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Evaluation of Migrating Corrosion Inhibitors Used in the Restoration and Repair of Reinforced Concrete Structures

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ABSTRACT

Corrosion inhibitors used in reinforced concrete structures can greatly increase service life and reduce long term maintenance costs. In this work, migrating corrosion inhibitors have been utilized in the repairs of concrete structures that were deteriorating due to corrosion of embedded reinforcement. These two projects show that migrating inhibitors have a direct and significant impact on the reduction of corrosion.

The Randolph Avenue Bridge in Minnesota was repaired using an overlay incorporating a migrating corrosion inhibitor in the westbound lanes. The repair of the eastbound lanes did not contain a corrosion inhibitor. The rehabilitation was part of a Federal Highway Administration project and measurements were also taken as part of a Virginia Tech study. Updated readings were performed in 2000, 2003, 2007, and 2011.

The Apple Street Parking Garage in Ohio contained precast double tees that had advanced corrosion which led to full depth concrete repairs. Repairs were completed using concrete that included a migrating corrosion inhibitor, and the application of a penetrating corrosion inhibitor to the rest of the structure.

This paper will cover the corrosion rate data collection and present findings, which will include chloride level analysis, half-cell potential readings, concrete resistivity readings, and linear polarization resistance techniques.

Key words: Migrating corrosion inhibitor, concrete, reinforcement, half-cell potential, linear polarization resistance, repair.

INTRODUCTION

Originally constructed in 1963, the Randolph Avenue Bridge spans Interstate 35E in Saint Paul, Minnesota. Due to chloride induced corrosion, embedded reinforcement deteriorated to the point of causing major cracking and spalling on the concrete bridge decks. In 1986, the top deck of the Randolph Avenue Bridge was repaired in a project sponsored by the Minnesota Department of Transportation. Both sides of the deck were repaired using a low slump, dense concrete overlay that incorporated a migrating corrosion inhibiting admixture into one side while the other was left untreated as the control. The treated westbound lanes have served as a real world comparison of corrosion current reduction versus the untreated "control" eastbound lanes.

The rehabilitation of this bridge was part of a Federal Highway Administration project from 1986 to 1990 and a Virginia Tech Study in 1991 and 1992. Updated readings were performed by the Minnesota DOT in 2003 and by Cortec Corporation(1) in 2000, 2007, and 2011.

The Apple Street Parking Garage in Dayton, OH is a pre-topped, precast, double tee garage. The lower two levels were constructed in 1986 and the upper levels were added in 1989. During an inspection in the early 2000s, the precast double tees were found to have advanced corrosion which led to necessary full depth repairs of the concrete. In 2006, repairs were completed using ready mixed concrete that included a migrating corrosion inhibiting admixture. Surface treatments were also made to existing concrete outside of the patchwork using a penetrating corrosion inhibitor.

EXPERIMENTAL

Randolph Avenue Bridge

Background.

The rehabilitation process included the application of a low slump dense concrete that varied in depth from 2.3 to 4.2 inches (58.4-106.7 mm). The mix design of the overlay can be seen in Table 1. An aminoalcohol based migrating corrosion inhibiting admixture was added to the concrete overlay at 1 pint/yd^3 (0.62 L/m^3) for the two westbound traffic lanes. The eastbound lanes were repaired with the same type of concrete which did not contain the corrosion inhibitor to act as the control. Prior to application of the overlay, the deck was milled to a depth of 0.5 inches (13 mm) and the areas of unsound concrete were removed. The cavities from the removal of the unsound concrete were filled with the overlay concrete. The general slope of the bridge for water runoff appears to be towards the northeast.

(1) Trade name.

Table 1
Mix design parameters of the Randolph Avenue Bridge repair

Component	Control (lbs/yd^3)	Treated (lbs/yd^3)
Type I Cement	836	836
Water	270	270
w/c ratio	0.32	0.32
Coarse Aggregate	1385	1385
Fine Aggregate	1374	1374
Water Reducing Admixture	0.25	0.25
Air Entraining Agent	0.073	0.073
Corrosion Inhibitor	-	0.95

Corrosion assessments were conducted on the eastbound (control) and westbound (aminoalcohol) travel lanes of the structure by Virginia Tech researchers on two occasions, June 1991 and August 1992. The assessments included visual inspection, delamination survey, cover-depth survey, chloride contents as a function of depth, corrosion potentials, and estimates of corrosion current densities (i_{corr}) using 3LP(2) Meter (Linear Polarization Device 1). Prior to the assessments completed by Virginia Tech, the repair was part of a Federal Highway Administration Project until 1990.

