Comparative Corrosion Testing and Analysis of MMFX 2 Rebars for Reinforced Concrete Applications

Northbrook, Illinois

Final Report
19 February 2008
WJE No. 2003.0707.0

Prepared for:
MMFX Technologies Corporation

Prepared by:
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Comparative Corrosion Testing and Analysis of MMFX 2 Rebars for Reinforced Concrete Applications

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INTRODUCTION

Wiss, Janney, Elstner Associates, Inc. (WJE) was contacted by MMFX Technologies to conduct a laboratory study of the corrosion resistance of its MMFX 2 reinforcing bars. The objectives of this study were to compare the corrosion performance of MMFX 2 bars to A615 carbon steel bars and Type 304 stainless bars in accelerated laboratory tests.

Two laboratory tests, ASTM G109 and time-to-corrosion (also known as Southern Exposure) tests were included in this study. These two methods have been widely used to evaluate the corrosion resistance of reinforcing bars and are generally accepted by Federal and state DOT agencies. For comparison purposes, ASTM A615 carbon steel reinforcement (black bar) and Type 304 stainless steel reinforcement were tested under identical exposure conditions. Some MMFX 2 bar samples had mill scale and others did not. In order to meet the original project requirements of MMFX of completing the test program in five months, the standard test methods were slightly modified for this study. The ASTM G109 test, however, was extended as no bars started to corrode at the end of the initial 20 weeks (5 months) of testing.

MODIFIED ASTM G109 TEST

Background

Originally, the ASTM G109 Standard Test Method for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments test method was developed to evaluate the effectiveness of admixed corrosion inhibitors in two-mat laboratory concrete specimens exposed to a salt solution. The ASTM G109-99 test method employs a moderately good quality concrete, a monthly wet/dry cycle using mild salt exposure (3% NaCl solution) and a 100-ohm resistor inserted between top and bottom mats for macro-cell current measurement. These test parameters can result in slow corrosion initiation at the top mat bar and often the test duration must be extended to over one year. The presence of a 100-ohm resistor also introduces a slight obstruction to the macro-cell current flow and our previous laboratory data showed about a 13 percent reduction in measured current compared to samples having a smaller 1-ohm resistor. The moderate exposure conditions and slow corrosion response of the test specimens is believed by some to be more representative of field conditions compared to other more accelerated tests.

Test Procedure

For this test program, we employed a modified G109 test specimen by replacing the 100-ohm resistor with a direct (banana plug) electrical connection. This connection was periodically disconnected in order to measure the macro-cell current directly using a zero resistance ammeter (ZRA). This provided a continuous and resistance-free connection between the top and bottom bars during the test. A schematic
of the test specimen is shown in Figure 1 and photographs of the general testing are shown in Appendix A. The remaining test procedure was the same as the ASTM G-109 test method, that is, uncracked concrete test blocks, exposure to 50 ± 5 percent relative humidity (RH), and a 2-week wetting and 2-week drying cycle with 3% salt solution.

Examined in this study were four types of rebar materials, which included MMFX 2 (with and without mill scale), ASTM A615 with mill scale (control), and Type 304 stainless steel. The four different rebar types were embedded in four specimens each. All bottom mat bars were black A615 rebars. The open-circuit potential (corrosion potential of top bar only, OCP), short-circuit potential (coupled potential of the top and bottom bars, SCP), and macro-cell current data were collected at regular intervals. The test states that corrosion is sufficient for visual evaluations when a macrocell threshold current of 10 µA is reached. Prior to placing the bars in concrete, the initial weight of each bar was measured using a digital balance to allow for a weight loss measurements at the end of the testing. Macro-cell current was measured by insertion of a zero resistance ammeter (ZRA) between rebar mats. A saturated calomel reference electrode (SCE) was used to measure the half-cell potentials.

**Autopsy and Weight Loss Measurement**

At the end of the initial 20-week testing (Phase I), none of the specimens exhibited a threshold current of 10 µA. For each type of specimens, only the specimen with the highest macro-cell current was autopsied while further testing of the remaining specimens continued. During the extended testing (Phase II), the specimens were autopsied as soon as a 10 µA threshold current was exceeded. The bar condition was examined and an 1/8 in. slice of concrete immediately above the top bar was sampled for acid-soluble chloride analysis according to ASTM C1152 “Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete.” The bar imprint was ground off the concrete sample before testing to minimize interference from iron oxide residue to the chloride analysis.

The weight loss of the bars was determined to estimate the rate of corrosion for the extracted reinforcing bars. Prior to weight measurements, the corrosion products formed on the bars were removed with a wire brush and then the bars were chemically cleaned according to ASTM G1, “Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens”. The final weight of individual bars was measured and the weight loss of each bar was determined by subtracting the final weight of the bar from the initial value.

