

Evaluation of Corrosion-Resistant Steel Reinforcement

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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, in particular bridge engineers. In the United States, maintenance and replacement costs are measured in billions of dollars. Further, the use of deicing salts has resulted in steady deterioration of bridge decks due to corrosion.

These concerns have initiated continual development of protective measures. Application of carbon fiber reinforced polymer or corrosion-resistant steel reinforcement for the replacement of existing mild steel reinforced concrete bridge decks has great potential due to the inherent corrosion resistant properties associated with the material.

To investigate corrosion prevention through the use of corrosion-resistant alloys, MMFX Microcomposite steel reinforcement, a high-strength, high chromium steel reinforcement, is evaluated for corrosion resistance performance. The steel is compared to epoxy-coated and uncoated mild steel reinforcement. Principal emphasis is placed on corrosion performance of the steel, which is evaluated using ASTM and Rapid Macrocell accelerated corrosion tests.

Ongoing research study at Iowa State University will determine if MMFX Microcomposite steel reinforcement provides superior corrosion resistance to epoxy-coated mild steel reinforcement in bridge decks. After 12 weeks, the associated ASTM ACT corrosion potentials indicate neither MMFX Microcomposite nor epoxy-coated mild steel reinforcement steel have undergone active corrosion. However, the uncoated mild steel underwent active corrosion with the second week. Within the second week, Rapid Macrocell ACT produced severe corrosion risk potentials for all reinforcement types.

INTRODUCTION

Reinforced concrete is a versatile, economical, and proven construction material. Able to be placed to a variety of shapes and finishes, it is durable and strong, performing well throughout its service life. However, the corrosion of steel reinforcement in an aging highway infrastructure is a major problem currently facing the transportation engineering community, in particular bridge engineers. In the United States, this results in billions of dollars spent to maintain and replace existing bridge decks. In 1979, an estimated \$6.3 billion of federal-aid was allocated for rehabilitations due to corrosion incurred bridge damage (1). By 1992, the estimate totaled \$51 billion (2). With skyrocketing bridge maintenance costs, protective measures to arrest chloride-induced corrosion have been actively developed for over 30 years.

The deteriorating infrastructure requires use of innovative protective methodologies, which are commonly subdivided into two categories. First, protection is attained through methods that slow the initiation of corrosion, or lengthen the time it takes chlorides to reach the embedded steel reinforcement. The second includes methods that lengthen the active corrosion period, the time between initiation of corrosion and the end of service life (3).

For the last three decades, the principle techniques of corrosion prevention for bridge decks incorporate increased concrete cover depth and application of epoxy coating over steel reinforcement. In 1976, the Iowa Department of Transportation implemented the use of epoxy-coated mild steel reinforcement for top layer of reinforcement in bridge decks. Within 10 years, bridge deck designs had integrated epoxy-coated mild steel reinforcement to both top and bottom layers of reinforcement (4).

Both increasing concrete cover depth and infusing epoxy coating over steel reinforcement are believed to delay corrosion initiation and extend the active corrosion period. Increased concrete cover depth lengthens the required time for chlorides to propagate to steel reinforcement and lessens the availability of oxygen and moisture for the corrosion process. Epoxy coating additionally limits the access of chlorides, oxygen, and moisture to the surface of steel reinforcement. Even in regions with holidays in the epoxy coating, it is believed the corrosion process will be abated due to the epoxy coating still limiting access of oxygen and moisture despite chloride contact (3).

Integration of increased concrete cover depth and epoxy-coated reinforcement has greatly lengthened the service life of bridge decks. However, it is not a perfect solution. Increased concrete cover depth increases both dead load and construction costs, virtually unnecessary for structural purposes. In addition, epoxy-coated reinforcement adds only slightly to the cost of bridge construction. However, holidays in the epoxy coating and high chloride concentrations could result in corrosion of steel reinforcement that affects the performance of a concrete structure. Further, epoxy coatings become brittle and delaminate from the steel reinforcement under exposure to high chloride concentrations (5).

Poorly adhering epoxy coatings have actually increased corrosion problems (6). All epoxy coating are susceptible to delamination from the steel reinforcement. Small breaks in the epoxy coating allow for the bond between the coating and steel to be lost. The epoxy coating remains generally intact, but the chloride concentration increases in the solution underneath the coating in an environment that is low in oxygen. The result involves hydrochloric acid attack of the steel. This has been attributed for poorly applied

epoxy coatings in premature substructure chloride-induced corrosion. In 1986, six years after construction, epoxy-coated reinforcement of bridge substructures in the Florida Keys possessed chloride-induced corrosion (6). This provided initial indication that long-term protection provided by epoxy coating may be less than was intended. Further, there is clear evidence given enough time, even well applied epoxy coatings lose adhesion by the time chlorides reach the level of steel reinforcement (7). Therefore, deteriorated epoxy coatings will not protect the steel reinforcement effectively (8).

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 in current development. Application of carbon fiber reinforced polymer or corrosion-resistant steel reinforcement for the replacement of existing mild steel reinforced concrete bridge decks has great potential due to the inherent corrosion resistant properties associated with the material.

