**INTERIM REPORT**

# INVESTIGATION OF THE RESISTANCE OF SEVERAL NEW METALLIC REINFORCING BARS TO CHLORIDE-INDUCED CORROSION IN CONCRETE

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**ABSTRACT**

The Virginia Department of Transportation recently initiated a search for metallic reinforcing bars that are not only more durable and corrosion resistant than the epoxy-coated bars currently used, but also economical. In the last few years, several new bars have shown promise; one is still in the developmental stage. These bars are (1) stainless steel-clad carbon steel bars, (2) bars made of an MMFX-2 “microcomposite” steel, (3) bars made of a new “lean” duplex stainless steel called 2101 LDX, and (4) a carbon steel bar coated with a 2-mil layer of arc-sprayed zinc and then epoxy. These bars were embedded in concrete blocks, which were then subjected to severe weekly cycles of ponding with a saturated salt solution and drying. For comparison, two solid stainless steel (304 and 316LN) bars and a carbon steel bar (ASTM A 615) were also included. The times-to-corrosion of these bars were estimated through almost weekly monitoring of the macrocell current, open-circuit potential, and polarization resistance of for up to 3 years. From a chloride concentration-vs.-time profile established for the test blocks, the amount of chloride ions each bar was able to tolerate was estimated and compared. Based on such information, an analysis of the long-term costs associated with the use of these bars in a bridge deck in Virginia was also conducted.

This interim report was prepared to provide bridge engineers with this timely information. The information should be valuable in making a rational selection of the most cost-effective metallic reinforcing bars that will satisfy the specified design life for concrete bridge components that will be exposed to different degrees of salting.

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## INTRODUCTION

As reflected in a 2000 news released by the Federal Highway Administration in their website that highway construction costs had increased by an average of 12 percent in the preceding 13 years, it is clear that the costs of maintaining the existing highway system and replacing structures that have become deficient are spiraling beyond control. With much of the national highway system already in poor condition and many structures and roadways deteriorating faster than they can be replaced, Congress concluded that there would be insufficient funds to repair or replace all deficient facilities. Many states are encountering increasing grassroots resistance to tax increases, even when they are earmarked specifically for highway improvements. Expecting to face this prospect for decades to come, many state transportation agencies have prudently raised the design life of many new highways and bridges, including minor and major bridges, to at least 75 years and 100 years, respectively, without major repairs (per AASHTO Load and Resistance Factor Design Specifications). However, to allow for sustainable economic development, some experts have advocated an even higher goal—a minimum service life of not less than 150 years for major bridges in urban environments.

Since corrosion of reinforcing bars has been a major cause of premature deterioration of many concrete bridge components, many transportation agencies have adopted a multiple-measure approach to achieving the higher design-life goals. The measures adopted in Virginia include the use of low-permeability concrete and the provision of a relatively thick concrete cover of 70 mm (2.75 in) over the top-mat of reinforcing bars in new concrete bridge decks, in addition to the use of epoxy-coated reinforcing bars (ECR). It is uncertain what the average life of the bridges built with these combined measures will eventually be, especially with reports of increased cracking in newly constructed concrete bridges in recent years and an increased awareness of the susceptibility of the epoxy coating on ECR to damage arising from improper construction practices. If the coating withstands the abuses typically encountered during construction and the concrete remains free of damaging cracks, it is possible for bridges to have a service life of 50 to 75 years, but not likely 100 years. For this longer life, either significant improvements to the current ECR or development of a new bar that is not only more durable and corrosion resistant but also reasonably affordable must occur.

In response to this need, Virginia initiated a research program in 1999 to evaluate the relative effectiveness of the then-introduced stainless steel-clad bars, which hold promise as a durable, corrosion-resistant bar with an associated cost of only a fraction of that of solid stainless steel bars. In this evaluation, the chloride corrosion threshold of the clad bars was compared with those of conventional carbon steel bars and selected solid stainless steel bars in concrete blocks exposed to salt and in solutions of various chloride contents and pHs.[1, 2]

Shortly after the introduction of clad bars, three new metallic bars were introduced in 2001: (1) bars made of an MMFX-2 "microcomposite" steel; (2) bars made of a new "lean" duplex stainless steel called 2101 LDX; and (3) a carbon steel bar coated with a 2-mil layer of arc-sprayed zinc (Zn) and then epoxy, hereinafter designated Zn/EC bars. The MMFX-2 alloy contains 9 to 10 percent chromium. The 2101 LDX is a new stainless steel with nominal chromium and nickel contents of 21 and 1.5 percent, respectively. With the Zn/EC bars, the Zn layer is intended to provide galvanic protection to the underlying steel where the epoxy coating is damaged during construction.

Prompted by the prospect that at least some of these bars might significantly increase the service life of concrete bridges in a cost-effective manner, another project was initiated to evaluate and examine these bars. This report discusses the observations of the test concrete blocks reinforced with these new bars and additional clad bars. The latest observations of the earlier series of concrete blocks reinforced with the clad bars and other bars used for comparison are also presented.

## EXPERIMENTAL PROCEDURE

### Reinforcing Bars Tested

Both straight and U-bent forms of these new bars were used in this second series of test concrete blocks. For comparison, concrete blocks with carbon (black) steel bars were also constructed. Only bent bars were used in the top of these blocks, and only straight bars were used in the bottom (see Figure 1). Unlike the solid 304 and the 316LN stainless steel bars and all the clad bars used in the first series of concrete blocks, the MMFX-2 and the 2101 LDX bars were not pickled. With the exception of the MMFX-2 and the clad bars, which had nominal diameters of 13 and 19 mm, respectively, the bars had a nominal diameter of 16 mm.

As indicated in the earlier report, the thickness of the cladding on the clad bars was 1.08 mm, with a standard deviation of 0.23 mm.[1] The minimum and maximum thicknesses were 0.44 and 1.43 mm, respectively. To investigate the possible adverse effects of defects in the cladding, two 3-mm-wide holes were intentionally drilled through the cladding in several bars tested in the first series of concrete blocks. After approximately 700 days of weekly ponding with a saturated salt solution followed by 4 days of drying, no corrosion activity was observed on the bars—indicating that the size of cladding defects can be a factor in time-to-corrosion. Therefore, for the second series of concrete blocks, a cut 25 mm long by 2 mm wide was made through the cladding of several bars to simulate larger cladding defects, with the hope of diminishing their corrosion resistance.

To investigate how the Zn/EC bars might behave if the composite coating system was damaged, a 25-mm cut was introduced through the Zn and the epoxy coatings to expose the

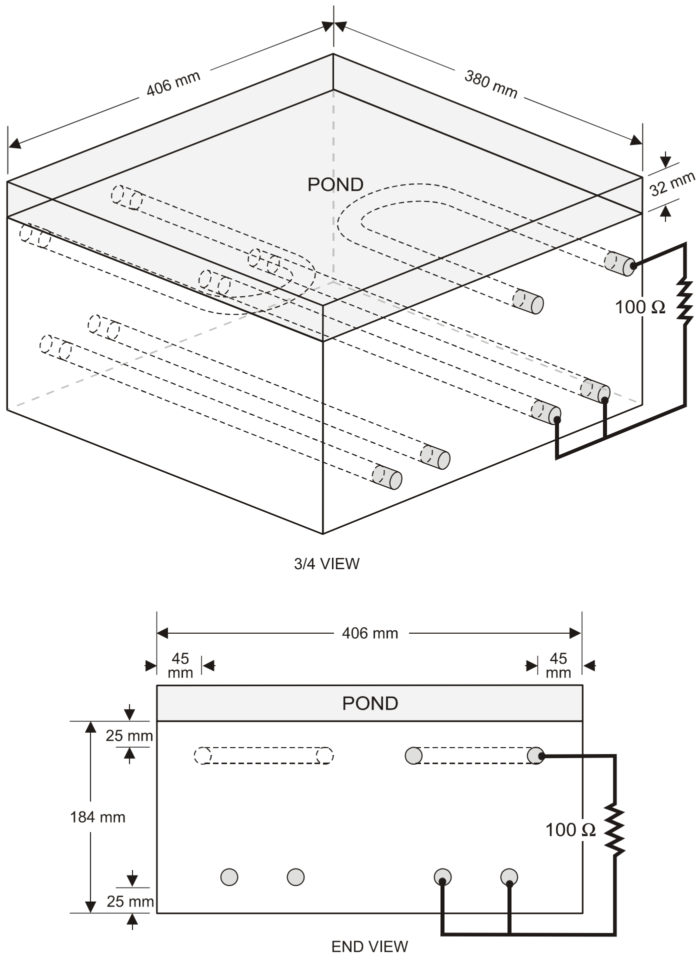


**Figure 1. Test Concrete Blocks**

carbon steel on some of the bars, which were designated Zn/EC-1. The widths of the cuts were estimated to be 0.025 to 0.076 mm (1 to 3 mil). On another group of Zn-EC bars, designated Zn/EC-2, the 25-mm cut was introduced on the epoxy coating only. On a third group, designated Zn/EC-3, the composite Zn and epoxy coating system was left undamaged. It must be emphasized, though, that the cuts were likely not representative of the types of coating damage to which such bars may be subjected at construction sites, which are mostly caused by abrasion with hard objects such as other bars and concrete vibrators.

