

# RAPID MACROCELL TESTS OF ENDURAMET<sup>®</sup> 32 STAINLESS STEEL BARS

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A Report on Research Sponsored by  
TALLEY METALS

Structural Engineering and Engineering Materials  
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THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.  
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## **ABSTRACT**

The corrosion resistance of EnduraMet® 32 stainless steel bars was evaluated using the rapid macrocell test outlined in Annexes A1 and A2 of ASTM A955-10. Based on the test results, the EnduraMet® 32 stainless steel bars 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® 32 stainless steel reinforcing bars. Six specimens are tested in accordance with Annexes A1 and A2 of ASTM A955-10.

## EXPERIMENTAL WORK

### Materials

Tests were performed on No. 5 (No. 16) EnduraMet® 32 stainless steel bars. The bars were inspected upon receipt and found to be in good condition.

The EnduraMet® 32 bars underwent pickling prior to shipment. According to the supplier, pickling consists of 30 minutes in hot Cleanox, a product of Henkel Corporation, followed by five minutes in nitric acid. Cleanox is a mixture of hydrofluoric and sulfuric acids with concentrations of 20g/L and 125g/L, respectively. The bars are removed from the acid and rinsed using high-pressure water every 10 minutes while in Cleanox. The temperature is maintained at 130°F for the duration of the process.

The chemical composition of the EnduraMet® 32 stainless steel is given in Table 1.

**Table 1:** Chemical Composition of EnduraMet® 32 Stainless Steel (Provided by Manufacturer)

Material Composition Report (%)												
Material	Cr	Ni	C	Mn	N	P	S	Mo	Si	Cu	Co	B
EnduraMet® 32	17.8	0.74	0.05	12.2	0.29	0.019	0.001	0.18	0.29	0.07	0.03	0.0022

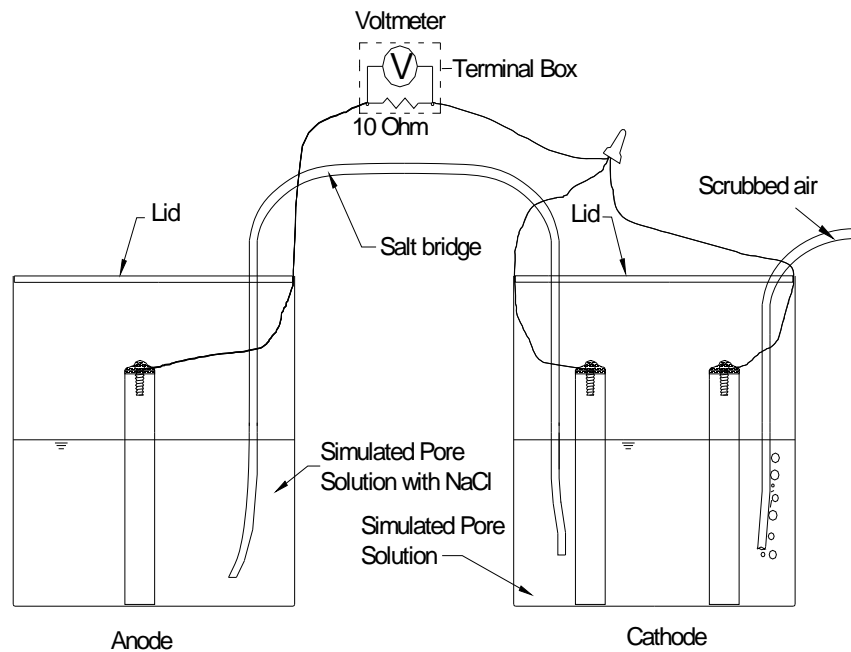
### Experimental Procedures

#### Rapid Macrocell Test

Six 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. Each bar used in the

rapid macrocell is 5 in. long and 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 an 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).



**Figure 1:** Rapid Macrocell Test Setup



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).