While the potential exists for durable bridges decks constructed with MMFX Microcomposite steel reinforcement, corrosion performance of the new material can only be evaluated through a series of monitoring programs.

Objective

This paper summarizes an ongoing research study at Iowa State University, the objective of which is to determine if MMFX Microcomposite steel reinforcement will provide superior corrosion resistance to epoxy-coated mild steel reinforcement in bridge decks. To this end, MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement were evaluated per tensile strength and corrosion resistance. With emphasis placed on corrosion resistance performance, the objective of this paper is the comparison of MMFX, epoxy-coated, and uncoated reinforcement through accelerated corrosion testing.

The aforementioned objective was accomplished by completing the following tasks. Prior research studies of MMFX Microcomposite steel and corrosion resistance performance were assessed to provide applicable test methods for evaluating corrosion resistance performance. ASTM and Rapid Macrocell accelerated corrosion tests were conducted for the corrosion resistance performance evaluation of MMFX, epoxy-coated, and uncoated reinforcement (9, 3). First, ASTM accelerated corrosion tests with pre-cracked concrete subjected to elevated chloride levels represent one procedure for gauging corrosion resistance. Second, Rapid Macrocell accelerated corrosion tests are also used for evaluation. Both ASTM and Rapid Macrocell accelerated corrosion tests were performed to determine general and pitting corrosion properties. Half-cell corrosion potential data was compiled statistically to determine corrosion rate and the onset of corrosion for chloride concentration analysis. Comparisons of the compiled corrosion potentials were made between MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement. The nature of the corrosion products on the surrounding concrete was also evaluated with scanning electron microscopy.

The results obtained from this research further the available information on the use of MMFX Microcomposite steel as reinforcement in bridge decks.

CORROSION PROCESS

Corrosion of steel reinforcement in concrete can be modeled in a two-stage process. The first stage is known as an initiation, diffusion, or incubation period in which chloride ions migrate and reach a corrosion threshold at the level of reinforcement.

Among the model available to estimate the service life of a bridge deck is the diffusion-spalling model that utilizes the concept of a chloride diffusion period, T_1 , plus a deterioration period, T_2 . The length of the chloride diffusion period, T_1 , can be calculated using two methods. The first approach uses a deterministic model in conjunction with Fick's Law that assumes a constant diffusion and surface chloride concentration is used (10). The length of the diffusion period can also be estimated by utilizing a probabilistic approach that takes into account the effect of the uncertainties associated with the variables included in Fick's Law when calculating the length of the chloride diffusion period (11).

CHLORIDE THRESHOLD

For uncoated mild steel reinforcement, corrosion threshold of chloride concentration at the reinforcement level was estimated to be 0.2 percent of the weight of the cement content of concrete (12, 13). Based on 6.5 sacks of cement per cubic yard of concrete, this chloride threshold for uncoated reinforcement was equated to 1.2 lb/yd³ of concrete (14). Unlike the case for uncoated reinforcement, no published literature presents definitive chloride threshold values for MMFX or epoxy-coated 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/yd³ and 1.2 to 3.6 lb/yd³ at reinforcement level was suggested, respectively for MMFX and epoxy-coated reinforcement (15). The lower bound of the range for epoxy-coated reinforcement was recommended as an empirical chloride threshold for uncoated reinforcement (12, 13).

METHOD OF MONITORING CORROSION

The technique of corrosion monitoring is well established for reinforced concrete structures.

The advantage of long-term monitoring is that the progression of condition changes can be monitored. The growth of anodic area, using half-cells, changes in corrosion rates using macrocell approaches, and the changes in concrete resistivity with time are more helpful in predicting long-term durability than the instantaneous approach that a survey entails.

A system using embedded half-cells only. The ladder macrocell system, with variations, is used in new construction.

Half-cell Monitoring Protocol

The corrosion potential of any half-cell can be recorded against a standard electrode. Half-cell potentials are a function of concentration as well as the metal and the solution. Generally, a solution of higher chloride concentration is more corrosive. As a result, a current will flow in a cell made up a single metal in two different concentrations of the

same solution. Therefore, the corrosion of steel in concrete can be considered as a concentration cell.

The corrosion risk in that cell is measured by introducing an external half-cell. Placing a half-cell on the concrete surface and connecting it via a voltmeter to the steel, a circuit is formed. The electrical potential difference will be a function of the iron in the pore water environment.

At the anode, iron can easily go into solution. At the cathode, the passive layer is still strong and being strengthened further by cathodic reaction, so the steel resists dissolution. As a result higher corrosion potentials are associated in anodic, corroding areas and lower potentials in the cathodic, passive areas.

PREVIOUS RESEARCH RELATED TO CORROSION RESISTANT STEEL REINFORCEMENT

Several advanced materials have been recently introduced for structural purposes, but without the corrosion characteristic typically found in mild steel reinforcement. Two alloys identified as MMFX steel are among those developed.

