CORROSION PERFORMANCE OF CHROMX 2100, 4100, and 9100 BARS

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ABSTRACT

The corrosion resistance of ASTM A1035 CL (nominal Cr content of 2%), CM (nominal Cr content of 4%), and Type CS (nominal Cr content of 9%) steel reinforcing bars produced by MMFX Technologies under the respective trade names ChromX 2100, 4100, and 9100 were evaluated in uncracked concrete. The bars were tested both in the as-rolled condition as well as after sandblasting to remove mill scale. The corrosion performance of the ChromX bars was compared to that of conventional (ASTM A615) reinforcement in previous studies.

The ChromX bars exhibited a critical chloride corrosion threshold between 1.4 and 2.9 times greater than the critical chloride threshold of conventional reinforcement, with the ChromX 9100 bars exhibiting higher chloride thresholds and lower corrosion rates after initiation than the other ChromX bars. The average corrosion rate after initiation of ChromX bars ranged from 15% to 31% that of conventional reinforcing steel. Sandblasting was effective in decreasing the corrosion rate after initiation for ChromX bars, but did not significantly alter the chloride threshold.

Keywords: ASTM A1035, chromium, ChromX, concrete, corrosion, reinforcing steel

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INTRODUCTION

This report describes the results of corrosion tests of ChromX 2100, 4100, and 9100 reinforcing bars produced by MMFX Technologies, which respectively satisfy the requirements of ASTM A1035 CL (nominal chromium content of 2%), CM (nominal chromium content of 4%), and Type CS (nominal chromium content of 9%) steel reinforcing bars. The bars were evaluated both as-rolled and after sandblasting to remove mill scale. Specimens were evaluated in terms of corrosion rate, time to corrosion initiation, and chloride threshold at initiation.

EXPERIMENTAL PROCEDURE

Three bar types were tested in this study. ChromX 2100, 4100, and 9100 bars, designated as ChromX-2%, ChromX-4%, and ChromX-9% throughout this report, with nominal chromium contents of 2%, 4%, and 9% (ASTM A1035 type CL, CM, and CS, respectively) were tested both as-received and after removing the mill scale using sand blasting. The chemical composition of the bars is provided in Table 1.

Table 1: Chemical composition of ChromX bars

	C	**Mn**	**P**	**S**	**Si**	**Cu**	**Ni**	**Cr**	**V**	**Mo**	**Sn**	**N_2**
ChromX 2100	0.29	0.99	0.013	0.007	0.031	0.16	0.08	2.46	0.004	0.02	0.009	0.008
ChromX 4100	0.12	0.64	0.012	0.016	0.34	0.18	0.08	4.72	0.011	0.02	0.009	0.01
ChromX 9100	0.08	0.58	0.011	0.007	0.41	0.15	0.07	9.86	0.022	0.01	0.007	0.014

The bars were evaluated using a corrosion initiation beam specimen, described in the following section.

Corrosion Initiation Beam Specimens

Description

The corrosion initiation beam specimens (shown in Figure 1) have dimensions of 6 × 12 × 7 in. (152 × 305 × 178 mm). Two layers (mats) of reinforcement are used in the specimens. The top mat and bottom mat consist of one and two No. 5 (No. 16) reinforcing bars, respectively. Bars were 12 in. (305 mm) long with 1-in. (25-mm) clear cover. The top and bottom mats are electrically connected through a terminal box across a 10-ohm resistor via external wiring to allow the macrocell corrosion rate to be measured. To allow the specimens to be ponded with salt solution, a 0.75 in. (19 mm) concrete dam is cast integrally with the specimens.

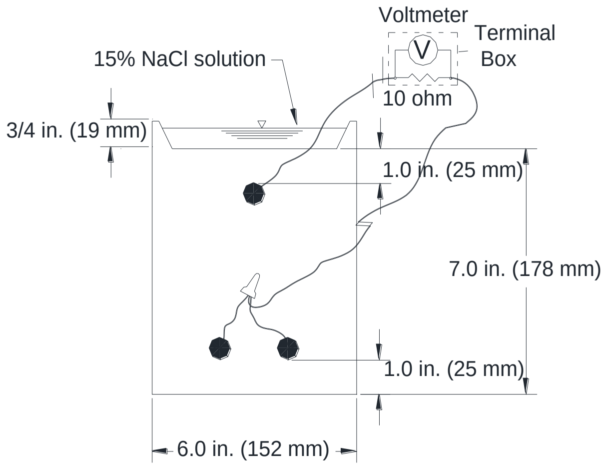

Figure 1— Beam (B) specimens

Test Procedure

To fabricate the 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. Bars are submerged in acetone for at least two hours to remove any oil from bar surface. Forms are built from 0.75 in. (19 mm) plywood, with 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 × 4.5 × 0.75 in. (267 × 267 × 19 mm) piece of plywood is attached and centered to the base. 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 is consolidated using internal vibration.

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

The duration of the initiation beam tests is 96 weeks. The test involves 12 weeks of wet-dry cycles followed by 12 weeks during which the specimens are continuously ponded. 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 the surface of the specimens, and the specimens are then placed under a heat tent at 100 ± 3 °F (38 ± 2 °C) for 3 days. This procedure is repeated for 12 weeks. After 12 weeks of wet-dry cycles, specimens are continuously ponded with a 15% NaCl solution and kept covered at room temperature for 12 weeks. Deionized water is added 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 corrosion threshold of reinforcement, specimens are sampled upon corrosion initiation. Corrosion initiation on an uncoated bar is defined as a measured macrocell corrosion rate exceeding 0.3 µm/yr or a corrosion potential more negative than –0.350 V with respect to a copper/copper sulfate electrode (CSE). Samples for chloride testing are taken using a 0.25 in. (6.4 mm) masonry drill bit with the top of the bit level with the top of the top mat of reinforcing steel (as shown in Figure 2). Twenty samples (ten from each side) are taken upon onset of corrosion. At each sample site, the 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. Ten of the twenty samples are analyzed for water-soluble chloride content of concrete samples per ASTM C1218. The remaining ten samples are analyzed for acid-soluble chloride content per ASTM C1152.

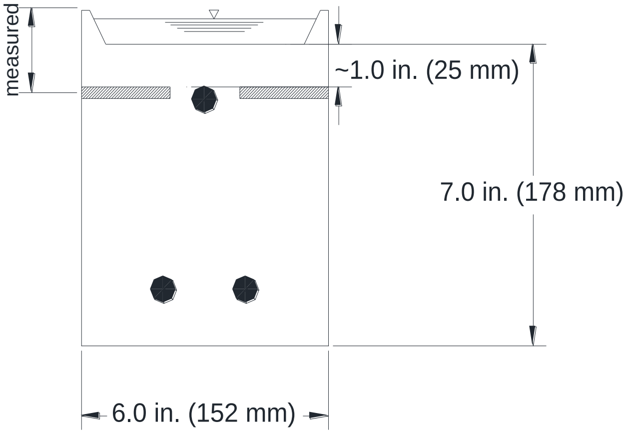

Figure 2— Beam specimen chloride sampling

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:

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

where i_{corr} is current density (μA/cm^2); V is the measured voltage drop across the resistor (volts); R is the resistance of resistor (10 ohms); and A is the surface area of anode (cm^2). The top mat of steel is the anode.

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

$$r = k\frac{i_{corr}a}{nF\rho} \tag{2}$$

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

Corrosion Potential:

After measuring the voltage drop, the connection between anode and cathode across the resistor is disconnected for at least two hours to allow the potentials to stabilize, and then the corrosion potential of the top and bottom mats in is measured using a silver chloride electrode (AgCl). These readings are converted to an equivalent reading with respect to a copper/copper sulfate electrode (CSE) for this report.

Linear Polarization Resistance:

In addition to the weekly voltage drop and corrosion potential measurements, linear polarization resistance (LPR) is measured on a monthly basis. Linear polarization resistance is used to determine the total corrosion rate of reinforcement, including both macrocell corrosion (where the anode and cathode are on separate bars), and microcell corrosion (where the anode and cathode on the same bar). In a corroding specimen, both forms of corrosion are present simultaneously; voltage drop across the 10-ohm resistor only provides a measure macrocell corrosion.