## Construction of Concrete Blocks and Their Accelerated Exposure to Salt

Figure 1 shows the design of this series of test concrete blocks (Table 1), each with a dam on its top surface to allow for salt to be introduced into the block from the top, as is the case in concrete bridge decks exposed to deicing salts. With the exception of having twice as many bars, this block design is practically the same as that specified in ASTM G 109 for determining the effects of chemical admixtures on the corrosion of bars in concrete exposed to chloride. The concrete mix proportion used was identical with the one used in the earlier series (Table 2).

**Table 1. Series 2 Test Concrete Blocks**

| Bar | Bar Combination | | Number of Blocks | Block Designation |
|---|---|---|---|---|
| | Top Bars | Bottom Bars | | |
| 2101 LDX | U-Bent 2101 LDX | Straight 2101 LDX | 4 | 2101 |
| MMFX-2 | U-Bent MMFX-2 | Straight MMFX-2 | 4 | MMFX |
| Zn/EC | U-Bent Zn/EC (1) | Straight Zn/EC (3) | 4 | Zn/EC-1 |
| | U-Bent Zn/EC (2) | Straight Zn/EC (3) | 4 | Zn/EC-2 |
| | U-Bent Zn/EC (3) | Straight Zn-EC (3) | 4 | Zn/EC-3 |
| SS Clad Bar | U-Bent Clad Bar (w/cut) | Straight Clad Bar | 4 | Clad (w/cut) |
| Carbon Steel | U-Bent Carbon Steel | Straight Carbon Steel | 4 | CS |

**Table 2. Concrete Mixture Used for Test Blocks**

| | |
|---|---|
| Water-cement ratio (w/c) | 0.50 |
| Cement (kg/m$^3$) | 390 |
| Coarse aggregates (kg/m$^3$) | 1,059 |
| Fine aggregates (kg/m$^3$) | 828 |

Several days after their fabrication, the form was removed from each block before a wooden dam was built on its top surface. All the blocks were then covered with sheets of heavy plastic and allowed to cure outdoors for approximately 4 weeks before the sides were coated with a rapid-setting epoxy mix. Following this, the blocks were subjected to weekly cycles of ponding with a saturated solution of NaCl for 3 days and drying for 4 days.

So that results from the first and the second series of blocks could be compared, any possible differences in their outdoor exposure conditions—in particular the seasons—were minimized by starting the exposure of the second series of blocks to the salt solution on September 17, 2001, since the exposure of the first series started on September 8, 2000.

## Measurements on the Test Concrete Blocks

To determine the initiation of corrosion on the different bars, the macrocell current flowing between each top bar and its two corresponding bottom bars in each concrete block was measured weekly. This measurement was made using the voltage-drop method, whereby a 100-ohm resistor was connected between each top bar and the two bottom bars (as shown in Figure 1). The positive terminal of a high-impedance multimeter was connected to the end of the resistor that was connected to the top bar, and the negative terminal was connected to the resistor's end connected to the bottom bars. Finally, the macrocell currents for the same set of concrete blocks were averaged to yield the mean macrocell current.

The open-circuit potential of each of the top bars in each block was also measured in the same frequency, using a $Cu/CuSO_4$ (CSE) reference electrode and after disconnecting the corresponding bottom bars. Likewise, the polarization resistance of each of the top bars was also measured with a Cortest Instrument PR Monitor. The probe of this instrument uses a guard ring to confine and allow for better definition of the bar area being polarized during each measurement. As with macrocell currents, the measured open-circuit potentials and polarization resistances of all individual top bars in the same set of test concrete blocks in that week were averaged. It must be noted that the polarization-resistance data are not presented in this interim report, since calculation of this parameter involved assumption of the actual size of the bar area being polarized during the measurement and it is uncertain with the bars with the intentionally introduced defects that the actual area being polarized is that of the defects. So, this type of data will be presented later after autopsy of many of these blocks at appropriate times.

To allow for estimation of the amount of chloride ions that penetrated the blocks after various salt exposure cycles, the concentrations of the total, or acid-soluble, chloride in 16 concrete blocks at depths ranging from 13 to 51 mm (0.50 to 2.00 in), in 13-mm (0.50-in) intervals, and exposure times ranging from 114 to 661 days were determined in accordance with ASTM C 1152.

## RESULTS AND DISCUSSION

### Electrochemical Characteristics

#### Macrocell Currents

As a concrete bridge deck is exposed to deicing salts, because of the direction from which chloride ions enter the concrete and the nature of the ion transport process in the concrete, the top bars are exposed to more chloride ions than are the bottom bars. This slowly leads to a potential difference between these bars whereby the top bars become anodic and the bottom bars cathodic. Once the concentration of chloride ions surrounding the top bars reaches the corrosion threshold of the particular material of which these bars are made, the potential difference becomes sufficient to serve as the driving force of a flow of (macrocell) galvanic current between the bars, which eventually results into the all-too-familiar corrosion of the top bars and the resulting delamination of the surrounding concrete. It is believed by many that macro-corrosion cells have a greater role in the corrosion of reinforcing bars in concrete bridge components, especially in bridge decks, than do micro-corrosion cells found along individual bars. Perhaps this accounts for, as indicated in the earlier report, the macrocell current being a definitive indicator of the beginning of corrosion on a bar—much better than polarization resistance.[1]

This point is demonstrated in Figure 2, which shows the weekly macrocell currents—in terms of mean, minimum, and maximum values—of the concrete blocks with the carbon steel bars as measured during the first 735 days (approximately 105 weekly cycles of ponding and drying) of salt exposure. From approximately 0 to 92 days, the macrocell currents for these blocks were 0.1 μA, which is insignificant, since the accuracy of this measurement was estimated to be ± 0.1 μA. Then on day 92 ± 5 days, the macrocell current increased to 0.4 μA, and as illustrated in Figure 2, then rose rapidly to the hundreds—reaching as high as 534.9 μA on day 665. The trend of the weekly macrocell currents clearly indicates that the carbon steel bars became depassivated, or began corroding, at 92 days, perhaps even slightly earlier. This is in agreement with the 90-95 days observed for the carbon steel bars in the previous series of

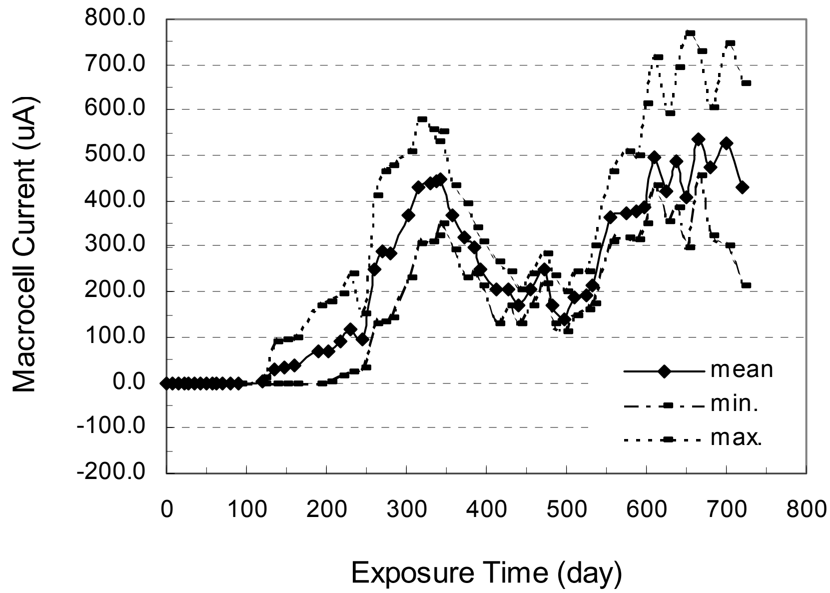


**Figure 2. Weekly Macrocell Currents of Concrete Blocks with Black Steel Bars During First 735 Days of Weekly Salt Exposure**

concrete blocks made with the identical concrete mix proportions and subjected to the same severe weekly salt exposure cycles.[1]

As observed in the series 1 concrete blocks, Figure 2 clearly illustrates that the extent of corrosion activity on the black steel bars (and other bars, as illustrated in the following two figures) is greatly affected by weather or the season, in particular the combination of temperature and amount of rainfall. This is clearly illustrated by the correlation of the peaks in macrocell current in Figure 2 and the times of year corresponding to the various exposure times, with the first peak at approximately 310 days, corresponding to July 29, 2002; the lows (valleys) at around 460 days to December 17, 2002; and the peaks at around 660 days to June 30, 2003.