In November 2000, technicians returned to the bridge and took new measurements. These included linear polarization readings obtained by a Gecor 6(3) (Linear Polarization Device 2) instrument, and copper/copper sulfate half-cell potentials. A new chloride analysis was also taken at various depths.

In June 2007 and July 2011, chloride analysis, alkalinity testing, and half-cell potential readings were performed. Linear polarization readings using a Galvapulse(4) (Linear Polarization Device 3) instrument, of corrosion current, corrosion rate, and concrete resistivity were also taken.

Apple Street Parking Garage

Background.

The concrete reinforcement is a steel mesh that is located 1.75-2 inches (44.5-50.8 mm) deep and is 0.19 inches (4.76 mm). The mesh was laid out in a 4 foot by 8 foot (1.22 m by 2.44 m) grid. In November 2006, patchwork was completed using ready mixed concrete that incorporated an amine carboxylate based migrating corrosion inhibiting admixture dosed at 1.5 pints/yd^3 (1 L/m^3).

Also in 2006, a water-based penetrating corrosion inhibitor was applied to both the deck and to the underside at a coverage rate of 150 ft^2/gal (3.68 m^2/L). The substrate was allowed to dry for a week and was then shot blasted prior to application of a 40% silane water repellant to the deck surfaces.

On July 1, 2009, linear polarization readings were obtained using Linear Polarization Device 3. Ten corrosion current readings were taken at five different locations within the garage.

(2) Trade name.
(3) Trade name.
(4) Trade name.

Chloride Contamination Levels.

At the Randolph Avenue Bridge, powdered concrete samples for chloride analysis were taken at mean depths of 0-1, 1-2, and 2-3 inches (0-25, 25-51, and 51-76 mm) from six total locations, three on each side of the bridge.

Samples were taken using a rotary impact type drill with a 0.5 inch (12.7 mm) sized bit. Three-gram samples that passed through a #20 sieve were obtained from each depth. The powder was then mixed with 20 ml of digestion solution for a total of 3 minutes and then 80 ml of stabilizing solution was added. A calibrated electrode coupled to an Orion[(5)] Model 720-pH/ISE meter was then immersed in the solution, and the chloride-ion concentration was recorded. This method was consistent with the AASHTO: T260 Procedure C. The standard deviation for this chloride test was determined by testing the six pulverized concrete Quality Assurance (QA) samples of known chloride content. Each QA sample was tested five times.

Corrosion Current Measurements.

Corrosion current density (i_{corr}) estimates were taken at the Randolph Avenue Bridge in June 1991 and August 1992 using Linear Polarization Device 1. Readings were also performed in November 2000, July 2007, and July 2011 using both Linear Polarization Device 2 and Linear Polarization Device 3. Corrosion current density readings were also obtained at the Apple Street Parking Garage in July 2009 using Linear Polarization Device 3.

The i_{corr} measurement is proportional to the corrosion rate through Faraday's Law. The instruments used measure the corrosion rate of steel in concrete by "polarization resistance" or "linear polarization" techniques. This is a non-destructive technique that works by applying a small current to the rebar and measuring the change in the potential. Then the polarization resistance, Rp, (the change in potential measured), is divided by the applied current. The corrosion rate, i_{corr}, is obtained from the polarization resistance, R_p, by means of the "Stearn and Geary" relationship:

$$i_{corr} = B/R_p, \text{ where } B = 26 \text{ mV} \tag{1}$$

Each device used has different criteria for evaluating the corrosion rates which are described in Table 2, Table 3, and Table 4.[1]

Table 2
Corrosion intensity versus corrosion current and rate of corrosion found by Linear Polarization Device 1

Corrosion Current ($\mu A/cm^2$)	**Corrosion Rate (µm/year)**	**Intensity of Corrosion**
<0.5	<5.8	Passive Condition
0.5-2.7	5.8-31.3	Low corrosion (damage possible in 1-15 years)
2.7-27	31.3-313.2	Moderate corrosion (damage possible in 2-10 years)
>27	>313.2	High corrosion (damage expected in 2 years or less)

(5) Trade name.

