# Evaluation of corrosion resistance of different steel reinforcement types

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## ABSTRACT

The corrosion of steel reinforcement in an aging highway infrastructure is a major problem currently facing the transportation engineering community. This is particularly true for bridge engineers. These concerns have initiated continual development of measures to reduce the likelihood of corrosion.

To investigate corrosion prevention through the use of corrosion-resistant alloys, the performance of corrosion resistance for MMFX Microcomposite steel reinforcement, a high-strength, high chromium steel reinforcement, was evaluated. The study presented herein presents parallel field and laboratory studies conducted at Iowa State University to determine if MMFX reinforcement provides superior corrosion resistance to epoxy-coated mild steel reinforcement in bridge decks. In the laboratory investigation, which is the focus of this paper, the evaluation process was based on both the ASTM and the Rapid Macrocell accelerated corrosion tests. Powder samples were also collected to estimate the corrosion threshold for different reinforcing bar types.

After 40 weeks of testing, the associated ASTM ACT corrosion potentials indicate corrosion has not initiated for either the MMFX or the as-delivered epoxy-coated reinforcement. The uncoated mild steel underwent corrosion within the fifth week and the epoxy-coated reinforcement with induced holidays underwent corrosion between 15 and 30 weeks. For the uncoated mild reinforcement, a chloride-ion concentration at corrosion initiation of 1.06 lb/yd$^3$ was obtained. This value matches the 1.00 to 1.40 lb/yd$^3$ commonly believed to be the chloride threshold of uncoated mild steel. For the epoxy-coated reinforcement with induced holidays, the chloride-ion concentration at corrosion initiation was 1.74 lb/yd$^3$.

## INTRODUCTION

Corrosion of steel reinforcement is the primary and most costly form of deterioration currently impacting the performance of reinforced concrete (RC) bridge structures. As an example, in the United States alone this deterioration results in billions of dollars spent to maintain and replace existing bridge decks (*1, 2*). With ever increasing bridge maintenance costs, protective measures to arrest chloride-induced corrosion have been actively studied for over 30 years.

Eliminating or slowing the deterioration of RC structures due to the corrosion of steel reinforcement requires the use of innovative methodologies, which are commonly subdivided into two categories. First, deterioration is slowed through methods that lengthen the time it takes chloride ions to reach the steel reinforcement. The second includes methods that lengthen the time between initiation of corrosion and the end of service life (*3*).

Over the last three decades, the principal techniques for corrosion prevention in bridge decks incorporate increased concrete cover depth and the application of epoxy coating over the steel reinforcement (*4*). Increased concrete cover depth lengthens the time for chlorides to propagate to the level of the steel reinforcement and also reduces the availability of oxygen and moisture for the corrosion process. Epoxy coatings have been implemented to act as a barrier between the steel and the environmental elements needed for corrosion. However, it has been debated by researchers that holidays in the epoxy coating, in combination with high chloride concentrations, could result in corrosion of the steel reinforcement that affects the overall performance of the bridge. Published literature reports that poorly adhering epoxy coatings may not increase the corrosion resistance of epoxy-coated reinforcement. An example of this occurred in 1986 where six years after construction, epoxy-coated reinforcement used in bridge substructures in the Florida Keys showed signs of chloride-induced corrosion (*5*). This provided an initial indication that the long-term protection provided by epoxy coating may be less than was originally intended.

These concerns have initiated continual development of other protective measures. The use of dense concretes, corrosion inhibitors, and both nonmetallic and steel-alloy corrosion-resistant reinforcement are among the most common techniques being developed. The later of which is the focus of this paper.

## OBJECTIVE

This paper presents a portion of a dual-phase investigation at Iowa State University (ISU), the objective of which was to determine if MMFX Microcomposite steel reinforcement will provide superior corrosion resistance to epoxy-coated mild steel reinforcement (ECR) in bridge decks. The investigation is comprised of both field and laboratory evaluations of MMFX, epoxy-coated, and uncoated reinforcement. Although not discussed herein, two twin, side-by-side bridge decks reinforced entirely with either MMFX or epoxy-coated steel were constructed and instrumented to investigate the “field” performance of the two steels through periodic monitoring for corrosion. As the field evaluation may require several years of monitoring to make a valid comparison, procedures to accelerate corrosion in a laboratory setting were also conducted. In the laboratory the mechanical properties and corrosion resistance performance of MMFX, epoxy-coated, and uncoated reinforcement were evaluated. The ASTM G 109 and Rapid Macrocell accelerated corrosion tests were utilized to evaluate the general and pit corrosion properties of the reinforcement. At the onset of corrosion, a chloride-ion concentration analysis was performed.

In both the field and laboratory evaluations, emphasis is placed on the corrosion resistance performance. This was accomplished by identifying the initiation of corrosion and the subsequent intensity of corrosion growth and quantitatively and qualitatively assessing the difference in corrosion resistance between MMFX, epoxy-coated, and uncoated reinforcement.

## CORROSION THRESHOLD

Initially, at least, the alkaline nature of the surrounding concrete prevents embedded steel reinforcement from corroding. The alkaline condition leads to the formation of a "passive" layer on the steel reinforcement surface (*6*). This passive layer is a dense, impenetrable film which, if fully established and maintained, prevents further corrosion of the steel reinforcement. However, in reality the passive environment is not always maintained in an RC environment. Most notably, the chloride attack mechanism can break down the alkaline condition in concrete resulting in a corrosion susceptible environment.

A "small" concentration of chloride ions in the pore water will not break down the previously described passive layer. This is especially true if the system is effectively reestablishing itself. However, there is a "chloride threshold" for corrosion, which is given in terms of the chloride-hydroxyl ratio, that represents the concentration of chloride-ion required to initiate corrosion. Several researchers have studied uncoated reinforcement in laboratory tests with calcium hydroxide solutions to establish a chloride threshold.

For uncoated mild steel reinforcement, when the chloride concentration exceeds 0.6 of the hydroxyl concentration, corrosion is typically observed (*7*). This approximates to a concentration of 0.4 percent chloride by weight of cement if chlorides are cast into concrete and 0.2 percent if they diffuse into concrete (*8, 9*). Based on an assumed 6.5 sacks of cement per cubic yard of concrete, the chloride threshold for uncoated reinforcement has been estimated to be 1.2 pounds of chloride per cubic yard of concrete (*10, 11*).

Unlike the case for uncoated reinforcement, no published literature presents definitive chloride threshold values for MMFX Microcomposite or epoxy-coated mild steel reinforcement. This could have been due to several factors such as uncertainties associated with the quality of the organic coating of the epoxy, damage that could have occurred during transportation or storage of the epoxy-coated reinforcement, or due to loss of adhesion between the coating and the base metal. For these reasons, a range of chloride threshold from 3.3 to 3.6 lb/yd$^3$ and 1.2 to 3.6 lb/yd$^3$ at the reinforcement level has been suggested, respectively, for MMFX and epoxy-coated reinforcement (*3, 12*). The lower bound of the range for epoxy-coated reinforcement was recommended as an empirical chloride threshold for uncoated reinforcement (*8, 9*).

## METHODS OF CORROSION MONITORING

Techniques for corrosion monitoring are generally well established for reinforced concrete structures. During corrosion of steel reinforcement, electrons are released as a product of the anode chemical reaction. The electrons flow from the site of corrosion, the anode, to a non-corroding site, the cathode. This allows for corrosion risk and corrosion rate to be evaluated through electronic means (i.e., voltmeter measurements). Among the many possible techniques for corrosion monitoring, three techniques were utilized in this study. Each of these three techniques is described in the following sections.

### Half-cell Potential Monitoring

The corrosion risk of any steel reinforcement can be measured by using a saturated calomel reference electrode like the one shown in Figure 1. By placing the electrode on the concrete surface and connecting it via a voltmeter directly to the top or bottom reinforcement, a current will flow and voltage is measured. The electrical potential difference (voltage) is a function of the iron in the pore water environment. As such, the electric potential is a measurement of the corrosion risk.

### Macrocell Corrosion Monitoring

In the case of chloride attack, the formation of anodes and cathodes are often separated with areas of corrosion separated by areas of non-corroded steel. This is known as the macrocell phenomenon. In macrocell corrosion in bridge decks, the anode and cathode can be located on different steel reinforcement or between adjacent sections on the same bar.