First, described as “dual phase” steel, involves an alloy that is quenched after rolling. The quenching process results in the formation of a ferritic-martensitic, low carbon steel that has improved corrosion resistance and produces strength properties that are equal or exceed those of conventional ASTM A 615 mild steel reinforcement. The lack of industrial complexes able to quench steel reinforcement led developers to formulate a second alloy, a “micro composite” steel that can be manufactured without the quenching operation. Initial runs of the MMFX Microcomposite steel produced a material with yield strength of 126 ksi, more than twice that required of conventional ASTM A 615 mild steel reinforcement. Further, based on anodic polarization tests, the steel has significantly improved corrosion resistance (16). That corrosion resistance both delays corrosion initiation and slow active corrosion period.

While MMFX Microcomposite steel appears to offer significant advantages of lowering construction costs and increasing service life for concrete bridge decks, a number of questions remain. In particular, none of the corrosion tests reported involved corrosion of the steel reinforcement in which a “macrocell” has formed. The tests reported by the developers involved accelerated testing in non-cementitious environments. Since corrosion in highly alkaline environments is significantly different from corrosion in the atmosphere, testing the steel reinforcement in cementitious systems is mandatory, as is testing the steel within a macrocell, such as will form between the top and bottom layers of reinforcement in a bridge deck.

LABORATORY TEST PROGRAM

Steel reinforcement used in this research was obtained in coordination with the Iowa Department of Transportation. The reinforcement consisted of one heat of No. 5 MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement. A single “chip mix” batch of concrete was utilized in all specimen fabrication to preserve uniformity among the individual test specimens as well as between accelerated corrosion tests.

Physical and mechanical tests were employed to determine yield and tensile strength, elongation, and coating thickness. Compressive strength and modulus of

rupture for the concrete mix proportions used in corrosion resistance performance tests were conducted.

Accelerated Corrosion Test Program

The corrosion resistance of MMFX reinforcement is compared to that of epoxy-coated and uncoated reinforcement using ASTM ACT. An additional test procedure introduced as Rapid Macrocell ACT was used for evaluation of MMFX, epoxy-coated, and uncoated reinforcement. These tests have been shown to provide valid comparisons using realistic exposure conditions.

First, ASTM G 109 accelerated corrosion tests with pre-cracked concrete subjected to elevated chloride levels represent one procedure for gauging corrosion resistance. Second, Rapid Macrocell accelerated corrosion tests are also used for evaluation. Corrosion performance is evaluated based on relative corrosion rates, changes in corrosion potential, and chloride concentrations needed for corrosion initiation. Both ASTM ACT and Rapid Macrocell ACT tests induce general and pitting corrosion. Pitting corrosion is the dominant form of corrosion in the field and in the current tests.

ASTM G 109 Accelerated Corrosion Test

The ASTM G 109 accelerated corrosion test was first developed to study the effect of chemical admixtures on the corrosion performance of steel reinforcement (9). The test method is used to evaluate materials intended to inhibit chloride-induced corrosion of steel in concrete.

Over the past two decades, ASTM ACT tests have been used most often to evaluate the corrosion performance of corrosion-resilient steel reinforcement. Although these tests typically require one to two years for completion, they qualify as accelerated tests considering the service life of actual structures should be in excess of 30 times as long.

The ASTM ACT is used to model the corrosion of steel reinforcement in concrete where two layers of reinforcement are present. A fabricated alteration produces an artificial crack, leaving a direct path for chlorides to the top layer of steel reinforcement. The crack is either simulated parallel or perpendicular to and above the top steel reinforcement through the insertion and removal of a 0.012 inch stainless steel shim when the specimen is fabricated. The specimen is subjected to cycles of wetting and drying with a 3 percent sodium chloride solution, continuing up to 96 weeks.

Rapid Macrocell Accelerated Corrosion Test

The comparisons of corrosion response are made using the Rapid Macrocell ACT, a test originally developed at the University of Kansas under the SHRP program (17, 18) and updated under the NCHRP-IDEA program (3). The goal of the technique is to obtain a realistic measure of the performance of corrosion protection systems in a short period of time. The basic test specimen consists of either a bare reinforcement specimen or a mortar-clad specimen. The contact surface between the mortar and the reinforcement simulates the concrete/reinforcement interface in actual structures. When epoxy-coated mild steel reinforcement is tested, the ends of the reinforcement are protected with epoxy.

The Rapid Macrocell ACT requires two containers. The test specimen, either bare or mortar-clad, is placed in one container, along with a simulated pore solution containing sodium chloride. Two specimens are placed in the second container and immersed in simulated pore solution with no chlorides added. 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, scrubbed to remove CO₂, is bubbled into the pore solution surrounding the cathode to ensure an adequate supply of oxygen is present. The air causes some evaporation, which is countered by adding distilled water to the container to maintain a constant volume of the solution.

The simulated pore solution is based on ASTM G 109 ACT.

Specimen Fabrication

The 30 ASTM ACT concrete beams were cast in a single frame of formwork. The beams were 6 inches in width by 12 inches in length and 7 inches in height. The forms were constructed with holes in the appropriate side forms to position the No. 5 reinforcement to maintain exactly 1 inch of clear cover, as illustrated in Figure 1.

The MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement were tested in “as-delivered” condition. Additionally, epoxy-coated mild steel reinforcement was evaluated whereby the coating was breached by four 1/8-inch diameter holes drilled equidistantly in line. Epoxy coated mild steel reinforcement specimens were evaluated where the coating was chipped by off at random locations through the use of a razor blade removing approximately 2-1/2 in².

No. 5 reinforcement was cut with a chop saw to a length of 16 inches and both ends were ground removing any sharp edges. One end of each bar was drilled 1/2 inch to accommodate a self-tapping No. 6 x 3/8 stainless steel sheet metal screw. The bars were soaked in hexane until clean of grease, dirt, and hydraulic fluid, and allowed to air dry. Each end of the bar was wrapped with electroplating tape so a 9-inch portion in the middle of the bar was bare. A 3-1/2-inch length of neoprene tubing was placed over the electroplating tape at each end of the bar, and the length of tubing protruding from the bar ends was filled with two applications of 3M Scotchkote 413/215 PC Patch Compound two-part epoxy to prevent external interference.

The bars were placed in the molds so 1-1/2 inches was protected within each exit and from the concrete. This exposed the center 9 inches of steel. The epoxy-coated mild steel reinforcement with drilled holidays was placed with the line of holes facing the top surface. As the epoxy-coated mild steel reinforcement with chipped holidays was randomly breached, attention was not paid to aligning the holes in particular.

The concrete specimens were made using the same source of materials. The concrete was placed in two layers and consolidated by vibration. A float finish was applied after consolidation. Additional un-reinforced concrete beams were cast for background chloride analysis.

A fabricated alteration produces an artificial crack, leaving a direct path for chlorides to the top layer of steel reinforcement. The crack is either simulated parallel or perpendicular to and above the top steel reinforcement through the insertion and removal of a 0.012 inch stainless steel shim when the specimen is fabricated. The shim is

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 slabs were covered with wet burlap and plastic sheets for the initial overnight curing. They were then stripped from the forms and cured under the wet burlap and plastic sheets until age 21 days. The top test surfaces were slightly sanded at age 18 to 20 days to remove the portland cement skin or laitance, which normally wears off by natural weathering. At age 21 days, they were then stored on their sides in air in a laboratory room at 68 to 78 degrees F for 7 days on air drying. At about age 28 days, the four sides and bottom of each test specimen were coated with two applications of Sierra Performance Manufacturing two-part epoxy concrete paint to minimize lateral moisture movement in the slabs during the accelerated corrosion tests.

A reservoir with dimensions 3 inches in width by 7 inches in length and 3 inches in height was attached to the specimen, and about 2.5 in. from each side so that it does not extend over the taped sections of the bars. A silicone caulk is used to seal the dam from the outside, and epoxy sealer is applied to the top surface outside of the dam.

The two layers of steel reinforcement were connected electrically across a 10-ohm resistor and ponding regimen commenced.

For the Rapid Macrocell ACT, MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement were tested in as-delivered condition. Additionally, epoxy-coated mild steel reinforcement was evaluated whereby the coating was breached by four 1/8-inch diameter holes drilled equidistantly in line.

As illustrated in Figure 2, No. 5 reinforcement was cut with a chop saw to a length of 5 inches. One end of the reinforcement is then drilled 1/2 inch to accommodate a self-tapping No. 6 x 3/8 stainless steel sheet metal screw and both ends were ground removing sharp edges. Bars were then soaked in hexane to remove grease, dirt, and hydraulic fluid from the surface, and dried at room temperature. The end of the epoxy-coated reinforcement that was submerged was protected using 3M Scotchkote 413/215 PC Patch Compound two-part epoxy.

Mortar-clad bars were cast in a mold consisting of PVC pipe. The bars were centered. The mortar sheathing covered the exterior surface of the bar and projected one inch past one end of the reinforcement. The mix proportions represented the mortar constituent of concrete. Mortar was placed in the cylindrical mold in four layers. Each layer was rodded 25 times using a 1/8-inch diameter rod, followed by external vibration for 30 seconds.

Specimens were cured in the molds for 24 hours. Specimens were then removed from the molds and cured in saturated water for 13 days. After 14 days of curing, the specimens were dried for one day. For both bare and mortar-clad specimens, a 14-gauge copper electrical wire is secured to the tapped end of each specimen with a self-tapping No. 6 x 3/8 stainless steel sheet metal screw. The top of the screw, exposed wire, and mortar are then coated with two applications of 3M Scotchkote 413/215 PC Patch Compound two-part epoxy and Sierra Performance Manufacturing two-part epoxy concrete paint, respectively.

Chloride Exposure Condition

The ASTM ACT chloride exposure condition was based upon a weekly cycle. The beams are subjected to a seven day alternate ponding and drying regime. For the first 4

days of each week, the test surface was ponded with about 1-1/2 inches of 3 percent sodium chloride solution in a laboratory at 68 to 78 degrees F. 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 F. After this exposure the test surface was immediately reponded with a 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 for remainder of the test period.