Table 3
Corrosion intensity versus corrosion current and rate of corrosion found by Linear Polarization Device 2

Corrosion Current ($\mu A/cm^2$)	Corrosion Rate (μm/year)	Intensity of Corrosion
<0.5	<1.2	Negligible corrosion
0.5-2.7	1.2-5.8	Low corrosion
2.7-27	5.8-11.6	Moderate corrosion
>27	>11.6	High corrosion

Table 4
Corrosion intensity versus corrosion current and rate of corrosion found by Linear polarization Device 3

Corrosion Current ($\mu A/cm^2$)	Corrosion Rate (μm/year)	Intensity of Corrosion
<0.5	<5.8	Passive condition
0.5-5	5.8 to 58	Low corrosion
5-15	58 to 174	Moderate corrosion
>15	>174	High corrosion

Concrete Resistivity Measurements.

Linear Polarization Device 2 calculates the concrete resistivity by means of the formula,

$$\text{Resistivity} = 2 \times R \times D \qquad (2)$$

where R = resistance by the “iR drop” from a pulse between the sensor counter-electrode and the rebar network and D = counter-electrode diameter of the sensor

The value of the concrete’s resistance is used as an additional parameter for the interpretation of the rate of corrosion. Table 5 shows the interpretation of the results.[2]

Table 5
Correlation of resistivity measurements to corrosion rate using Linear Polarization Device 2

Resistivity	Corrosion Rate
>100-200 $k\Omega \cdot cm$	Very low, even with high chloride and carbonation
50-100 $k\Omega \cdot cm$	Low
10-50 $k\Omega \cdot cm$	Moderate to high where steel is active
<10 $k\Omega \cdot cm$	Resistivity is not the parameter controlling corrosion rate

Half-Cell Potentials.

ASTM C 876 corrosion half-cell potentials were measured on the Randolph Avenue Bridge for both the eastbound and westbound travel lanes with Linear Polarization Device 2 in November 2000, June 2007, and July 2011. The Minnesota Department of Transportation also conducted half-cell potential readings in 2003. According to ASTM C 876, the results can be interpreted in Table 6.

Table 6
Corrosion potential using half-cell potential readings from Linear Polarization Device 2

Potential	Probability of Corrosion
>-200 mV	Less than 10%
-200 mV to -350 mV	50%
<-350 mV	Greater than 90%

Carbonation.

Carbonation of concrete is a process by which carbon dioxide from the air penetrates the concrete and reacts with the hydroxides, such as calcium hydroxide, to form carbonates. This process increases shrinkage on drying (promoting crack development) and reduces the alkalinity of the concrete. High alkalinity is needed to protect embedded rebar from corrosion; consequently, concrete should be resistant to carbonation to prevent steel corrosion.[3] The carbonation of powdered concrete samples taken from the Randolph Avenue Bridge was determined by using phenolphthalein (alkalinity) measurements.

RESULTS AND DISCUSSION

Randolph Avenue Bridge

Chloride Threshold.

Chloride threshold refers to the concentration of chlorides at which corrosion in the steel is initiated. Based on the service life prediction model, Life 365, the chloride threshold of the concrete used in the Randolph Avenue Bridge is 0.05 percent of the concrete.[4] This converts to 0.4% by weight of the cement and 3.35 lbs/yd^3 (1.98 kg/m^3).

Chloride content readings were taken at 0-1, 1-2, and 2-3 inches (0-25, 25-51, and 51-76 mm) from 3 different locations on each side of the bridge. These readings indicated that the overall chloride levels in the control side were slightly higher than in the treated side. As can be seen in Table 7, the chloride levels have continued to rise at the level of the steel.

Table 7
Average chloride levels of Randolph Avenue Bridge

	Treated Side (lbs/yd^3)			Control Side (lbs/yd^3)		
Depth	(0-1")	(1-2")	(2-3")	(0-1")	(1-2")	(2-3")
1991	3.5	0	0.7	7.7	2.5	1.9
1992	6.5	1.1	1.9	9.5	3.5	2.5
2000	11.7	1.6	1.3	17.2	6.2	2.4
2007	11.7	1	2.6	20	7.4	2.3
2011	12.3	4.9	1.8	14.7	6.6	3.5

Corrosion Current Readings.

