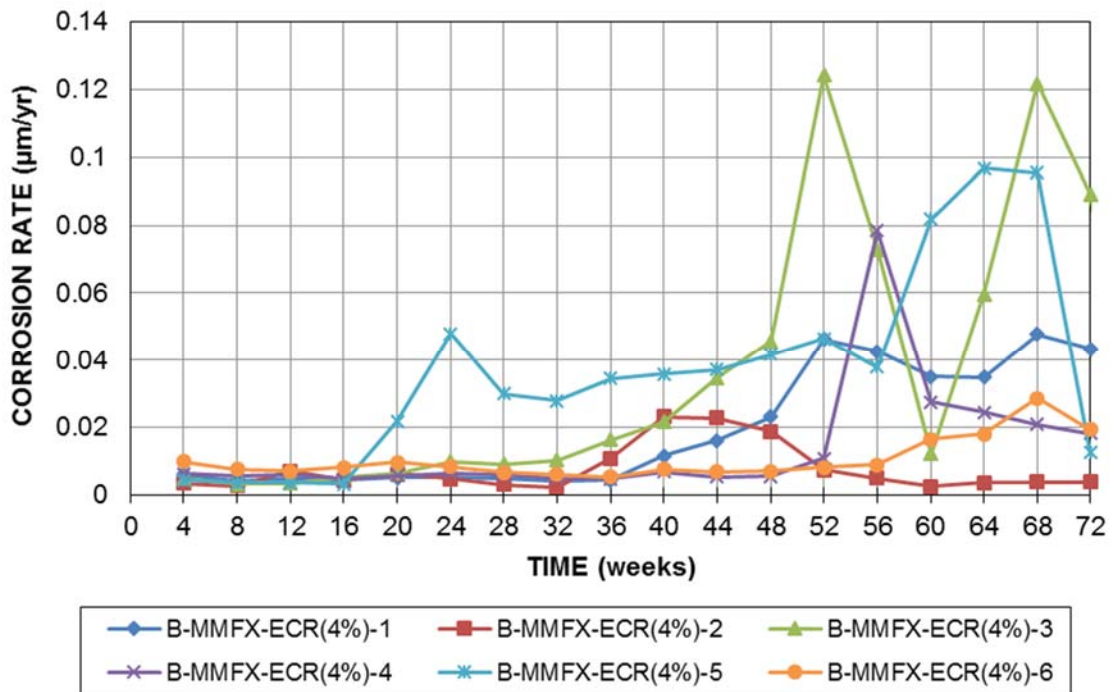


Figure A.50— LPR test corrosion rates (μm) based on total area of reinforcement for beam specimens containing MMFX-ECR(4%) bars

