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

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Corrosion inhibitors used in reinforced concrete structures can greatly increase service life and reduce long-term maintenance costs. In this work, migrating corrosion inhibitors were utilized in the repairs of two 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 two projects covered in this article are the Randolph Avenue Bridge in St. Paul, Minnesota, and the Apple Street Parking Garage in Dayton, Ohio. The bridge was built in 1963 and chloride-induced corrosion of the reinforcing steel eventually caused major spalling and cracking of the concrete decks. In 1986 the top deck was repaired with a concrete overlay that incorporated a migrating corrosion inhibitor in one side, while the other was left untreated as the control. The garage is of pre-topped precast double tee construction. The lower two levels were built in 1986 and upper levels in 1989. In the early 2000s, the double tees exhibited advanced corrosion. Repairs were completed in 2006 using a ready-mixed concrete containing a migrating corrosion inhibitor.

Experimental Procedures

Randolph Avenue Bridge

Background

Constructed in 1963, the Randolph Avenue Bridge spans Interstate 35E in Saint Paul, Minnesota (Figure 1). 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 bridge was repaired in a project sponsored by the Minnesota Department of Transportation (DOT). Both sides of the deck were repaired using a low-slump, dense concrete overlay that incorporated a migrating corrosion inhibiting admixture in 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 vs. the untreated "control" eastbound lanes (Figure 2).

The rehabilitation of this bridge was part of a Federal Highway Administration (FHWA) 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 Corp. in 2000, 2007, and 2011.

TABLE 1

MIX DESIGN PARAMETERS OF THE RANDOLPH AVENUE BRIDGE REPAIR

Component	Control (lb/yd^3)	Treated (lb/yd^3)
Type I cement	836	836
Water	270	270
w/c ratio	0.32	0.32
Coarse aggregate	1,385	1,385
Fine aggregate	1,374	1,374
Water-reducing admixture	0.25	0.25
Air-entraining agent	0.073	0.073
Corrosion inhibitor	—	0.95

The rehabilitation process included the application of a low-slump dense concrete that varied in depth from 2.3 to 4.2 in (58.4 to 106.7 mm). Table 1 shows the mix design of the overlay. An amino alcohol-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 in (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 toward the northeast.

Corrosion assessments were conducted on the eastbound (control) and westbound (amino alcohol) travel lanes of the structure by Virginia Tech researchers on two occasions that took place in 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 a 3LP[†] Meter (Linear Polarization Device 1). Prior to the assessments completed by Virginia Tech, the repair was part of a FHWA Project until 1990.

FIGURE 1

Constructed in the early 1960s, the Randolph Avenue Bridge in St. Paul, Minnesota, required extensive repairs from the results of chloride-induced corrosion of the reinforcing steel.

FIGURE 2

The westbound lanes of the Randolph Avenue Bridge were treated with a migrating corrosion inhibiting admixture and compared to the eastbound lanes that were refurbished with an untreated concrete overlay.

[†] Trade name.

TABLE 2

CORROSION INTENSITY VS. CORROSION CURRENT AND RATE OF CORROSION FOUND BY LINEAR POLARIZATION DEVICE 1

Corrosion Current (μA/cm²)	Corrosion Rate (μm/year)	Intensity of Corrosion
<0.5	<5.8	Passive condition
0.5–2.7	5.8–31.8	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)