TEST PROGRAM

Six initiation beam specimens were cast for each of the six types of reinforcement, ChromX as-rolled bars containing 2%, 4%, and 9% chromium (ChromX-2%, ChromX-4%, and ChromX-9%, respectively) and ChromX sandblasted bars containing 2%, 4%, and 9% chromium (ChromX-2%-S, ChromX-4%-S, and ChromX-9%-S, respectively). The specimens were cast with four batches of concrete. For each of the first three batches, two initiation beam specimens were cast for each reinforcement type. Two specimens from the first three batches exhibited early corrosion at the electrical connection; these specimens were discarded and replaced using the fourth batch of concrete. The casting order for the specimens is shown in Table 2. The concrete contained Type I/II portland cement and had a water-cement ratio *(w/c)* of 0.45, a target air content of 6 ± 1%, and target slump of 3 ± 1 in. (75 ± 25 mm). Aggregate properties and mixture proportions are shown in Table 3. The average 28-day concrete compressive strength for batches 1 through 4 were 4850, 4180, 4540, and 4700 psi (33.4, 28.8, 31.3, and 32.4 MPa).

Table 2: Specimens cast in each batch

	Specimens			
Steel	**Batch 1**	**Batch 2**	**Batch 3**	**Batch 4**
ChromX-2%	1,*	3, 4	5,6	2
ChromX-2%-S	1, 2	3, 4	5,6	
ChromX-4%	1, 2	3, 4	*,6	5
ChromX-4%-S	1, 2	3, 4	5,6	
ChromX-9%	1, 2	3, 4	5,6	
ChromX-9%-S	1, 2	3, 4	5,6	

*Specimen discarded due to corrosion at electrical connection.

Table 3: Mix proportions (SSD basis)

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

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

TEST RESULTS

Macrocell Corrosion Rate

The macrocell corrosion rates of the initiation beam specimens for the bars containing 9% chromium in the as-rolled and sandblasted conditions are shown in Figures 3 and 4, respectively. For the as-rolled ChromX-9% bars, all six specimens initiated corrosion-five within the 96 week test, and the sixth at 99 weeks. The average age at initiation was 42 weeks, but the range was wide – 11 to 99 weeks. The maximum corrosion rates ranged from 3.11 to 9.30 µm/yr (excluding specimen ChromX-9%-4, which was terminated shortly after initiation). For the sandblasted bars ChromX-9%-S bars, all six specimens initiated corrosion. The average age at initiation was 52.2 weeks, with a range of 28 to 85 weeks. The maximum corrosion rates ranged from 2.33 to 5.21 µm/yr.

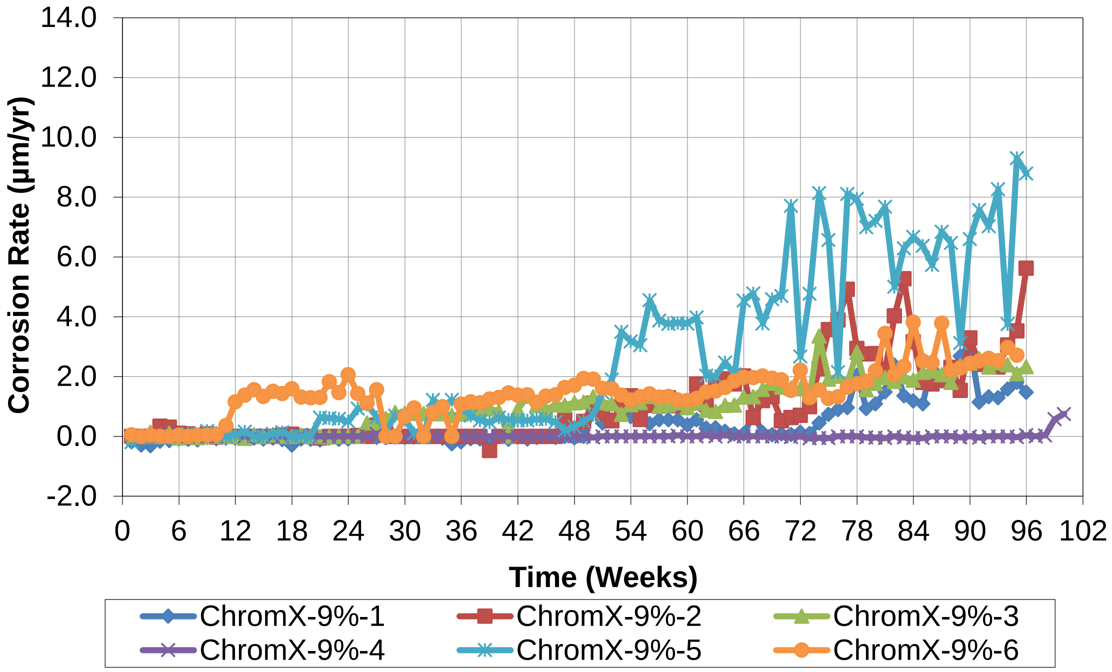

Figure 3— Macrocell corrosion rates (µm/yr) for specimens containing the as-received ChromX-9% bars

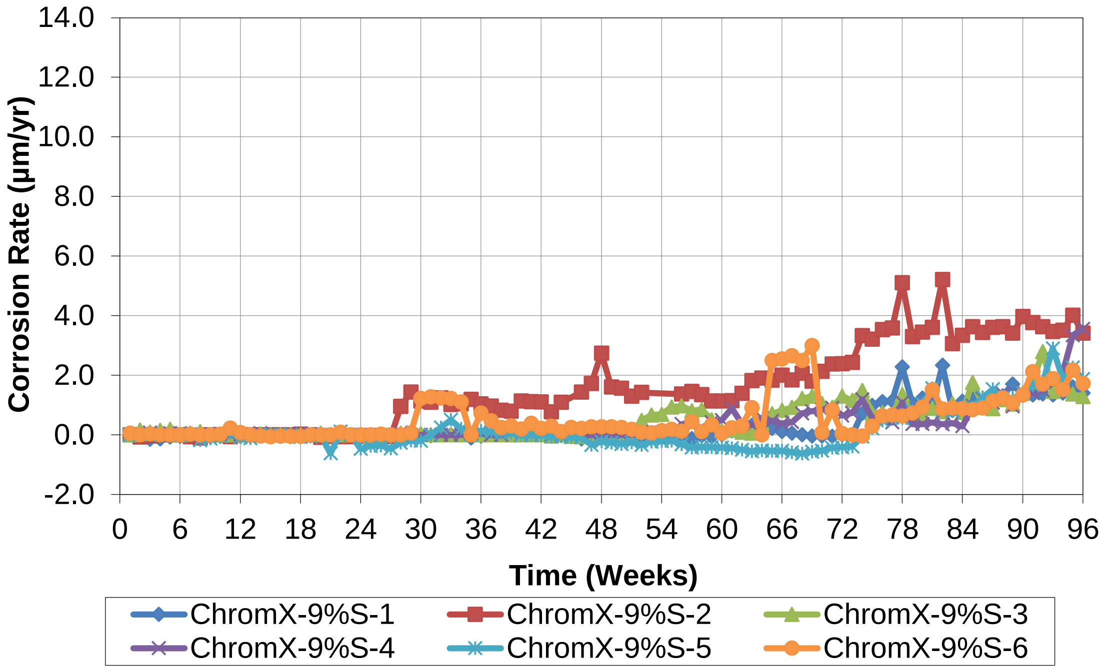

Figure 4— Macrocell corrosion rates (µm/yr) for specimens containing the sand blasted ChromX-9%-S bars

The macrocell corrosion rates of initiation beam specimens for the bars containing 4% chromium in the as-rolled and sandblasted conditions are shown in Figures 5 and 6, respectively. For the as-rolled ChromX-4% bars, four of the six specimens initiated corrosion within the 96-week test-specimens 5, 1, 2, and 6 at week 60, 74, 89, and 93 respectively. It should be noted that specimen ChromX-4%-6 exhibited net corrosion on the bottom bar (shown as a negative corrosion rate in the figure) from week 54 to 87. This may have prevented corrosion initiation from being promptly observed. Testing on specimens 3 and 4 was continued past 96 weeks; these specimens initiated at weeks 99 and 97, respectively. The maximum corrosion rates ranged from 0.876 to 8.70 µm/yr. For the sandblasted bars containing 4% chromium (ChromX-4%-S), all six specimens initiated corrosion. The average age at initiation was 42.2 weeks, with a range of 17 to 80 weeks. The maximum corrosion rates ranged from 2.39 to 11.3 µm/yr.