**Results and Discussion**

**Phase I: 20-week exposure**

The first 20-week exposure results of the modified G-109 testing are presented in Figures 2 to 4. The data indicates that corrosion activity had not yet begun in these specimens. The OCP readings generally remained high and larger (more positive) than -0.1 V. This is well above the usual ~-0.28 V (-0.350 V vs CSE) upper limit for active corrosion in reinforced concrete. The SCP is also high and well above levels that normally indicate the presence of active corrosion.

The macro-cell current data, shown in Figure 3, supports the findings of the potential measurements. The low levels of current combined with stable values indicate that the onset of corrosion had not begun. The onset of corrosion will always be accompanied by a significant increase in the measured current.
Due to the lack of corrosion activity, only one specimen of each bar type was removed from the testing regime for autopsy after 20 weeks. The bars with the highest macrocell readings of each group were selected (specimens BM-3, S-3, M-2 and MM-4). The bars were cleaned and weighed. The weight loss data is shown in Figure 4. The black A615 bar showed some slight weight loss while the pristine appearance and the lack of any significant weight loss confirm that corrosion had not yet begun in the other test samples. Concrete samples were taken from each of the autopsied specimens, and Table 1 shows the chloride concentration at the bar level.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Chloride, wt% (lbs/cy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black bar</td>
<td>0.067 (2.6)</td>
</tr>
<tr>
<td>MMFX without scale</td>
<td>0.087 (3.3)</td>
</tr>
<tr>
<td>MMFX with scale</td>
<td>0.068 (2.6)</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>0.115 (4.4)</td>
</tr>
</tbody>
</table>

**Phase II: Continuation of G109 Testing**

The testing of the remaining modified G109 specimens (three for each bar type) was continued after the initial twenty weeks of testing. As shown in Figure 5, the specimens were subjected to normal ponding cycles of 2-week wetting and 2-week drying, except for three periods when the samples were maintained at the 50% RH but were not ponded.

Figure 5 shows the open-circuit potential profiles of the specimens. A significant drop in the potential profile and corresponding increase in the macrocell corrosion current indicates initiation of corrosion activity of the top bar. As shown, the black bar specimens (BM) started to corrode on day 434, 664, and 758. MMFX bars with mill scale (MM) started to corrode on day 1169, 1266, and 1352. Two MMFX bars without mill scale started to corrode on day 1310 and 1575, while one specimen (M1) remained passive through 1625-days (although the M1 bar had a trace of corrosion product when autopsied). All stainless steel 304 specimens remained passive throughout the total 1625-day test period.

Figure 6 shows the macrocell current measured between the top bar and the bottom bars of each specimen. Corresponding to the potential drop events described above, macrocell currents higher than 10 $\mu$A were registered confirming the onset of corrosion activity.

Table 2 shows the time of activation (corrosion initiation) for specimens reinforced with black bars and MMFX bars (with and without mill scale). As noted, one specimen with MMFX without mill scale (M-1) remained passive through the 1625-day test period, but showed a trace of corrosion on the bar when autopsied. All three specimens with stainless steel 304 bars remained passive throughout the testing period. The table also shows the chloride concentrations at the top bar level after the test exposure was terminated. Since the exposure of the black bar control specimens was continued for additional time after corrosion initiation, the chloride concentrations obtained after exposure termination were higher than the actual chloride concentrations at which corrosion started. Therefore, the chloride threshold for the black bar was estimated based on the well-known solution to Fick’s Law, using 1 in. concrete cover, a corrosion initiation time of 434 days (BM-2), and a surface chloride concentration of 0.75 wt% (29 lbs/cu. yd.). This surface chloride concentration was estimated from a regression analysis of a detailed chloride profile.
of Specimen MM1 (shown in Table 3). The lowest level of chloride for each test condition at corrosion initiation was conservatively assumed as the chloride threshold for MMFX reinforcement.

