

**EFFECTIVENESS OF
ELECTROCHEMICAL CHLORIDE
EXTRACTION
FOR THE IOWA AVENUE
PEDESTRIAN BRIDGE**

Final Report

By

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**Sponsored by
Iowa Department Transportation
Iowa Highway Research Board
Project # TR-499**

**PUBLIC POLICY CENTER
CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF IOWA
March 2005**

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The opinions, finding, and conclusions expressed in this publication are those of the author and not necessarily those of the Iowa Department of Transportation.

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ABSTRACT

The main objective of this study is to determine the effectiveness of the Electrochemical Chloride Extraction (ECE) technique on a bridge deck with very high concentrations of chloride. This ECE technique was used during the summer of 2003 to reverse the effects of corrosion, which had occurred in the reinforcing steel embedded in the pedestrian bridge deck over Highway 6, along Iowa Avenue, in Iowa City, Iowa, USA. First, the half cell potential was measured to determine the existing corrosion level in the field. The half-cell potential values were in the indecisive range of corrosion (between -200 mV and -350 mV). The ECE technique was then applied to remove the chloride from the bridge deck. The chloride content in the deck was significantly reduced from 25 lb/cy to 4.96 lb/cy in 8 weeks. Concrete cores obtained from the deck were measured for their compressive strengths and there was no reduction in strength due to the ECE technique. Laboratory tests were also performed to demonstrate the effectiveness of the ECE process. In order to simulate the corrosion in the bridge deck, two reinforced slabs and 12 reinforced beams were prepared. First, the half-cell potentials were measured from the test specimens and they all ranged below -200 mV. Upon introduction of 3% salt solution, the potential reached up to -500 mV. This potential was maintained while a salt solution was being added for six months. The ECE technique was then applied to the test specimens in order to remove the chloride from them. Half-cell potential was measured to determine if the ECE technique can effectively reduce the level of corrosion.

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INTRODUCTION

Corrosion, by general definition, is the deterioration of metal by the electrochemical reaction in an aqueous environment, resulting in rust and metal loss. This phenomenon takes place in the steel used for concrete reinforcement, causing the structure to be broken down earlier than its design life. It was reported in 1996 that this electrochemical reaction resulted in over 60% of all interstate highway bridges needing serious repair. These repairs would cost over \$225 billion (Fuhr, 1998). Furthermore, it is estimated that the U.S. annually spends \$8.3 billion to repair highway bridges degraded by corrosion, according to the final report on cost of corrosion in March of 2002 (Koch, 2003).

Electrochemical Chloride Extraction (ECE) is a method which treats corrosion damage of reinforced concrete structures by chloride removal. The Kansas Department of Transportation (KDOT) developed this method in 1973. It has since been widely used in many situations such as bridge decks, and the vertical surfaces of piers. However, few studies in Iowa have been performed on the ECE process in reinforced concrete structures.

This study was designed to evaluate the effectiveness of ECE on the useful life of bridge decks. It will also provide a better understanding of the ECE process to local engineers and contractors. This report will explain how corrosion occurs in reinforced concrete structures and how ECE affects the structure. In addition, the effectiveness will be shown with field and laboratory tests.

The four parts of this report discuss (1) a background study and literature review on corrosion, (2) experimental method, (3) results and discussion, and (4) conclusion and future work. The sections on literature review of corrosion describe the principles of corrosion of steel in concrete, corrosion monitoring techniques and the method of applying ECE to reverse some of the effects of corrosion. The sections on experimental method will explain the procedure to measure the effectiveness of ECE in the laboratory as well as in the field. Results from these tests will be discussed in the third section. The final section will summarize the effectiveness of the ECE method and then review this research to suggest future work.

BACKGROUND STUDIES

Corrosion of Steel in Concrete

Generally, reinforcing steel in a concrete structure does not corrode in the beginning of its service life, because a passive oxide film forms on its surface and protects it from the corrosive environment. However, reinforcing steel is likely to corrode when chloride ions from de-icing chemicals are present, even if the concrete structure is built with good quality. The threshold value for steel corrosion is approximately 1.5 lb of chloride per cubic yard of concrete. If chlorides sufficiently infiltrate the concrete, the passive film on the rebar is ruined, and corrosion is initiated in a local area. This produces rust leading to a volume increase, which produces tensile forces within the concrete. Subsequently, cracks originate from near the reinforcing steel. Concrete fractures at a very low tensile stress. If the cracks reach the surface, a piece of concrete

separates from the reinforced concrete structure. The concrete must be repaired to recover its strength for safety (Daily, 2003). The electrochemical corrosion mechanism in concrete induced by chloride can be seen in Figure 1.