TABLE 3

CORROSION INTENSITY VS. CORROSION CURRENT AND RATE OF CORROSION FOUND BY LINEAR POLARIZATION DEVICE 2

Corrosion Current (μA/cm²)	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

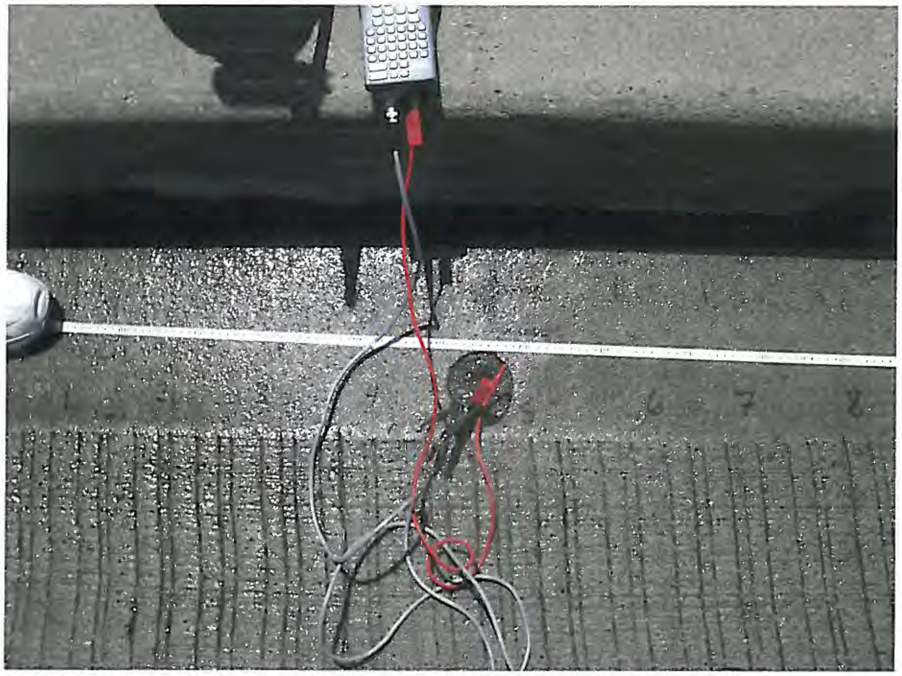
CORROSION INTENSITY VS. CORROSION CURRENT AND RATE OF CORROSION FOUND BY LINEAR POLARIZATION DEVICE 3

Corrosion Current (μA/cm²)	Corrosion Rate (μm/year)	Intensity of Corrosion
<0.5	<1.2	Passive condition
0.5–5	5.8–58	Low corrosion
5–15	58–174	Moderate corrosion
>15	>174	HIgh corrosion

In November 2000, technicians returned to the bridge and took new measurements. These included linear polarization readings obtained by a Gecor 6† (Linear Polarization Device 2) instrument, and copper/copper sulfate (Cu/CuSO$_4$) 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 Linear Polarization Device 2 and a Galvapulse† (Linear Polarization Device 3) instrument (Figure 3) were also taken to determine corrosion current, corrosion rate, and concrete resistivity.

FIGURE 3



Linear Polarization Device 3 was used to help determine corrosion current, corrosion rate, and concrete resistivity on the concrete bridge decks.

Chloride Contamination Levels

Powdered concrete samples for chloride analysis were taken at mean depths of 0 to 1, 1 to 2, and 2 to 3 in (0 to 25, 25 to 51, and 51 to 76 mm) from six locations, three on each side of the bridge. Samples were taken using a rotary impact type drill with a 0.5-in size 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 min and then 80 mL of stabilizing solution was added. A calibrated electrode coupled to an Orion† 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[1] Procedure C. The standard deviation for this chloride test was determined by testing the six pulverized concrete quality assurance (QA) samples of

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†Trade name.

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.

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 nondestructive technique that works by locating the rebar (Figure 4), applying a small current to it, and measuring the change in the potential. Then the polarization resistance, R_p (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:

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

Each device used on the bridge has different criteria for evaluating the corrosion rates (Tables 2-4[2-4]).

Concrete Resistivity Measurements

Linear Polarization Device 2 also calculates the concrete resistivity by means of Equation (2):

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

where R = resistance by the "IR drop" from a pulse between the sensor counter-electrode and the rebar network and D = the 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.[3]

TABLE 5

CORRELATION OF RESISTIVITY MEASUREMENTS TO CORROSION RATE USING LINEAR POLARIZATION DEVICE 2

Resistivity	Corrosion Rate
>100–200 kΩ·cm	Very low, even with high chloride and carbonation
50–100 kΩ·cm	Low
10–50 kΩ·cm	Moderate to high where steel is active
<10 kΩ·cm	Resistivity is not the parameter controlling the corrosion rate

TABLE 6

CORROSION POTENTIAL OF HALF-CELL POTENTIAL READINGS USING A CSE

Potential	Probability of Corrosion
>–200 mV	Less than 10%
–200 mV to –350 mV	Indeterminate corrosion risk
<–350 mV	Greater than 90%

FIGURE 4

Ground-penetrating radar was used to locate reinforcing steel in the bridge.