The macrocell phenomenon can be exploited as a way of measuring the corrosion rate. The current flow between the top and bottom steel reinforcement layers is monitored by measuring the voltage across a resistor connecting the layers of reinforcement, as illustrated in Figure 2. By Faraday’s Law, the mass loss rate (i.e., corrosion rate) is directly proportional to the monitored current.

### Chloride-ion Concentration Monitoring

The concentration of chloride-ion in concrete at the level of reinforcement is one major factor in the corrosion of reinforcing steel. The chloride-ion migrates to the reinforcement by permeating through the concrete or by penetrating through cracks in the concrete. To initiate corrosion of steel reinforcement, the concentration of the chloride-ion must reach a corrosion threshold at the steel reinforcement level.

The chloride-ion concentration of concrete can be evaluated by several different methods. The AASHTO T 260-94 Test (Sampling and Testing for Chloride-ion in Concrete and Concrete Raw Materials) suggests three procedures (Procedure A, B, and C) for determining the chloride-ion content in concrete (13). Both time consuming and complicated tests, Procedure A determines the chloride-ion concentration using potentiometric titration whereas Procedure B utilizes an atomic absorption process to determine the concentration of chloride-ion. In Procedure C, the chloride-ion concentration is determined using a specific ion probe.

An alternative to the three aforementioned procedures is the nondestructive use of X-ray fluorescence (XRF) spectroscopy to analyze the chloride-ion concentration in the powder samples. XRF spectroscopy provides an analytical means to identify and quantify the concentration of elements contained in a solid, powdered, and liquid sample (14).

## LABORATORY TEST PROGRAM

As previously stated, the principal reason for selecting a new reinforcement material for concrete bridge decks is to improve the life expectancy and cost effectiveness of the structural system. A requirement of the material, which presumably is more expensive, is that it provides a significant improvement in corrosion resistance compared to the current material of choice, epoxy-coated mild steel reinforcement, while at the same time meeting the requirements of ASTM A 775. In light of this requirement, this study compared the corrosion resistance of MMFX Microcomposite steel reinforcement with that of epoxy-coated and uncoated mild steel reinforcement using the ASTM G 109 accelerated corrosion. An additional test method, introduced by the University of Kansas Center for Research and referred to as the Rapid Macrocell accelerated corrosion test, was also used for the evaluation presented herein.

## Material Properties

Steel reinforcement used in the laboratory test program described herein consisted of one heat of 16 mm diameter (No.5) MMFX, epoxy-coated, and uncoated reinforcement. The MMFX reinforcement was obtained from the Iowa Department of Transportation from stock used in the field bridge described above. Construction Material Incorporated of Des Moines, Iowa provided the epoxy-coated reinforcement and the uncoated reinforcement was acquired through a local distributor. A single batch of concrete for the laboratory was utilized to preserve uniformity among the individual test specimens and between the tests. The following paragraphs describe the properties of the materials used in the subsequently described corrosion-monitoring program.

### *Steel Reinforcement*

Although published data exists, the MMFX, epoxy-coated, and uncoated reinforcement used in the laboratory study were tested to determine yield strength, tensile strength, and elongation. Three specimens of each steel type were tested to determine the mechanical properties following ASTM E8 provisions.

The results of the mechanical tests are presented in Table 1, including yield strength, tensile strength, and elongation for each of the steel reinforcement types tested. Yield strengths were determined based on a well-defined yield point for epoxy-coated and uncoated steels and based on the 0.2 percent offset method for MMFX steel.

### *Concrete Mix*

To ensure that the MMFX, epoxy-coated, and uncoated steel reinforcement were subjected to similar conditions, all of the test specimens were constructed from a single 1-1/2 yd$^3$ batch of ready-mix concrete (Type II cement). Compressive strength, modulus of rupture, and other important information are summarized in Table 2.

## Accelerated Corrosion Test Program

### *Test Configuration*

Corrosion resistance performance was evaluated by accelerating the corrosion process in laboratory specimens. Changes in corrosion potential, relative corrosion rates, and chloride concentrations needed for corrosion initiation were all monitored. Additionally, interval powder samples were collected and analyzed through X-ray fluorescence spectrometry for chloride content comparison. Both the ASTM and Rapid Macrocell accelerated corrosion tests, utilized in this study, induce general and pitting corrosion and are believed to provide valid comparisons using realistic exposure conditions.

**ASTM G 109 Accelerated Corrosion Test** Comparisons of corrosion response were made using the ASTM G 109 accelerated corrosion test (ACT), a test first developed to study the effective corrosion protection of chemical admixtures on steel reinforcement (17). Over the past two decades the test method has been most notably used to evaluate the corrosion response of corrosion-resistant steel reinforcement.

The ASTM ACT is used to model the corrosion of steel reinforcement in concrete where two layers of reinforcement are utilized, providing distinct anode and cathode bars. The test specimen consists of a small beam constructed with two layers of steel reinforcement. The top layer of reinforcement consists of one bar, while the bottom layer consists of two bars. The layers are connected electrically with a 10-ohm resistor and the sides of the concrete are sealed with epoxy. A reservoir is secured to the beam to retain liquid on the upper surface. A schematic of the test is shown in Figure 3.

In brief, the test subjects 229 mm (9 in.) of reinforcement below the concrete surface to alternating cycles of wetting and drying with a 3 percent sodium chloride solution. The cycles of wetting allow for chloride ingress to the reinforcement level while the cycles of drying allow for oxygen levels in the system to replenish.

To leave a direct path for chlorides to the top layer of steel reinforcement, an artificial crack was fabricated in the specimens. The crack was oriented either parallel or perpendicular to, and directly above, the top steel reinforcement through the insertion and removal of a 0.3 mm (0.012 in.) stainless steel shim when the specimen was fabricated. The shim was removed within 24 hours of placement, leaving a direct path for chlorides to the steel reinforcement and simulating the effects of a settlement crack over the bar.

The half-cell corrosion potentials for the top and bottom layers were measured as an indicator for the onset of corrosion. At the initiation of corrosion, concrete powder samples were obtained by impact-drilling the ACT specimen at the level of the top reinforcement to estimate the chloride-ion concentration required for corrosion initiation. Additionally, corrosion current and the corresponding corrosion rates were determined by measuring the voltage drop across the resistor.

**Rapid Macrocell Accelerated Corrosion Test** An additional test method introduced as the Rapid Macrocell ACT was also used to compare the corrosion response of the various steel reinforcement types. The Rapid Macrocell ACT was originally developed at the University of Kansas under the SHRP program (20, 21) and updated under the NCHRP-IDEA program (3). The goal of the test is to obtain a realistic measure of the performance of corrosion protection systems over a shorter period of time than traditional accelerated corrosion tests (i.e., ASTM ACT).

The basic test system requires two containers and consists of either bare or mortar-clad steel reinforcement. This is illustrated in Figure 4. The contact surface between the mortar and the bar simulates the concrete-reinforcement interface in actual structures. A single bar, either bare or mortar-clad, is placed in a 1-quart container with a simulated pore solution containing a 3 percent concentration of sodium chloride. Two bars are placed in a second 5-quart container and immersed in simulated pore solution with no chlorides added. The solution in both containers places 76 mm (3 in.) of reinforcement below the surface. The solutions in the two containers are connected by a salt bridge and the test specimen in the pore solution containing sodium chloride (anode) is electrically connected through a single 10-ohm resistor to the two specimens in the simulated pore solution (cathode). Air is bubbled into the pore solution surrounding the cathode to ensure an adequate supply of oxygen is present for the cathodic reaction. The air causes some evaporation, which is countered by adding distilled water to this container to maintain a constant volume of solution.

Similar to the ASTM ACT, half-cell corrosion potentials for the anode and cathode were measured to, again, establish corrosion initiation. The corrosion current and the rate of corrosion were also determined by measuring the voltage drop across the resistor.

### *Accelerated Corrosion Monitoring*

Half-cell potentials were measured using a reference electrode. The steel reinforcement layers were isolated (i.e., each bar is disconnected from the resistor) before the measurement of the half-cell potential to avoid interference from the other steel elements. After the measurements were performed, the steel elements were again electrically connected through the resistor. In this work the half-cell corrosion potential of the anode and cathode were measured using a saturated calomel electrode. The half-cell was maintained in accordance with ASTM C 876 for the stabilization of corrosion potential. In the study presented herein, a corrosion potential of more than 276 mV was considered as active corrosion of the metal. In addition to half-cell measurement, current for the macrocell was recorded. In the study, the macrocell current was utilized for the calculation of corrosion rate, which is not presented in this paper.