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

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

where the Rate is given in  $\mu\text{m}/\text{yr}$ , and

$K$  = conversion factor =  $31.5 \cdot 10^4 \text{ amp} \cdot \mu\text{m} \cdot \text{sec} / \mu\text{A} \cdot \text{cm} \cdot \text{yr}$

$V$  = measured voltage drop across resistor, millivolts

$m$  = atomic weight of the metal (for iron,  $m = 55.8 \text{ g/g-atom}$ )

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

$F$  = Faraday’s constant = 96485 coulombs/equivalent

$D$  = density of the metal,  $\text{g}/\text{cm}^3$  (for iron,  $D = 7.87 \text{ g}/\text{cm}^3$ )

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

$A$  = surface area of anode exposed to solution,  $39.9 \text{ cm}^2$

Using the values listed above, the corrosion rate simplifies to:

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

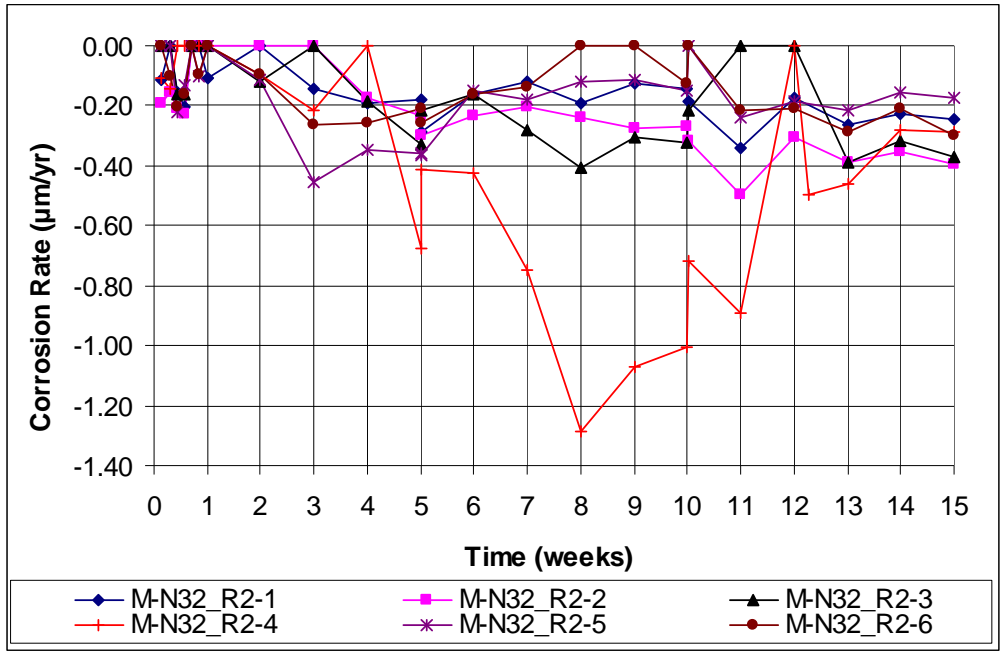
To satisfy ASTM A955, no individual corrosion rate may exceed  $0.50 \mu\text{m}/\text{yr}$  and the average rate of all specimens may not exceed  $0.25 \mu\text{m}/\text{yr}$ . In both cases, the corrosion current must be such as to indicate net corrosion at the anode. Current indicating a “negative” 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.