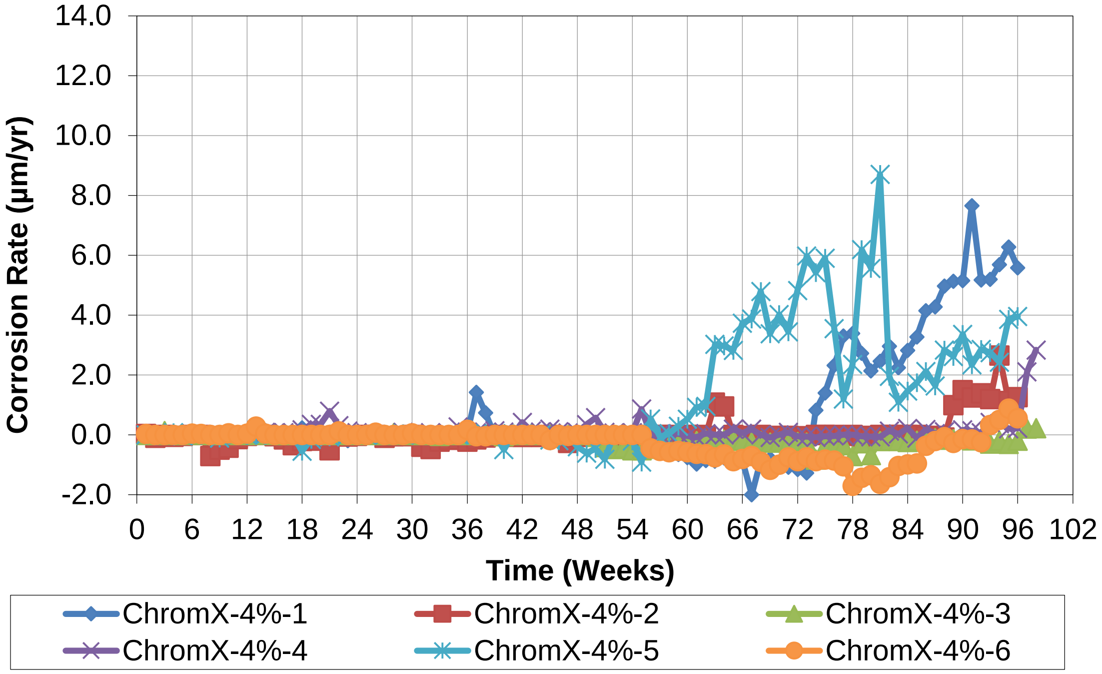

Figure 5— Macrocell corrosion rates (µm/yr) for specimens containing ChromX-4% bars

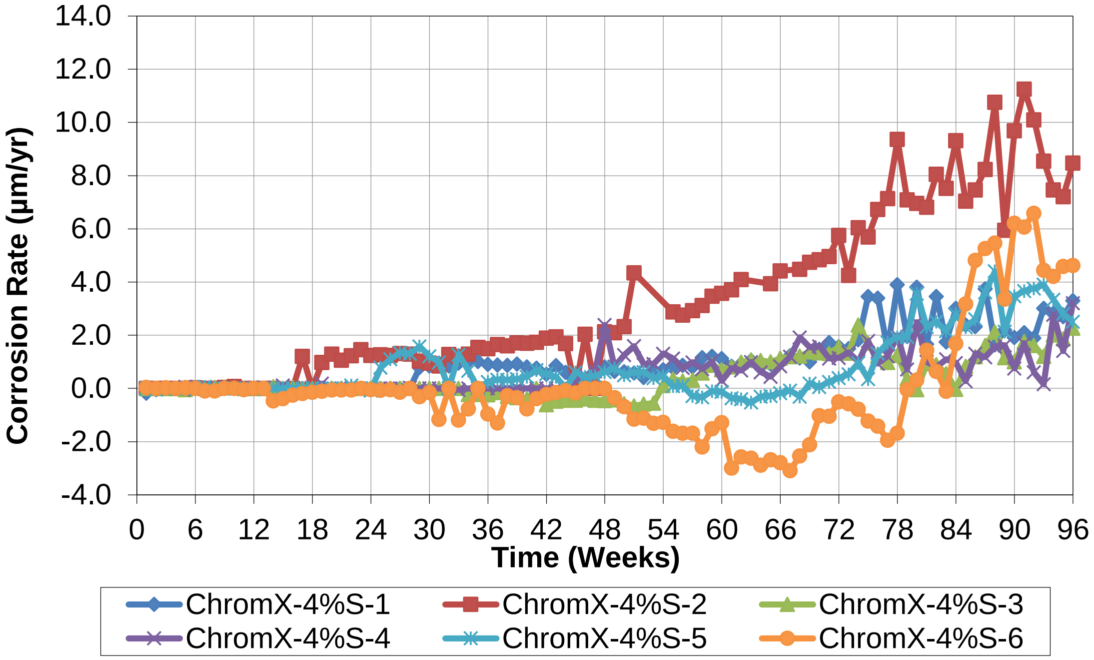

Figure 6— Macrocell corrosion rates (µm/yr) for specimens containing ChromX-4%-S bars

The macrocell corrosion rates of initiation beam specimens for the bars containing 2% chromium in the as-rolled and sandblasted conditions are shown in Figures 7 and 8, respectively. For the as-rolled ChromX-2% bars, all six specimens initiated corrosion. The average initiation age was 29.2 weeks, with a range of 15 to 59 weeks. The maximum corrosion rates ranged from 3.32 to 18.2 µm/yr. For the sandblasted bars containing 2% chromium (ChromX-2%-S), all six specimens initiated corrosion. The average age at initiation was 45.8 weeks, with a range of 28 to 63 weeks. The maximum corrosion rates ranged from 2.91 to 8.00 µm/yr.

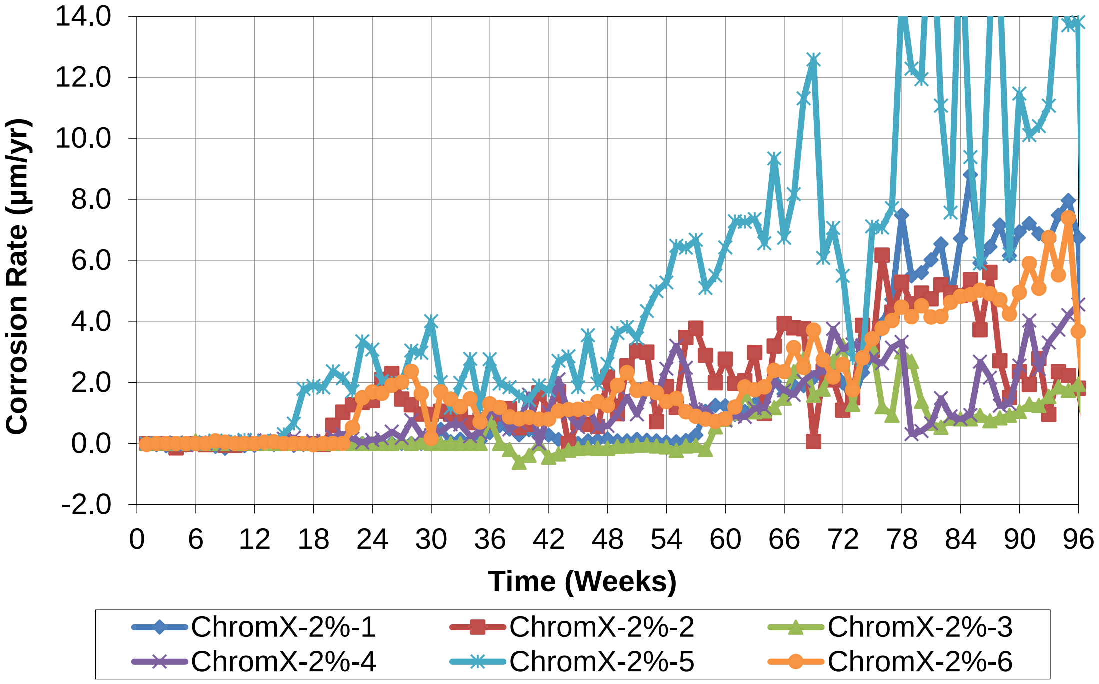

Figure 7— Macrocell corrosion rates (µm/yr) for specimens containing ChromX-2% bars