The mortar-clad Rapid Macrocell ACT specimen was placed in a 1-quart container, along with a simulated pore solution containing a 3 percent concentration of sodium chloride. Two specimens are placed in the second container, 5-quart, and immersed in simulated pore solution with no chlorides added. The solution places 3 inch of reinforcement below the surface of the pore solution and was maintained for the duration of the test period.

Concrete Mix Properties

All accelerated corrosion test specimens were constructed from a single 1-1/2 yd³ batch of “chip mix” concrete to ensure the MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement were subject to uniform standards. Compressive strength and modulus of rupture for the concrete mix proportions used in corrosion resistance performance tests were conducted. Table 1 shows the significant average properties for the fresh and hardened concrete.

ACT CORROSION RESULTS

The test results described in the following section demonstrate the corrosion resistance performance of MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel. Specific findings are presented in terms of half-cell corrosion potential for the ASTM G 109 ACT and Rapid Macrocell ACT tests.

Significant differences in “average” corrosion potential occurred when compared by reinforcement material under the same test conditions in duplicate specimens. The following section shows average corrosion potential obtained from the duplicate accelerated corrosion tests.

ACT Corrosion Monitoring

The half-cell corrosion potential of the anode and cathode are measured using a saturated calomel electrode. The half-cell was maintained in accordance with ASTM C 876 for the stabilization of corrosion potential. Table 2 shows the associated corrosion condition with varying half-cell corrosion potentials from the saturated calomel electrode (19). Corrosion potentials more negative than -276 mV indicate that active corrosion of the metal.

The individual saturated calomel electrode half-cell corrosion potential readings for the MMFX Microcomposite, epoxy-coated mild, uncoated mild steel reinforcement in the duplicate ASTM and Rapid Macrocell ACT tests are shown in the following section.

The specimens in duplicate accelerated corrosion tests are shown by different symbols in the same figure.

The typical corrosion potential data show that variations among the reinforcement material in duplicate test specimens can be significant at a given time and that significant corrosion potential data variation can occur within accelerated corrosion tests of differing reinforcement material. Such variations may be caused by variations in local anode and cathode locations, epoxy coating performance, and reinforcement material (20).

ASTM G 109 ACT

30 ASTM G 109 ACT simulate the corrosion behavior of reinforcement in decks in which chloride has rapid access to the steel due to the formation of cracks in the concrete. The tests were conducted with the configuration shown in Table 3. The MMFX, epoxy-coated, and uncoated reinforcement were tested in “as-delivered” condition. Additionally, epoxy-coated reinforcement was evaluated whereby the coating was breached by four 1/8-inch diameter holes drilled equidistantly in line. Two epoxy coated reinforcement specimens were evaluated where the coating was chipped by off at random locations through the use of a razor blade, removing approximately 2-1/2 in².

The 12-week average corrosion potentials for specimens with longitudinal and transverse artificial cracks to the top layer of steel reinforcement are shown in Figures 3(a) and 3(b), respectively.

The corrosion potentials at the anode dropped rapidly for the uncoated reinforcement with both longitudinal and transverse cracks, dropping below -276 mV by the first week. At 12 weeks, the uncoated reinforcement exhibited the greatest corrosion potential, with values of -428 and -424 mV, respectively for longitudinal and transverse cracked specimens.

The corrosion potential for drilled and chipped holiday conditions of epoxy-coated reinforcement with longitudinal crack experienced nearly identical corrosion potentials, -163 and -166 mV, respectively. The drilled holiday condition of the epoxy-coated reinforcement with transverse cracks exhibited a corrosion potential of -33 mV.

Longitudinal and transverse cracked specimens with as-delivered epoxy-coated reinforcement exhibited the lowest corrosion potential, with values of -24 and -14, respectively.

The MMFX reinforcement exhibited corrosion potentials of -96 and -88 mV, for longitudinal and transverse cracked specimens, respectively.

No corrosion products were observed on the concrete surface for any reinforcement type.

Rapid Macrocell ACT

Rapid Macrocell ACT of mortar-clad specimens included six tests each of MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement. Additionally, epoxy-coated mild steel reinforcement was evaluated whereby the coating was breached by four 1/8-inch diameter holes drilled equidistantly in line. The tests were carried out with the test configuration shown in Table 4, modified with a plastic sheet over the test specimens. This maintained a high humidity environment over the portion of the reinforcement not submerged in the solution.

Twelve-week average corrosion potentials for the anode steel reinforcement are shown in Figure 4.

After the first week, all reinforcement types were undergoing active corrosion at the anode. At 12 weeks, the drilled holiday condition of the epoxy-coated and uncoated reinforcement exhibit the greatest corrosion potential, with values of -592 and -600 mV, respectively.

The epoxy-coated reinforcement exhibited a corrosion potential, -562 mV, while MMFX reinforcement exhibited the lowest average corrosion potential, -504 mV.

Corrosion products were observed on the mortar sheathing and within the solution of the anode, with the exception of the as-delivered and drilled holiday conditions of epoxy-coated reinforcement. Corrosion products appeared on the sheathing above and below the surface level of solution.