Figures 3 and 4 show the weekly macrocell currents of the concrete blocks with the 2101 LDX and the MMFX-2 bars, respectively. Figure 3 shows that the 2101 LDX bars were passive for the first 147 days of weekly salt exposure, after which time the macrocell current began to increase steadily, indicating that these bars had become depassivated just as the black steel bars had earlier. As shown in Figure 4, the MMFX-2 bars became depassivated after approximately 245 days. Note also that the general correlation of macrocell current with seasons or times of the year is also reflected in the data for the 2101 LDX and MMFX-2 bars as in the data for the black steel bars—indicating that, as could be expected, this general relationship (between corrosion activity or rate and moisture and temperature) holds, regardless of the type of bars.

Compared to these bars, the experimental coated bars, as a group, were relatively stable during the first 735 days of weekly salt exposure. The weekly macrocell currents of the Zn/EC-3 bars, which had no damage in either the Zn or the epoxy coating, ranged from only –0.2 to

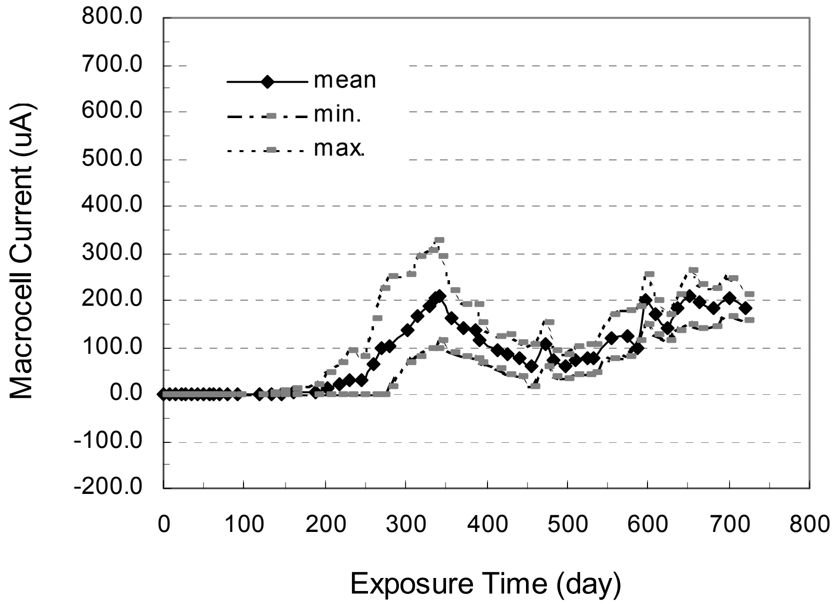


**Figure 3. Weekly Macrocell Currents of Concrete Blocks with 2101 LDX Bars**

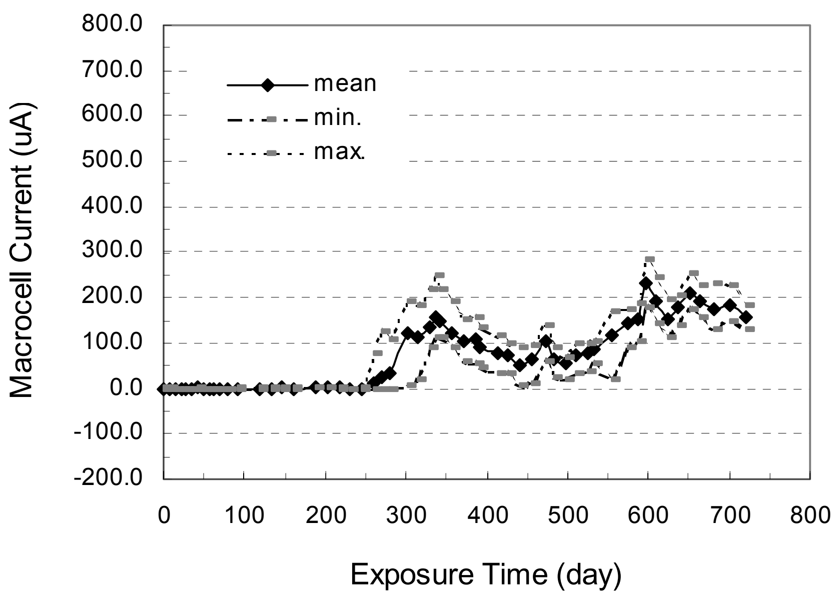


**Figure 4. Weekly Macrocell Currents of Concrete Blocks with MMFX-2 Bars**

+0.3 μA., with a mean of 0.0 μA (Figure 5). Likewise, the macrocell currents of the Zn/EC-2 bars, which had a 25-mm cut through only the epoxy coating, were similarly very low or very stable—at least for the first 637 days of severe weekly salt exposure, after which their measured macrocell currents may be signaling the beginning of activity on these bars. Even then, the maximum current between 650 to 735 days on these bars was only 0.7 μA (Figure 6). However, when the cut was through both the Zn and epoxy coatings, as in the Zn/EC-1 bars, the macrocell current began to indicate activity on the bars earlier, at approximately 532 days (Figure 7). These results are encouraging, when it is taken into consideration that (1) it is likely that all the

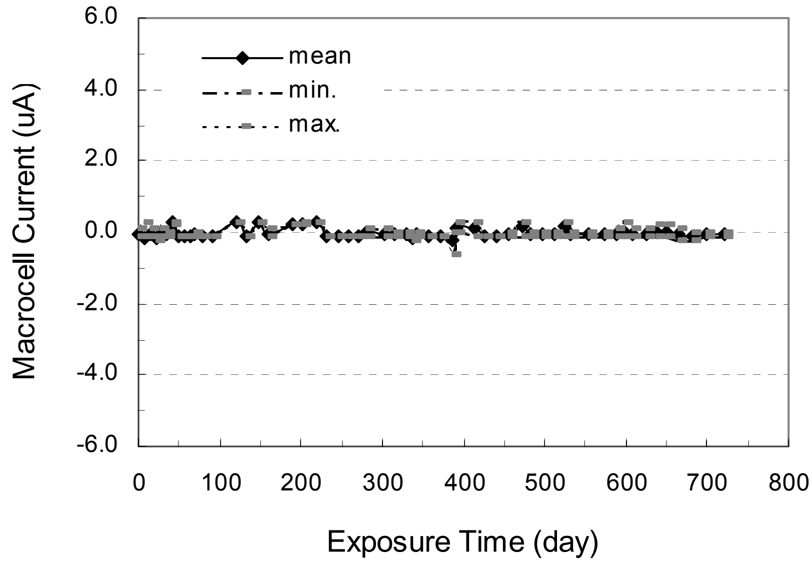


**Figure 5. Weekly Macrocell Currents of Concrete Blocks with Zn/EC-3 Bars with No Damage to Either Coating**

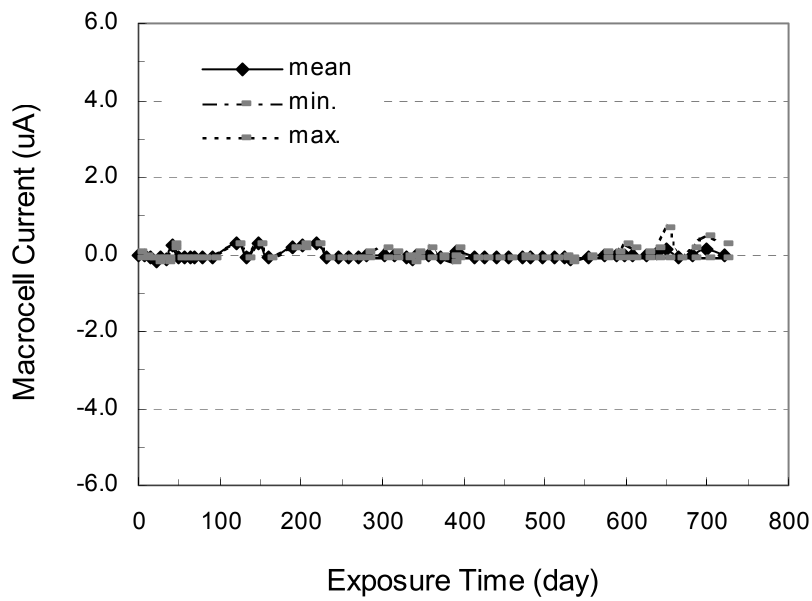


**Figure 6. Weekly Macrocell Currents of Concrete Blocks with Zn/EC-2 Bars with 25-mm Cut Through Epoxy-Coating Only**

Zn/EC bars may not have a chance to dry out between consecutive weekly cycles of 3-day ponding and 4-day drying, and (2) that with many ECR used in concrete members surrounded by seawater, where the concrete is always wet, there is generally a reduction in the adhesion of the coating to the underlying steel and its effectiveness to protect the steel.

