RAPID MACROCELL TESTS OF ENDURAMET® 33, ENDURAMET® 316LN, and ENDURAMET® 2205 STAINLESS STEEL BARS

By
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A Report on Research Sponsored by

TALLEY METALS

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ABSTRACT

The corrosion resistance of EnduraMet® 33, EnduraMet® 316LN, and EnduraMet® 2205 stainless steel reinforcing bars is evaluated using the rapid macrocell test outlined in Annexes A1 and A2 of ASTM A955-10. Based on the test results, all three types of stainless steel satisfy the requirements of ASTM A955-10.

Keywords: chlorides, concrete, corrosion, macrocell, reinforcing steel, stainless steel

ACKNOWLEDGEMENTS

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INTRODUCTION

This report describes the test procedures and results of rapid macrocell tests to evaluate the corrosion performance of EnduraMet® 33, 316LN, and 2205 stainless steel reinforcing bars. Four EnduraMet® 33 as well as six EnduraMet® 316LN and EnduraMet® 2205 specimens are tested in accordance with Annexes A1 and A2 of ASTM A955-10.

EXPERIMENTAL WORK

Materials

Tests were performed on No. 6 (No. 19) EnduraMet® 33 stainless steel bars as well as No. 5 (No. 16) EnduraMet® 316LN and EnduraMet® 2205 reinforcing bars. The bars were inspected upon receipt and found to be in good condition.

According to the supplier, the bars were cleaned using an acid solution to remove the mill scale and then rinsed with water.

The chemical compositions of the EnduraMet® 33, 316LN, and 2205 stainless steel are given in Table 1.

Table 1: Chemical composition of 33, 316LN, and 2205 stainless steel (provided by manufacturer).

Material Composition Report (%)												
Material	**Cr**	**Ni**	**C**	**Mn**	**N**	**P**	**S**	**Mo**	**Si**	**Cu**	**Co**	**B**
EnduraMet® 33	17.92	3.51	0.04	12.08	0.37	0.03	< 0.001	0.27	0.52	0.08	0.06	-
EnduraMet® 316LN	17.65	10.2	0.02	1.4	0.13	0.03	0.003	2.04	0.89	0.32	0.28	0.0028
EnduraMet® 2205	21.32	4.72	0.02	1.72	0.18	0.03	0.004	2.56	0.45	0.21	-	0.0015

Experimental Procedures

Rapid Macrocell Test

Specimens were tested in accordance with the rapid macrocell test outlined in Annexes A1 and A2 of ASTM A955/A955M-10 and detailed in Figure 1, with the exception that four 4-in. long, No. 6 (No. 19) EnduraMet® 33 bars were tested, rather than six 5-in. long, No. 5 (No. 16) bars as called for the ASTM A955 and used for the other two steel types. Each bar used in the rapid macrocell is drilled and tapped at one end to accept a 0.5-in., 10-24 stainless steel machine screw. Bars are cleaned prior to testing with acetone to remove oil and surface contaminants introduced by machining. A length of 16-gauge insulated copper wire is attached to each bar via the machine screw. The electrical connection is coated with epoxy to protect the wire from corrosion.

A single rapid macrocell specimen consists of an anode and a cathode. The cathode consists of two bars submerged to a depth of 3 in. in simulated pore solution in a plastic container, as shown in Figure 1. One liter of pore solution consists of 974.8 g of distilled water, 18.81 g of potassium hydroxide (KOH), and 17.87 g of sodium hydroxide (NaOH). The solution has a pH of about 13.4. Air, scrubbed to remove carbon dioxide, is bubbled into the cathode solution. The anode consists of a single bar submerged to a depth of 3 in. in a solution consisting of simulated pore solution and 15 percent sodium chloride (NaCl). Because No. 6 (No. 19) bars are used for the EnduraMet® 33 specimens, the anode and cathode bars of these four macrocells are submerged to a depth of 2.5 in. to obtain approximately the same solution contact area as obtained with the No. 5 (No. 16) bars. The contact area for the EnduraMet® 33 specimens is 40.9 cm^2 compared to 39.9 cm^2 for the EnduraMet® 2205 and 316LN specimens, a 2.5% difference. Corrosion rates are normalized to the solution contact area.

The "salt" solution is prepared by adding 172.1 g of NaCl to one liter of pore solution. The solutions are changed every five weeks to limit the effects of carbonation. The anode and cathode are connected electrically across a 10-ohm resistor. A potassium chloride (KCl) salt bridge provides an ionic connection between the anode and the cathode (Figure 1).

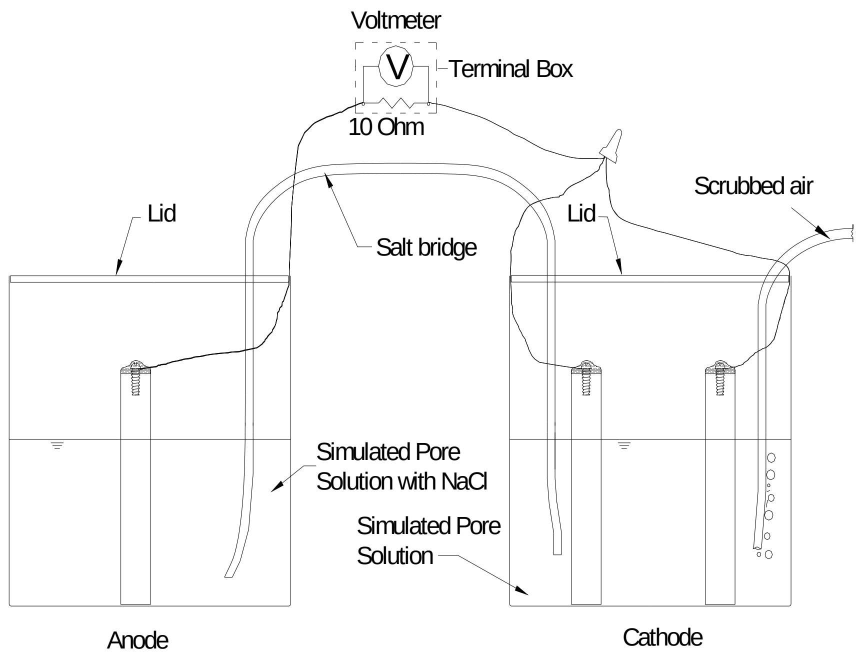

Figure 1: Rapid Macrocell Test Setup

The corrosion rate is calculated based on the voltage drop across the 10-ohm resistor using Faraday's equation.

$$\text{Rate} = K \frac{V \cdot m}{n \cdot F \cdot D \cdot R \cdot A} \qquad (1)$$

where the Rate is given in μm/yr, and

K = conversion factor = $31.5 \cdot 10^4$ amp·μm ·sec/μA·cm·yr

V = measured voltage drop across resistor, millivolts

m = atomic weight of the metal (for iron, m = 55.8 g/g-atom)

n = number of ion equivalents exchanged (for iron, n = 2 equivalents)