Table 2 - Bar-top chloride contents determined after exposure termination

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample</th>
<th>Estimated corrosion initiation time (days)</th>
<th>Total exposure time (days)</th>
<th>Chloride, wt% (lbs/cy)</th>
<th>Estimated chloride threshold, wt% (lbs/cy)</th>
<th>Threshold ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 615 Black</td>
<td>BM 1</td>
<td>758</td>
<td>924</td>
<td>0.218 (8.4)</td>
<td>0.10 (3.8)**</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>BM 2</td>
<td>434</td>
<td>924</td>
<td>0.213 (8.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BM 4</td>
<td>664</td>
<td>939</td>
<td>0.209 (8.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MMFX-2 without mill scale</td>
<td>M 1</td>
<td>1625</td>
<td>1625</td>
<td>0.450* (17.3)</td>
<td>0.33 (12.7)</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>M 2</td>
<td>1575</td>
<td>1625</td>
<td>0.405 (15.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M 3</td>
<td>1310</td>
<td>1310</td>
<td>0.328 (12.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MMFX-2 with mill scale</td>
<td>MM 1</td>
<td>1266</td>
<td>1266</td>
<td>0.405 (15.6)</td>
<td>0.30 (11.5)</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>MM 2</td>
<td>1169</td>
<td>1169</td>
<td>0.297 (11.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MM 3</td>
<td>1352</td>
<td>1352</td>
<td>0.405 (15.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless Steel 304</td>
<td>S 1</td>
<td>--</td>
<td>1625</td>
<td>0.555* (21.4)</td>
<td>&gt;0.54 (&gt;20.8)</td>
<td>&gt;5.4</td>
</tr>
<tr>
<td></td>
<td>S 2</td>
<td>--</td>
<td>1625</td>
<td>Not tested*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S 4</td>
<td>--</td>
<td>1625</td>
<td>0.539* (20.7)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Did not reach chloride current threshold values
**Fick’s law estimate

Table 3 Chloride profile of Specimen MM-1 after 1266 days of exposure

<table>
<thead>
<tr>
<th>Depth (in.)</th>
<th>Chloride, wt% (lbs/CY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8 - 1/4</td>
<td>0.640 (24.6)</td>
</tr>
<tr>
<td>7/8 - 1</td>
<td>0.405 (15.6)</td>
</tr>
<tr>
<td>2 - 2 1/8</td>
<td>0.002 (0.08)</td>
</tr>
</tbody>
</table>
Using the G109 test procedure and as shown in Table 2, the chloride thresholds for black bars, MMFX bars with mill scale and without mill scale are approximately 0.10, 0.30, and 0.33 wt% (or 3.8, 11.5, and 12.7 lbs/cu. yd), respectively. The removal of mill scale appears to have only a minor beneficial effect on the corrosion resistance of MMFX bars.

Chloride threshold values determined from accelerated laboratory test programs of this kind may overestimate the actual threshold for corrosion in bridge decks, since deck structures often accumulate chlorides more slowly, only see intermittent deicer applications, and are often at low temperatures. It is common to use the ratio of the threshold values when modeling and comparing the service life of bar alternatives. While varying with many factors such as cementitious material contents, temperature and exposure conditions, a value of 0.03 wt% (1.2 lbs/cu. yd) is commonly used as the chloride threshold for modeling service life of black bars in bridge decks. Based on findings from this program, it is conservatively projected that the field chloride threshold of MMFX bars is three times that of the black A615 steel or 0.09 wt% (3.5 lbs/cu. yd). Stainless 304 bars resisted chloride levels over five times the black bars without corrosion. It is conservatively projected that the chloride threshold of the stainless 304 bars is greater or much greater than 0.16 wt% (6.2 lbs/cu. yd).

Table 4 summarizes the weight loss data of autopsied specimens. Black bar specimens were not immediately autopsied after the first sign of corrosion activation, while MMFX bar specimens were autopsied immediately after observation of corrosion activation. Consequently, weight loss for black bars is generally higher than MMFX bars.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Before exposure (g)</th>
<th>After exposure (g)</th>
<th>Weight loss (g)</th>
<th>Weight loss (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM1</td>
<td>314.8</td>
<td>314.3</td>
<td>0.5</td>
<td>0.16</td>
</tr>
<tr>
<td>BM2</td>
<td>317.4</td>
<td>313.0</td>
<td>4.4</td>
<td>1.39</td>
</tr>
<tr>
<td>BM4</td>
<td>311.6</td>
<td>310.9</td>
<td>0.7</td>
<td>0.22</td>
</tr>
<tr>
<td>BM3*</td>
<td>317.6</td>
<td>317.0</td>
<td>0.6</td>
<td>0.19</td>
</tr>
<tr>
<td>M3</td>
<td>319.0</td>
<td>318.7</td>
<td>0.3</td>
<td>0.09</td>
</tr>
<tr>
<td>M2*</td>
<td>339.8</td>
<td>339.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MM1</td>
<td>334.9</td>
<td>334.5</td>
<td>0.4</td>
<td>0.12</td>
</tr>
<tr>
<td>MM2</td>
<td>344.2</td>
<td>344.0</td>
<td>0.2</td>
<td>0.06</td>
</tr>
<tr>
<td>MM3</td>
<td>317.7</td>
<td>317.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MM4*</td>
<td>319.6</td>
<td>319.5</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>S3*</td>
<td>291.7</td>
<td>291.8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*20-week Phase 1 results

The testing was stopped after 1625 days, and all remaining samples were autopsied. A trace of corrosion was found on sample M-1 during the autopsy, even though the corrosion current remained well below 10 μA. Active corrosion product was noted on sample M-4, as expected based on the high measured corrosion current. None of the stainless steel bars showed any signs of corrosion, and the bars appeared pristine. Photos 1-6 show the typical condition of the test bars after exposure.
Figure 1. Schematic of modified G-109 test specimen.