Corrosion currents of rebar have increased on both sides of the bridge since the year 2000, when the treated side had very low corrosion currents, an average of 0.0081 µA/cm^2, approximately 42% below readings taken on the control side (average of 0.014 µA/cm^2).

The corrosion current readings that were taken in July of 2011 are substantially higher at almost all points on the bridge. As shown in Table 7 the control side has reached the chloride threshold at the depth of the reinforcing steel. As seen in Table 8, the average corrosion rate of the treated side is 35% of the level on the control side. The highest rate of corrosion was measured in the center section of the control side which was 1.2755 µA/cm^2 compared to the treated center section which is 0.4202 µA/cm^2.

a reduction of 67%. This reduction is confirmed by the half-cell potentials which show a high probability of corrosion in the control South Central section seen in Table 10.

In Table 8, the average corrosion current data is presented comparing segments of the bridge using Linear Polarization Device 2. In 2011 all readings taken on the treated areas of the bridge were much lower than the readings taken on the control side. Additionally, all three control locations had average corrosion rate readings that would be considered active, whereas the treated side readings were all in the passive range. This indicates the corrosion inhibiting admixture is functioning as expected.

Table 8
Average corrosion rates for each bridge section of Randolph Avenue Bridge

	Treated Lanes			**Control Lanes**		
Year	**Northwest ($\mu A/cm^2$)**	**North Central ($\mu A/cm^2$)**	**Northeast ($\mu A/cm^2$)**	**Southwest ($\mu A/cm^2$)**	**South Central ($\mu A/cm^2$)**	**Southeast ($\mu A/cm^2$)**
2000	0.0081	0.0006	0.0077	0.093	0.175	0.145
2007	0.1258	0.2522	0.4231	0.2982	0.1878	0.368
2011	0.2659	0.4202	0.3196	0.6254	1.2755	0.8607

Figure 1 shows the comparison of corrosion rate readings on the control side versus the treated side using Linear Polarization Device 2. Prior to 2007, both sides of the bridge showed average corrosion rates in the passive range, however the treated side exhibited 40% lower readings. Now that the control side has entered active corrosion, the treated side is exhibiting corrosion rates that are approximately 85% less.