F = Faraday's constant = 96485 coulombs/equivalent

D = density of the metal, g/cm^3 (for iron, D = 7.87 g/cm^3)

R = resistance of resistor, ohms = 10 ohms for the test

A = surface area of anode exposed to solution, 39.9 cm^2 for 2205 and 316LN specimens, 40.9 cm^2 for 33 specimens

Using the values listed above, the corrosion rate for the EnduraMet® 2205 and 316LN specimens simplifies to:

$$\text{Rate} = 29.0V \qquad (2)$$

While the corrosion rate for the EnduraMet® 33 specimens simplifies to:

$$\text{Rate} = 28.4V \qquad (3)$$

To satisfy ASTM A955, no individual reading may exceed 0.50 μm/yr and the average rate of all specimens may not exceed 0.25 μm/yr. In both cases, the corrosion current must be such as to indicate net corrosion at the anode. Current indicating a "negative" value of corrosion, independent of value, does not indicate corrosion of the anode and is caused by minor differences in oxidation rate between the single anode bar and the two cathode bars.

In addition to the corrosion rate, the corrosion potential is measured at the anode and cathode using a saturated calomel electrode (SCE). Readings are taken daily for the first week and weekly thereafter.

RESULTS

The individual corrosion rates of the EnduraMet® 33 specimens are shown in Figure 2, and the average corrosion rate for all four specimens is shown in Figure 3. Corrosion rates average between 0.05 μm/yr and –0.25 μm/yr, with the maximum corrosion rate of 0.185 μm/yr exhibited by specimen 1 in week 15 of the test. As shown in Figure 3, the average corrosion rate is negative for the majority of the test, varying about a value of about –0.1 µm/yr. "Negative" corrosion is caused by minor differences in oxidation rate between the single anode bar and the two cathode bars. Throughout the duration of the test, no individual specimen exhibits a corrosion rate above 0.50 µm/yr and the average corrosion rate is below 0.25 µm/yr, meeting the requirements of ASTM A955.

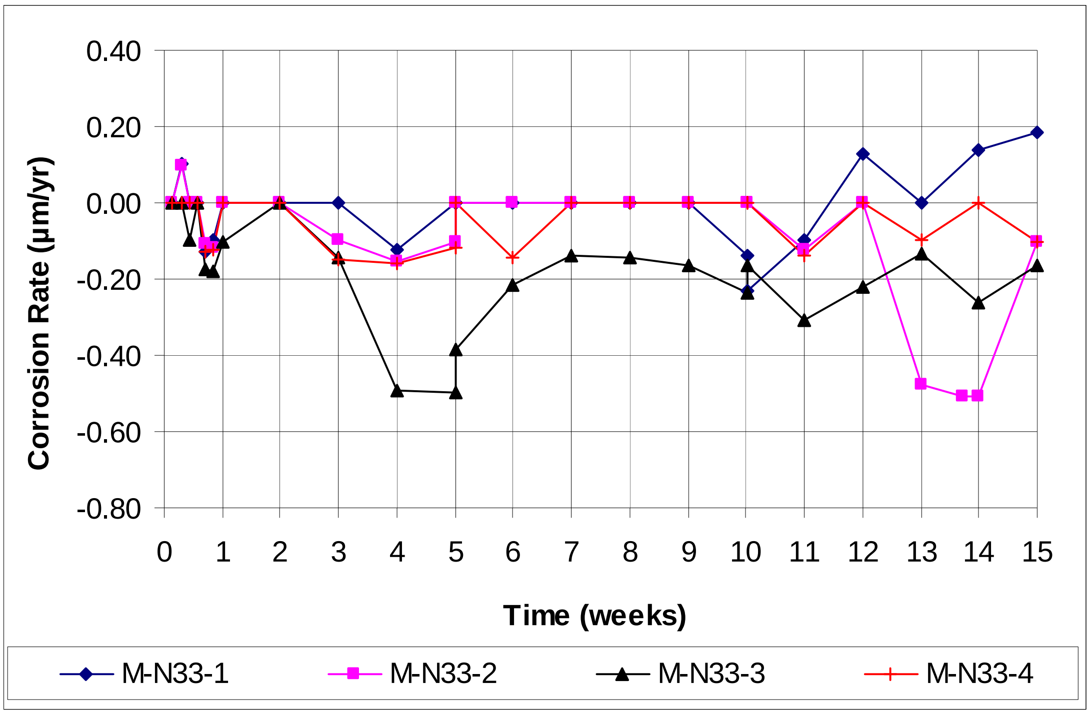

Figure 2: Individual corrosion rate of EnduraMet® 33 stainless steel. Specimens 1-4.

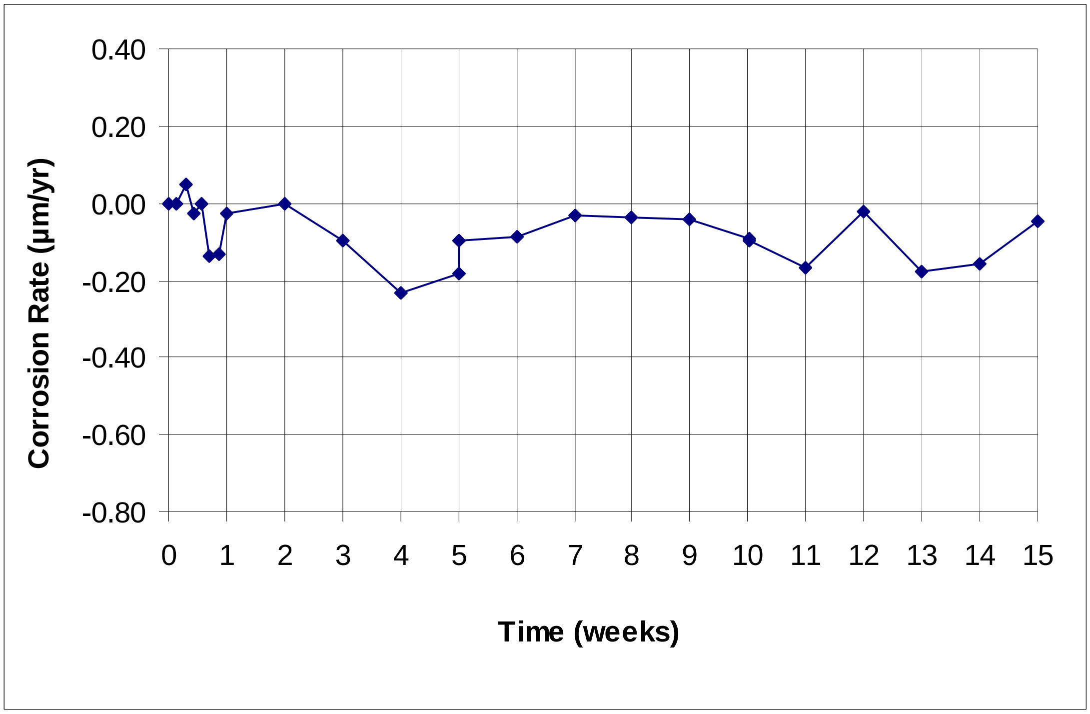

Figure 3: Average corrosion rate of EnduraMet® 33 stainless steel. Specimens 1-4.