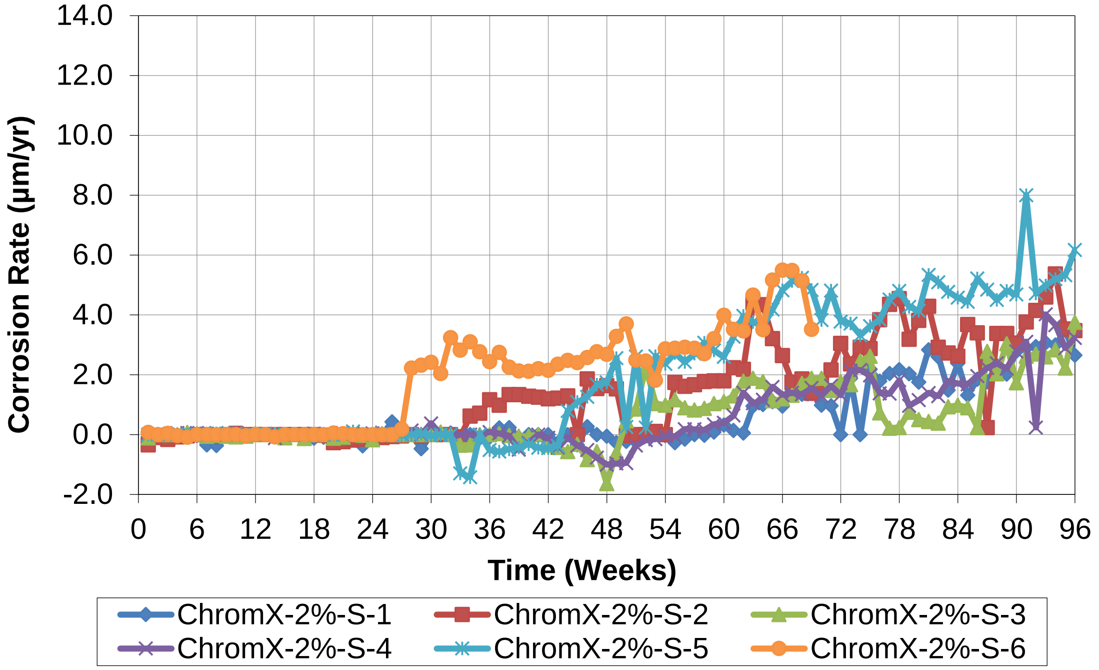

Figure 8— Macrocell corrosion rates (µm/yr) for specimens containing ChromX-2%-S bars

Macrocell Corrosion Loss

The individual and average corrosion losses for the specimens through the end of week 96 are tabulated in Table 4. The corrosion losses were obtained by integrating the corrosion rates expressed in terms of thickness loss given in Eq. (2) with respect to time. To determine the statistical significance of the differences in corrosion losses between bars, a two-tailed Student's t-test is used. Student's t-test is a method of statistical analysis that compares the means and variances of two data sets to determine the probability, p, that differences between the two datasets could have arisen by chance; that is, differences in the mean values are due to the natural variability of the test program, not differences in the effectiveness of the corrosion protection systems. In this study, a value of 0.20 is used as the maximum threshold for statistical significance.

As described earlier, specimen ChromX-4%-6 exhibited corrosion on the bottom mat of steel for much of the test; it is, therefore, excluded from the average. ChromX bars with 9% and 2% chromium showed lower corrosion losses at 96 weeks when they were sandblasted than when they were tested in the as-rolled condition. The average corrosion losses for ChromX-9% bars without and with sandblasting were 2.38 and 1.04 µm, respectively, and the average corrosion losses for ChromX-2% bars without and with sandblasting were 3.81 and 2.07 µm, respectively; in both cases, the differences in corrosion loss between specimens with and without sandblasting were statistically significant ($p = 0.194$ and 0.095, respectively). The average corrosion losses for ChromX-4% with and without sandblasting were 1.27 and 1.85 µm, respectively; these differences are not statistically significant ($p = 0.661$).

Table 4: Macrocell corrosion losses (µm) through week 96

Steel	Specimen number						Average	COV
	1	2	3	4	5	6		
ChromX-2%	3.29	3.35	1.04	2.21	9.37	3.62	3.81	0.756
ChromX-2%-S	1.16	2.70	1.21	1.16	3.72	2.45	2.07	0.514
ChromX-4%	1.46	0.108	**	**	2.25	*	1.27	0.852
ChromX-4%-S	1.92	5.71	0.767	1.17	1.49	0.042	1.85	1.081
ChromX-9%	0.773	1.90	1.90	**	4.72	2.63	2.38	0.614
ChromX-9%-S	0.566	2.79	0.849	0.718	0.27	1.04	1.04	0.861

*Specimen excluded due to corrosion on bottom mat

**Specimen did not initiate prior to week 96

Linear Polarization Resistance (LPR)

The corrosion rates obtained from the LPR tests on specimens with ChromX bars containing 9% chromium without and with sandblasting are shown in Figures 9 and 10, respectively. For the bars tested in the as-rolled condition, specimen ChromX-9%-4 exhibited the greatest maximum corrosion rate, 16.5 µm/yr at week 20. No other specimen exhibited a corrosion rate greater than 6.5 µm/yr. For specimens with sandblasted bars, specimen ChromX-9%-S-4 exhibited the greatest maximum corrosion rate, 9.69 µm/yr at week 72. Specimens 2 and 3 exhibited maximum corrosion rates of 8.48 and 4.94 µm/yr, respectively. The other specimens exhibited corrosion rates no greater than 3 µm/yr. For specimens both with and without sandblasting, corrosion rates were generally low at the start of testing and gradually increased through 96 weeks; some specimens showed isolated spikes in corrosion rate for a single month before returning to near the previous value.

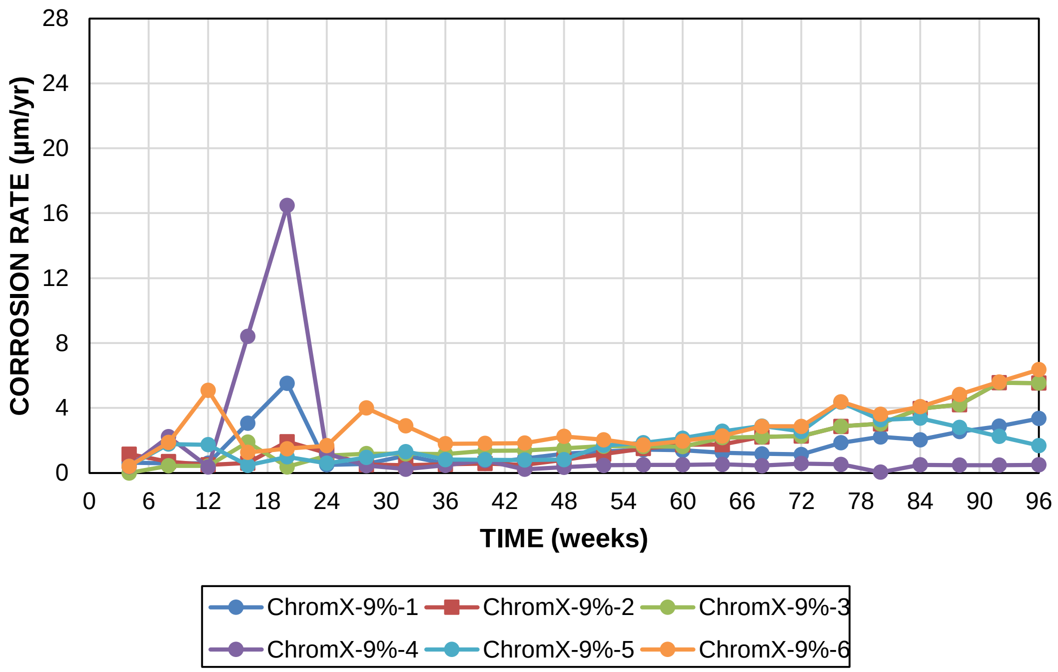

Figure 9— LPR test corrosion rates (µm/yr) for specimens containing ChromX-9% bars