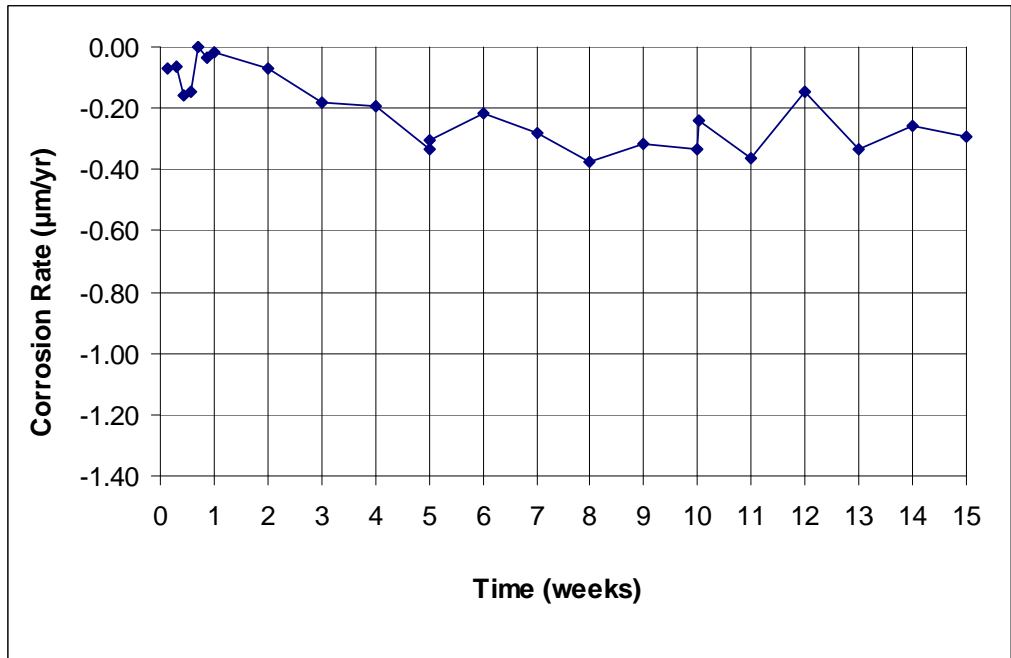
## RESULTS

The individual corrosion rates of the six specimens tested are shown in Figure 2, and the overall average corrosion rate for all six specimens is shown in Figure 3. Throughout the duration of the test, no individual specimen exhibited a positive corrosion rate. The average corrosion rate ranged from 0 to  $-0.400 \mu\text{m}/\text{yr}$  with a maximum negative corrosion rate of  $-1.285 \mu\text{m}/\text{yr}$  for specimen 4 in week 8 of the test. As shown in Figure 3, the average corrosion rate was negative and was close to  $-0.300 \mu\text{m}/\text{yr}$  throughout most of the test. “Negative” corrosion is caused by minor differences in oxidation rate between the single anode bar and the two cathode bars. Thus, no individual specimen or the average exhibits a positive corrosion rate. Therefore, the individual specimens and the average are below the allowable maximums of  $0.50 \mu\text{m}/\text{yr}$  and  $0.25 \mu\text{m}/\text{yr}$ , respectively.

Individual corrosion potential data taken with respect to a saturated calomel electrode (SCE) for the bars in pore solution with salt (anode) and bars in pore solution (cathode) are shown in Figures 4 and 5, respectively. As shown in Figure 4, the bars in pore solution plus salt show potentials ranging from  $-0.100$  to  $-0.200$  V versus the SCE. The bars in pore solution have potentials, shown in Figure 5, 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) indicates a 90% probability that corrosion is occurring. Two