Individual and average corrosion rates for the six EnduraMet® 316LN specimens tested are shown in Figures 4 and 5, respectively. The EnduraMet® 316LN specimens show corrosion rates between 0.20 µm/yr and –0.55 µm/yr during the test, with an average corrosion rate of –0.1 µm/yr. Specimen 2 exhibits the maximum individual corrosion rate, 0.203 µm/yr, after the week 10 solution change. Spikes in corrosion rates are typical after a solution change and have been observed in previous tests. Regardless, this maximum rate is below the allowable rate of 0.50 µm/yr. The maximum average corrosion rate is observed several times throughout the first week of testing as 0.02 µm/yr, well below the limit of 0.25 µm/yr. The bars meet the requirements of ASTM A955.

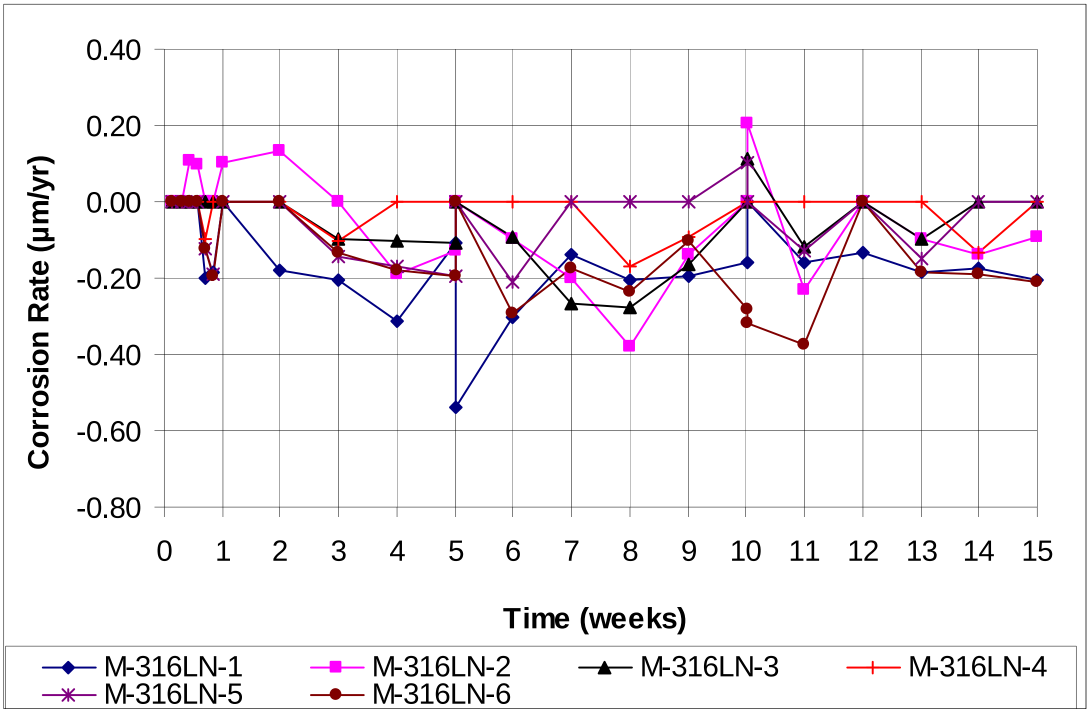

Figure 4: Individual corrosion rate of EnduraMet® 316LN stainless steel. Specimens 1-6.

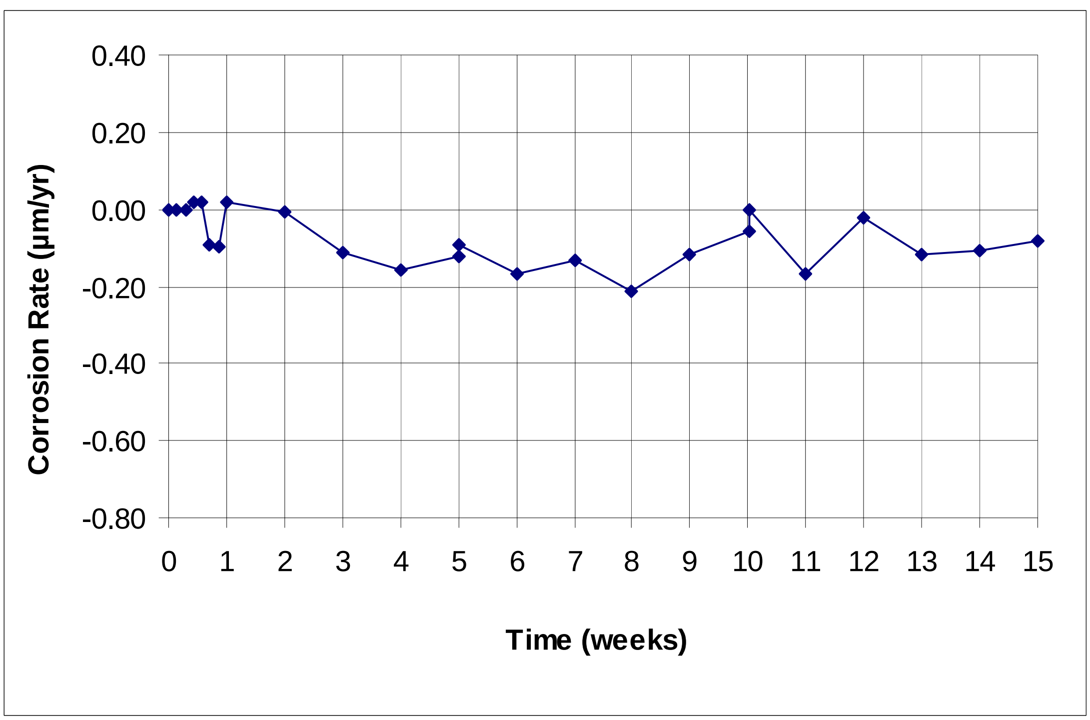

Figure 5: Average corrosion rate of EnduraMet® 316LN stainless steel. Specimens 1-6.