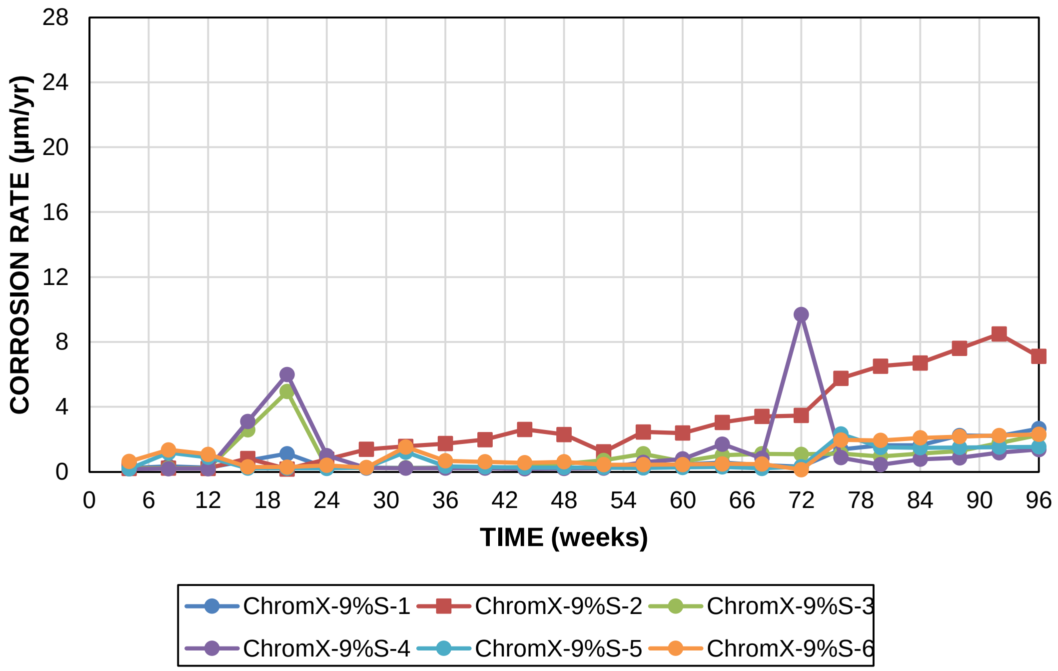

Figure 10— LPR test corrosion rates (µm/yr) for specimens containing ChromX-9%-S bars

The corrosion rates obtained from the LPR test on specimens with ChromX bars containing 4% chromium without and with sandblasting are shown in Figures 11 and 12, respectively. For the bars tested in the as-rolled condition, specimen ChromX-4%-6 exhibited low corrosion rates through week 20 before corrosion activity dropped to near zero; activity increased suddenly after week 64 with a maximum corrosion rate of 18.1 µm/yr at week 84. No other specimen exhibited a corrosion rate greater than 8 µm/yr. For specimens with sandblasted bars, specimen ChromX-4%-S-2 exhibited the greatest maximum corrosion rate, 9.23 µm/yr at week 84; corrosion rates dropped to near 6 µm/yr by week 96. No other specimen exhibited a corrosion rate greater than 4 µm/yr. With the exception of the specimens described above, corrosion rates were generally low at the start of testing and gradually increased through 96 weeks.

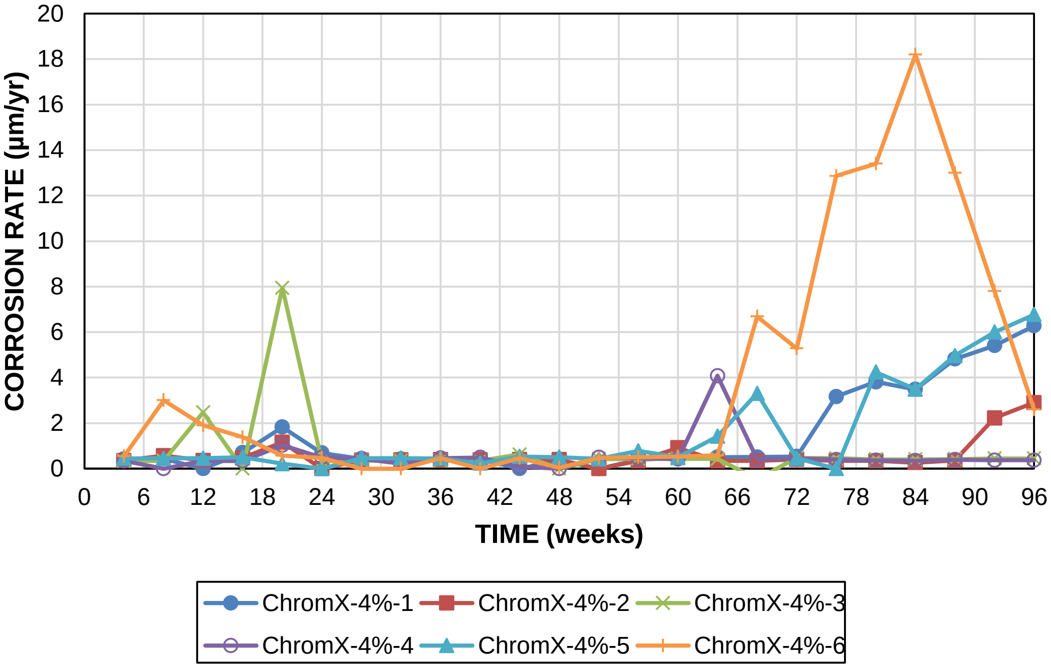

Figure 11— LPR test corrosion rates (µm/yr) for specimens containing ChromX-4% bars

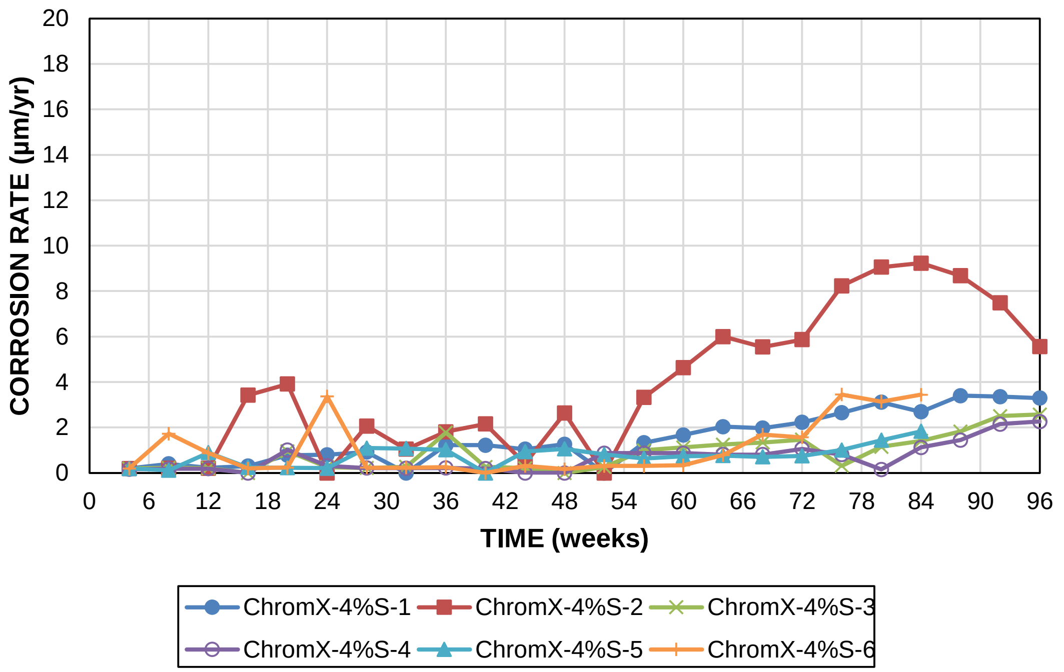

Figure 12— LPR test corrosion rates (µm/yr) for specimens containing ChromX-4%-S bars