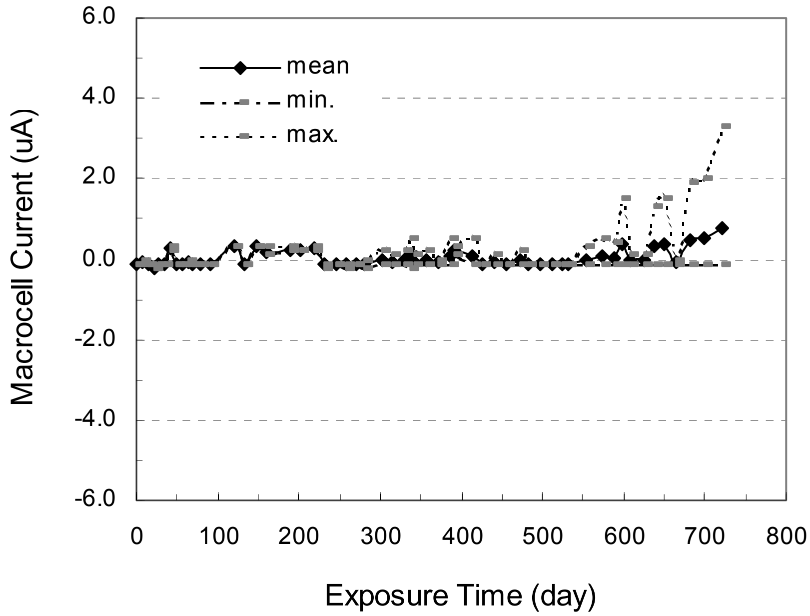


**Figure 7. Weekly Macrocell Currents of Concrete Blocks with Zn/EC-1 Bars with 25-mm Cut Through Zn and Epoxy Coatings**

Examination of the weekly macrocell currents of the series 1 concrete blocks with the stainless steel 316LN and 304 bars and the 316L clad bars (Figures 8, 9, and 10, respectively) revealed that even after 1,082 days of the same severe salt exposure, these bars were still passive. As shown in Table 3, the mean weekly macrocell currents for these three types of bars were only 0.0 ± 0.1 μA. The clad bars, even with three 3-mm holes drilled through the cladding, did not exhibit any discernible adverse effect of the presence of such defects (see Figure 11). However, when the defects were larger, such as a 25-mm cut, the bars appeared to lose their passivity after approximately 392 days, as indicated by the relatively small rise in the macrocell currents of the concrete blocks containing them (Figure 12). This may indicate that the carbon steel core exposed by the cut in the cladding had begun to corrode, perhaps still slowly since the maximum macrocell current observed was only 20.2 μA. An autopsy of some of these concrete blocks to expose some of these bars is being planned.

Tables 3 and 4 summarize some of the statistics for the weekly macrocell currents of these different types of bars. The following is a ranking of the bars (excluding those with intentionally introduced defects), in the order of increasing corrosion resistance, based on these results:

Black steel < 2101 LDX < MMFX-2 << Zn/EC ≈ (?) Clad ≈ (?) 304 ≈ (?) 316LN

The question marks are used to emphasize that the relative rankings are still not clear because corrosion activity is not yet indicated for four of the bars tested. It must be emphasized that all tests were made on concrete blocks with no intentionally introduced concrete cracks over the top bars, a method used by some investigators to accelerate chloride ingress. That method was not used in this investigation because it is extremely difficult to create uniform and consistent concrete cracks, especially from specimen to specimen.