Half-Cell Potentials

ASTM C876[5] corrosion half-cell potentials were measured for both the eastbound and westbound travel lanes with a $Cu/CuSO_4$ electrode (CSE) in June 1991, August 1992, November 2000, June 2007, and July 2011 and with Linear Polarization Device 2 in November 2000, June 2007, and July 2011. According to ASTM C876, the results can be interpreted in Table 6.[6]

Carbonation

Carbonation of concrete is a process by which carbon dioxide (CO_2) from the air penetrates the concrete and reacts with the hydroxides, such as calcium hydroxide [$Ca(OH)_2$], 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

TABLE 7

AVERAGE CHLORIDE LEVELS OF RANDOLPH AVENUE BRIDGE

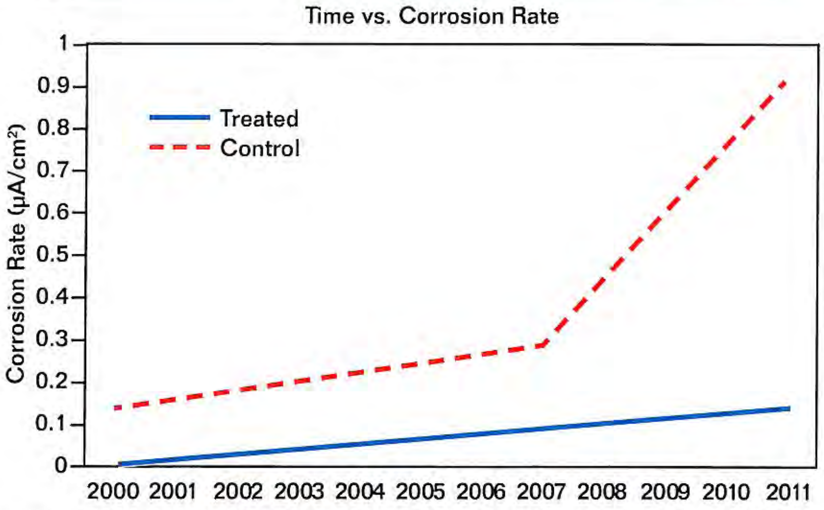
Year	Treated Side (lb/yd^3)			Control Side (lb/yd^3)		
	0–1 in	1–2 in	2–3 in	0–1 in	1–2 in	2–3 in
1991	3.5	0	0.7	7.7	2.5	1.9
1992	6.5	1.1	1.9	9.5	3.5	2.5
2000	11.7	1.6	1.3	17.2	6.2	2.4
2007	11.7	1	2.6	20	7.4	2.3
2011	12.3	4.9	1.8	14.7	6.6	3.5

TABLE 8

AVERAGE CHLORIDE LEVELS OF RANDOLPH AVENUE BRIDGE

	Treated Lanes			Control Lanes		
Year	Northwest (µA/cm^2)	North Central (µA/cm^2)	Northeast (µA/cm^2)	Southwest (µA/cm^2)	South Central (µA/cm^2)	Southeast (µA/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 5



Average corrosion rates of the Randolph Avenue Bridge.

corrosion; consequently, concrete should be resistant to carbonation to prevent steel corrosion.[7] The carbonation of powdered concrete samples taken from the Randolph Avenue Bridge was determined by using phenolphthalein (alkalinity) measurements.

Apple Street Parking Garage

Background

The Apple Street Parking Garage in Dayton, Ohio 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 that 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.

> ***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 of 0.4202 µA/cm^2, a reduction of 67%.***

The concrete reinforcement is a steel mesh that is located 1.75 to 2 in (44.5 to 50.8 mm) deep. The mesh was laid out in a 4 ft by 8 ft (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 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. Table 4 shows the interpretation of these readings.

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% of the concrete.[8] This converts to 0.4% by weight of the cement and 3.35 lb/yd^3 (1.98 kg/m^3).

Chloride content readings were taken at 0 to 1, 1 to 2, and 2 to 3 in (0 to 25, 25 to 51, and 51 to 76 mm) from three 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. The chloride levels have continued to rise at the level of the steel (Table 7).