CONCLUSIONS

The test results from the accelerated corrosion tests justify the following conclusions for MMFX Microcomposite, epoxy-coated mild, and uncoated mild steel reinforcement.

Variations were observed in the saturated calomel electrode half-cell corrosion potentials between individual reinforcement types within duplicate specimens. The variations were probably caused by variations in crack width, locations of local anodes and cathodes, coating performance, pinholes in the coating, and deterioration of the concrete surface. However, a reasonable correlation did exist between the average half-cell corrosion potentials obtained from the duplicate specimens.

After 12 weeks, ASTM ACT only produced severe corrosion risk potentials for uncoated mild reinforcement. ASTM ACT generally produced only low to intermediate corrosion risk potentials for MMFX and all epoxy-coated reinforcement regardless of coating condition. All ASTM ACT specimens had essentially identical surface appearances at 12 weeks.

Within the second week, Rapid Macrocell ACT produced severe corrosion risk potentials for all reinforcement types. With the Rapid Macrocell ACT, the drilled holiday condition of the epoxy-coated and uncoated specimens had the greatest corrosion risk potential, while the as-delivered condition of the epoxy-coated had less corrosion potential. The MMFX specimens had the least corrosion risk potential. Rapid Macrocell ACT concrete surrounding MMFX and uncoated reinforcement discolored due to deposition of corrosion products.