### *Chloride Exposure Protocol*

The ASTM ACT chloride exposure condition was based upon a weekly cycle. The beams were subjected to a seven day ponding and drying regime. For the first 4 days of each week, the test surface was ponded with a depth of approximately 38 mm (1-1/2 in.) of 3 percent sodium chloride solution in a laboratory at 68 to 78 degrees Fahrenheit. During this period, the reservoir was covered with a plastic sheet to minimize evaporation. Following this 4 day exposure, the NaCl solution was removed, and the test surface was rinsed with distilled water and drained.

These unponded beams remained dry for three days in a laboratory at 68 to 78 degrees Fahrenheit. After this dry exposure, the test surface was immediately reponded with the 3 percent NaCl solution. The ponding and drying regime was continued for 12 weeks where upon completion the test surface was subject to continuous ponding for 12 weeks. Following the 12-week interval of continuous ponding, the alternating ponding and drying regime was resumed. The two regimes were continued on the same basic schedule for remainder of the test period.

For the Rapid Macrocell ACT, the mortar-clad specimen was placed in a 1-quart container, along with a simulated pore solution containing a 3 percent concentration of sodium chloride for the duration of the test period. When needed, simulated pore solution was added to maintain the 3 inches of reinforcement below the surface.

## LABORATORY TEST RESULTS

The test results described in the following section describe the corrosion resistance performance of MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement under accelerated laboratory conditions. Specific findings are presented in terms of half-cell voltage (corrosion potential) for the ASTM G 109 ACT and Rapid Macrocell ACT tests. The different reinforcement type for a particular accelerated corrosion test specimens are distinguished by line type in the same figure. The designation for each reinforcement and specimen type is as listed in Table 3.

## ASTM G 109 Accelerated Corrosion Test

As previously discussed, to leave a direct path for chlorides to the top layer of steel reinforcement, an artificial crack, oriented either longitudinally or transversely was fabricated in the specimen. The results from each of these will be discussed separately. Only one half-cell measurement was collected on each embedded bar per week. For the initial weeks of testing, the electrode was moved throughout the solution without any noticeable change to the half-cell measurement.

The 280-day (40-week) average anode (top reinforcement layer) and cathode (bottom reinforcement layer) corrosion potentials for specimens with a longitudinal artificial crack over the top layer of steel reinforcement are shown in Figure 5. The corrosion potential for the top layer of reinforcement (anode) for the MMFX reinforcement with longitudinally cracked specimens remained at a relatively constant value of 100 mV through 217 days (31 weeks). At 217 days, a single MMFX specimen began corroding which caused the rapid increase and continued increase to 183 mV through 280 days (40 weeks). The corrosion potential for all the uncoated reinforcement specimens increased beyond 276 mV (i.e., high risk of corrosion) by 35 days (5 weeks). After 35 days, the uncoated specimens experienced a continued corrosion potential value greater than 400 mV. The corrosion potential rose to a maximum of 493 mV at 245 days (35 weeks) and has remained constant through 280 days (40 weeks), indicating a continued severe risk for corrosion. Specimens with the as-delivered epoxy-coating exhibited a relatively constant corrosion potential value of 25 mV through 280 days (40 weeks), indicating a low risk for corrosion. The corrosion potential for the drilled holiday epoxy-coated reinforcement experienced spikes of 300 mV throughout days 105 to 217 (weeks 15 to 31) as the specimens began to corrode throughout the period. The corrosion potential rose to a maximum of 430 mV at 224 days (32 weeks) and has continued indicating a severe corrosion risk through 280 days (40 weeks). The chipped holiday condition for the epoxy-coated reinforcement exhibited a corrosion potential of 100 mV through the first 217 days (31 weeks). At 217 days, a single specimen began corroding which caused the maximum of 316 mV. However, by 238 days (34 weeks), the corrosion potential value decreased and has remained a constant 200 mV. The corrosion potential for the bottom layer of reinforcement (cathode) for all reinforcement types remained below 276 mV, indicating that none had undergone active corrosion through 180 days of monitoring. Additionally, no corrosion products were observed on the concrete surface for any reinforcement type.

### *Results for Transversely Cracked Specimens*

The 280-day (40-week) average anode (top reinforcement layer) and cathode (bottom reinforcement layer) corrosion potentials for specimens with transverse artificial cracks over the top layer of steel reinforcement are shown in Figure 6. The corrosion potential for the top layer of reinforcement (anode) for the MMFX reinforcement with transversely cracked specimens remained a relatively constant value of 80 mV through 280 days (40 weeks), indicating a low risk for corrosion. Similar to the longitudinally cracked specimens, the corrosion potentials for all the uncoated reinforcement specimens with transverse cracks increased beyond 276 mV by 35 days (5 weeks). By 98 days (14 weeks), the uncoated specimens experienced a corrosion potential value greater than 400 mV and continued to rise to 501 mV through 280 days (40 weeks), indicating a continued severe risk for corrosion. Specimens with the as-delivered epoxy coating exhibited relatively constant corrosion potential values of 20 mV through 161 days (23 weeks). At 161 days, a single specimen began corroding which caused a rapid increase which remained constant with a corrosion potential of 300 mV through 280 days (40 weeks). Similar to the longitudinally cracked specimens, the drilled holiday epoxy-coated reinforcement with transverse cracks experienced spikes of 250 mV throughout days 105 to 217 (weeks 15 to 31) as the specimens began to corrode. A subsequent continued decrease in corrosion potential resulted in a 280-day (40-week) corrosion potential of 171 mV.

The corrosion potential for the bottom layer of reinforcement (cathode) for all reinforcement types remained below 276 mV, indicating none had undergone active corrosion. Additionally, no corrosion products were observed on the concrete surface for any reinforcement type.

### Rapid Macrocell Accelerated Corrosion Test

The 280-day (40-week) average corrosion potentials for the anode (reinforcement in the container with sodium chloride solution) and cathode (reinforcement in the container with distilled water) steel reinforcement are shown in Figure 7. Within 35 days (5 weeks), all reinforcement types in the container with 3 percent sodium chloride solution (anode) were undergoing corrosion. Through 280 days (40 weeks), the MMFX reinforcement experienced a constant corrosion potential of 500 mV. From 105 to 217 days (15 to 31 weeks), the uncoated reinforcement specimens exhibited a corrosion potential of 600 mV. At 217 days and continuing through 273 days (39 weeks), a single specimen ceased corroding which caused corrosion potential to decrease to 515 mV. After 273 days, the corrosion potential returned to 600 mV. After 280 days (40 weeks), the as-delivered epoxy-coated specimens experienced a constant corrosion potential of 600 mV. Similar to the as-delivered epoxy-coated specimens, the drilled holiday epoxy-coated specimens experienced a constant corrosion potential of 600 mV after the initial 35 days.

The corrosion potential for all reinforcement types in the container with distilled water (cathode) remained below 276 mV, indicating none have undergone active corrosion. With the exception of the as-delivered and drilled holiday conditions of epoxy-coated reinforcement, corrosion products were visually observed on the mortar sheathing and within the solution of the anode.

### Chloride-ion Concentration

To investigate the chloride-ion concentration in the ASTM ACT specimens, concrete powder samples were collected. Powder samples were collected from a particular ACT specimen as soon as the reinforcement within that specimen began to corrode, and were also collected from the same specimen on an interval basis. Additionally, two unreinforced beams were cast at the same time as the other laboratory ACT specimens to access the background chloride concentration of the concrete mix.