Corrosion Current Readings

Corrosion currents of the 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 taken in July of 2011 are substantially higher at almost all points on the bridge. As shown in

TABLE 9

ALKALINITY RESULTS ORGANIZED BY SECTION OF THE RANDOLPH AVENUE BRIDGE

Treated			Control		
Sample (in)	Alkalinity (mg/L)	Average (mg/L)	Sample (in)	Alkalinity (mg/L)	Average (mg/L)
NW 0-1	1,680	1,800	SW 0-1	1,800	1,800
NW 1-2	1,800		SW 1-2	1,920	
NW 2-3	1,920		SW 2-3	1,680	
NC 0-1	1,800	1,840	SC 0-1	1,920	1,800
NC 1-2	1,800		SC 1-2	1,800	
NC 2-3	1,920		SC 2-3	1,680	
NE 0-1	1,920	1,760	SE 0-1	1,560	1,640
NE 1-2	1,800		SE 1-2	1,680	
NE 2-3	1,560		SE 2-3	1,680	

TABLE 10

HALF-CELL POTENTIAL VALUES FROM EACH SEGMENT OF THE RANDOLPH AVENUE BRIDGE

	Treated Side (lb/yd^3)			Control Side (lb/yd^3)		
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

TABLE 11

CORROSION CURRENT READINGS FOR TREATED AREAS OF THE APPLE STREET PARKING GARAGE

Reading	Location 1 ($\mu A/cm^2$)	Location 2 ($\mu A/cm^2$)	Location 3 ($\mu A/cm^2$)	Location 4 ($\mu A/cm^2$)	Location 5 ($\mu A/cm^2$)
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	0.60	0.26	0.52
8	2.15	8.22	0.40	0.92	0.22
9	6.43	9.71	0.45	0.62	6.63
10	5.28	3.37	0.38	1.20	2.86
Average	2.94	3.60	0.43	0.84	1.55

Table 7, the control side has reached the chloride threshold at the depth of the reinforcing steel. Table 8 indicates 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 $\mu A/cm^2$ compared to the treated center section of 0.4202 $\mu A/cm^2$, 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 (Table 10).

Table 8 shows the average corrosion current data and compared 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.

Figure 5 shows the comparison of corrosion rate readings on the control side vs. the treated side using Linear Polarization Device 2. Prior to 2007, both sides of the bridge showed average corrosion rates in the passive range, but 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.

> ***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.***

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 1,640 and 1,840 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. Table 9 shows the results from the 2011 samples.

Half-Cell Potentials

Table 10 shows the half-cell potential readings taken in 2011. 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.

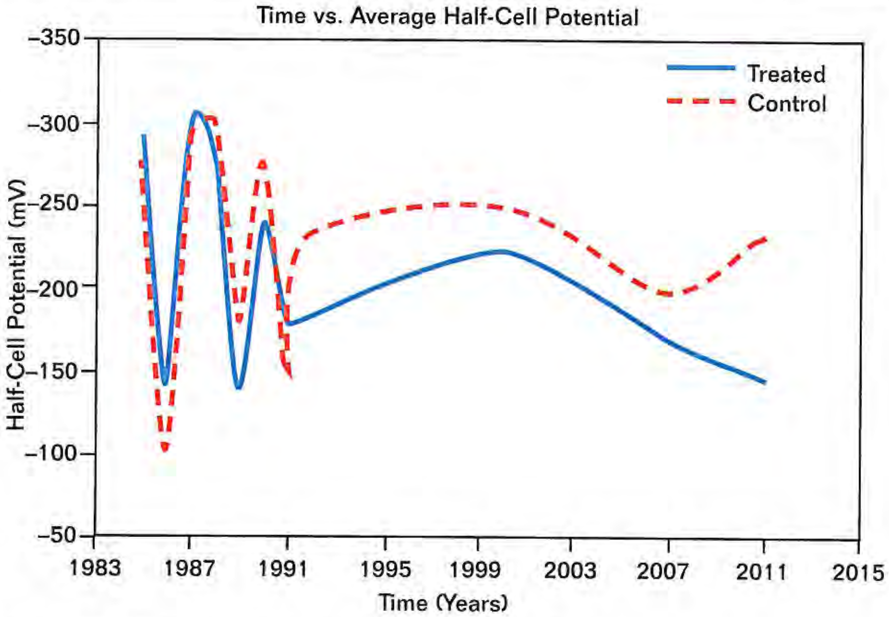
The time vs. average half-cell potential results, shown in Figure 6, shows that the potential for corrosion within the bridge is higher on the control side and has been for 20 years. These data along with the rest of the supporting information suggest that levels of corrosion in the treated side are lower than in the control.

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 (Table 4). Fifty readings were taken in total; 10 readings at five different locations throughout the garage. Table 11 presents all readings taken in 2009.

FIGURE 6



Average half-cell potentials of the Randolph Avenue Bridge.

Conclusions

Amino alcohol 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 amino alcohol 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 amino alcohol 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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