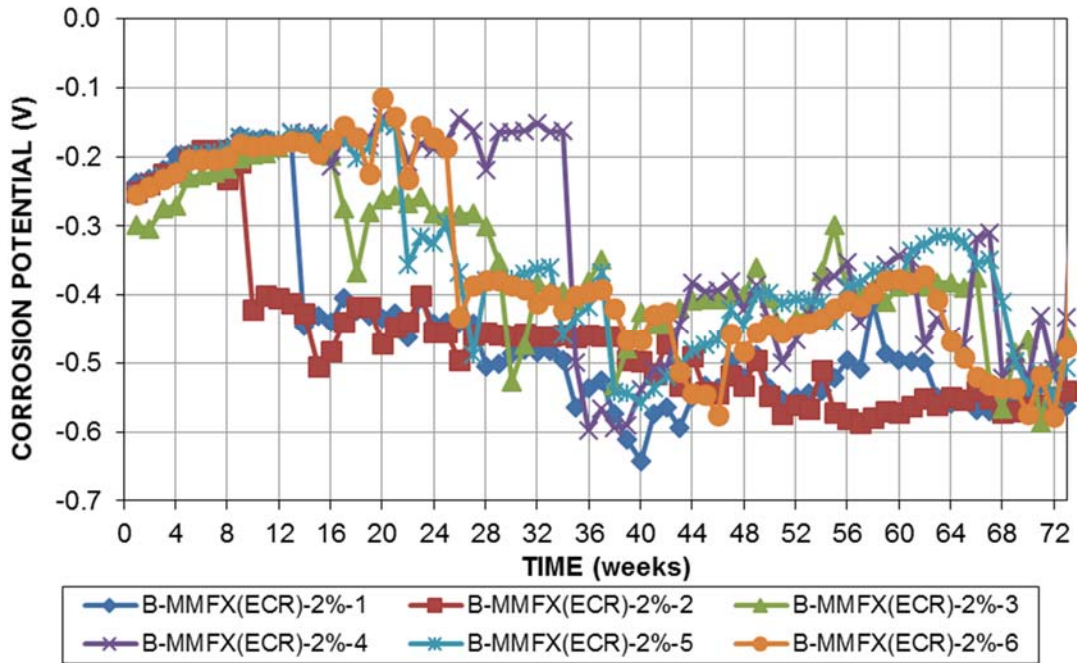


Figure A.51—Top mat (anode) corrosion potential (CSE) versus time for beam specimens containing MMFX-ECR(2%) bars

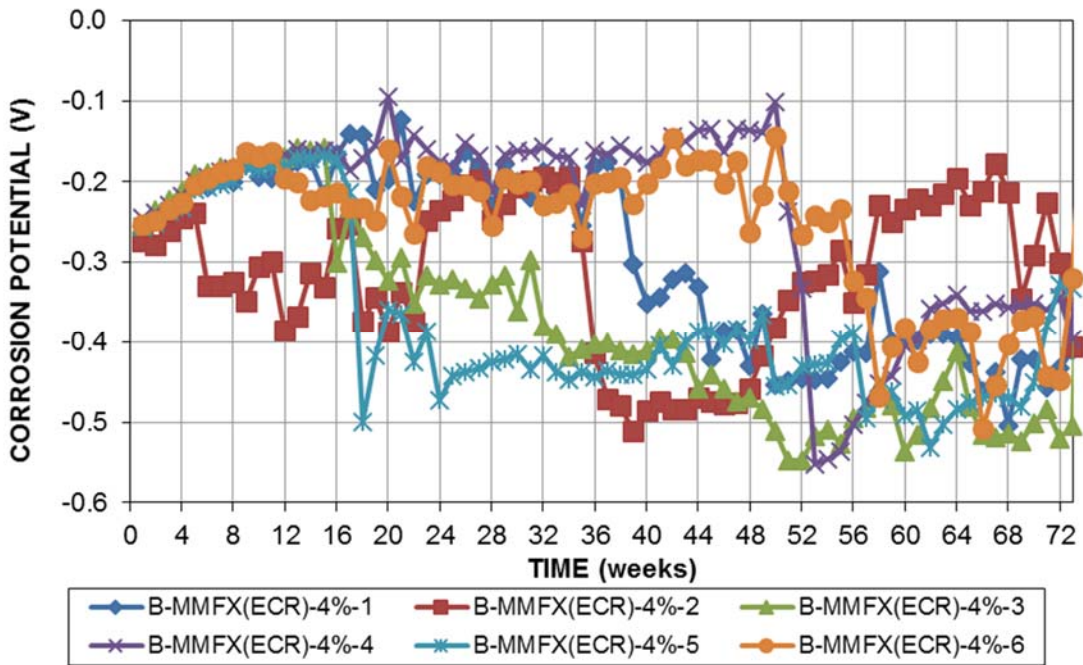


Figure A.52—Top mat (anode) corrosion potential (CSE) versus time for beam specimens containing MMFX-ECR(4%) bars