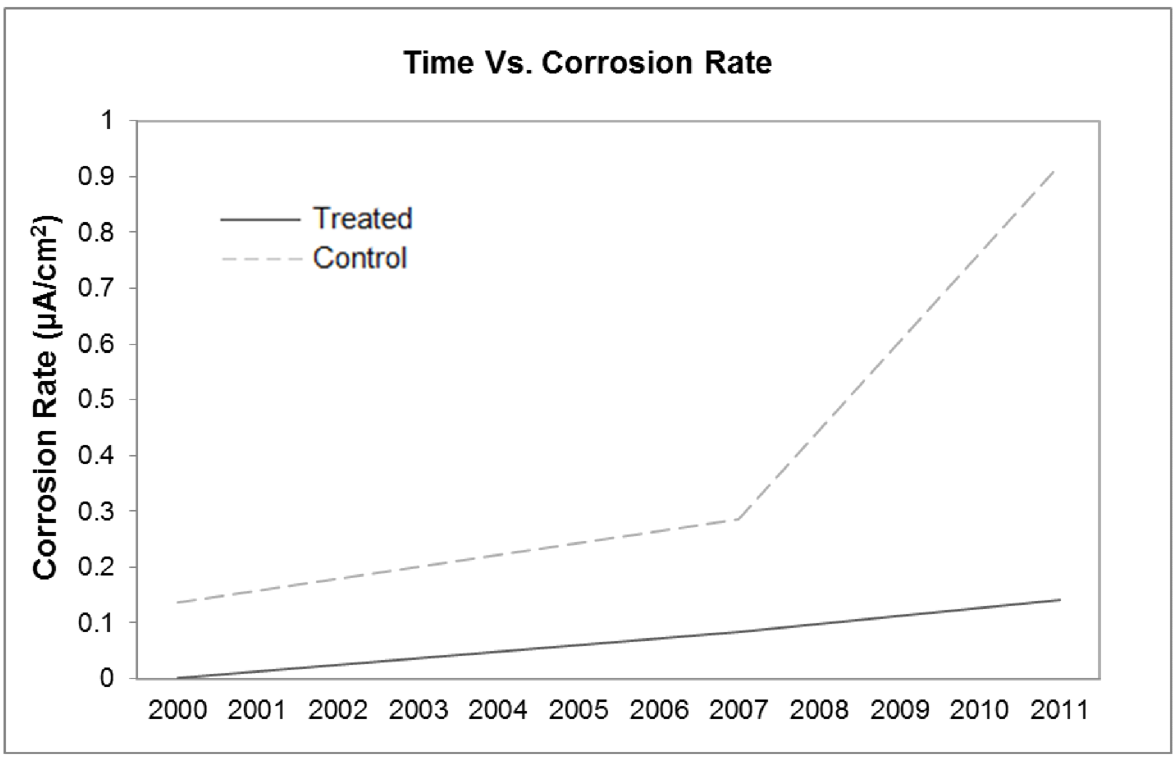

Figure 1: Average corrosion rates of the Randolph Avenue Bridge

Weather can be a factor that affects readings. Of particular importance is the humidity level as the moisture in the concrete affects the conductivity and readings that are taken. To mitigate the effects of the weather, the surface was prepared using ASTM C876. This method requires a specific pattern of adding moisture to the concrete so a consistent environment is achieved across all areas.

Alkalinity Levels.

The core samples from 2011 were tested and exhibited average alkalinity levels between 1640 and 1840 mg/L. The samples that were taken from the treated side of the bridge show results of higher alkalinity levels, which can signify the presence of corrosion inhibitor and resistance to carbonation. The data is compiled in Table 9.

Table 9
Alkalinity results organized by the section of the Randolph Avenue Bridge

Treated			Control		
Sample	Alkalinity (mg/L)	Average (mg/L)	Sample	Alkalinity (mg/L)	Average (mg/L)
NW 0-1"	1680	1800	SW 0-1"	1800	1800
NW 1-2"	1800		SW 1-2"	1920	
NW 2-3"	1920		SW 2-3"	1680	
NC 0-1"	1800	1840	SC 0-1"	1920	1800
NC 1-2"	1800		SC 1-2"	1800	
NC 2-3"	1920		SC 2-3"	1680	
NE 0-1"	1920	1760	SE 0-1"	1560	1640
NE 1-2"	1800		SE 1-2"	1680	
NE 2-3"	1560		SE 2-3"	1680	

Half-Cell Potentials.

The half-call potential readings taken in 2011 can be seen in Table 10. The average reading for each side of the bridge shows that the potential for corrosion is higher on the control side than that of the treated side according to Table 6.

Table 10
Half-cell potential values from each segment of the Randolph Avenue Bridge

	Treated			Control		
Rebar	NW (mV)	NC (mV)	NE (mV)	SW (mV)	SC (mV)	SE (mV)
1	-378	-130	-130.3	-84	-332	-231
2	-331.3	-128.7	-93.3	-91.5	-397.5	-248.5
3	-294.3	-98.3	-59.7	-88.5	-381.5	-187
4	-239.7	-83.3	-68.3	-104	-400	-150
5	-227.3	-72.3	-82.7	-97.5	-392	-125.5
6	-183.7	-79	-37	-99	-400	-117.5
7	-185	-69.3	-36.7	-122	-404.5	-140
8	-170.3	-72	-46.3	-163.5	-381.5	-147
9	-156	-78	-79.3	-231	-397.5	-181
10	-172	-76.3	-167	-	-	-206.5
11	-190.7	-74.3	-192	-	-	-270.5
12	-	-97.3	-189.7	-	-	-
13	-	-96.3	-191.7	-	-	-
14	-	-	-218.7	-	-	-
Average	-229.8	-88.9	-113.8	-120.1	-387.4	-182.2

The time versus average half-cell potential results, shown in Figure 2, shows that the potential for corrosion within the bridge is higher on the control side and has been for 20 years. This data along with the rest of the supporting information suggests that levels of corrosion in the treated side are lower than in the control.