*Cement Mortar Powder Collection*

As electrochemical investigations indicated corrosion initiation (i.e., 276 mV) for an individual ASTM ACT specimen, concrete powder samples were collected at the depth of the top reinforcement (anode) layer using a hammer drill with a stop gage as described by ASTM C 1152/C 1152 M and ASTM C 1218/C 1218 M (Standard Test Method for Acid-Soluble Chloride and Water-Soluble Chloride in Mortar and Concrete, respectively) (*22, 23*). To accomplish this, the specimen was marked for two adjoining holes to be drilled to obtain a representative sample of at least 20 grams of concrete powder. A 5/8 in. drill bit was selected to ensure the majority of the powder collected was cement mortar and not course aggregate (i.e., 1-1/2 times larger than the nominal course aggregate). Each of the adjoining holes was first drilled to a depth of 1/2 in. After drilling both initial holes, the powder was vacuumed from each hole and discarded and the top surface blown clean. The final 5/8 in. diameter holes were then drilled. The powder from the two adjoining holes was removed and combined into the first composite sample and the specimen ID is recorded on the bag. The process was repeated to obtain a second composite powder sample for a total of two composite samples for each ASTM ACT specimen. From the two composite samples an average specimen chloride-ion concentration was determined.

The collected powder samples were tested using the Phillips PW 2404 X-ray fluorescence spectrometer at the ISU Material Analysis and Research Laboratory. XRF spectroscopy provides a means to identify and quantify the concentration of elements contained in a solid, powdered, and liquid sample.

*Chloride-ion Concentration Results*

The chloride-ion content data collected from the powder collected were used to determine a comparative chloride-ion concentration for each reinforcement type after the first high corrosion risk (i.e., 276 mV) was measured in the ASTM ACT specimens. The average results are shown in Table 4 for the MMFX, epoxy-coated, and uncoated steel reinforcement, respectively. Additionally, chloride-ion concentrations for the concrete were also analyzed on 90-day intervals to determine if the rate of chloride ingress was similar among all the ASTM ACT specimens. The chloride-ion concentration presented was determined from concrete powder samples collected from the very ACT specimens tested.

**MMFX Microcomposite Steel Reinforcement** One specimen containing MMFX reinforcement experienced high corrosion risk measurements (i.e., 276 mV). Subsequently, powder samples from that specimen were collected and chloride-ion concentration was measured as a weight concentration on a cubic yard basis. This MMFX reinforcement had a chloride-ion concentration of 2.73 lb/yd$^3$.

**Uncoated Mild Steel Reinforcement** High corrosion risk was measured for all five specimens containing uncoated reinforcement. The corresponding chloride-ion concentration values ranged from a low of 1.03 lb/yd$^3$ to a high of 1.11 lb/yd$^3$ with an average value of 1.06 lb/yd$^3$.

**As-delivered Epoxy-coated Mild Steel Reinforcement** A single specimen containing epoxy-coated reinforcement in the as-delivered condition exhibited a high corrosion potential. The chloride-ion concentration for this reinforcement was 1.96 lb/yd$^3$. The authors believe that the 1.96 lb/yd$^3$ may not be representative of epoxy-coated reinforcement in a pure as-delivered condition since chloride-ion concentrations in other as-delivered epoxy-coated specimens have been found higher than 1.96 lb/yd$^3$ without an indication of corrosion (i.e., 276 mV). The authors believes that the 270-day concentration is a lower bound, with the understanding that an even higher chloride-ion concentration is expected before the remaining four specimens undergo corrosion. Strict observation of the aforementioned bar should determine whether corrosion occurred at a site where an unintended holiday was present.

**Drilled Holiday Epoxy-coated Mild Steel Reinforcement** All five specimens with a drilled holiday in the epoxy-coating experienced high corrosion risk measurements. Chloride concentration alues for the drilled holiday condition ranged from a low of 1.14 lb/yd$^3$ to a high of 2.82 lb/yd$^3$ with an average value of 1.74 lb/yd$^3$.

**Chipped Holiday Epoxy-coated Mild Steel Reinforcement** A high corrosion risk was measured for a single specimen containing the chipped holiday condition of the epoxy coating. The corresponding chloride-ion concentration value was 2.08 lb/yd$^3$.

## Discussion of Laboratory Test Results

The following discussion for the results from the accelerated corrosion tests and chloride-ion concentration analyses should be interpreted as short-term findings for an otherwise long-term (20+ years) effort. While these results are utilized to make comparisons of corrosion performance for MMFX, epoxy-coated, and uncoated reinforcement, the reader should be aware that a degree of uncertainty exists. This is especially true for the MMFX and the as-delivered epoxy-coated reinforcement, where corrosion has initiated for only a single ASTM ACT specimen.

At a given time, the corrosion potential for specimens containing the same reinforcement type has shown significant variation between the specimens. This variation may be caused by dissimilarities in anode and cathode locations, epoxy coating performance, and reinforcement material. The rates of consumption and renewal of the fundamental factors (i.e., chloride ions, oxygen, and water) to sustain active corrosion may also cause specimens reinforced with the same steel type to behave differently (22). However, a reasonable correlation does exist when the average of the corrosion potentials for each reinforcement type is compared under the same test conditions.

Through 280 days (40 weeks), the ASTM ACT generally showed evidence of low to intermediate corrosion risk potentials for the MMFX reinforcement, with the exception of a single longitudinally cracked specimen. This specimen began corroding at 217 days (31 weeks). The corrosion potential increased rapidly for the uncoated reinforcement. In fact, after 35 days (5 weeks) all specimens indicated corrosion had initiated. Both longitudinal and transverse cracked specimens with the as-delivered epoxy-coated reinforcement exhibited the lowest corrosion potential, although a single transversely cracked specimen began corroding at 161 days (23 weeks). The corrosion potential, for epoxy-coated reinforcement with induced holidays, indicated corrosion initiated in the specimens between 105 to 217 days (15 to 31 weeks).

Within the first week, the Rapid Macrocell ACT produced severe corrosion risk potentials for all the reinforcement types. The specimens with MMFX reinforcement had the least severe corrosion risk potential, while the uncoated, as-delivered condition, and drilled holiday condition of the epoxy-coated had the most severe corrosion risk potential. Since the Rapid Macrocell ACT specimens are an alteration of the ASTM ACT beam specimens, the almost immediate severe corrosion risk potentials measured for all the reinforcement types was unexpected. The authors attribute the difference to the continuous renewal of oxygen to the Rapid Macrocell ACT. By continuously replenishing oxygen, the Rapid Macrocell ACT creates an environment more conducive to initiating and sustaining corrosion than the ASTM ACT, which replenishes oxygen through the previously described ponding and drying regime. Additionally, the Rapid Macrocell ACT was carried out with a plastic sheet placed over the entire test system. This maintained a high humidity environment over the portion of the cylindrical test specimen not submerged in the solution.

Since only severe corrosion risk potentials were observed, more significance was placed on the measurements obtained from the ASTM ACT specimens. However, through 280 days (40 weeks), the concrete surrounding the MMFX and uncoated reinforcement Rapid Macrocell ACT specimens had discolored due to deposition of corrosion products.

For the study presented herein, a corrosion potential greater than 276 mV was employed as the indication of corrosion initiation. At the time of the first measurement greater than 276 mV, concrete powder specimens were collected at the top reinforcement depth. The chloride-ion concentration for the single specimen containing MMFX reinforcement was 2.73 lb/yd$^3$. For uncoated mild reinforcement, the chloride-ion concentration of 1.06 lb/yd$^3$ was obtained. This value matches the 1.00 to 1.40 lb/yd$^3$ commonly believed to be the chloride threshold of uncoated mild steel. For the single specimen containing as-delivered epoxy-coated reinforcement the chloride-ion concentration was 1.96 lb/yd$^3$, while the chloride-ion concentration for the epoxy-coated reinforcement with induced holidays was 1.74 lb/yd$^3$. For the metric equivalent, 1 kg/m$^3$ equals 0.593 lb/yd$^3$.

## CONCLUSIONS

The test results from the accelerated corrosion tests are the basis for the following conclusions related to the relative corrosion performance of MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement. After 40 weeks of testing, the associated ASTM ACT corrosion potentials indicate corrosion has not initiated for either the MMFX or as-delivered epoxy-coated reinforcement. However, the uncoated mild steel underwent corrosion within the fifth week, while the epoxy-coated reinforcement with holidays underwent corrosion between 15 and 30 weeks. Within the fifth week of testing, the Rapid Macrocell ACT produced corrosion risk potentials indicative of active corrosion for all reinforcement types tested.

The laboratory results also indicate a chloride-ion threshold for the uncoated mild reinforcement of 1.06 lb/yd$^3$. For the epoxy-coated reinforcement with induced holidays the chloride-ion concentration was 1.74 lb/yd$^3$. Chloride-ion concentrations will continue to be monitored for the remaining MMFX and as-delivered epoxy-coated reinforcement through the duration of the ASTM accelerated corrosion test.