The corrosion rates obtained from the LPR test on specimens with ChromX bars containing 2% chromium without and with sandblasting are shown in Figures 13 and 14, respectively. For bars tested in the as-rolled condition, specimen ChromX-2%-5 exhibited the greatest maximum corrosion rate, 24.8 µm/yr at week 76. Specimens 1, 2, and 6 each exhibited maximum corrosion rates exceeding 10 µm/yr at some point. The other ChromX-2% specimens exhibited corrosion rates of less than 10 µm/yr. As was the case with ChromX-9% and ChromX-4% specimens, corrosion rates were generally low at the start of testing and increased after week 48; for the ChromX-2% specimens, however, the increase in rate was more dramatic than in other specimens. For specimens with sandblasted bars, specimen ChromX-2%-S-5 exhibited the greatest maximum corrosion rate, 8.21 µm/yr at week 76. No other specimen exhibited a corrosion rate greater than 6 µm/yr. Unlike the ChromX-2% bars in the as-rolled condition, the increase in corrosion rate over time for the ChromX-2%-S specimens was gradual.

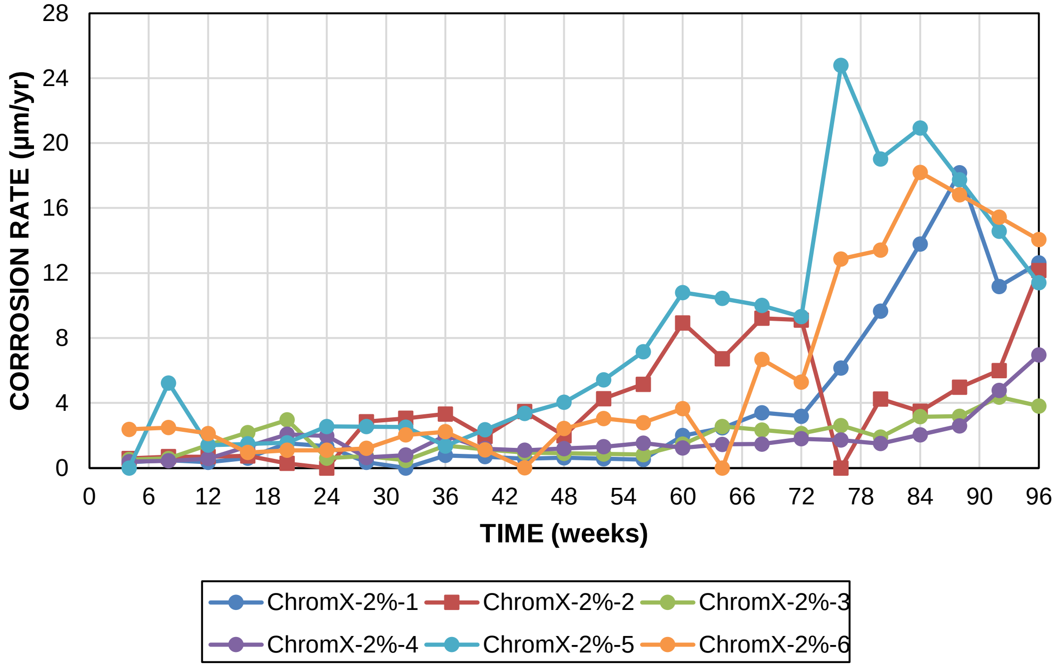

Figure 13— LPR test corrosion rates (µm/yr) for specimens containing ChromX-2% bars

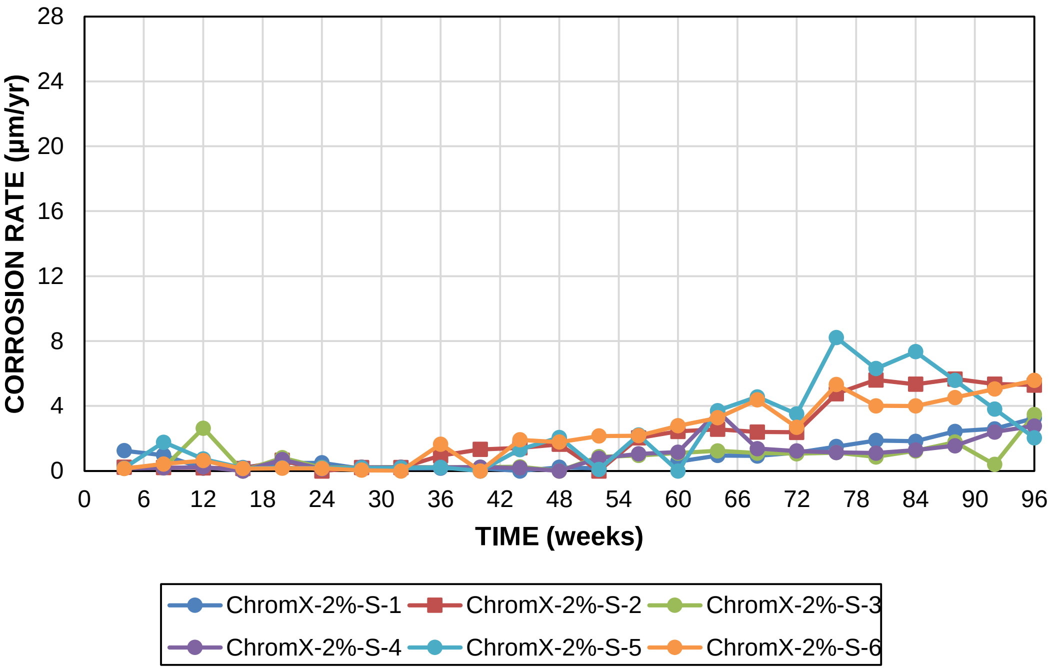

Figure 14— LPR test corrosion rates (µm/yr) for specimens containing ChromX-2%-S bars

The individual and average corrosion losses obtained from the LPR test results through week 96 are tabulated in Table 5. Among as-rolled specimens, the ChromX-4% exhibited the lowest average corrosion loss, 2.67 µm, followed by ChromX-9% and ChromX-2% at 3.61 and 7.58 µm. The difference in corrosion loss between ChromX-4% and ChromX-9% was not statistically significant (p = 0.366), but the differences in loss between ChromX-2% and the other bar types were significant (p < 0.052). In all cases, sandblasting reduced the average LPR corrosion loss. For ChromX-4%-S, this the effect was negligible, with an average loss of 2.60 µm (p = 0.962), but for other bar types, this difference was significant (p < 0.152). ChromX-9%-S had the lowest corrosion loss of any bar in this study, at 2.39 µm.

Table 5: Corrosion losses (μm) for specimens based on LPR through week 96

Steel	Specimen number						Average	COV
	1	2	3	4	5	6		
ChromX-2%	7.03	7.22	3.31	3.23	14.6	10.1	7.58	0.570
ChromX-2%-S	1.66	3.92	1.57	1.69	4.20	4.07	2.85	0.467
ChromX-4%	2.73	1.08	1.37	0.98	2.85	6.98	2.67	0.851
ChromX-4%-S	2.77	7.05	1.60	1.22	1.21	1.75	2.60	0.866
ChromX-9%	2.95	3.48	3.74	2.85	3.30	5.31	3.61	0.249
ChromX-9%-S	1.41	5.55	1.87	2.41	1.31	1.80	2.39	0.666

Corrosion Potential

The average top mat corrosion potentials (with respect to a copper-copper sulfate electrode) for the ChromX specimens are shown in Figure 15. The average top mat potential for all specimens was between –0.23 V and –0.29 V at the start of the test. The potential of the ChromX-4% specimens remained relatively constant through week 84, dropping to –0.40 V at week 89. The other specimens saw gradual declines in potential starting between week 18 and 36, with the potential dropping to below –0.50 V by week 96. The drops in potential correspond to the initiation of corrosion for a specimen in the series.