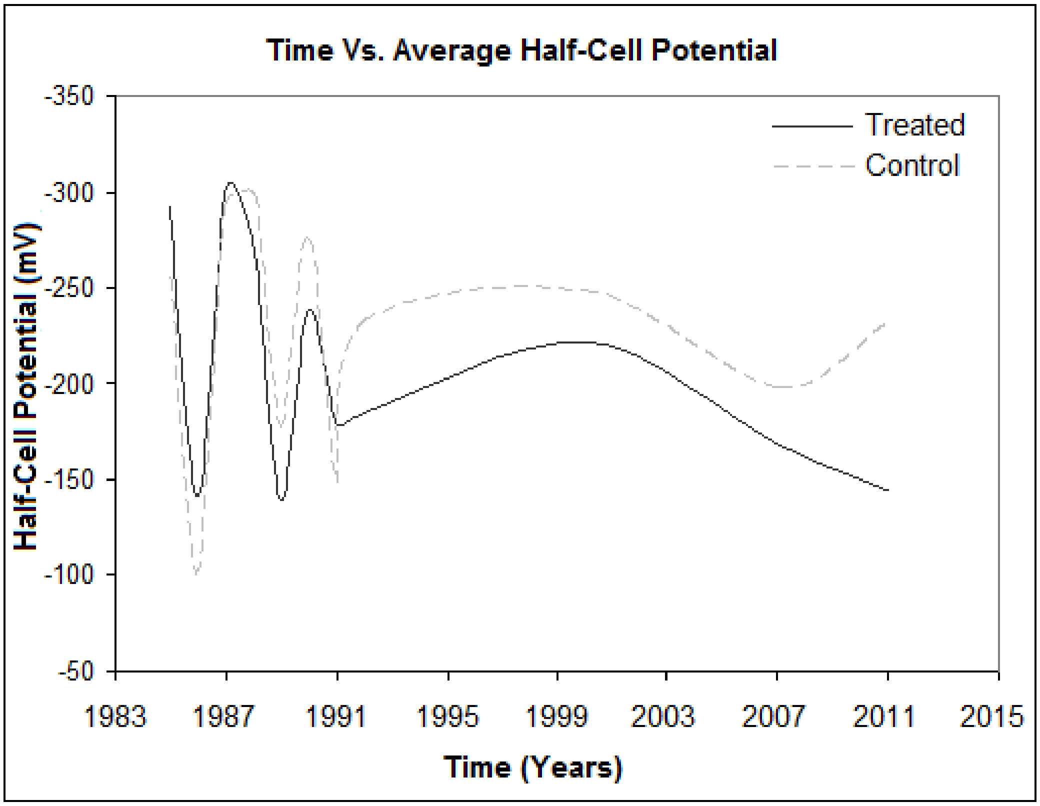

Figure 2: Average half-cell potentials of the Randolph Avenue Bridge

Apple Street Parking Garage

Corrosion Rate Readings.

All readings at the Apple Street Parking Garage were performed using Linear Polarization Device 3. All locations had average readings in the passive to low levels according to Table 4. Fifty readings were taken in total; 10 readings at 5 different locations throughout the garage. All readings can be seen in Table 11.

Table 11
Corrosion current readings for treated areas of the Apple Street Parking Garage

Reading	Location 1 (μA/cm^2)	Location 2 (μA/cm^2)	Location 3 (μA/cm^2)	Location 4 (μA/cm^2)	Location 5 (μA/cm^2)
1	2.97	1.75	0.51	1.62	3.12
2	1.76	1.35	0.57	0.65	0.89
3	3.01	1.08	0.47	0.81	0.36
4	1.22	1.37	0.26	1.17	0.38
5	1.59	6.76	0.32	0.96	0.25
6	3.48	1.38	0.41	0.24	0.24
7	1.55	0.96	0.6	0.26	0.52
8	2.15	8.22	0.4	0.92	0.22

9	6.43	9.71	0.45	0.62	6.63
10	5.28	3.37	0.38	1.2	2.86
Average	2.94	3.6	0.43	0.84	1.55

CONCLUSIONS

Aminoalcohol and amine carboxylate based corrosion inhibitors have proven beneficial when used in repair of concrete that has cracked and spalled due to chloride induced corrosion of the embedded reinforcing steel. In the Randolph Avenue Bridge, corrosion was significantly decreased compared to the control due to the presence of the aminoalcohol corrosion inhibiting admixture. The Apple Street Parking Garage is showing very low corrosion currents due to the high affinity of the amine carboxylate corrosion inhibiting admixture and the penetrating corrosion inhibitor. The lower corrosion currents are due to the adsorption of the aminoalcohol and amine carboxylate molecules on the embedded reinforcing steel, showing that these molecules can displace existing chloride and water molecules. Thus, corrosion rates can be decreased significantly.

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