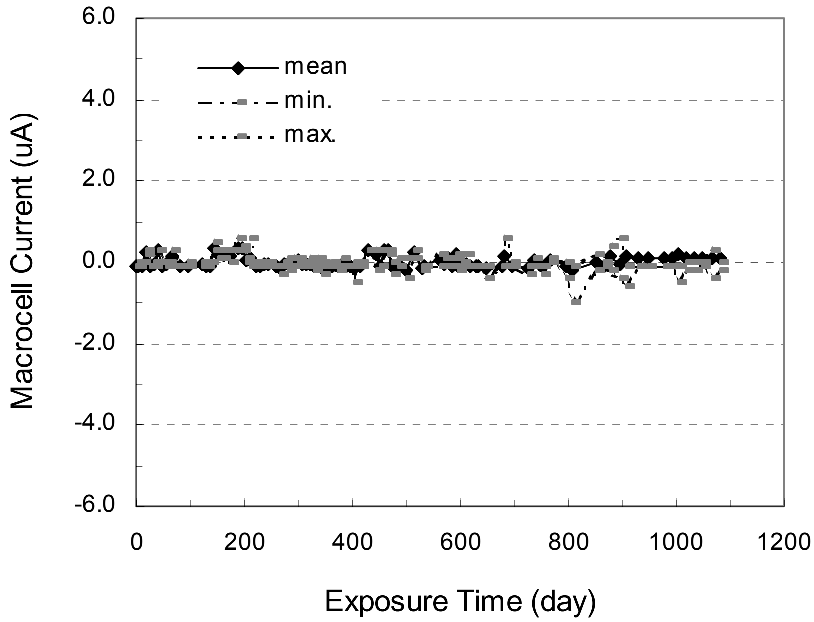


**Figure 8. Weekly Macrocell Currents of Concrete Blocks with 316LN Bars**

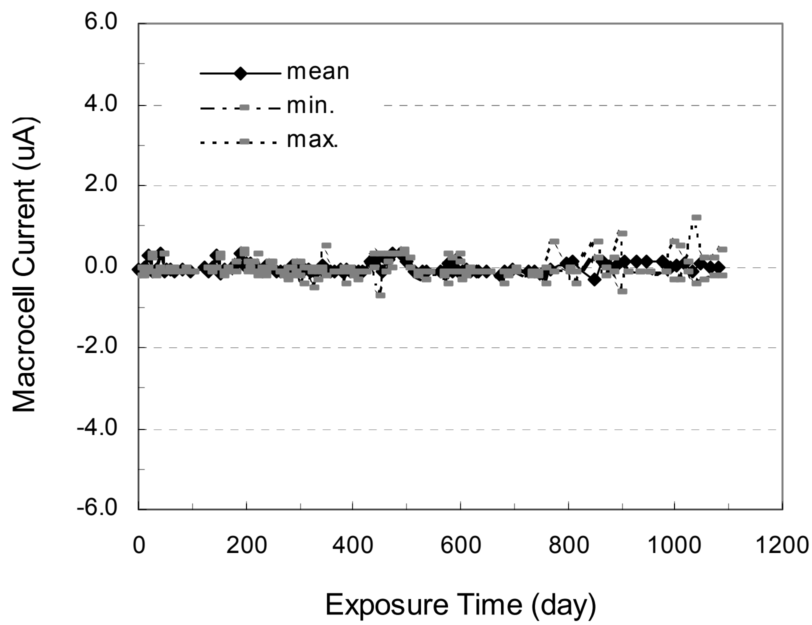


**Figure 9. Weekly Macrocell Currents of Concrete Blocks with 304 Bars**

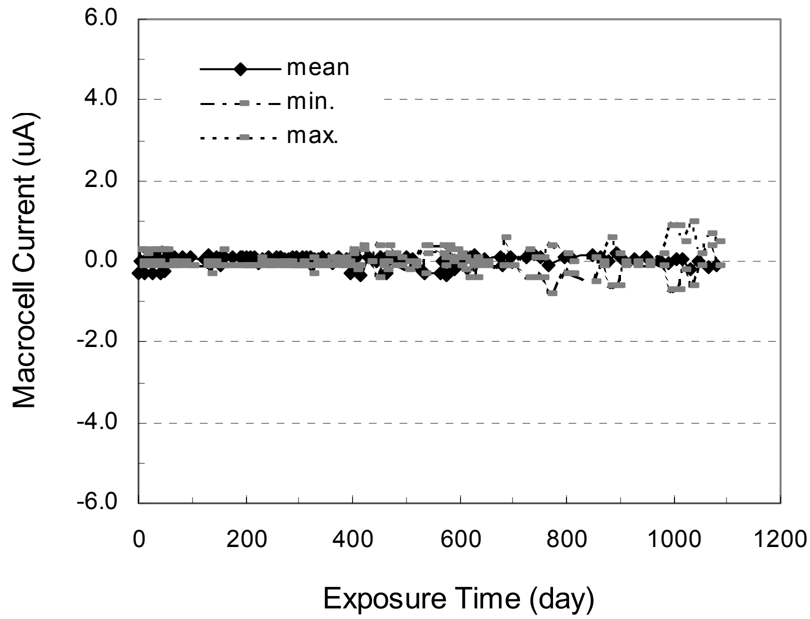


**Figure 10. Weekly Macrocell Currents of Concrete Blocks with Stainless Steel-Clad Bars**

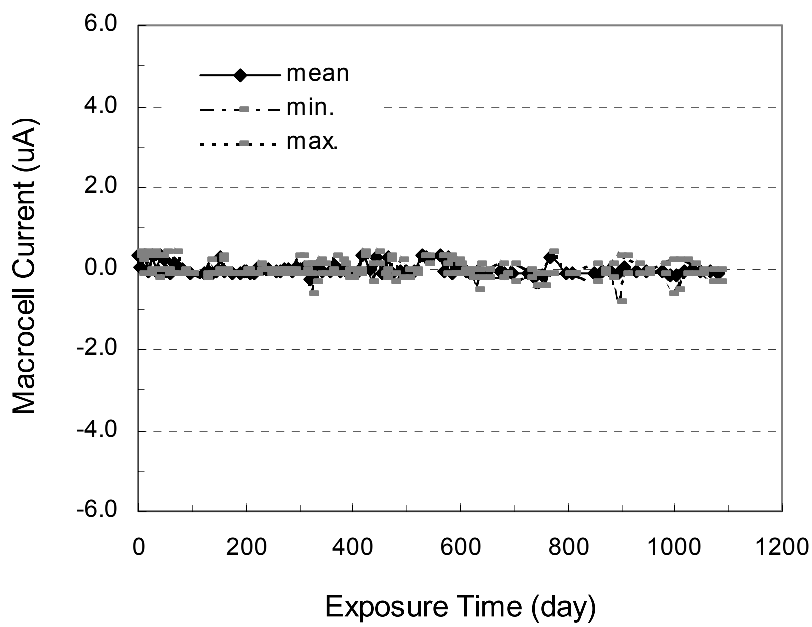


**Figure 11. Weekly Macrocell Currents of Concrete Blocks with Stainless Steel-Clad Bars with 3-mm Holes Through Cladding**

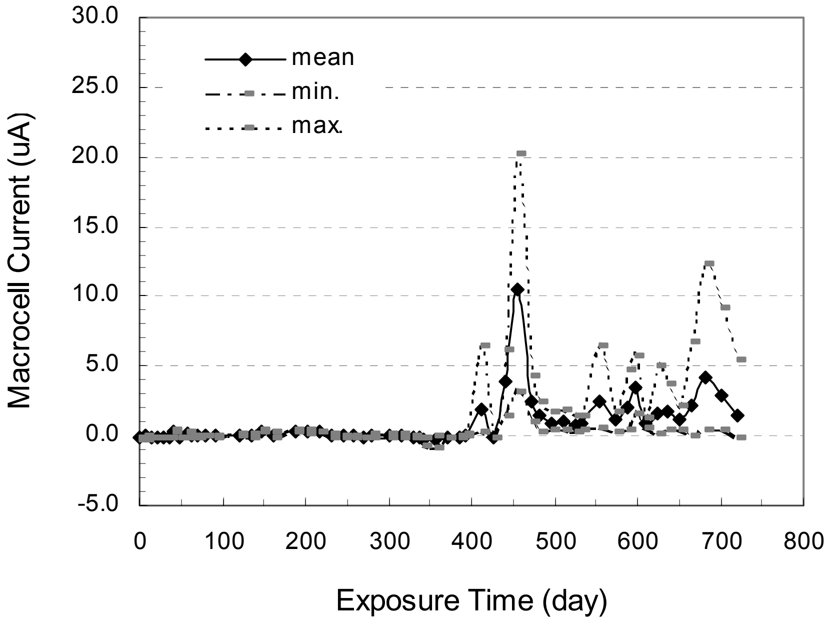


**Figure 12. Weekly Macrocell Currents of Concrete Blocks with Clad Bars with 25-mm Cuts**

**Table 3. Mean and Maximum Weekly Macrocell Currents (μA) of Bars**

| Bar | Mean | Maximum |
|---|---|---|
| Black Steel | 217.5 ± 0.1 | 534.9 ± 0.1 |
| 2101 LDX | 84.3 | 209.8 |
| MMFX-2 | 73.0 | 231.2 |
| Zn/EC-1 | 0.0 | 0.7 |
| Zn/EC-2 | 0.0 | 0.3 |
| Zn/EC-3 | 0.0 | 0.3 |
| 316L-Clad | 0.0 | 0.2 |
| Clad (w/ 3-mm holes) | 0.0 | 0.3 |
| Clad (w/ 25-mm cut) | 0.0 | 10.5 |
| 304 | 0.0 | 0.3 |
| 316LN | 0.0 | 0.4 |

**Table 4. Estimated Time-to-Corrosion of Different Bars Based on Presence of Galvanic Macrocell Currents**

| Bar | Estimated Time-to-Corrosion (days) | Time-to-Corrosion Ratio |
|---|---|---|
| Black Steel | 92 ± 3 | 1.0 |
| 2101 LDX | 147 | 1.6 |
| MMFX-2 | 245 | 2.7 |
| Zn/EC-1 | 532 | 5.8 |
| Zn/EC-2 | 637 | 6.9 |
| Zn/EC-3 | >735* | >8.0 |
| 316L-Clad | >1,082* | >11.8 |
| Clad (w/ 3-mm holes) | >1,082* | 11.8 |
| Clad (w/ 25-mm cut) | 392 | 4.3 |
| 304 | >1,082* | >11.8 |
| 316LN | >1,082* | >11.8 |

*Exposure of these bars is still in progress.

Examination of the concrete blocks with the black steel, the 2101 LDX, and the MMFX-2 bars on day 575 showed that many of the blocks already had rust stains on their surface, confirming that these materials had already begun to corrode. In this case, the data represented in Figures 2 through 4 can be useful. According to Faraday's law, if the electrochemical equivalent (*k*) of a particular material is known, the amount of that mass loss attributable to corrosion (M) can be estimated by integrating the amount of current (*i*) over the entire exposure period (*t*) in each graph:

$$M = k\sum it$$

Unfortunately, of the three materials, the electrochemical equivalent of black steel is the only one known. Therefore, in this investigation, only the total electrical charges, i.e., the summation of the product of *i* and *t* over the entire period, can be compared, not the mass losses. Figures 2 through 4 show that not only did the black steel bars became depassivated or begin to corrode earlier than the 2101 LDX and MMFX-2 bars, in that order, but when integrated (with respect to exposure time, as shown in Figure 13), the comparative or normalized respective charges were black steel : 2101 LDX : MMFX-2 = 1.00 : 0.38 : 0.33. Even though the only electrochemical equivalent known is that of the black steel, which is 11,619 mm·cm$^2$·s/coulomb ·year, it is possible to how these three metals may compare in terms of mass losses during the entire exposure period. Given that the values for several common stainless steels ranged between 10,415 and 10,965 mm·cm$^2$·s/coulomb·year—approximately 90 to 94 percent that of the black steel—and assuming that those of the other two new alloys could be between the lowest values for the stainless steel and the black steel, it is not unrealistic to conclude that the mass losses for the 2101 LDX and MMFX-2 bars would not be far from the ratios for total charges.

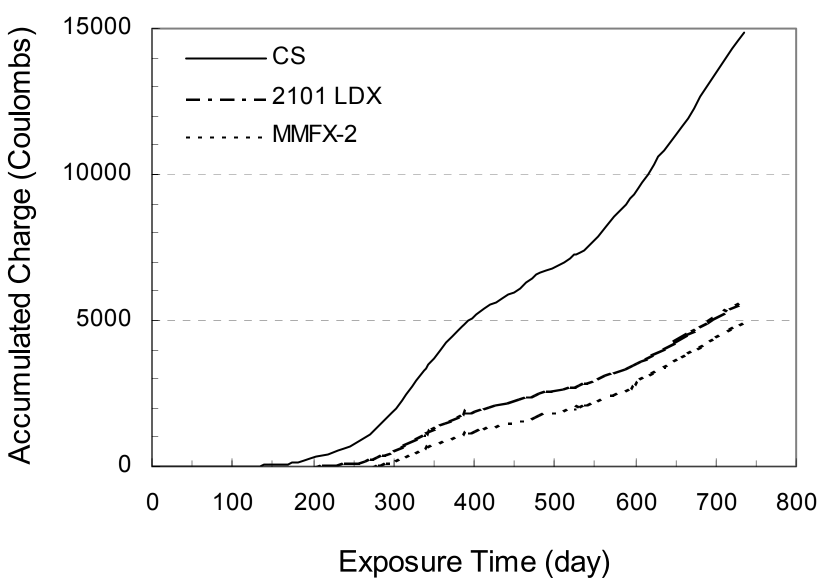


**Figure 13. Accumulated Electrical Charges for Black Steel, 2101 LDX, and MMFX-2 Bars**

Of course, there were still no losses of material on the 304 and the 316LN stainless steel bars, the defect-free clad bars, and the Zn/EC bars. However, for the clad bars with the cut through the cladding and the Zn/EC bars with the cut through both coatings, i.e., the Zn/EC-1 bars, there were some very low total charges, especially for the Zn/EC-1 bars, as shown in Figure 14. The comparison would be black steel : clad w/cut : Zn-EC-1 = 1.00 : 0.004 : 0.0003. However, the very slight macrocell current exhibited by the Zn/EC-1 bars is likely attributable to the comparatively more active layer of zinc than to the black steel substrate. It is clear that even with these defects, the clad, and perhaps even the Zn/EC, bars were still considerably more stable than the black steel bars by 3 to 4 orders of magnitude. An autopsy of many of these concrete blocks is being planned to shed light on the actual status of these different materials.