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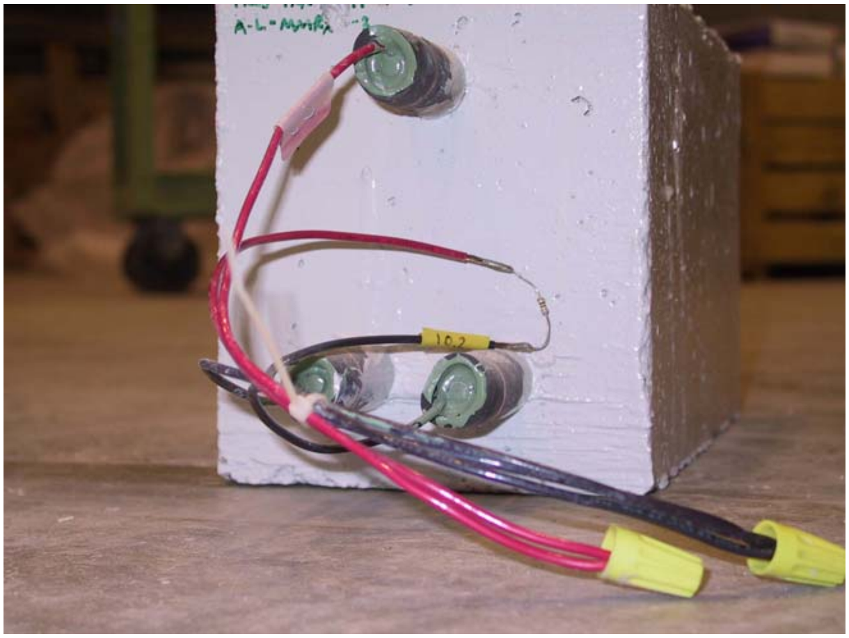
## LIST OF FIGURES

LIST OF TABLES

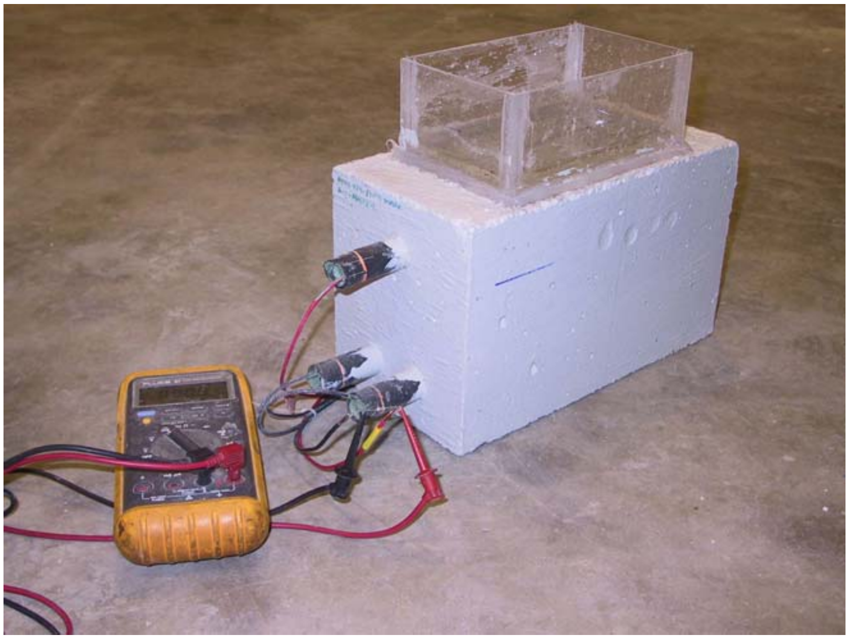
**(a)** – Saturated calomel reference electrode