Figure 2. Mean OCP data of G-109 test specimens for the first 20 weeks.
**Figure 3.** Mean macro-cell current data of G-109 test specimens for the first 20 weeks.

**Figure 4.** Mean percent weight loss of G-109 test specimens after 20 weeks of exposure.
Figure 5. Open circuit potential G-109 test specimens. (BM: black bar with mill scale; S: stainless steel; M: MMFX 2 without mill scale; MM: MMFX 2 with mill scale)

Figure 6. Mat-to-mat macro-cell current; (BM: black bar with mill scale; S: stainless steel; M: MMFX 2 without mill scale; MM: MMFX 2 with mill scale)
Photo 1. Black bar before cleaning: BM2 has extensive corrosion; moderate rust on BM1 and BM4.

Photo 2. Black bars after cleaning: superficial attack on BM1 and BM1; significant attack on BM2.

Photo 3. Sample MM2 corroded at a rib, and the corrosion product is black and liquid after 1169 days.
Photo 4. Sample M1 showing small trace of corrosion on bar after 1625 days.
Photo 5. Sample M4 showing minor corrosion products that are black and liquid after 1625 days.
Photo 6. Stainless 304 bars samples showing no corrosion after 1625 days.
20-WEEK MODIFIED SOUTHERN EXPOSURE TEST

Background

The macro-cell current test slab program, as reported in the 1983 FHWA-RD-83-012 report entitled “Time to Corrosion of Reinforcing Steel in Concrete Slabs, Vol. 5” has become the most common method used to evaluate the corrosion resistance of reinforcement in concrete. A majority of the recent corrosion studies have used specimens similar to the macro-cell slab specimens. Landmark research projects performed by WJE using these macro-cell test slabs include the 1987 FHWA-RD-86-193 report entitled “Protective Systems for New Prestressed and Substructure Concrete” and the 5-year (1993-1998) FHWA project (FHWA-RD-98-153) entitled “Corrosion Evaluation of Epoxy-Coated, Metallic-Clad, and Solid Metallic Reinforcing Bars in Concrete.”

This accelerated test procedure has become a standard in the industry for testing high performance reinforcing steels in concrete. The following wetting and drying cycles were employed for the FHWA RD-98-153 study:

- Three-day drying at 100 °F (38 °C) and 60-80 percent RH followed by four-day ponding under a 15 percent NaCl solution at 60-80 °F (16-27 °C) for 12 weeks.
- Continuous ponding under a 15 percent NaCl solution at 60-80 °F (16-27 °C) and 60-80 RH for another 12 weeks.
- The cyclic ponding and continuous ponding cycles were repeated four times for a total exposure period of 96 weeks.

The 15 percent salt solution was chosen to represent the high salt concentrations occurring on in-land bridge structures from deicing salts. The long continuous ponding period was utilized to simulate a sustained period of submersion or long periods of high concrete moisture common in marine structures in winter months. The concrete slabs used in the FHWA study measured 12 x 12 x 7 in. and contained two layers of 11.5-in. long and 5/8-in. diameter reinforcement. The top mat acts as a macro-anode and contained either two straight or bent reinforcing bars, while the bottom mat was a macro-cathode that contained four straight reinforcing bars. One top mat bar was connected to two bottom mat bars through a 10 Ω resistor. A clear cover of 1.0 in. was used in all specimens.

Test Procedure

WJE used a modified geometry of the Southern Exposure (time-to-corrosion) test slabs without altering the test basics in order to accelerate the test to accommodate the desired 20-week test period. Figure 7 shows the schematic of the test slab and photographs of the general testing are shown in Appendix A. First, the clear cover to the top mat bars was reduced from 1.0 in. to 0.5 in. in order to reduce the time-to-corrosion. Secondly, the number of rebars in the bottom mat was doubled, from two bottom bars (cathode) to four bottom bars for each single top bar (see Figure 7). This change was introduced to increase the corrosion activity of the top bar by increasing the cathodic area, where oxygen is reduced, of the corrosion cell. Thirdly, the thickness of the test slab was reduced from 7 in. to 5 in. and consequently the clear spacing between top and bottom mats was reduced from 3.75 in. to 2.25 in. This lowers the concrete resistance between mats and improves the flow of macro-cell current. Lastly, the width of the test slab was increased from 12 in. to 16 in. to accommodate a corrosion rate measurement probe (7.5 in. diameter) over each of the top bars. A Gamry Electrochemical Testing Instrument was used to measure
the corrosion rates of the test bars. The electrochemical testing software (Framework®) uses the principle of linear polarization for a 3-electrode system.