The individual and average corrosion rates of the EnduraMet® 2205 specimens are shown in Figures 6 and 7, respectively. The corrosion rates of the EnduraMet® 2205 specimens exhibit high scatter in during the first 10 weeks of the test, varying from 0.30 µm/yr to –0.60 µm/yr. After week 10, the corrosion rates exhibit less scatter, with most values between –0.20 and –0.40 µm/yr. The average corrosion rate for the six specimens tends to become more negative throughout the test, starting around –0.20 µm/yr and ending at –0.34 µm/yr by the end of the test. The bars meet the requirements of ASTM A955.

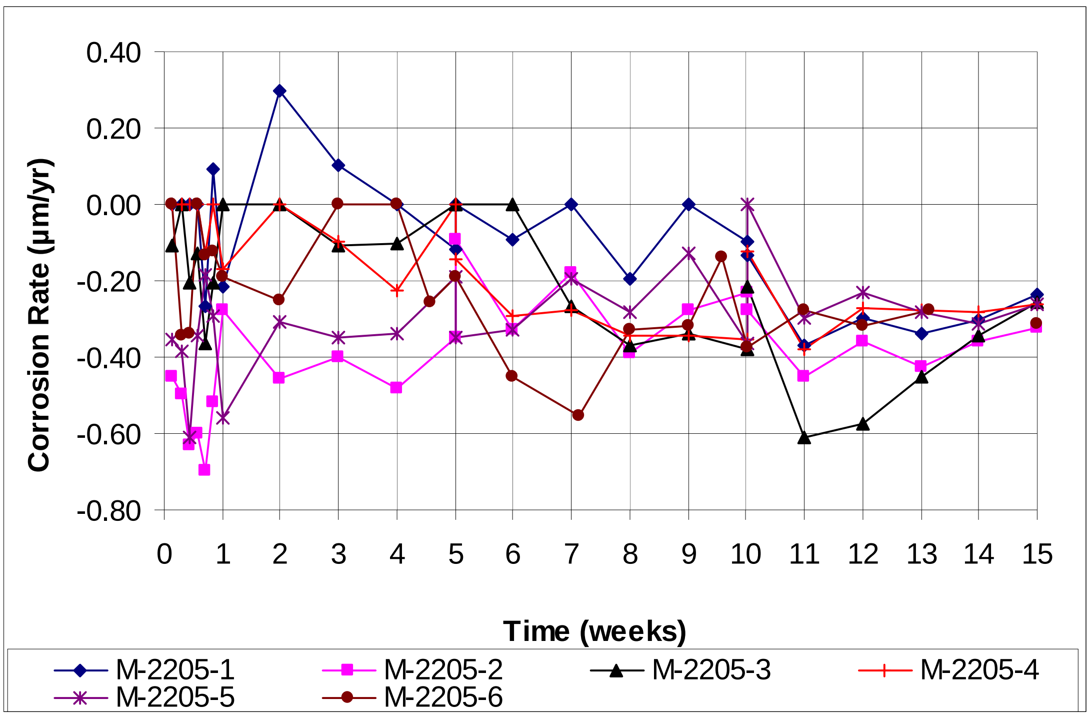

Figure 6: Individual corrosion rate of EnduraMet® 2205 stainless steel. Specimens 1-6.

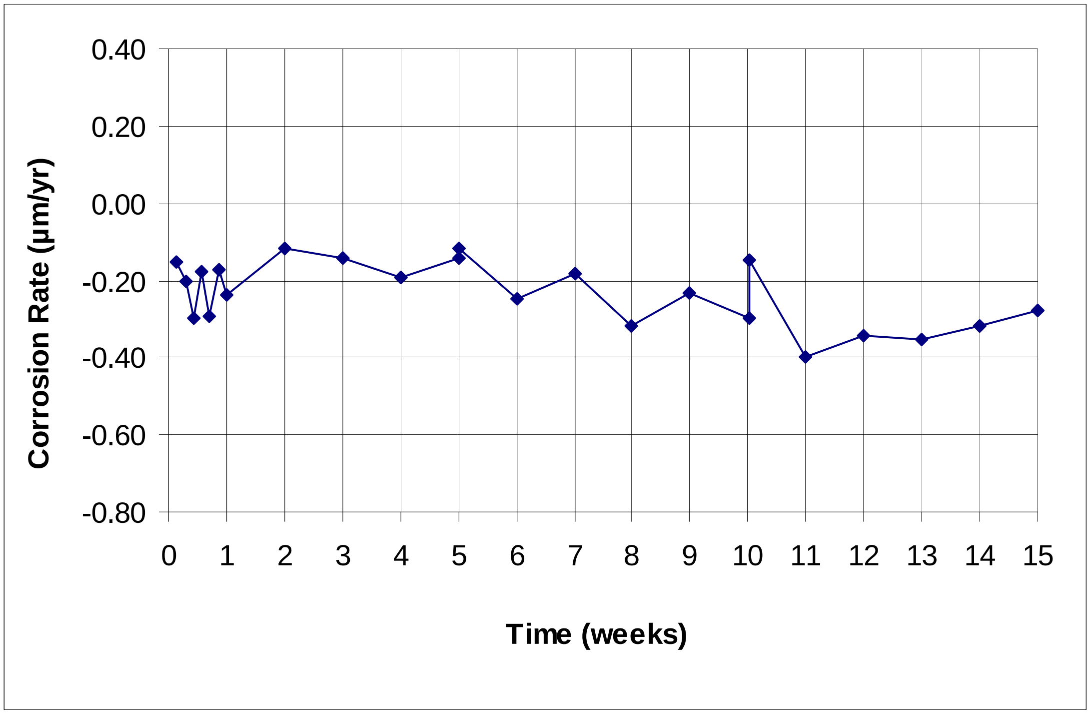

Figure 7: Average corrosion rate of EnduraMet® 2205 stainless steel. Specimens 1-6.

The individual corrosion potentials taken with respect to a saturated calomel electrode (SCE) for the EnduraMet® 33 bars in pore solution with salt (anode) and in pore solution (cathode) are shown in Figures 8 and 9, respectively. As shown in Figure 8, the bars in pore solution plus salt show potentials ranging from −0.150 to −0.275 V verses the SCE. The bars in pore solution have potentials, shown in Figure 9, within the range of −0.100 to −0.300 V. ASTM C876 states that a potential more negative than −0.275 V with respect to an SCE (−0.350 with respect to a copper/copper sulfate electrode) in concrete indicates a 90% probability that corrosion is occurring. Two important differences between this macrocell test and ASTM C876 prevent a direct comparison of this test to ASTM C876: the bars being tested are stainless steel, not a conventional steel alloy, and they are placed in a pore solution, not concrete. Overall, the average potential, shown in Figure 10, is more negative for bars in pore solution than for bars in pore solution plus salt by 0.010 to 0.040 V throughout the test. This further explains the negative corrosion values.