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LIST OF FIGURES

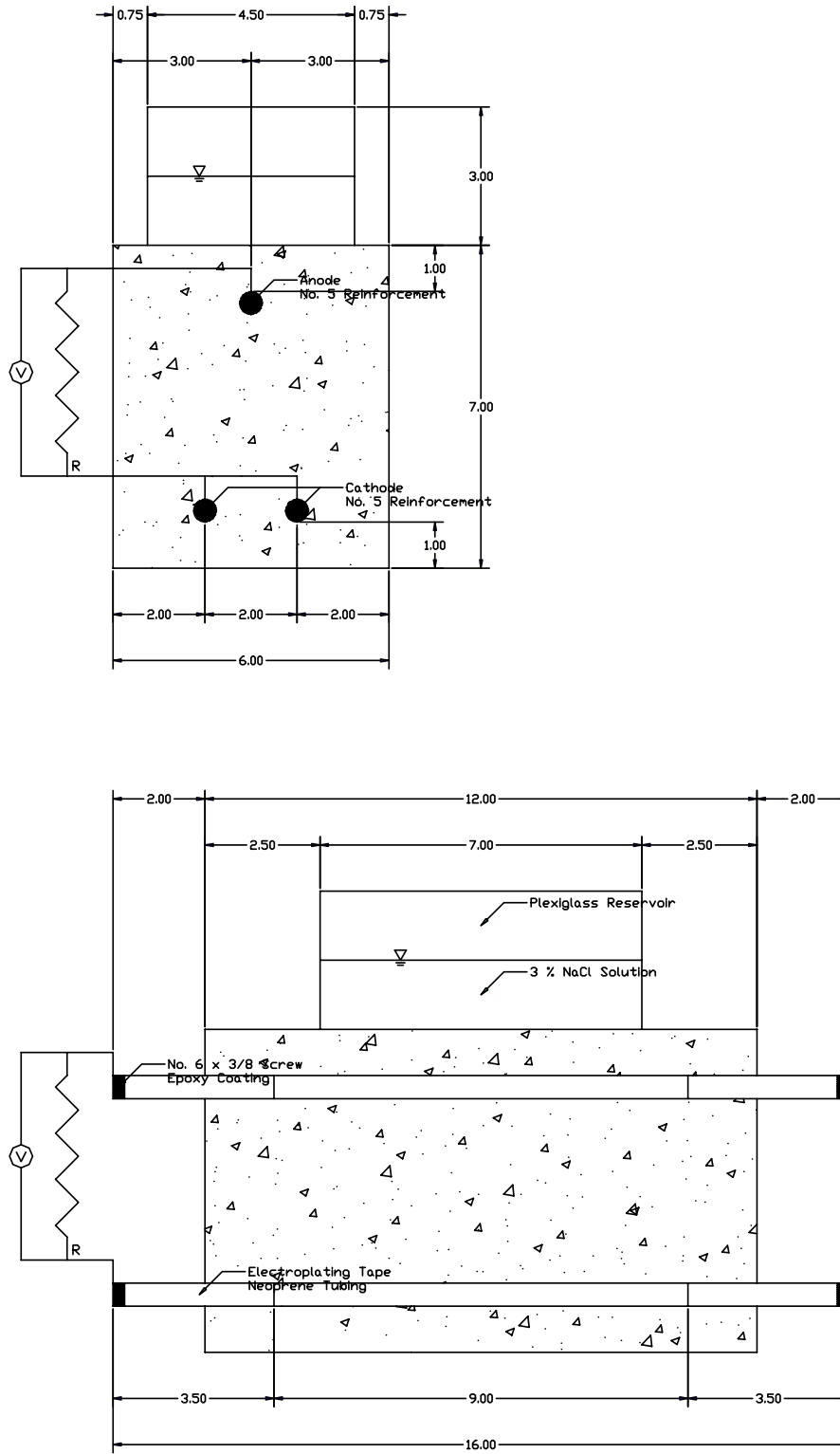


Figure 1 – Schematic of ASTM G 109 ACT specimen

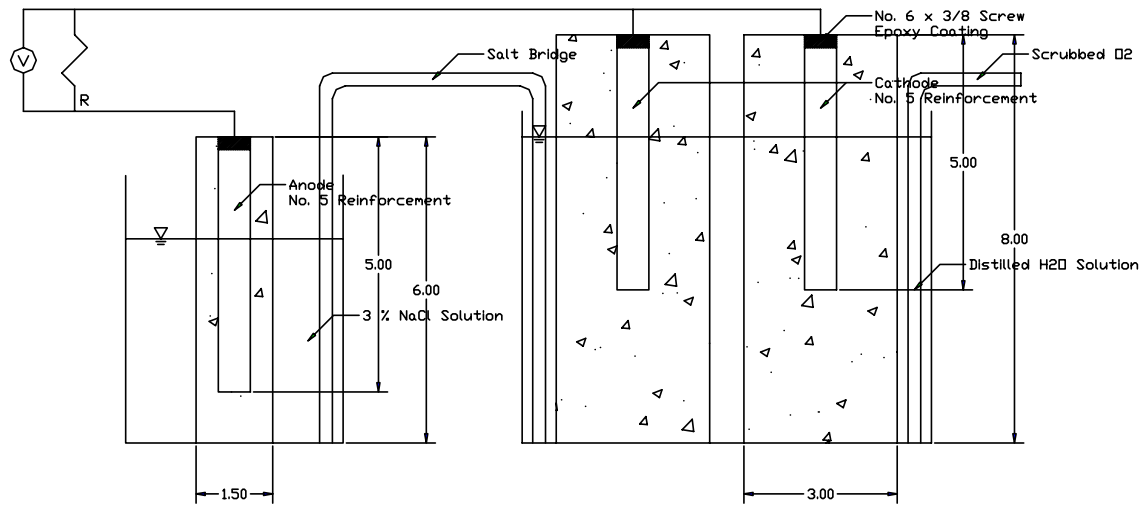


Figure 2 – Schematic of Rapid Macrocell ACT mortar-clad anode and cathode test specimens

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
Water/cement Ratio	0.43
Slump	3.0 in
Average 28-day compressive strength	5964 psi
Average 28-day modulus of rupture	623 psi

Table 1 – Mix proportions and concrete properties per cubic yard

Saturated Calomel Electrode	Corrosion Condition
Less than -126 mV	Low (10 percent risk of corrosion)
-126 mV to -276 mV	Intermediate corrosion risk
Greater than -276 mV	High (90 percent risk of corrosion)
Greater than -426 mV	Severe corrosion

Table 2 – ASTM criteria for corrosion of steel in concrete for saturated calomel electrode

Specimen Identification	NaCl Concentration	Number of Specimens	Notes
Artificially cracked specimens			
A-L ¹ -MMFX ²	3 percent	3	
A-T ³ -MMFX	3 percent	2	
A-L-UC ⁴	3 percent	3	
A-T-UC	3 percent	2	
A-L-AD-EC ⁵	3 percent	3	As-delivered condition
A-T-AD-EC	3 percent	2	As-delivered condition
A-L-DH-EC	3 percent	3	Drilled holiday condition
A-T-DH-EC	3 percent	2	Drilled holiday condition
A-T-CH-EC	3 percent	2	Chipped holiday condition

1 L – Artificial longitudinal crack

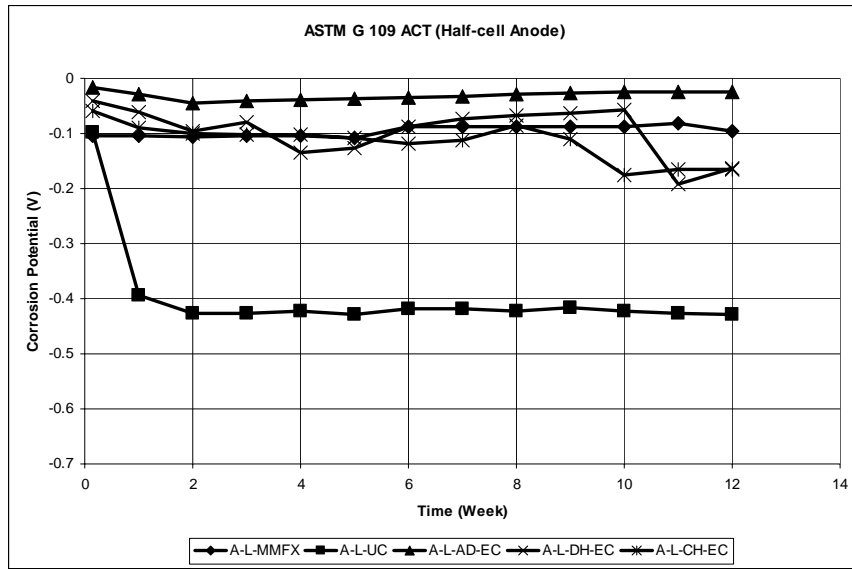
2 MMFX – MMFX Microcomposite steel reinforcement