Uncracked specimens were made containing each of the four reinforcing bar materials: A615 with mill scale, Type 304 stainless steel, and MMFX 2 with and without mill scale. Three specimens of the A615 and stainless steel bar types and six specimens of each of the MMFX bar types were fabricated. For weight loss measurement purposes, the initial weight of each bar was measured using a digital balance prior to casting.

A multi-channel Hewlett Packard data logger was used to collect short-circuit potential (SCP) and macro-cell current several times each day. Macro-cell measurements were made with the data logger without the need of a circuit resistor. In order for the data logger to measure the SCP of a bar while the bar was connected to the bottom mat, a pseudo-reference electrode was cast into the concrete next to each top bar. This is shown in Figure 7. Baseline potentials of each pseudo-reference electrode were measured soon after casting with respect to an external saturated calomel reference electrode (SCE) and periodic calibration checks were made during the exposure testing. The pseudo-reference electrode baseline and subsequent calibration data were used to convert the SCP data collected with the pseudo-reference electrode to potential values with respect to the SCE. The SCP data provided information about the electrochemical behavior of the bars in a coupled condition, indicating either anode control or cathode control.

In addition, open-circuit potential (OCP) of the top bar only was periodically measured with respect to an external SCE half-cell after disconnecting the circuit between top and bottom mats. The OCP data provides useful information about the electrochemical state of the bars in a depolarized (freely corroding) condition. Corrosion rate measurements were made using the Gamry Frameworks system at the beginning and at the end of the testing.

Mat-to-mat AC resistance was measured periodically and can be an indicator of the concrete condition and of physical deterioration around the bar/concrete interface. Normally as concrete ages, its AC resistance steadily increases. However, when a rebar is severely corroding and the corrosion progresses to cause microscopic cracks and delaminations at the bar interface, the AC resistance can change rapidly.

Autopsy of the test slabs was performed at the end of the 20-week testing. Powder samples were collected by drilling along the top bar/concrete interface of selected slabs, and they were analyzed for acid-soluble chloride according to ASTM C1152 “Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete.”

Weight loss was determined to estimate actual rate of corrosion (metal loss) for the extracted reinforcing bars. Prior to weight measurements, the corrosion products formed on the bars were removed with a wire brush, and then the bars were chemically cleaned according to the chemical method specified in ASTM G-1, "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens." The final weight of individual bars was measured and weight loss of each bar was determined by subtracting the final weight of the bar from the initial value. Photo documentation of the typical bar conditions as they were removed from the slabs and after cleaning are shown in Appendix B.

**Results and Discussion**

The results of the modified Southern Exposure testing are presented in Figures 8-14. All specimens, except the stainless steel 304 bars, showed considerable corrosion activity during the testing period. The
OCP data presented in Figure 8 shows that the A615, the MMFX with mill scale, and MMFX without mill scale bars are all in a similar potential range, with the MMFX bars only slightly lagging the A615 bars. The values indicated active corrosion after about 14 to 28 days and potentials remained below -350 mV after approximately week 8 (day 56). At about this same time, an increase in macro-cell current data in Figure 10 was seen indicating the onset of corrosion.

The SCP and Macro-Cell current data (Figures 10-11) show that the MMFX bar types behaved similarly, and their corrosion activities lie somewhere between that of the A615 and stainless steel. The MMFX bars (both with and without mill scale) had macrocell corrosion currents of about 1/3 less than the A615 black bars with a final 20-week macro-cell current values around 0.27 mA, compared to approximately 0.44 mA for the A615 black bars. The stainless steel bars remained passive and close to 0.00 mA for the duration of the testing. Due to an equipment or connection failure, the SCP and current data for the 18th week were not collected for the MMFX samples and, as a result, there is a discontinuity in the data.

The mean corrosion rates, measured using the Gamry equipment, at the end of the 20-week test, as seen in Figure 12, of both MMFX bar types was similar. The MMFX with mill scale specimens had a final mean corrosion rate of 2.08 μA/cm² and the MMFX without mill scale specimens had a final mean corrosion rate of 1.89 μA/cm². These values are approximately 66% and 70% lower, respectively, than the final mean corrosion rate for the A615 black bar specimens of 6.27 μA/cm².

The measured weight loss of the test bars, shown in Figure 13, was determined after the autopsied bars were cleaned, weighed, and compared to their initial weights. The MMFX with mill scale specimens had a mean percent weight loss of 0.44 % and the MMFX without mill scale specimens had a mean percent weight loss of 0.28 %. These values are much lower than the mean percent weight loss for the A615 specimens of 1.35%. The measured stainless 304 steel bar weight loss was zero.

Table 5 lists the estimated chloride content at bar level after the 20-week southern exposure. The chloride contents at the bar level were high and ranged from 0.38 to 0.60 wt%. (14.7 to 23.0 lbs/cu. yd.) As described, all A615 black bars and MMFX bars were corroding at the end of the 20-week test and none of the stainless 304 bars were corroding.