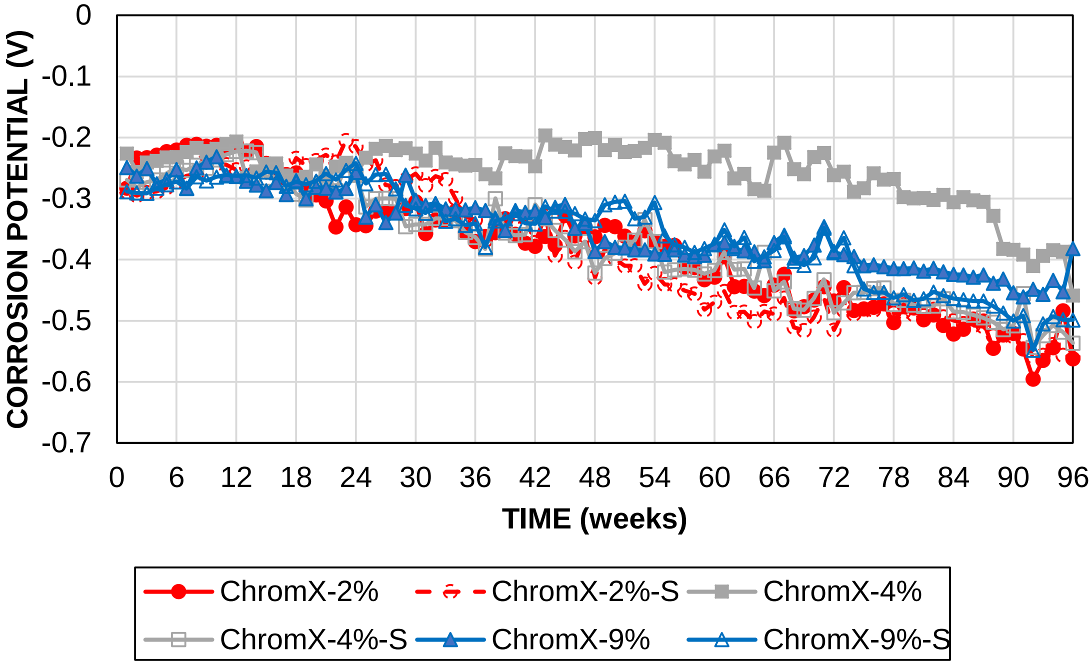

Figure 15—Top mat (anode) corrosion potential (CSE) versus time specimens containing ChromX bars

Average LPR Corrosion Rate After Initiation

The individual and average corrosion rates after initiation for each system are determined from the total corrosion loss plots obtained from LPR test results. The calculation is described by Farshadfar et al. (2017). The average corrosion rates based on the LPR test results for each system in this study are tabulated in Table 6. The corrosion rates after initiation for conventional reinforcement obtained by Farshadfar et al. (2017) are also presented as a reference. All ChromX bars exhibited average corrosion rates after initiation significantly lower than that observed for conventional reinforcement ($p < 0.00004$), with values ranging from 2.09 µm/yr for ChromX-9%-S specimens to 4.44 µm/yr for ChromX-2% specimens compared to 14.5 µm/yr for conventional reinforcement (Farshadfar et al 2017). The average corrosion rate decreased as chromium content increased, though the difference in corrosion rate between ChromX-2% and ChromX-4%

was not statistically significant (*p* = 0.707). Among the bars tested in the as-rolled condition, ChromX-9% had the lowest corrosion rate after initiation (*p* < 0.137). In all cases sandblasting resulted in a reduction in the average corrosion rate after initiation, a difference that was statistically significant for ChromX-2% and ChromX-4% bars (*p* = 0.078 and 0.150), but not for ChromX-9% bars (*p* = 0.668)

Table 6: Individual and average corrosion rates (µm/yr) after corrosion initiation based on LPR test corrosion losses

Steel	Specimen number						Average	COV
	1	2	3	4	5	6		
ChromX-2%	4.48	5.00	1.93	1.97	8.53	4.75	4.44	0.548
ChromX-2%-S	1.83	3.07	1.27	1.62	3.58	2.78	2.36	0.388
ChromX-4%	4.50	2.56	*	*	1.89	6.51	3.86	0.538
ChromX-4%-S	2.03	4.65	1.45	1.10	0.92	2.65	2.13	0.650
ChromX-9%	1.83	2.82	2.40	*	1.93	2.49	2.29	0.179
ChromX-9%-S	1.96	3.87	1.22	1.74	1.77	2.00	2.09	0.437
Conv.**	10.9	16.3	15.9	15.1	14.8	13.8	14.5	0.135

*Specimen did not initiate corrosion prior to 96 weeks

**Farshadfar et al. (2017)

Critical Chloride Corrosion Threshold

Specimens were sampled to determine the critical chloride corrosion threshold at corrosion initiation on both a water-soluble and acid-soluble basis. The water-soluble values are shown in Table 7. The chloride threshold of conventional reinforcement (Farshadfar et al. 2017) is shown for reference. All bars exhibited a water-soluble chloride threshold greater than that of conventional reinforcement; with the exception of Conv. and ChromX-2%, these differences were statistically significant (*p* < 0.120). ChromX-2% bars exhibited the lowest chloride threshold, 2.06 lb/yd^3 (1.22 kg/m^3), whereas both ChromX-9% and ChromX-2%-S exhibited chloride thresholds greater than 4.0 lb/yd^3 (2.37 kg/m^3). The difference in chloride threshold between ChromX-9% and ChromX-2% was statistically significant (*p* = 0.064); other differences were not statistically significant. Sandblasting did not have a consistent effect on the chloride threshold of ChromX bars, with only ChromX-2% and ChromX-2%-S exhibiting a statistically significant difference (*p* = 0.032).

Table 7: Water-soluble critical chloride corrosion threshold (lb/yd^3) of ChromX bars

Steel	Specimen number						Average	COV
	1	2	3	4	5	6		
ChromX-2%	4.04	4.06	0.60	1.12	1.55	0.97	2.06	0.764
ChromX-2%-S	2.88	6.25	4.21	5.66	3.36	3.01	4.23	0.337
ChromX-4%	1.65	4.37	*	0.62	2.27	*	2.23	0.708
ChromX-4%-S	3.53	0.48	3.53	3.00	2.31	*	2.57	0.495
ChromX-9%	5.60	4.38	5.29	*	4.50	0.46	4.04	0.512
ChromX-9%-S	6.64	1.27	8.07	2.64	2.16	1.42	3.70	0.786
Conv.**	*	1.06	2.18	0.86	2.50	0.70	1.46	0.562

1(lb/yd^3) = 0.593(kg/m^3)
*Data not available
**Farshadfar et al. (2017)

The acid-soluble values are shown in Table 8. Among as-rolled bars, ChromX-2% bars exhibited the lowest chloride threshold, 1.38 lb/yd^3 (0.82 kg/m^3), while both ChromX-9% and ChromX-2%-S exhibited chloride thresholds greater than 4.0 lb/yd^3 (2.37 kg/m^3). As for the water-soluble values, sandblasting did not have a consistent effect on the acid-soluble chloride threshold of ChromX bars; while sandblasting resulted in statistically significant differences in acid-soluble chloride threshold for both ChromX-2% and ChromX-9% bars, the ChromX-2% bars exhibited a statistically significant increase in chloride threshold after sandblasting, while ChromX-9% exhibited a statistically significant decrease in chloride threshold after sandblasting.