3 T – Artificial Transverse cracks

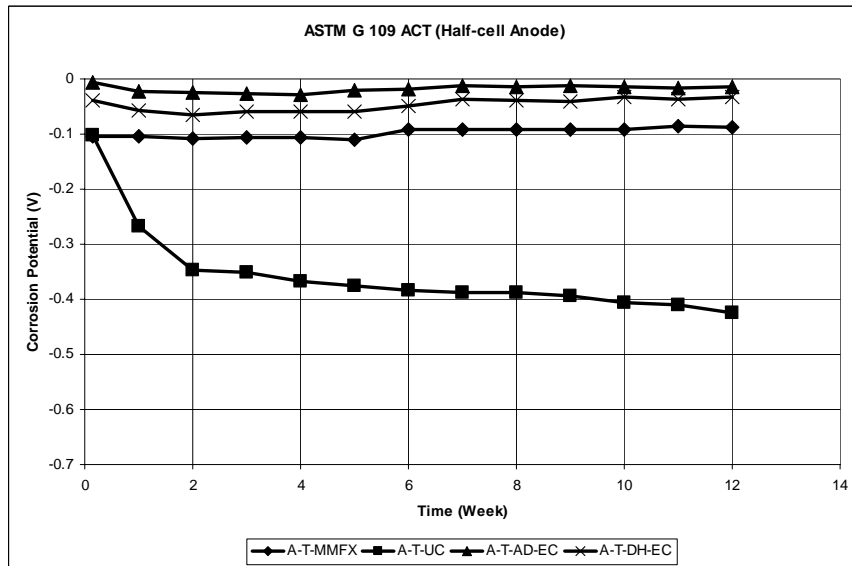
4 UC – Uncoated mild steel reinforcement

5 EC – Epoxy-coated mild steel reinforcement

Table 3 – ASTM G 109 ACT program



(a) - MMFX Microcomposite, epoxy-coated and uncoated mild steel reinforcement subjected to 3 percent NaCl solution through longitudinal crack.



(b) - MMFX Microcomposite, epoxy-coated and uncoated mild steel reinforcement subjected to 3 percent NaCl solution through transverse crack.

Figure 3 – ASTM G 109 ACT. Anode corrosion potential versus saturated calomel electrode.

Specimen Identification	NaCl Concentration	Number of Specimens	Notes
Mortar-clad specimens			
M-MMFX ¹	3 percent	6	
M-L-UC ²	3 percent	3	
A-L-AD-EC ³	3 percent	3	As-delivered condition
A-L-DH-EC	3 percent	3	Drilled holiday condition

1 MMFX – MMFX Microcomposite steel reinforcement

2 UC – Uncoated mild steel reinforcement

3 EC – Epoxy-coated mild steel reinforcement

Table 4 – Rapid Macrocell ACT program

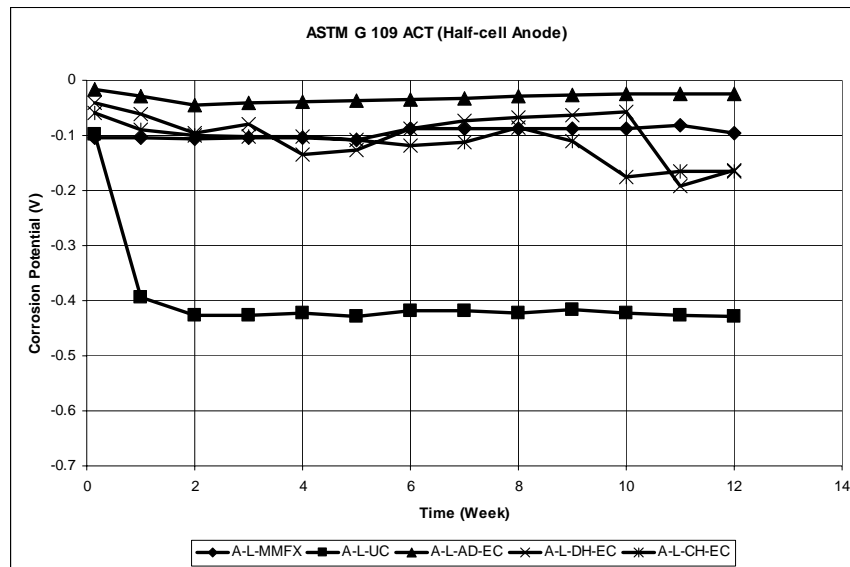


Figure 4 – Rapid Macrocell ACT. Anode corrosion potential versus saturated calomel electrode. MMFX Microcomposite, epoxy-coated and uncoated mild steel reinforcement subjected to 3 percent NaCl solution.