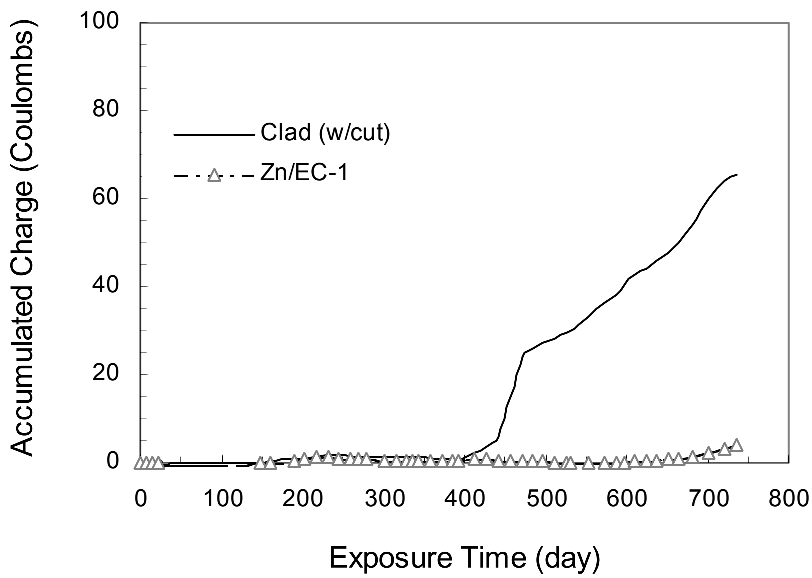


**Figure 14. Accumulated Electrical Charges for Clad Bars and Zn/EC Bars, Both with 25-mm Cut**

## Open-Circuit Potentials

When monitored regularly, the open-circuit potentials of each type of bar in the concrete blocks appeared to be useful in confirming the observations made with the macrocell current measurements, especially in terms of when corrosion has started on a particular bar. As shown in Figure 15, during the first 92 days of salt exposure, the potentials of the black steel bars were approximately –120 mV (CSE); after that, the potential shifted precipitously to become even more negative, by as much as 389 mV in 237 days to –509 mV. It is widely accepted that when the potential of black steel bars in concrete becomes more negative than –350 mV, the probability that the bars are corroding is very high. This turning point at 92 days also marked the point when the weekly macrocell current of the bars began to increase, signaling the beginning of corrosion activity.

Similarly, the potentials of the 2101 LDX bars began to shift electronegatively after 147 days—shifting by 228 mV in approximately 182 to 196 days (Figure 15). Again, this turning point is in good agreement with the 147 days observed in the weekly macrocell currents of this

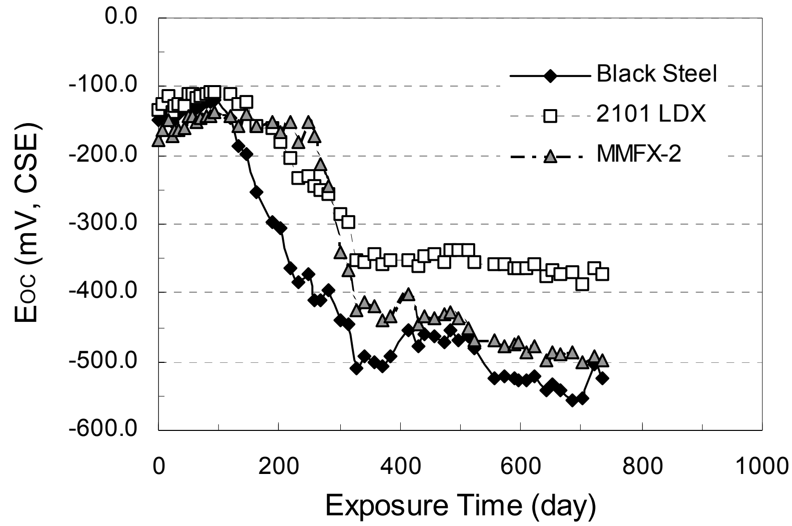


**Figure 15. Weekly Open-Circuit Potentials of Black Steel, 2101 LDX, and MMFX-2 Bars**

bar (Figure 3). After this large shift, the potential of this bar appeared to continue shifting negatively, albeit at a greatly reduced rate and never below –386 mV. As also illustrated in Figure 15, an abrupt electronegative shift in the potential of the MMFX-2 bars did not occur until after 247 days, which was practically the same time their weekly macrocell current began to increase (Figure 4). Comparing these three curves or the manners in which the potentials of the black steel, 2101 LDX, and MMFX-2 bars changed with exposure time, there was a noticeable similarity—each exhibited a distinctively abrupt and large negative shift, at the initiation of corrosion.

In contrast, as Figure 16 shows, the potentials of all three groups of Zn/EC bars were considerably more stable—shifting only 8, 60, and 20 mV in 735 days for the Zn/EC-1, Zn/EC-2, and Zn/EC-3 bars, respectively. It is difficult to conclude whether there are significant differences among the potentials of these three groups of Zn/EC bars. In all cases, their initial potentials—ranging from –305 to –360 mV—reflected the influence of the zinc coating, which is more anodic or reactive than the black steel substrate. Beyond this, it is difficult to elucidate the meaning of the stability of these potentials other than since it is in agreement with the absence of significant macrocell currents, it likely indicates the stability of this new corrosion protection system.

Additional measurements of the concrete blocks with the clad bars and the 304 and 316LN bars after the first 700 days showed that their potentials were still steadily and slowly shifting in the negative direction, with still no discernible difference among them (Figure 17). The important common characteristic of these three curves is that their shifts in potentials were very slow when compared to those of the black steel, 2101 LDX, and MMFX-2 bars.

When 3-mm-wide holes were drilled through the cladding, the potential drift increased just slightly by 0.20 mV/day (Figure 18) but was still similar to those of the perfect clad bars and the two solid stainless steel bars. However, when the defect was a 25-mm cut through the cladding, the potentials behaved distinctly different from those of the other two groups of clad