**Table 5 - Chloride Contents at bar level after 20-weeks SE**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Acid-Soluble Chloride, % by mass of sample (lbs/cy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black bar No.1</td>
<td>0.408 (15.7)</td>
</tr>
<tr>
<td>Black bar No.2</td>
<td>0.513 (19.7)</td>
</tr>
<tr>
<td>MMFX without scale No.1</td>
<td>0.506 (19.5)</td>
</tr>
<tr>
<td>MMFX without scale No.2</td>
<td>0.453 (17.4)</td>
</tr>
<tr>
<td>MMFX with scale No.1</td>
<td>0.513 (19.7)</td>
</tr>
<tr>
<td>MMFX with scale No.2</td>
<td>0.383 (14.7)</td>
</tr>
<tr>
<td>Stainless steel No.1</td>
<td>0.597 (23.0)</td>
</tr>
<tr>
<td>Stainless steel No.2</td>
<td>0.546 (21.0)</td>
</tr>
</tbody>
</table>
The correlation of the measured final corrosion rate and the determined weight loss is presented in Figure 14. The general trend correlates well, with high corrosion rates corresponding to high weight loss percentages. A linear function gives a fairly good fit, with an $R^2$ value of 0.785.

The Southern Exposure test, as modified for this test program, was a very aggressive and accelerated test. The MMFX 2 bars with and without mill scale performed better than the A615 bars but not nearly as well as stainless 304 bars with respect to macro-cell corrosion, final corrosion rates, and weight loss. The data does not indicate a significant difference in performance between the MMFX 2 bars with or without mill scale.

Figure 7. Schematic of modified southern exposure test specimen
Change of mean open-circuit potential of Southern Exposure top mat bars with time

- Open-circuit potential (V vs. SCE)
- Elapsed time (Day)

**Figure 8.** Mean open-circuit (OCP) half-cell potential data of Southern Exposure test specimens

Change of mean AC resistance for Southern Exposure specimens with time

- Resistance (ohm)
- Elapsed time (day)

**Figure 9.** Mean AC resistance data of Southern Exposure test specimens
Figure 10. Mean macro-cell current data of Southern Exposure test specimens

Figure 11. Mean short-circuit (SCP) half-cell potential data of Southern Exposure test specimens
Figure 12. Mean corrosion rate (Icorr) data of Southern Exposure test specimens (20-weeks).

Figure 13. Mean percent weight loss of Southern Exposure test specimens (20-weeks)
DISCUSSION

Carbon steel reinforcing bars are usually passive in new concrete because concrete provides a high pH (approximately 13) medium and also acts as a physical barrier isolating the steel from aggressive chemicals in the environment. However, steel will begin to corrode once those aggressive chemical species (e.g., chloride ions) penetrate through the concrete cover and reach a certain concentration (commonly called the chloride threshold, \( C_T \), in the case of chloride ions). The time required for chloride to reach \( C_T \) is called the \textbf{corrosion initiation time} \((t_1)\), since it is assumed that the corrosion will initiate once the threshold is exceeded. The corrosion products of steel in concrete occupy much more volume than the original steel, and this introduces significant stresses in the surrounding concrete. As corrosion continues, distress such as cracks or delamination in the concrete occurs and costly maintenance is required. The time required for corrosion products to induce concrete distresses is called the \textbf{corrosion propagation time} \((t_2)\), and the sum of \( t_1 \) and \( t_2 \) defines the total amount of time before corrosion-related damage is apparent at a given location. Figure 15 illustrates this corrosion sequence. The service life of a structure is defined as the time until the amount of damaged area exceeds some level of acceptability.

Corrosion of reinforced concrete is often caused by chloride ingress due to either usage of de-icing salts or exposure to marine saltwater environments. Chloride diffusion in concrete, driven by a concentration gradient, is described by Fick’s Second Law of Diffusion:

\[
\frac{dC}{dt} = D \cdot \frac{d^2C}{dx^2}
\]  

\((1)\)
where \( C \) is the chloride concentration at a depth of \( x \) from the concrete surface at time \( t \), and \( D \) is the effective chloride diffusion coefficient.

If the surface chloride concentration \( C_s \) and \( D \) are assumed to be constants, the concentration \( C(x, t) \) at depth of \( x \) and time \( t \) is given by:

\[
C(x, t) = C_s - (C_s - C_0) \times \text{erf} \left( \frac{x}{2 \sqrt{D t}} \right)
\]

(2)

where \( \text{erf}() \) is the Gaussian error function, and \( C_0 \) is the background or original chloride concentration in concrete.