Table 8: Acid-soluble critical chloride corrosion threshold (lb/yd^3) of ChromX bars

Steel	Specimen number						Average	COV
	1	2	3	4	5	6		
ChromX-2%	2.72	2.00	*	0.89	0.74	0.54	1.38	0.682
ChromX-2%-S	2.96	4.21	4.83	*	5.18	2.36	3.91	0.309
ChromX-4%	1.85	*	10.39	6.06	0.97	6.66	5.18	0.741
ChromX-4%-S	1.66	*	*	*	4.10	1.87	2.54	0.532
ChromX-9%	4.90	3.60	2.37	6.57	2.99	*	4.08	0.410
ChromX-9%-S	*	1.32	*	*	1.19	0.92	1.14	0.176

1(lb/yd^3) = 0.593(kg/m^3)
*Data not available

Prior studies at the University of Kansas (Ji et al. 2005, Farshadfar et al. 2018) using the test methods outlined in this study determined the water-soluble chloride threshold for ChromX-9% and 4% bars in the as-received condition. Results from these studies are shown in Table 9. The chloride thresholds for ChromX-9% found by Ji et al. and Farshadfar et al. (3.09 and 4.54 lb/yd^3, respectively) are comparable to that found in this study. Combining data from prior studies yields a weighted average water-soluble chloride threshold of 4.06 lb/yd^3. The chloride threshold for ChromX-4% found by Farshadfar et al. (4.25 lb/yd^3) is somewhat higher than the value found in this study, though it should be noted that the coefficient of variation in both studies is high. Combining data yields a weighted average water-soluble chloride threshold of 3.38 lb/yd^3. No prior studies on chloride threshold ChromX 2% are available; based on this study, ChromX-2% has an average water-soluble chloride threshold of 2.06 lb/yd^3.

Table 9: Water-soluble critical chloride corrosion threshold (lb/yd^3) of ChromX bars from previous studies

Study		**Specimen**								**Average**	**COV**
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
Farshadfar et al. (2018)	ChromX-4%	3.05	3.46	5.51	3.03	3.78	2.34	5.35	7.46	4.25	0.426
	ChromX-9%	4.24	5.59	2.76	4.12	1.87	1.59	5.45	10.7	4.54	0.324
Ji et al. (2005)	ChromX-9%	5.77	1.9	2.36	2.33					3.09	0.582

DISCUSSION

Both the water-soluble critical chloride corrosion thresholds and the corrosion losses match expectations for the specimens tested in the as-received condition, with the chloride threshold increasing and the corrosion rate decreasing as the chromium content of the bars increased. The ChromX-4% specimens did exhibit the lowest losses in this study, and losses far lower than those observed in prior tests on Chromx-4% bars (Farshadfar et al. 2018). It should be noted, however, that corrosion rates after initiation were lower for ChromX-9% bars than for ChromX-4% bars, indicating the low losses on ChromX-4% bars were due to a delayed corrosion initiation. Both corrosion rates and chloride thresholds showed high scatter, however, with many series exhibiting COV's near or over 0.5. Results were generally less consistent when testing bars after sandblasting, and for acid-soluble chloride threshold.

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 were evaluated in uncracked concrete. The bars were evaluated to determine time to corrosion initiation, chloride threshold at initiation, and corrosion rate after initiation. Bars were evaluated in both the as-rolled condition and after sandblasting to remove mill scale.

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

1. The critical chloride corrosion threshold of ChromX bars is between 1.4 and 2.9 times greater than the critical chloride threshold of conventional reinforcement. In general, increasing the chromium content increased the critical chloride corrosion threshold, though a fair amount of scatter was seen in the data.
2. The average corrosion rate after initiation of ChromX bars ranged from 15% to 31% that of conventional steel, with increased chromium content resulting in decreased corrosion rate.
3. ChromX-9% bars generally exhibited a higher critical chloride corrosion threshold and a lower corrosion rate after initiation than ChromX bars with lower chromium contents.
4. Sandblasting was effective in decreasing the corrosion rate after initiation for ChromX bars, but did not significantly alter the chloride threshold.
5. Combining current and prior studies yields a weighted average water-soluble chloride threshold of 4.06 lb/yd^3 for ChromX-9% and a weighted average water-soluble chloride threshold of 3.38 lb/yd^3 for ChromX-4%. ChromX 2% has an average water-soluble chloride threshold of 2.06 lb/yd^3.

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APPENDIX: STUDENT'S T-TEST RESULTS

Table A.1: Student's T-Test Results for Macrocell Corrosion Losses

	ChromX-2%	ChromX-2%-S	ChromX-4%	ChromX-4%-S	ChromX-9%	ChromX-9%-S
ChromX-2%	1	0.194	0.194	0.200	0.358	0.048
ChromX-2%-S	0.194	1	0.327	0.819	0.664	0.100
ChromX-4%	0.194	0.327	1	0.661	0.304	0.740
ChromX-4%-S	0.200	0.819	0.661	1	0.616	0.386
ChromX-9%	0.358	0.664	0.304	0.616	1	0.095
ChromX-9-S	0.048	0.100	0.740	0.386	0.095	1

Table A.2: Student's T-Test Results for LPR (Total) Corrosion Losses

	ChromX-2%	ChromX-2%-S	ChromX-4%	ChromX-4%-S	ChromX-9%	ChromX-9%-S
ChromX-2%	1	0.028	0.033	0.031	0.052	0.020
ChromX-2%-S	0.028	1	0.865	0.819	0.276	0.600
ChromX-4%	0.033	0.865	1	0.962	0.366	0.815
ChromX-4%-S	0.031	0.819	0.962	1	0.334	0.857
ChromX-9%	0.052	0.276	0.366	0.334	1	0.135
ChromX-9%-S	0.020	0.600	0.815	0.857	0.135	1

Table A.3: Student's T-Test Results for Average Corrosion Rate After Initiation

	ChromX-2%	ChromX-2%-S	ChromX-4%	ChromX-4%-S	ChromX-9%	ChromX-9%-S	Conv.
ChromX-2%	1	0.078	0.707	0.071	0.085	0.051	1E-05
ChromX-2%-S	0.078	1	0.150	0.749	0.886	0.629	8E-08
ChromX-4%	0.707	0.150	1	0.150	0.137	0.098	4E-05
ChromX-S-4%	0.071	0.749	0.150	1	0.814	0.954	2E-07
ChromX-9%	0.085	0.886	0.137	0.814	1	0.668	3E-07
ChromX-9%-S	0.051	0.629	0.098	0.954	0.668	1	7E-08
Conv.	1E-05	8E-08	4E-05	2E-07	3E-07	7E-08	1

Table A.4: Student's T-Test Results for Water Soluble Chloride Threshold

	ChromX-2%	ChromX-2%-S	ChromX-4%	ChromX-4%-S	ChromX-9%	ChromX-9%-S	Conv.
ChromX-2%	1	0.032	0.367	0.597	0.064	0.223	0.437
ChromX-2%-S	0.032	1	0.306	0.044	0.975	0.759	0.004
ChromX-4%	0.367	0.306	1	0.540	0.385	0.676	0.111
ChromX-4%-S	0.597	0.044	0.540	1	0.089	0.327	0.120
ChromX-9%	0.064	0.975	0.385	0.089	1	0.774	0.016
ChromX-9%-S	0.223	0.759	0.676	0.327	0.774	1	0.112
Conv.	0.437	0.004	0.111	0.120	0.016	0.112	1

Table A.5: Student's T-Test Results for Acid Soluble Chloride Threshold

	ChromX-2%	ChromX-2%-S	ChromX-4%	ChromX-4%-S	ChromX-9%	ChromX-9%-S
ChromX-2%	1	0.006	0.063	0.195	0.014	0.694
ChromX-2%-S	0.006	1	0.500	0.187	0.857	0.009
ChromX-4%	0.063	0.500	1	0.306	0.573	0.128
ChromX-4%-S	0.195	0.187	0.306	1	0.229	0.150
ChromX-9%	0.014	0.857	0.573	0.229	1	0.026
ChromX-9%-S	0.694	0.009	0.128	0.150	0.026	1