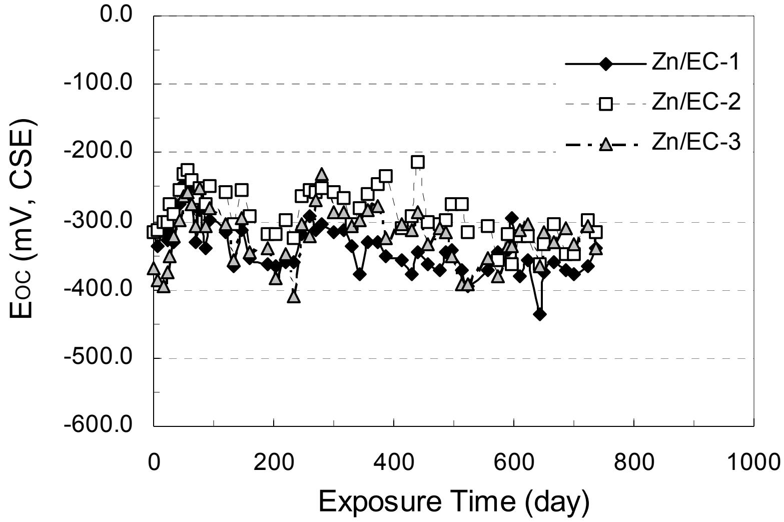


**Figure 16. Weekly Open-Circuit Potentials of Zn/EC Bars**

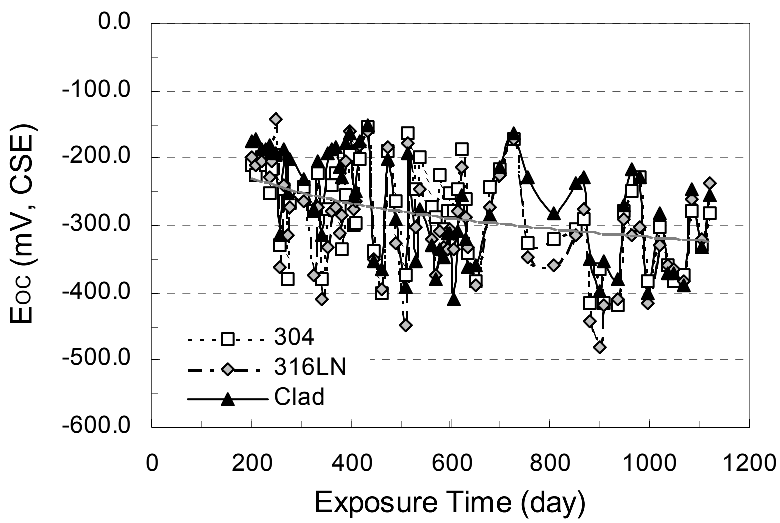


**Figure 17. Weekly Open-Circuit Potentials of 304 and 316LN Stainless Steel and 316L-Clad Bars**

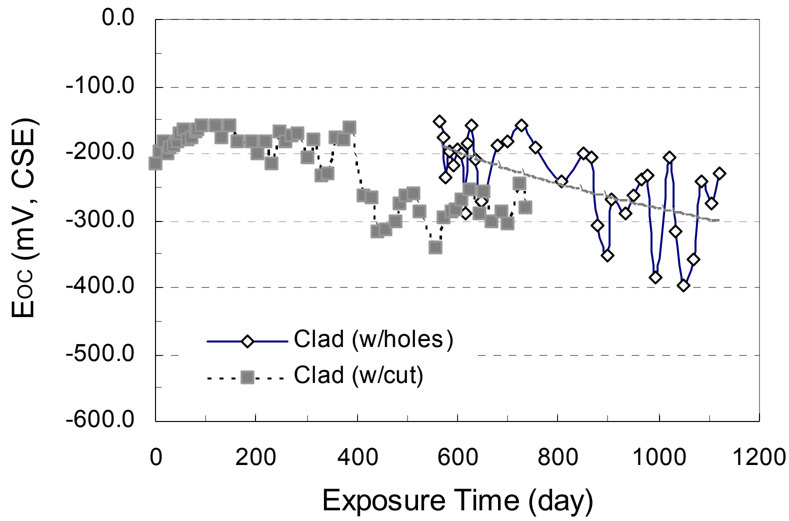


**Figure 18. Weekly Open-Circuit Potentials of Clad Bars with Different Introduced Cladding Defects**

bars and somewhat similar to those of the black steel, 2101 LDX, and MMFX-2 bars, decreasing after about 392 days (Figure 15). This turning point was the same as that for the weekly macrocell currents of the clad bars with the cuts. Interestingly, thereafter, the potential remained relatively stable, around –300 mV, perhaps an indication that the corrosion on the exposed black steel core may have slowed – after a noticeable increase at about 392 days.

## Estimation of Chloride Corrosion Thresholds of the Different Bars

As the preceding discussions have shown, weekly monitoring of the macrocell currents and open-circuit potentials of the different bars was very useful for determining the condition of the bars at any time during the weekly chloride-ponding of the blocks and, therefore, pinpointing the time-to-corrosion of a bar if it began to show signs of stability loss or corrosion. With knowledge of the latter, it is possible to estimate the maximum amount of chloride ions a particular type of bar can withstand in concrete before it begins to corrode—the chloride corrosion threshold of the bar—by estimating the chloride concentration in the concrete at its time-to-corrosion.

Figure 19 shows the mean chloride concentrations in the concrete blocks at different depths and exposure times as determined by analysis of the ground concrete samples obtained from 14 randomly selected test concrete blocks. From the best-fit curves, the mean chloride ion concentration as a function of exposure time can be derived for the depth of 33 mm, which was the depth of the top-mat bars (see Figure 20). This function, in turn, provided estimates of the chloride corrosion thresholds of the various reinforcing bars, which are presented in Table 5.

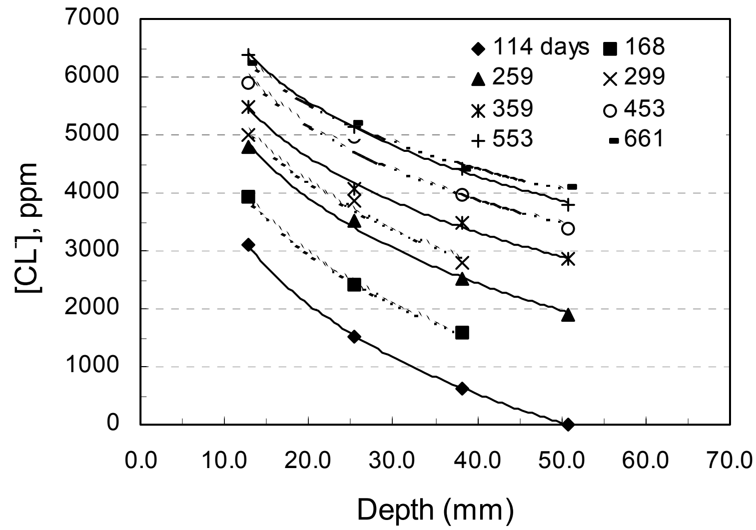


**Figure 19. Mean Chloride Concentrations at Different Depths in Concrete Blocks After Various Salt Exposure Times**

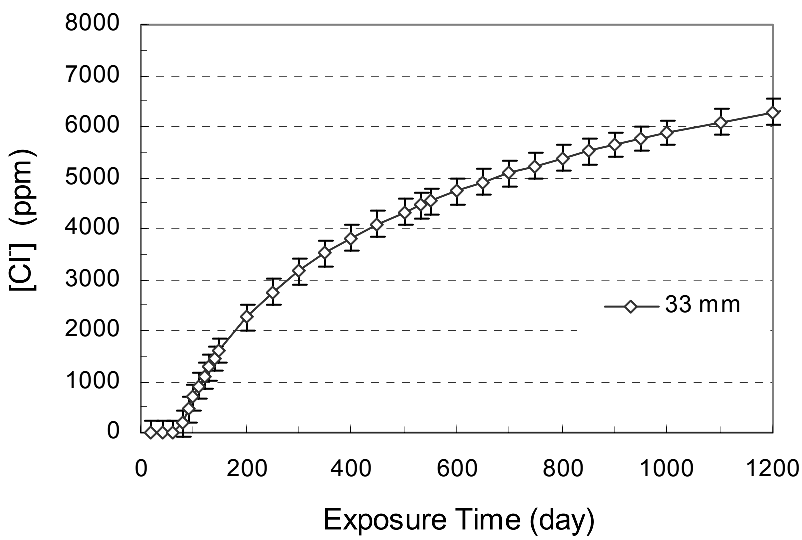


**Figure 20. Estimated Mean Chloride Concentrations in Concrete Blocks at Depth of Top Bars (33 mm) as Function of Exposure Time**

**Table 5. Estimated Chloride Corrosion Thresholds for the Different Bars**

| Bar | Chloride Corrosion Threshold (ppm) | Threshold Ratio** |
|---|---|---|
| Black Steel | 430 to 580 | 1.0 |
| 2101 LDX | 1,520 to 1,610 | 2.6 to 3.7 |
| MMFX-2 | 2,690 to 2,740 | 4.6 to 6.4 |
| Zn/EC-1 | 4,450 to 4,470 | 7.7 to 10.4 |
| Zn/EC-3 | > 5,190 * | > 8.9* |
| Clad (w/cut) | 3,750 to 3,790 | 6.5 to 8.8 |
| 316L-Clad | > 6,060 * | > 10.4* |
| 314 | > 6,060 * | > 10.4* |
| 316LN | > 6,060 * | > 10.4* |

*Exposure of these bars is still in progress.
**Compared to black steel bars.

As Table 5 indicated, the new, unpickled, 2101 LDX bars withstood about 3 times more chloride ions in the concrete than did the black steel bars. It is believed that the corrosion resistance of this bar can be improved by pickling the bars, since pickling can enhance the corrosion resistance of stainless steels—as evidenced by the high corrosion resistance of the pickled 304 and 316LN bars included in this investigation—by leaving a chromium oxide-rich film on these materials. The MMFX-2 bars were able to withstand 5 to 6 times more chloride ions. The most corrosion resistant were the two solid stainless steels, the clad, and the Zn/EC bars, since they were still not corroding. Again, even the imperfect clad and the imperfect Zn/EC bars were showing extremely good resistance to chloride attack.

## Long-Term Costs of Using the Different Bars

Chloride threshold values such as those presented are useful for estimating when corrosion will begin in a concrete bridge if a particular bar is used given such factors as the concrete cover provided over the bars, concrete mix used, expected salt exposure rate (based on location and historical weather data), installed cost of the bar, etc. Such information, in turn, is useful for estimating the long-term cost of the structure when a particular reinforcing bar is used, which is a valuable indirect measure of the long-term cost-effectiveness of that bar. In order for a bar to be cost-effective in the long term, it must have a reasonable cost and a high chloride threshold.

To facilitate comparison, the projected long-term costs for using these different bars in a new concrete bridge deck in Virginia, built with the current VDOT specifications for Type A4 concrete[3] and under the conditions and assumptions given in Table 6, were estimated using Life 365.[4] In using this model, some adjustments were made, including using the chloride threshold values presented in Table 5 and adjusting the propagation periods for the 2101 LDX and MMFX-2 bars to reflect their relatively lower values in comparison to that of the black steel bars, as shown in Figure 13.