The anode bar of EnduraMet® 33 specimen 1 exhibits a progressively negative potential bar starting in week 8 and continuing for the remainder of the test, reaching a final potential of –0.275 V. This specimen also exhibits a positive corrosion rate in weeks 12, 14, and 15.

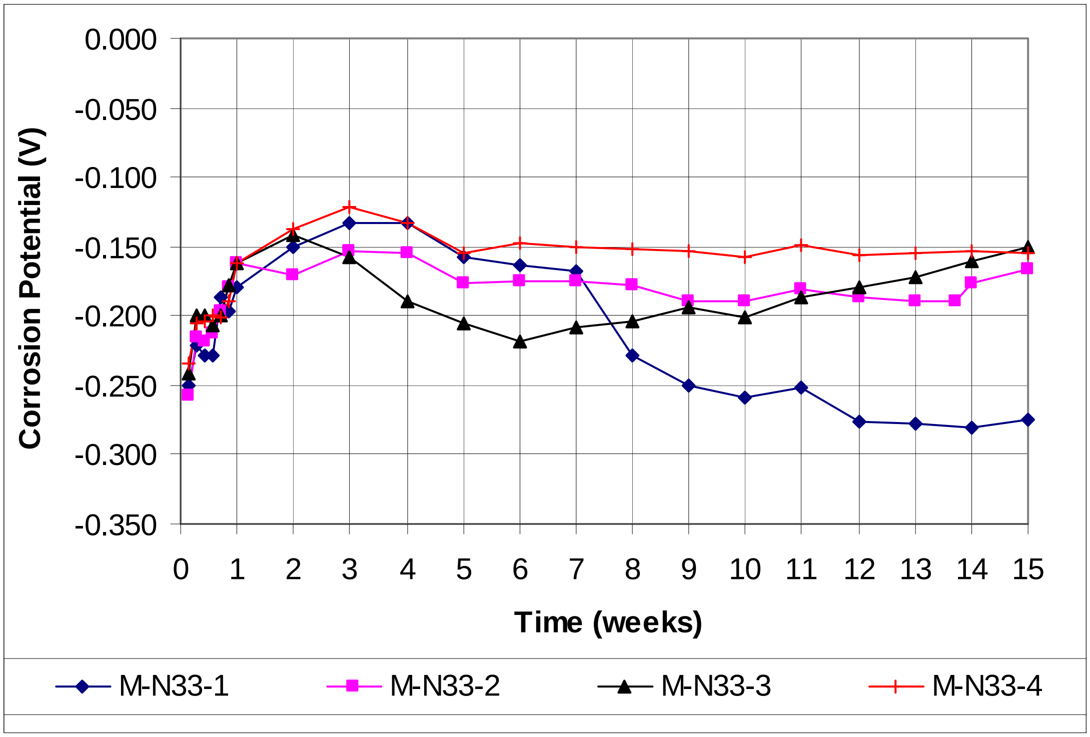

Figure 8: Individual corrosion potential with respect to SCE. EnduraMet® 33 stainless steel bars in salt solution (anode). Specimens 1-4.

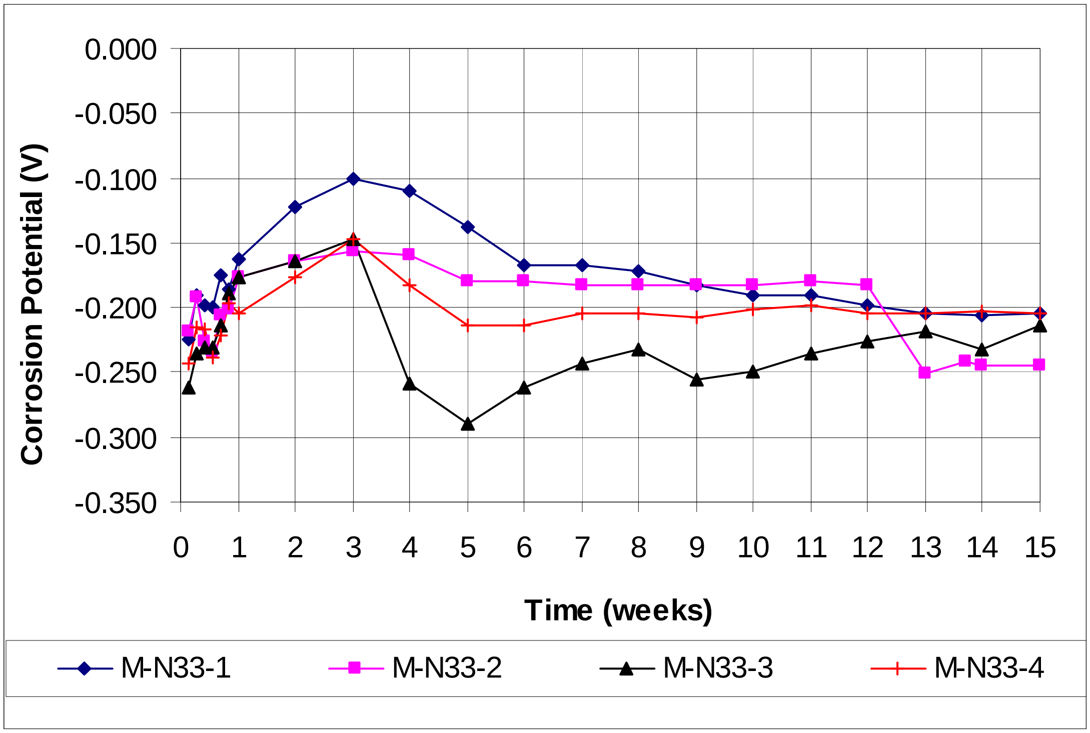

Figure 9: Individual corrosion potential with respect to SCE. EnduraMet® 33 stainless steel bars in pore solution (cathode). Specimens 1-4.