**Figure 2:** Individual corrosion rate of EnduraMet® 32 stainless steel, Specimens 1-6.

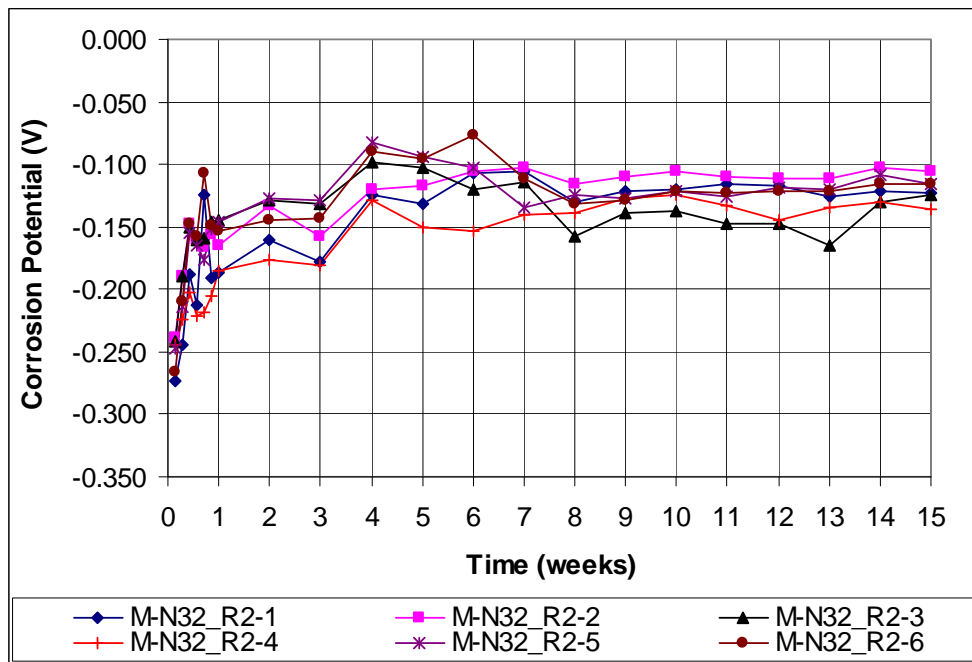


**Figure 3:** Average corrosion rate of EnduraMet® 32 stainless steel, Specimens 1-6.

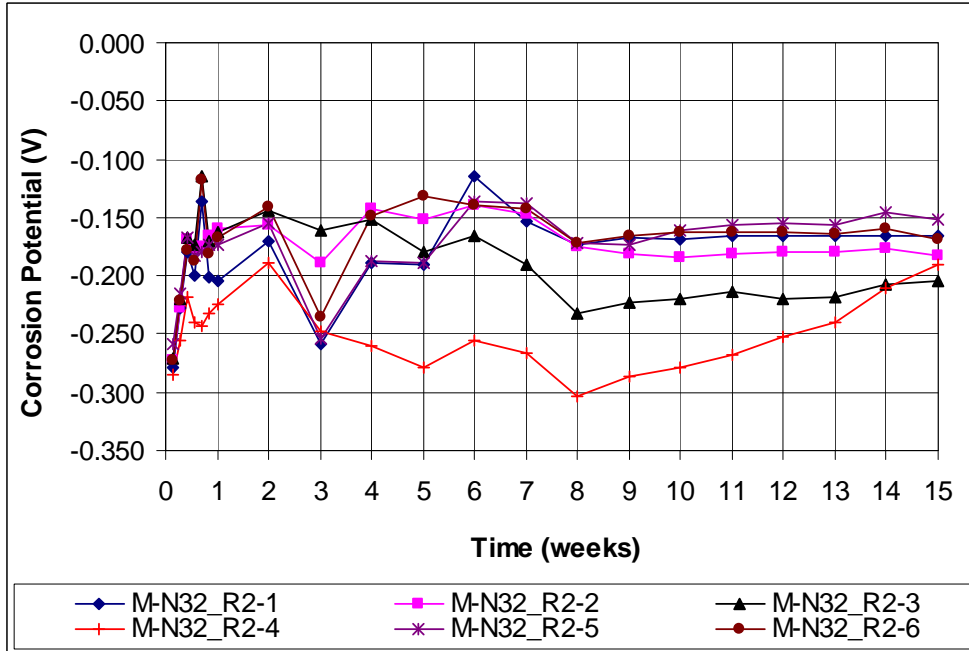
important differences between this macrocell test and ASTM C876 prevent a direct comparison of this test to ASTM C876: the bars being tested are stainless steel, not a conventional steel

alloy, and they are placed in a pore solution, not concrete. Overall, the average potentials, shown in Figure 6, are more negative for bars in pore solution than for bars in pore solution plus salt by 0.050 to 0.075 V throughout the test. This further explains the negative corrosion values.