**Table 6. Parameters Used in Estimating Long-Term Costs for Using the Different Bars in a Bridge Deck**

| | |
|---|---|
| **Dimension of Concrete Deck** | |
| Overall thickness | 0.229 m (9.0 in) |
| Clear concrete cover | 0.070 m (2.75 in) |
| **Base Concrete Mix Design** | |
| w/ (c + m) | 0.45 |
| Fly ash content | 25% |
| Chloride diffusion constant (at 28 days) | 1.05 x $10^{-11}$ $m^2/s$ |
| Mix cost | \$118/$m^3$ (\$90.00/$yd^3$) |
| **Bar** | |
| Percentage | 1.2 |
| Installed Cost | |
| Black steel | \$1.10/kg (\$0.50/lb) |
| 2101 LDX | \$3.30/kg (\$1.50/lb) |
| MMFX-2 | \$1.98/kg (\$0.90/lb) |
| Zn/EC | \$1.65/kg (\$0.75/lb) |
| 316L-Clad | \$2.54/kg (\$1.15/lb) |
| **Long-Term Salt Exposure** | |
| Location | Roanoke, VA |
| Exposure | Urban highway bridges |
| **Other Cost Information** | |
| Repair cost | \$431/$m^2$ (\$360/$yd^2$) |
| Area to repair | 10% of total area |
| Repair interval | 10 years |
| Discount rate | 3% |

As expected, the model predicted that initially a deck built with black steel bars would cost the least, at \$50.75/$m^2$ (Figure 21). However, once corrosion sets in and propagates sufficiently to damage the concrete so that the deck required repair (for the first time) at 63 years, the cost of the deck (including repair) begins to increase sharply, rising to \$62.28/$m^2$, then to \$68.67/$m^2$, and then to \$73.32/$m^2$, at around 75 years, 100 years, and 125 years, respectively.

In comparison, the initial cost of Zn/EC and the MMFX-2 bars is at \$62.62/$m^2$ and \$69.73/$m^2$, respectively, and by virtue of their comparatively higher tolerances to salt remained constant throughout the first 150 years. For the same reason, the clad bars, even the ones with a cut through the cladding, came in next with a constant cost of \$81.46/$m^2$ throughout the entire 150 years.

The least competitive bars appear to be the 2101 LDX bar, attributable entirely to its relatively high initial cost, which offsets its slightly higher corrosion threshold value or tolerance to salt. With this bar, the structure would cost \$98.21/$m^2$ for the first 122 years then rise stepwise to \$100.86/$m^2$ by 150 years. Not included in this exercise were the solid 304 and 316 stainless steel bars, which would have a long-term cost higher than that of even the 2101 LDX bars. Also not included in this exercise was the conventional ECR, which would have a cost-vs.-year function similar to that of the black steel bar, except with a slightly higher cost and a later time-to-first-repair of perhaps 10 years.

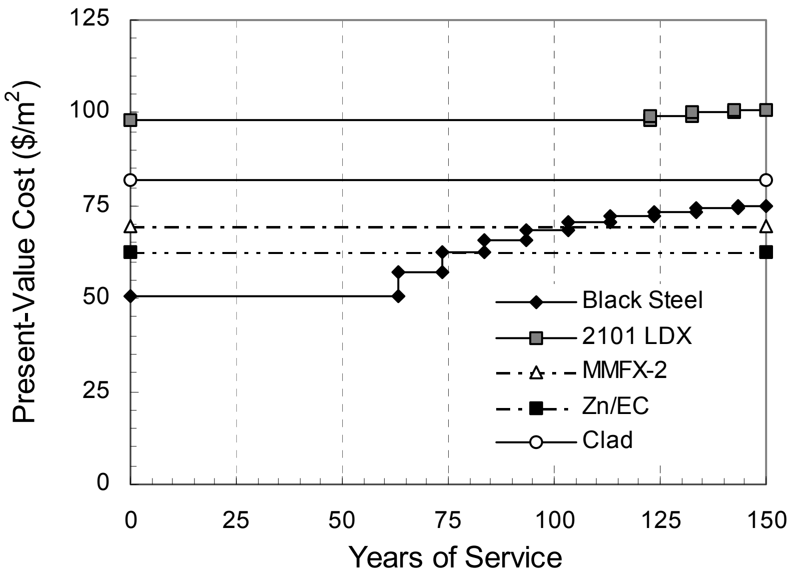


**Figure 21. Present-Value Cumulative Costs for Concrete Bridge Deck in Virginia Using Various Types of Reinforcing Bars**

As noted in Table 6, this exercise was for a salting rate assumed to be typical of urban highways in the Roanoke area of Virginia. A similar exercise for the same concrete structure located in the same general geographic region on a rural highway, where the salting rate is expected to be slightly less, would yield identical respective cost-vs.-year functions for the MMFX-2, Zn/EC, and the clad bars because of their high corrosion threshold values. However, for the black steel and 2101 LDX bars, their respective cost-vs.-year functions would shift slightly toward more years of service before the first repair.

Figure 21 may tempt some bridge designers to consider reverting to the use of only black steel bars. However, such a consideration would be risky if the goal is to design a bridge that will last for at least 75 to 100 years. First, it must be emphasized that the modeling in Life 365 assumed that the transport of chloride ions into the concrete is by a diffusion process only and did not account for the much faster gravitational process that can dominate when cracks form in concrete decks, which is not uncommon. In view of this, results such as those illustrated in Figure 21 should be used qualitatively, giving more emphasis to the trends rather than the absolute values of the cost estimates. Since the chloride ions will move into a concrete deck much quicker when there are cracks in the concrete, all the curves shown in Figure 21 will shift toward the direction of shorter service life, with the extent of the reduction in service life increasing with the severity of the cracks. This adverse effect would affect the black steel and 2101 LDX bars the most, and likely the conventional ECR too.

Another serious shortcoming of Life 365 is that it does not take into account such costs as traffic control during repair, loss in productivity of motorists, increased risk of traffic accidents arising from lane closure, etc. Since such costs tend to be considerably high for urban areas, it would be imprudent *not* to use bars such as the MMFX-2 or the clad bars in bridges to be located in major urban areas that will be heavily salted during the winter. If no unexpected anomaly is observed in the additional future data and the planned autopsy of the concrete blocks with the Zn/EC bars, this type of bar should also be included for consideration.

## CONCLUSIONS

- When measured regularly, the changes in macrocell current and potential of a reinforcing bar as a function of total salt exposure time comprise a simple and reliable means of defining the time-to-corrosion of a metallic reinforcing bar. The smaller the interval between consecutive measurements, the more accurate the definition.

- The ranking of the different bars in the order of increasing resistance to chloride-induced corrosion in concrete is:

  Black steel < 2101 LDX < MMFX-2 << Zn/EC ≈ (?) Clad ≈ (?) 304 ≈ (?) 316LN

  The question marks are used to emphasize that the relative rankings are still not clear because corrosion activity is not yet indicated on some of these materials.

- Based on the estimated long-term costs of using these different bars in a deck built in Virginia exposed to salting at a rate typical for urban highways (Figure 21), the four new bars may be ranked in the order of increasing long-term costs as:

  Zn/EC < MMFX-2 < Clad < 2101 LDX

- Although the electrochemical data for the Zn/EC bars have so far indicated that the intended function of the layer of zinc between a black steel bar and the epoxy coating appeared to be providing the intended beneficial effect, this needs to be verified with an autopsy of some of the concrete blocks containing this experimental bar. Since the Zn/EC coating system is new and complex, its electrochemical data should be interpreted cautiously but with optimism—especially when the macrocell current data were beginning to indicate corrosion activity on the bars with the cuts through both coatings, the Zn/EC-1 bars—perhaps an indication that the electrochemical data for this type of bar can be interpreted in the same manner as with the other bars.

- Depending on their size, defects in cladding may adversely affect the protection the cladding is intended to provide to the underlying black steel in a stainless steel-clad bar. For defects such as the 25-mm-long cuts introduced in this investigation (which will probably never be observed in the field), the remaining corrosion protection was still sufficient to yield a 150-year service life for a deck built with the current A4 concrete.

## RECOMMENDATIONS

1. For concrete bridges expected to be exposed to heavy salting, such as those on urban highways and heavily traveled primary and interstate routes, VDOT should consider using the MMFX-2 or the clad bars, or even the Zn/EC bars (pending the outcome of a planned autopsy of the concrete blocks containing these bars).

2. For concrete bridges to be located on low-volume highways that are not to be heavily salted, VDOT should consider using the MMFX-2 bars, or even the Zn/EC bars, or continuing to use ECR.

3. Since the MMFX-2 bar has shown promise as a cost-effective countermeasure for corrosion, VDOT should pursue its trial use in a new concrete bridge deck and establish special provisions for this bar. A trial use of the stainless steel-clad bars in a new concrete bridge deck has just been completed.[5]

## ACKNOWLEDGMENTS

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