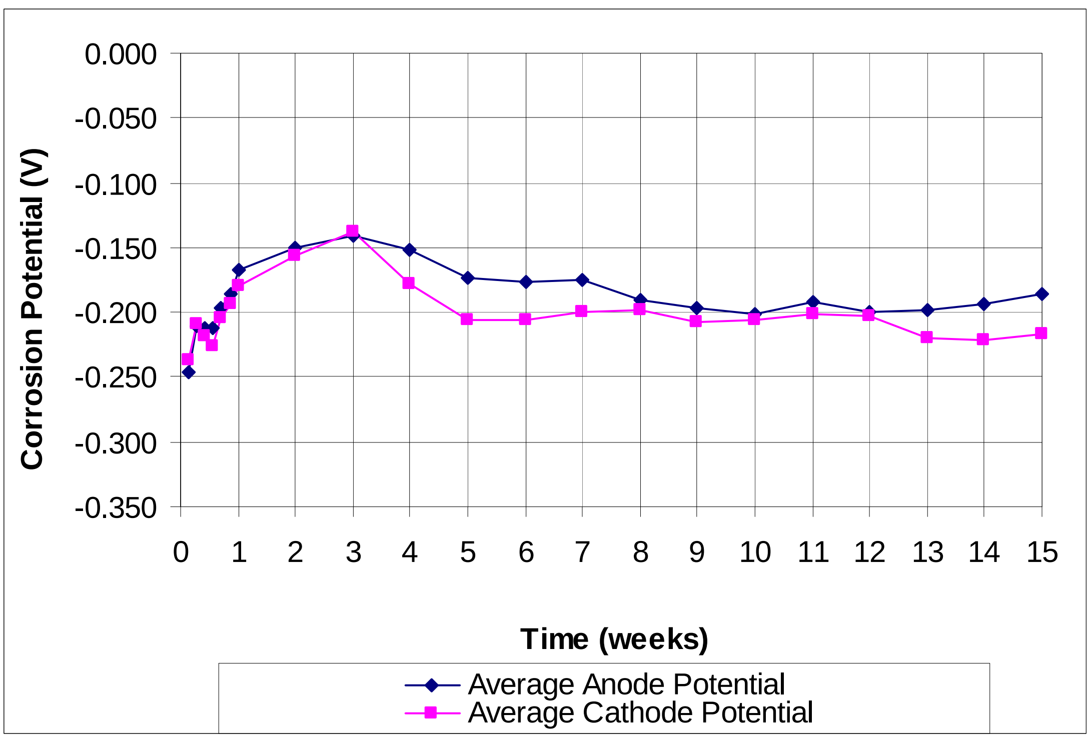

Figure 10: Average corrosion potential with respect to SCE. EnduraMet® 33 stainless steel bars. Specimens 1-4.

The individual corrosion potentials with respect to an SCE for EnduraMet® 316LN are shown in Figures 11 and 12 for the anode and cathode bars, respectively. The anode potentials vary between –0.075 V and –0.175 V. The cathode potentials show some variation, but stabilize after week 6, ranging from –0.075 V to –0.250 V. The average potentials, shown in Figure 13, are –0.025 V to –0.050 V more negative for the cathode bars that than the anode bars for most of the test, accounting for the observed negative corrosion rates.

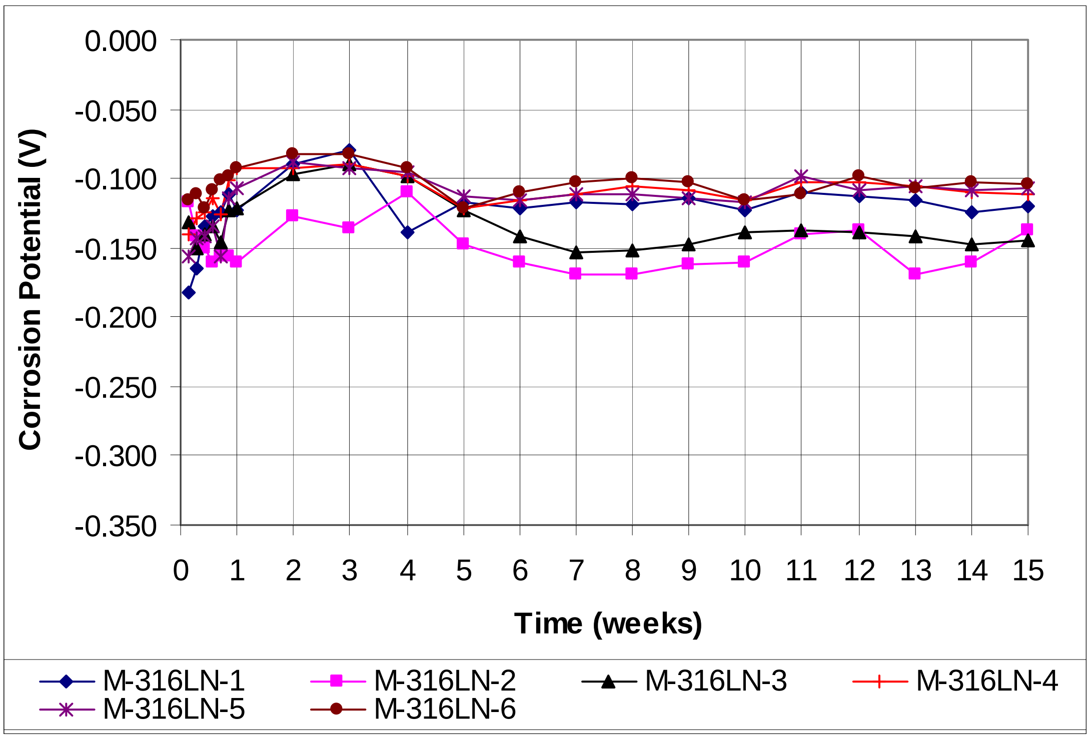

Figure 11: Individual corrosion potential with respect to SCE. EnduraMet® 316LN stainless steel bars in salt solution (anode). Specimens 1-6.