**(b)** – Measure of half-cell corrosion potential for the top layer of reinforcement

**Figure 1. Half-cell corrosion potential monitoring method.**

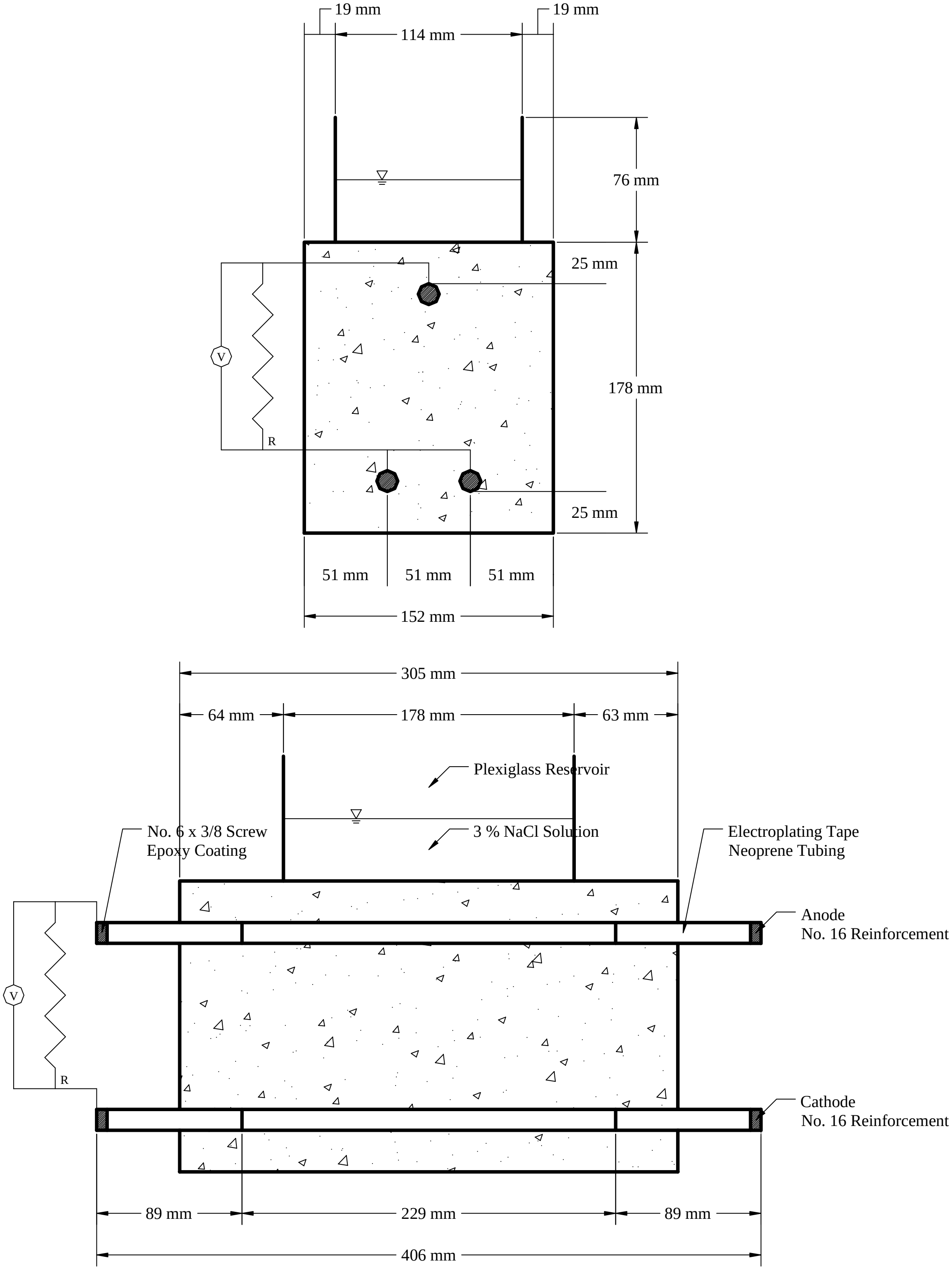


**(a) –** Top and bottom reinforcement layers connected via resistor



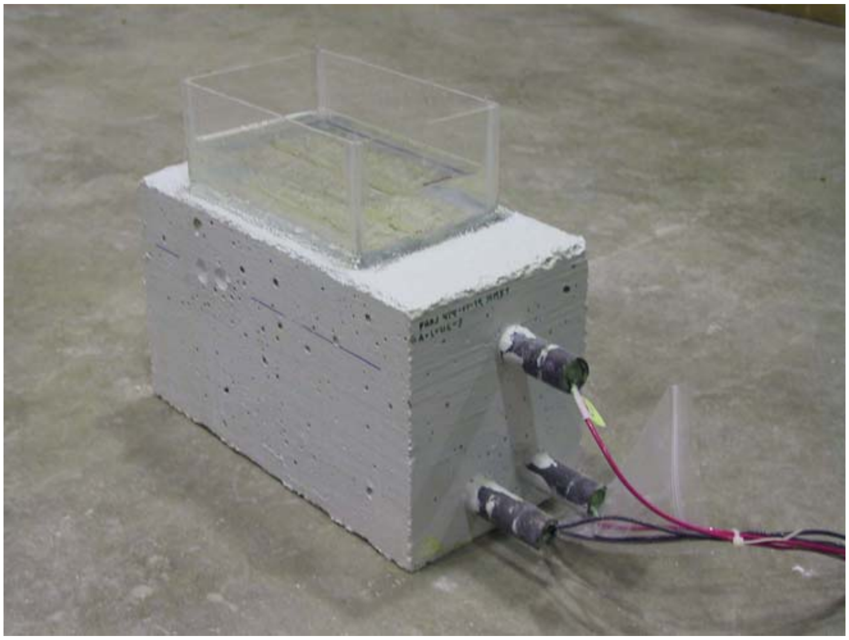
**(b) –** Measurement of macrocell corrosion

**Figure 2. Macrocell monitoring method.**



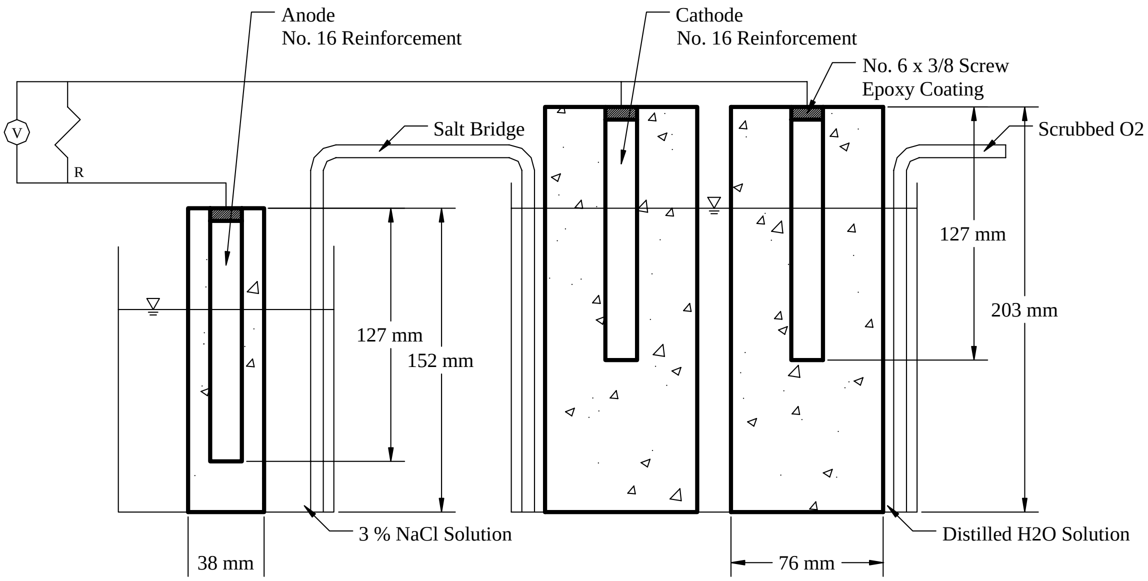
**(a)** – Schematic of ASTM G 109 ACT

**Figure 3. ASTM G 109 accelerated corrosion test specimen.**



**(b) –** Typical as-constructed ASTM G 109 ACT

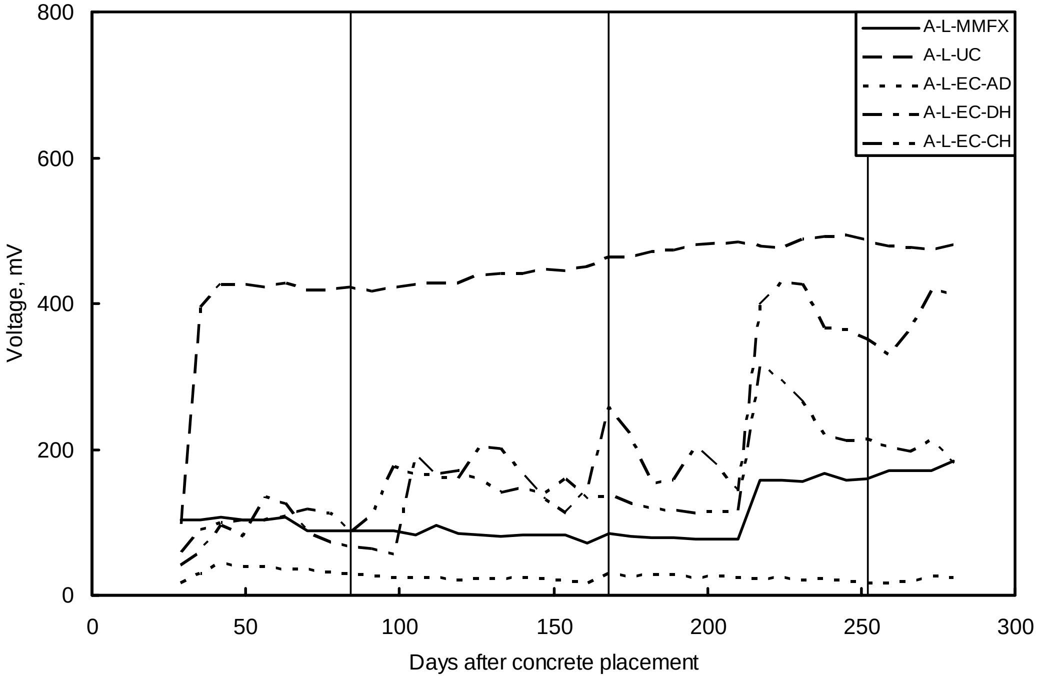
**Figure 3 – Continued.**



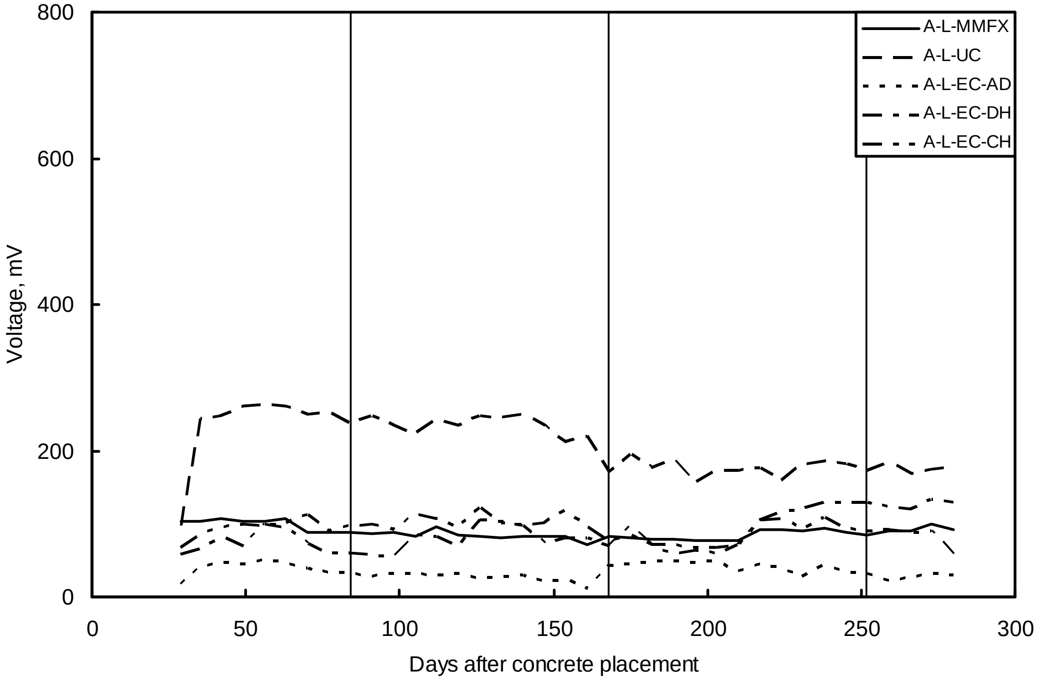
**(a)** – Schematic of Rapid Macrocell ACT