Reinforcing will start to corrode when the bar-level chloride concentration reaches or surpasses its chloride threshold \( C_T \). The corrosion initiation time \( t_1 \) can be calculated from:

\[
C_T = C_s - (C_s - C_0) \times \text{erf} \left( \frac{cc}{2 \sqrt{D t_1}} \right)
\]

(3)

where \( cc \) is the concrete cover.

In order to assess the service life extension offered by MMFX corrosion-resistant bars, a statistical model developed by Sagüés et al.\(^v\) was adapted to estimate the service life of reinforced structures representative of a marine environment (a pile exposed to splash of brackish water) and a northern bridge deck environment (a deck exposed to significant deicing salts). In this model, concrete structures are virtually divided into finite elements of equal size. Each element is randomly assigned with a unique value of surface chloride concentration, concrete cover and diffusion coefficient based on assumed normal distribution functions for these three parameters determined from data reported in the literature and measured from actual structures. Using the Fick’s Law solution, the model calculates \( t_1 \), the time for the chloride concentration at the steel to exceed the chloride threshold, for each element. The propagation time, \( t_2 \), is assumed to be a constant 3 years for both bar types. The MMFX bars may have a slightly longer propagation time than A615 bars based on the SE tests results. The MMFX bars tested in the SE test had macrocell corrosion currents about 1/3 less than the A615 bars and about 2/3 less weight loss. Assuming that the corrosion of the MMFX bars occurs at 1/3 to 2/3 the rate of A615 bars, this would potentially add an additional 1.5 to 9 years to the propagation time and service life of the MMFX bar structures.

Combining \( t_1 \) and \( t_2 \), damage functions (percentage of area deteriorated versus time) for the MMFX and black bar conditions can be generated and used to predict the service life of concrete structures. The chloride threshold for MMFX and black bars are assumed to be 0.09 wt% and 0.03 wt% (3.5 and 1.2 lbs/cu. yd.), respectively, based on the values estimated from the modified G-109 tests performed in this study.

Case 1 is for a marine concrete pile, with inputs shown in Table 6, which included actual data collected from a structure along the Intracoastal Waterway in Georgia\(^v\).
Table 6. Input values for modeling a marine pile

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete cover (in.)</td>
<td>3.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Chloride diffusion coeff. (in²/y)</td>
<td>0.045</td>
<td>0.025</td>
</tr>
<tr>
<td>Surface chloride conc. (wt%)</td>
<td>0.471 (18.1 lbs/CY)</td>
<td>0.148 (5.7 lbs/CY)</td>
</tr>
<tr>
<td>Background chloride (wt%)</td>
<td>0.002 (0.08 lbs/CY)</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 16 shows the projected damage functions for the pile reinforced with MMFX and black bars. Assuming 10% damage as the end of service life, the model projected that MMFX bars would have a service life of 43 years, while black bars have a service life of 24 years.

Case 2 is for a northern bridge deck using data, shown in Table 7, collected on decks in Iowa vi.

Table 7. Input values for modeling of a northern bridge deck

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete cover (in.)</td>
<td>2.75</td>
<td>0.45</td>
</tr>
<tr>
<td>Chloride diffusion coeff. (in²/y)</td>
<td>0.05</td>
<td>0.038</td>
</tr>
<tr>
<td>Surface chloride conc. (wt%)</td>
<td>0.350 (13.5 lbs/CY)</td>
<td>0.090 (3.5 lbs/CY)</td>
</tr>
<tr>
<td>Background chloride (wt%)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 17 shows the projected damage functions for a northern bridge deck reinforced with MMFX and black bars. Assuming 10% damage as the end of service life, the model projected that MMFX bars would have a service life of 27 years, while black bars have a service life of 14 years.

The modeling predicts that the MMFX bars will extend the service life of the marine pile by 1.8 times and the northern bridge deck by 1.9 times. Accounting for the reduced corrosion rates measured for the MMFX bars compared to A615 bars after corrosion initiates (during the propagation period), this service life extension could be over two times that of the A615 steel.
Comparative Correlative Corrosion Testing and Analysis of MMFX 2 Rebars for Reinforced Concrete Applications
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Figure 15. Corrosion sequence (Tuutti 1982)

Figure 16. Projected damage function for a marine concrete pile reinforced with MMFX and black bars.
Two test methods, Modified ASTM G-109 and 20-Week Modified Southern Exposure tests, were used in this project to investigate the corrosion performance of MMFX 2 deformed reinforcing bars with and without mill scale compared to black ASTM A615 and stainless steel 304 bars. The following conclusions can be drawn from the tests:

MMFX 2 steel bars have higher chloride thresholds than A615 bars, but less than Type 304 stainless steel. The ASTM G-109 test program suggested that the chloride threshold of MMFX bars is about three times that of black bars. The stainless 304 bars did not corrode during the test program and resisted chloride levels over five times that of the black bars. The removal of mill scale was found to have only slightly increased the corrosion resistance of MMFX bars in the G-109 test.