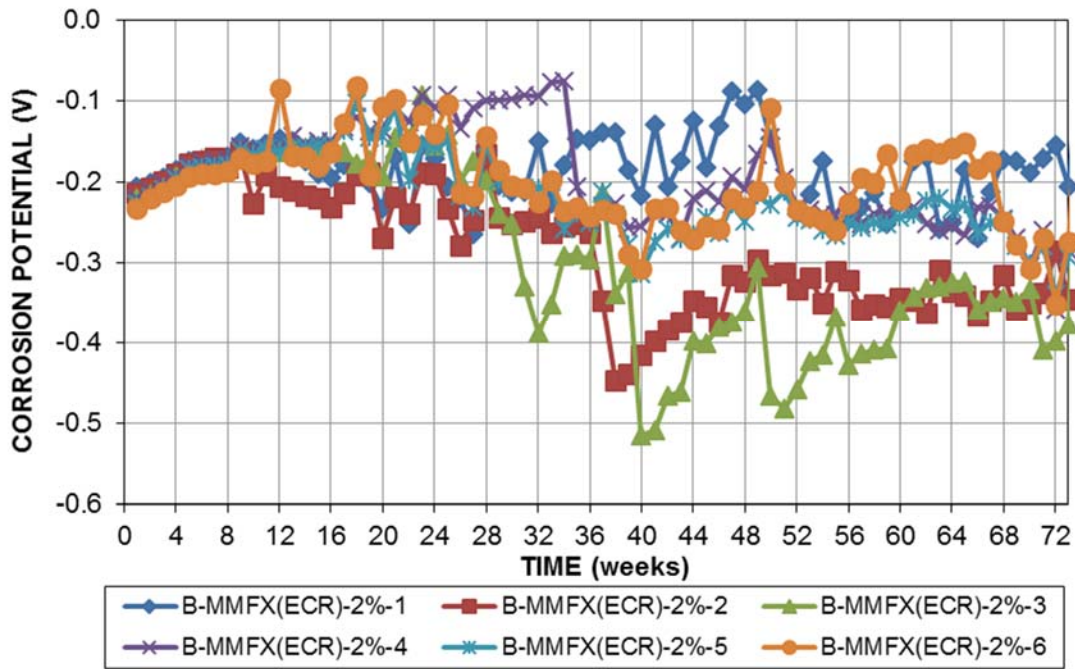


Figure A.53—Bottom mat (cathode) corrosion potential (CSE) versus time for beam specimens containing MMFX-ECR(2%) bars

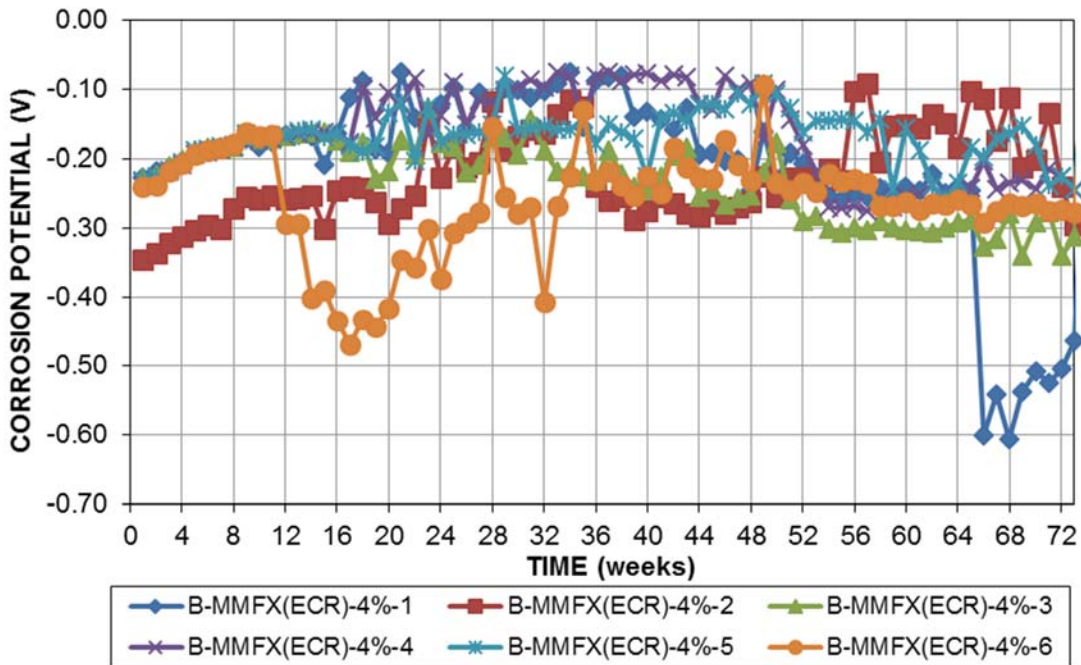


Figure A.54—Bottom mat (cathode) corrosion potential (CSE) versus time for beam specimens containing MMFX-ECR(4%) bars