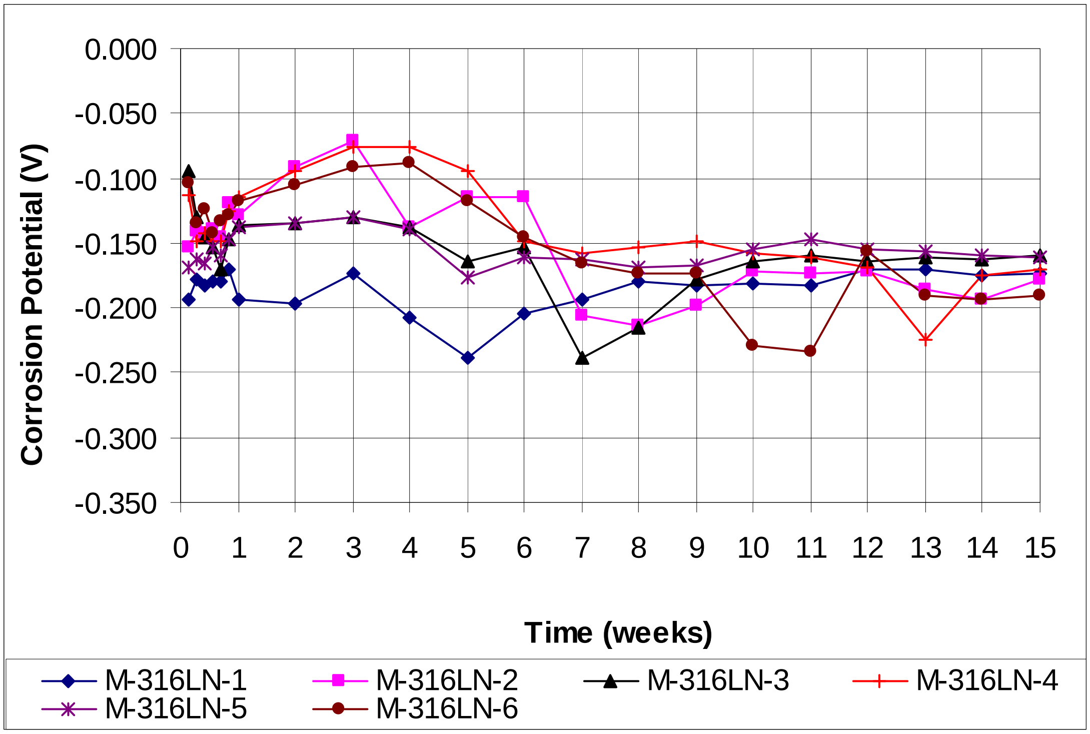

Figure 12: Individual corrosion potential with respect to SCE. EnduraMet® 316LN stainless steel bars in pore solution (cathode). Specimens 1-6.

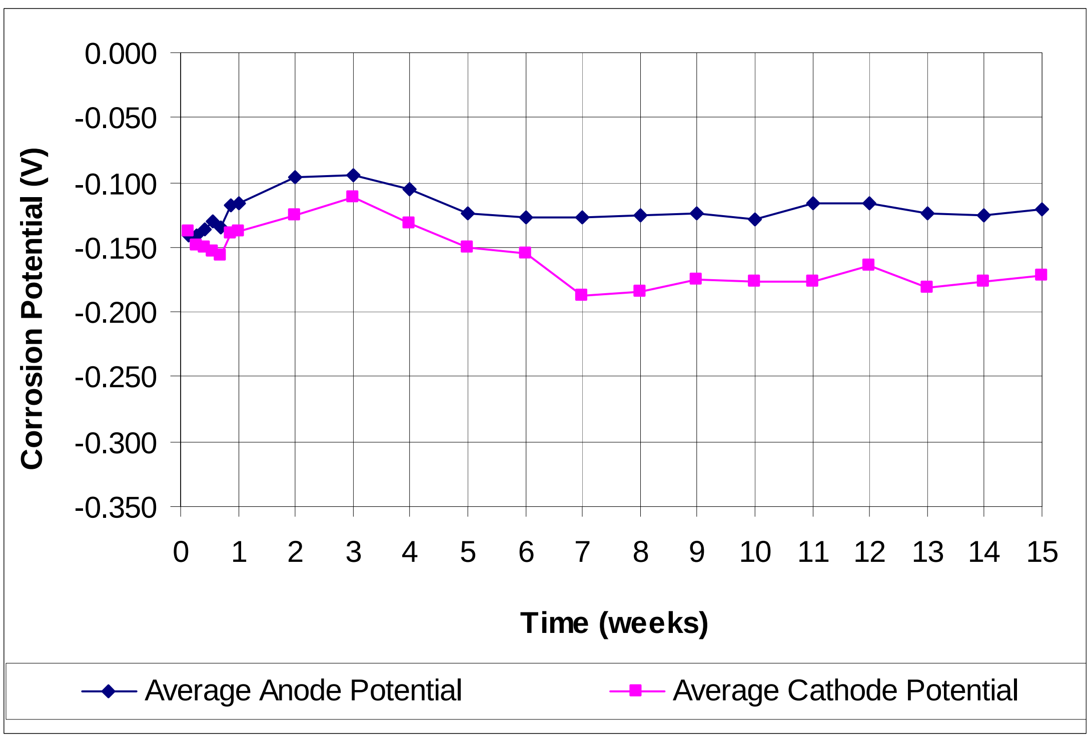

Figure 13: Average corrosion potential with respect to SCE. EnduraMet® 316LN stainless steel bars. Specimens 1-6.

The individual corrosion potentials for the EnduraMet® 2205 specimens are shown in Figures 14 and 15. The anode potentials vary between –0.100 V to –0.150 V while the cathode potentials vary between –0.075 V and –0.200 V. The average potential plots are shown in Figure 16 and exhibit cathode potentials that are about 0.040 V more negative than the anode potentials throughout most of the test.

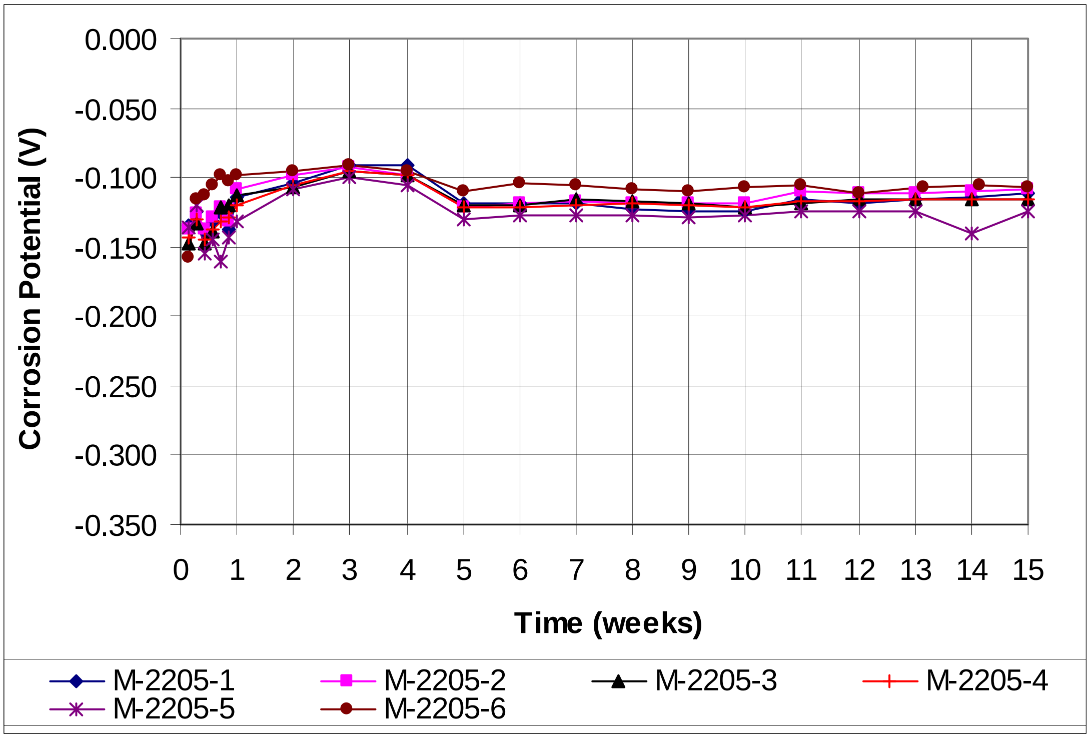

Figure 14: Individual corrosion potential with respect to SCE. EnduraMet® 2205 stainless steel bars in salt solution (anode). Specimens 1-6.