The modified Southern Exposure (SE) test was very aggressive and corrosion initiation of the MMFX bars occurred shortly after that of the black A615 bars. However, the macro-cell corrosion rate of the MMFX bars remained about 1/3 less than that of the A615 black bars. The final weight loss of the MMFX bars was 20% and 30% of the A615 black bars for the MMFX without and with mill scales, respectively. Stainless 304 bars did not corrode during the 20-week SE test, even at chloride levels of 0.54% by wt. (21.0 lbs/cy). Corrosion rates measured by the linear polarization technique and weight loss analysis of the bars correlated well.

Modeling analyses of a marine pile and a northern bridge deck exposed to deicers showed that the use of MMFX bars in lieu of black bars may extend the structure service life by about 1.8 times, assuming a chloride threshold for the MMFX bars of three times that of the A615 black bars. Slower corrosion rates for the MMFX bars during the propagation period could increase the service life further, to about twice that of A615 bars.
References

APPENDIX A

TESTING, SETUP, AND SPECIMEN PHOTOGRAPHS

Photo A2. ASTM G-109 test specimens just before putting them in a fog curing chamber.
Photo A3. ASTM G-109 test specimens in the RH and temperature controlled room.

Photo A4. ASTM G-109 test specimens in the first drying cycle.
Photo A5. Southern Exposure test specimens just before putting them in a fog curing chamber.

Photo A6. Collection of baseline data for Southern Exposure test specimen.
Photo A7. The first wetting cycle of Southern Exposure test specimens.

Photo A8. Data acquisition systems for Southern Exposure testing.
Photo A9. Close-up of wiring arrangement for a Southern Exposure test specimen.

Photo A10. Example of initial visible corrosion product above bar locations in a Southern Exposure test specimen (BM2).
Photo A11. Example of initial visible corrosion product above bar location in a Southern Exposure test specimen (MM1).
APPENDIX B

AUTOPIED REBAR PHOTOGRAPHS BEFORE AND AFTER CLEANING
SE TESTING AND ASTM G-109 TESTS
Specimen BM1 Autopsied Bars before Cleaning

Specimen BM1 Autopsied Bars After Cleaning
Specimen BM2 Autopsied Bars before Cleaning

Specimen BM2 Autopsied Bars After Cleaning
Specimen BM3 Autopsied Bars before Cleaning

Specimen BM3 Autopsied Bars After Cleaning
Specimen S1 Autopsied Bars before Cleaning

Specimen S1 Autopsied Bars After Cleaning
Specimen S2 Autopsied Bars before Cleaning

Specimen S2 Autopsied Bars After Cleaning
Specimen S3 Autopsied Bars before Cleaning

Specimen S3 Autopsied Bars After Cleaning
Specimen M1 Autopsied Bars before Cleaning

Specimen M1 Autopsied Bars After Cleaning
Specimen M2 Autopsied Bars before Cleaning

Specimen M2 Autopsied Bars After Cleaning
Specimen M3 Autopsied Bars before Cleaning

Specimen M3 Autopsied Bars After Cleaning
Specimen M4 Autopsied Bars before Cleaning

Specimen M4 Autopsied Bars After Cleaning
Specimen M5 Autopsied Bars before Cleaning

Specimen M5 Autopsied Bars After Cleaning
Specimen M6 Autopsied Bars before Cleaning

Specimen M6 Autopsied Bars After Cleaning
Specimen MM1 Autopsied Bars before Cleaning

Specimen MM1 Autopsied Bars After Cleaning
Specimen MM2 Autopsied Bars before Cleaning

Specimen MM2 Autopsied Bars After Cleaning
Specimen MM3 Autopsied Bars before Cleaning

Specimen MM3 Autopsied Bars After Cleaning
Specimen MM4 Autopsied Bars before Cleaning

Specimen MM4 Autopsied Bars After Cleaning
SE EXPOSURE TESTS

Specimen MM5 Autopsied Bars before Cleaning

Specimen MM5 Autopsied Bars After Cleaning
Specimen MM6 Autopsied Bars before Cleaning

Specimen MM6 Autopsied Bars After Cleaning
ASTM G109 TEST SAMPLES

Top

Bottom

Specimen BM3 G109 Autopsied Bars before Cleaning

Top

Bottom

Specimen BM3 G109 Autopsied Bars After Cleaning

Top

Bottom

Specimen S1 G109 Autopsied Bars before Cleaning
Specimen S1 G109 Autopsied Bars After Cleaning

Specimen M2 G109 Autopsied Bars before Cleaning

Specimen M2 G109 Autopsied Bars After Cleaning
Specimen MM4 G109 Autopsied Bars before Cleaning

Specimen M2 G109 Autopsied Bars After Cleaning