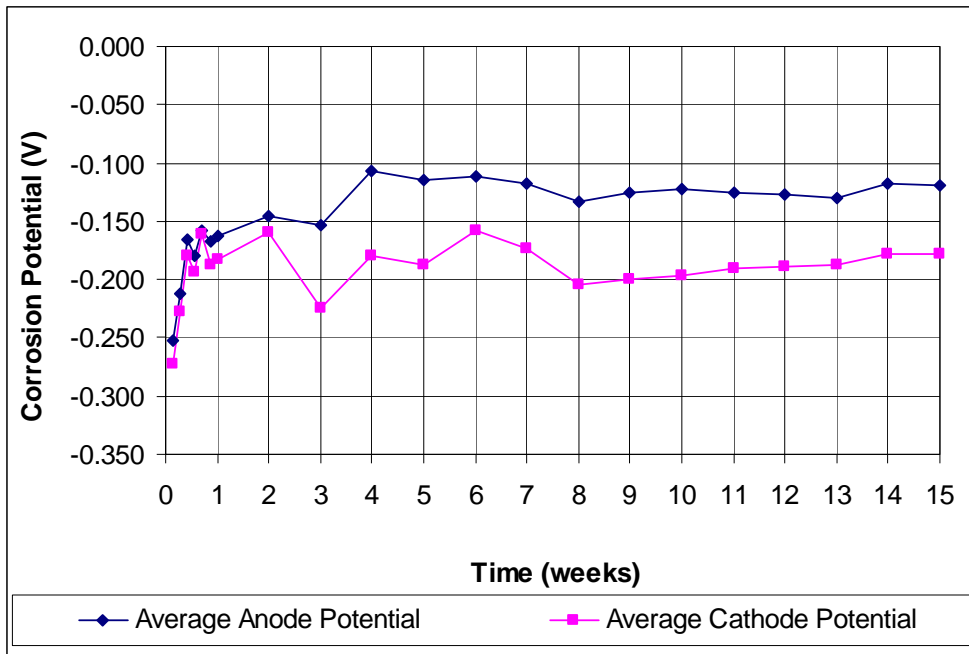
Specimen 4 exhibited the most negative corrosion rate in week 8, which is drastically more negative than the rest of the specimens. As shown in Figures 4 and 5, its anode potential falls in line with the other specimens. However, the cathode potential of specimen 4 is much more negative than the remaining specimens and peaks at about week 8 as well. The cathode potential at the peak is nearly 0.150 V more negative than the anode and would explain the large negative corrosion rate.



**Figure 4:** Individual corrosion potential with respect to SCE. EnduraMet® 32 stainless steel bars in salt solution (anode), specimens 1-6.



**Figure 5:** Individual corrosion potential with respect to SCE. EnduraMet® 32 stainless steel bars in pore solution (cathode), specimens 1-6.



**Figure 6:** Average corrosion potential with respect to SCE. EnduraMet® 32 stainless steel bars, specimens 1-6.

Once the specimens reached week 15, the test was terminated, and the specimens were removed from solution, rinsed with tap water, examined for corrosion, and photographed. All six specimens looked relatively clean along the length of the bar upon removal from solution.

### **SUMMARY AND CONCLUSIONS**

The corrosion resistance of EnduraMet® 32 stainless steel bars was tested in accordance with Annexes A1 and A2 of ASTM 955-10. The following conclusion is based on the test results presented in this report:

The EnduraMet® 32 stainless steel bars tested in this study satisfy the requirements specified in Annexes A1 and A2 of ASTM 955-10.

## **REFERENCES**

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.