**(b)** – Typical as-constructed Rapid Macrocell ACT

**Figure 4. Rapid Macrocell accelerated corrosion test set up.**

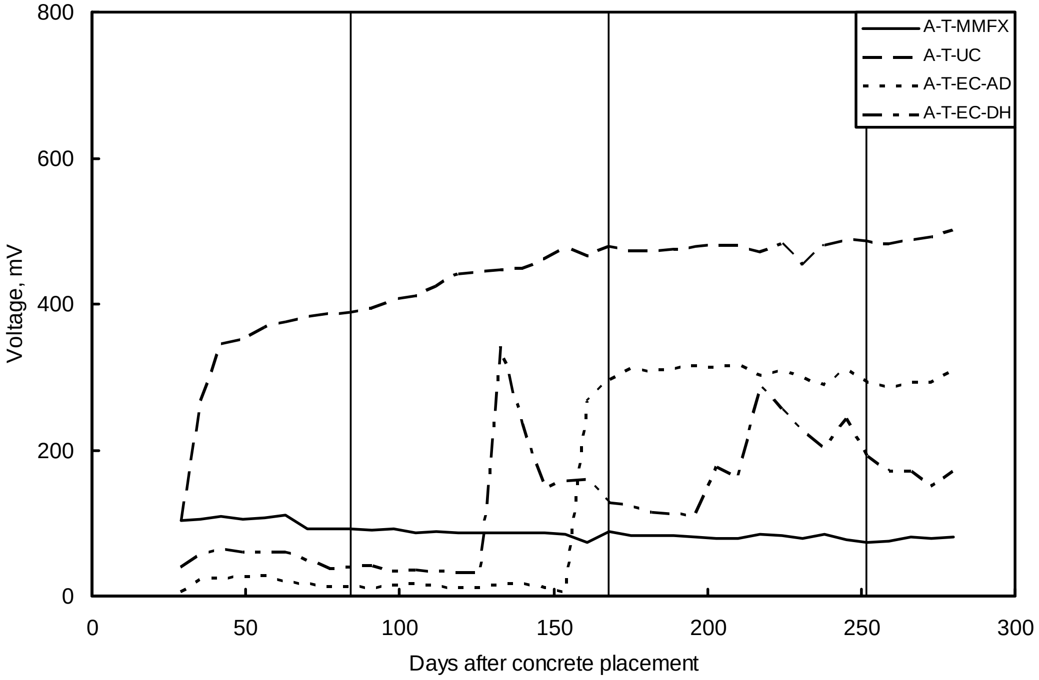


**(a)** – Corrosion risk of the top layer of steel reinforcement

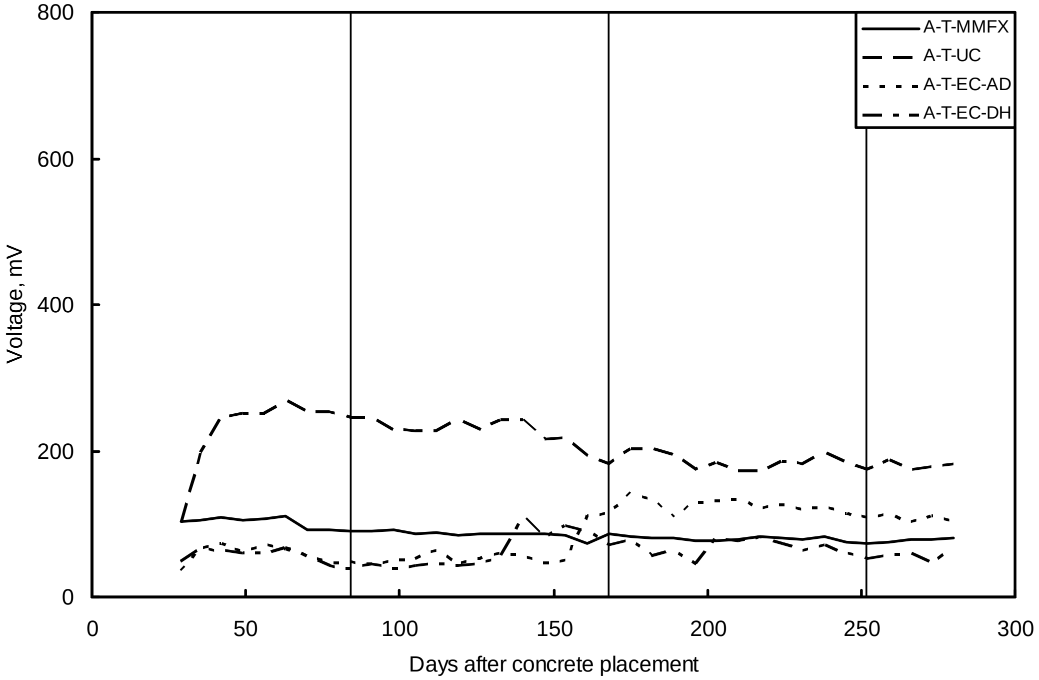


**(b)** – Corrosion risk of the bottom layer of steel reinforcement

**Figure 5. ASTM G 109 ACT subjected to 3 % NaCl solution with a longitudinal crack.**

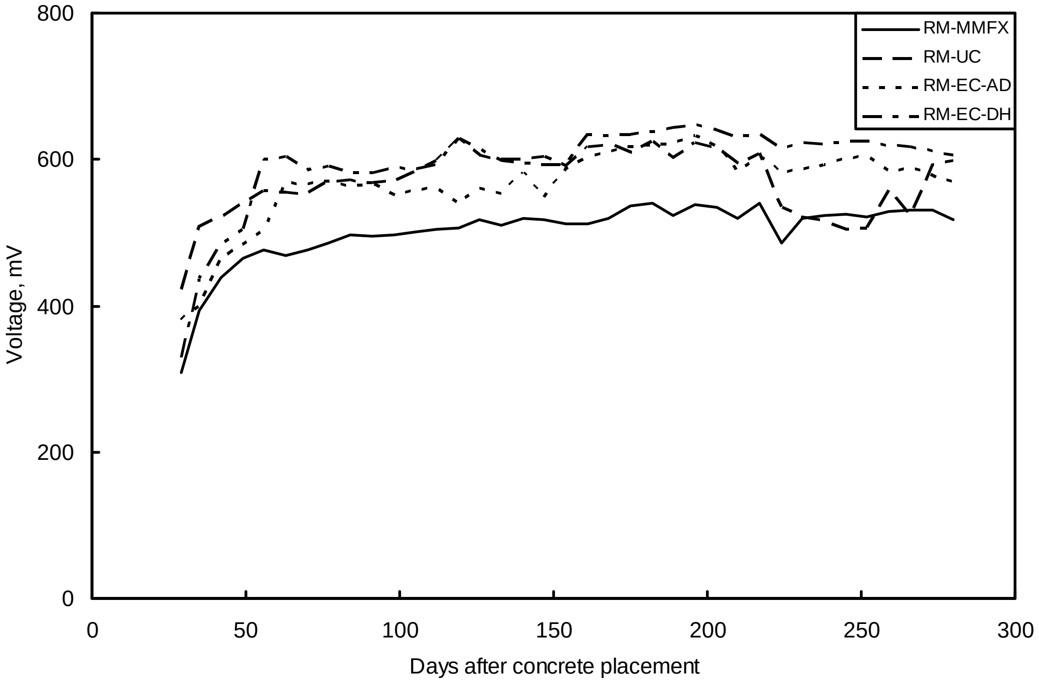


**(a)** – Corrosion risk of the top layer of steel reinforcement

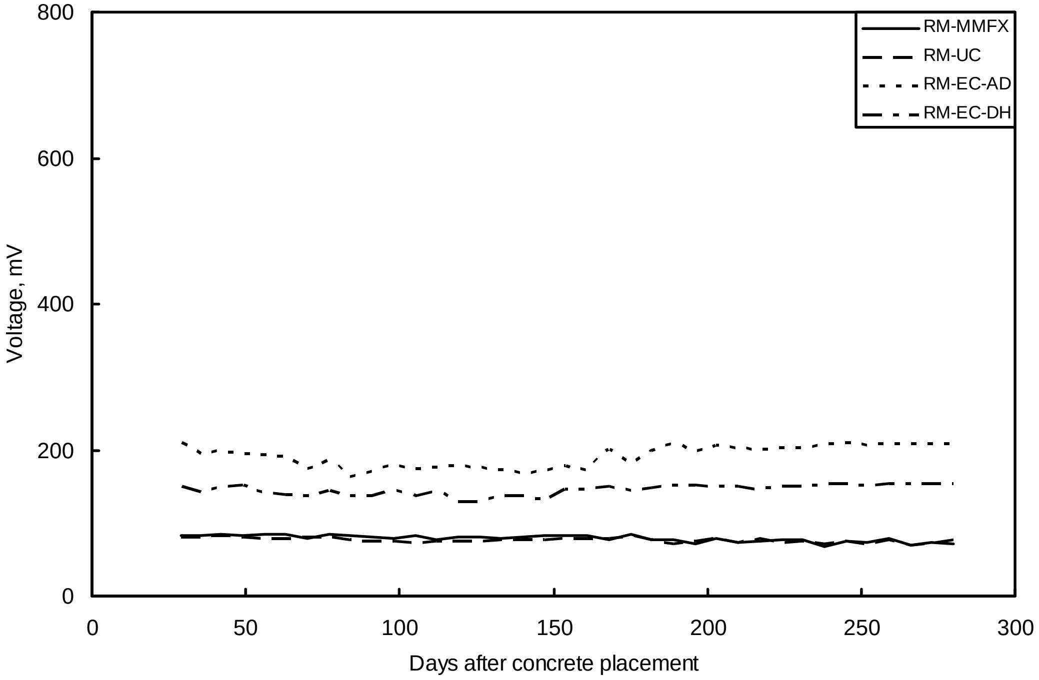


**(b)** – Corrosion risk of the bottom layer of steel reinforcement

**Figure 6. ASTM G 109 ACT subjected to 3 % NaCl solution with a transverse crack.**



**(a)** – Corrosion risk of the top layer of steel reinforcement



**(b)** – Corrosion risk of the bottom layer of steel reinforcement

**Figure 7. Rapid Macrocell ACT subjected to 3 % NaCl solution.**

**Table 1. Mechanical properties of steel reinforcement.**

| **Reinforcement Identification** | **Yield Strength, ksi** | **Tensile Strength, ksi** | **Elongation, percent in 24 in.** |
|---|---|---|---|
| MMFX[1] (1) | 114.2 | 165.1 | 7.5 |
| MMFX (2) | 110.6 | 158.0 | 7.3 |
| MMFX (3) | 118.4 | 167.5 | 6.9 |
| *MMFX Average* | *114.4* | *163.5* | *7.2* |
| UC[2] (1) | 58.5 | 96.0 | 16.4 |
| UC (2) | 60.1 | 96.0 | 16.6 |
| UC (3) | 60.1 | 95.6 | 16.2 |
| *UC Average* | *59.6* | *95.9* | *16.4* |
| EC[3] (1) | 66.7 | 106.6 | 14.3 |
| EC (2) | 67.1 | 106.3 | 13.5 |
| EC (3) | 65.7 | 104.1 | 9.8 |
| *EC Average* | *66.5* | *105.7* | *12.6* |

1 MMFX – MMFX Microcomposite steel reinforcement
2 UC – Uncoated mild steel reinforcement
3 EC – Epoxy-coated mild steel reinforcement

**Table 2. Mix proportions per cubic yard and concrete properties.**

| Property | Quantity |
|---|---|
| Type II cement | 500 lb |
| Sand | 1526 lb |
| Course aggregate | 1489 lb |
| Water | 217 lb |
| Fly ash | 64 lb |
| Air-entraining agent | 2 oz |
| Air content | 5.5 percent |
| Unit weight | 3815 pcy |
| Slump | 3.0 in. |
| Average 28-day compressive strength | 5964 psi |
| Average 28-day modulus of rupture | 623 psi |

**Table 3. Accelerated corrosion test program specimens.**

| Specimen Identification | NaCl Concentration | Number of Specimens |
|---|---|---|
| A[1]-L[2]-MMFX[3] | 3 percent | 3 |
| A-T[4]-MMFX | 3 percent | 2 |