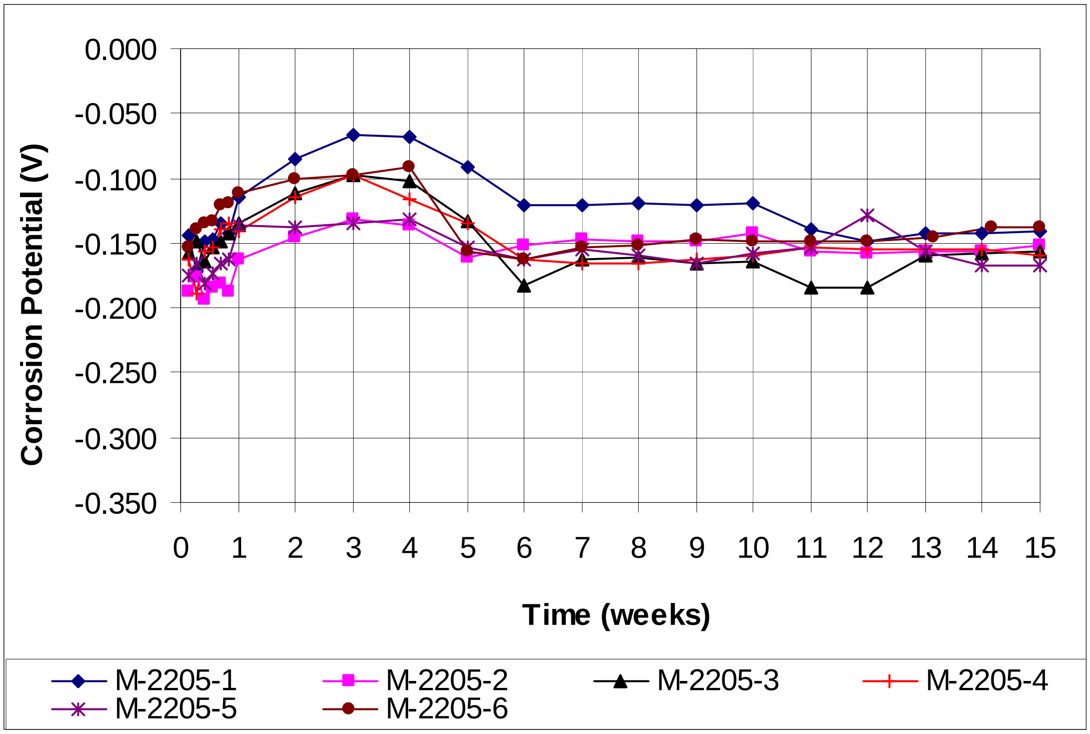

Figure 15: Individual corrosion potential with respect to SCE. EnduraMet® 2205 stainless steel bars in pore solution (cathode). Specimens 1-6.

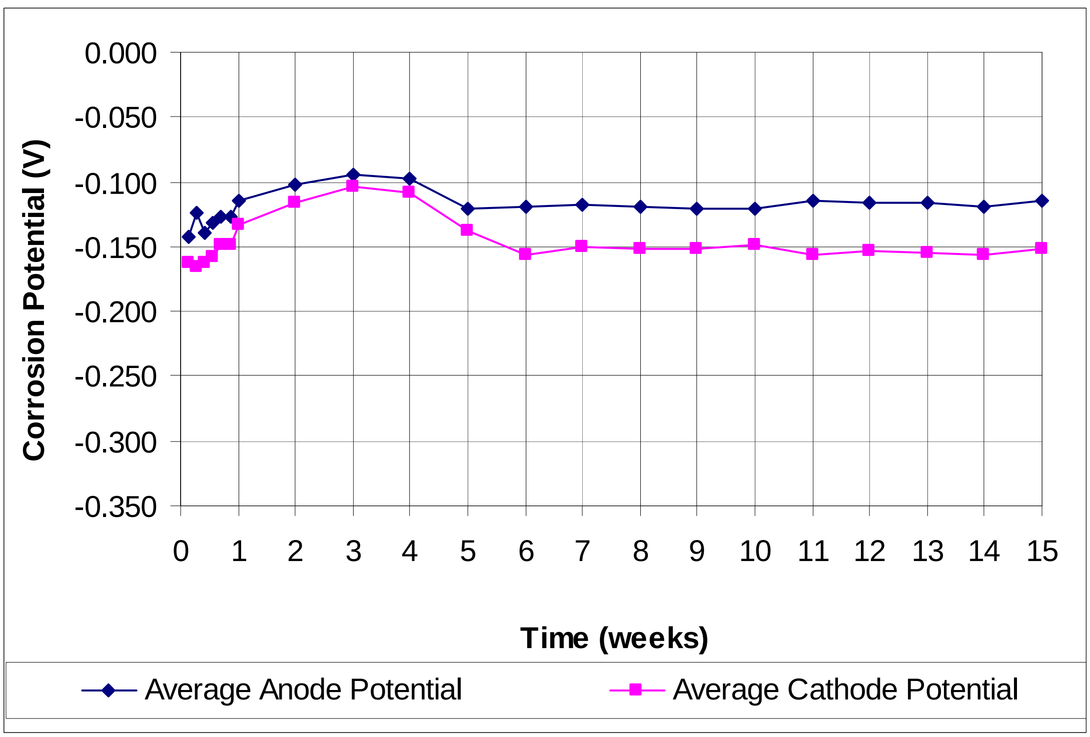

Figure 16: Average corrosion potential with respect to SCE. EnduraMet® 2205 stainless steel bars. Specimens 1-6.

SUMMARY AND CONCLUSIONS

The corrosion resistance of EnduraMet® 33, EnduraMet® 316LN, and EnduraMet® 2205 stainless steel reinforcing bars is evaluated using the rapid macrocell test outlined in Annexes A1 and A2 of ASTM A955-10. The following conclusion is based on the test results presented in this report:

All three types of stainless steel satisfy the requirements specified in Annexes A1 and A2 of ASTM 955-10.

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ASTM A955, 2010, "Standard Specification for Plain and Deformed Stainless-Steel Bars for Concrete Reinforcement (ASTM A955/A955M-10)," ASTM International, West Conshohocken, PA, 11 pp.

ASTM C876, 2009, "Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete (ASTM C876-09)," ASTM International, West Conshohocken, PA, 7 pp.