| A-L-UC[5] | 3 percent | 3 |
| A-T-UC | 3 percent | 2 |
| A-L-EC[6]-AD[7] | 3 percent | 3 |
| A-T-EC-AD | 3 percent | 2 |
| A-L-EC-DH[8] | 3 percent | 3 |
| A-T -EC-DH | 3 percent | 2 |
| A-T -EC-CH[9] | 3 percent | 2 |
| RM[10]-MMFX | 3 percent | 6 |
| RM-UC | 3 percent | 6 |
| RM-EC-AD | 3 percent | 6 |
| RM -EC-DH | 3 percent | 6 |

1 A – ASTM G 109 accelerated corrosion test
2 L – Artificial longitudinal crack
3 MMFX – MMFX Microcomposite steel reinforcement
4 T – Artificial Transverse cracks
5 UC – Uncoated mild steel reinforcement
6 EC – Epoxy-coated mild steel reinforcement
7 AD – As-delivered epoxy coating condition
8 DH – Drilled holiday epoxy coating condition
9 CH – Chipped holiday epoxy coating condition
10 RM – Rapid Macrocell accelerated corrosion test

**Table 4. Chloride-ion concentration at corrosion initiation and 90-day intervals.**

| **Specimen Identification** | **Chloride-ion at Corrosion Initiation** | | **90-day Chloride-ion Concentration** | **180-day Chloride-ion Concentration** | **270-day Chloride-ion Concentration** |
|---|---|---|---|---|---|
| | **Time, days** | **Concentration, pcy** | **Concentration, pcy** | **Concentration, pcy** | **Concentration, pcy** |
| A-L-MMFX (1) | 189 | 2.73 | 1.60 | 2.56 | 2.96 |
| A-L-MMFX (2) | | | 1.34 | 1.95 | 2.38 |
| A-L-MMFX (3) | | | | | 1.32 |
| A-T-MMFX (1) | | | | | 1.72 |
| A-T-MMFX (2) | | | | | 2.54 |
| *MMFX Average* | | *2.73* | *1.47* | *2.25* | *2.18* |
| A-L-UC (1) | 7 | 1.05 | 1.34 | 1.74 | 1.85 |
| A-L-UC (2) | 7 | 1.11 | 1.35 | 2.10 | 3.34 |
| A-L-UC (3) | 7 | 1.03 | | | 2.00 |
| A-T-UC (1) | 7 | 1.07 | | | 2.14 |
| A-T-UC (2) | 14 | 1.03 | | | 2.52 |
| *UC Average* | | *1.06* | *1.34* | *1.92* | *2.37* |
| A-L-EC-AD (1) | | | 1.35 | 1.83 | 1.93 |
| A-L-EC-AD (2) | | | 1.47 | 1.93 | 2.88 |
| A-L-EC-AD (3) | | | | | 2.23 |
| A-T-EC-AD (1) | 133 | 1.96 | | | 2.42 |
| A-T-EC-AD (2) | | | | | 2.99 |
| *EC-AD Average* | | *1.96* | *1.41* | *1.88* | *2.49* |
| A-L-EC-DH (1) | 77 | 1.14 | 1.16 | 1.58 | 2.19 |
| A-L-EC-DH (2) | 77 | 1.20 | 1.20 | 1.74 | 2.69 |
| A-L-EC-DH (3) | 98 | 1.43 | | | 3.68 |
| A-T-EC-DH (1) | 189 | 2.10 | | | 2.61 |
| A-T-EC-DH (2) | 105 | 2.82 | | | 3.32 |
| *EC-DH Average* | | *1.74* | *1.18* | *1.66* | *2.90* |
| A-L-EC-CH (1) | | | | | 2.00 |
| A-L-EC-CH (2) | 189 | 2.08 | | | 2.61 |
| *EC-CH Average* | | *2.08* | | | *2.31* |