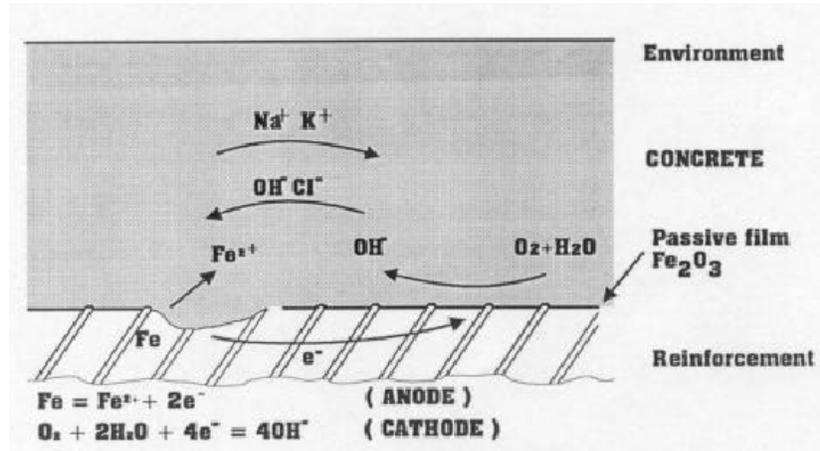
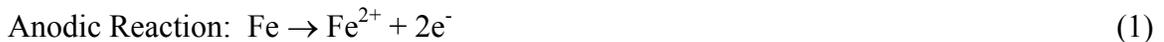


Figure 1 Mechanism of Reinforcement Corrosion (Klinghoffer, 1995)

The area where the metal ion goes into solution becomes the anodic region. If the metal is iron (Fe), it goes into the solutions to form ferrous ions (Fe^{2+}) and two electrons ($2e^-$) (Cho, 1997).



The cathodic reaction is slow in alkaline media because of the low concentration of hydrogen. However, it is accelerated due to the depolarizing action of dissolved oxygen. Therefore, the corrosion rate is proportional to the oxygen concentration as illustrated below.

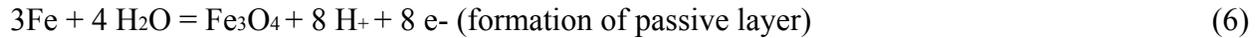
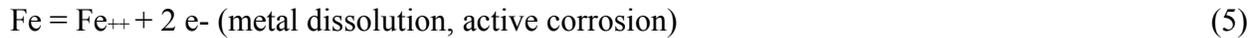


The quantity of electricity flowing through the local cells is related to the amount of corrosion. In ordinary conditions of steel reinforcement in concrete, where the pH is high, the hydrogen concentration is low, and the oxygen supply is minimal, an anodic coating builds up on the steel. However, when chloride containing deicing materials are applied, the protective anodic film of iron oxide and hydrogen are removed by forming the soluble chloride compounds and thus leaving the steel exposed to further electrochemical attack.

To maintain equilibrium of electrical charges, an equivalent quantity of hydrogen is plated out on adjacent surfaces of the metal, the cathode. The thin film of hydrogen inhibits further

corrosion unless the film is removed. Anodic and cathodic reactions may be represented as follows,

The anode reactions are:



The released electrons travel through the steel to the local cathode where they are used in the oxygen reduction reaction,



These reactions lead to the development of regions of differing electrochemical potentials and resulting in current flow within the concrete. Measuring the potentials and the magnitude of corrosion currents may, in principle, enable the detection of existing corrosion sites and allow the present rate of corrosion to be assessed.

Corrosion Monitoring with Half-cell Potential Technique

This method was first developed in the late 1950's and has since been used extensively for the assessment of concrete bridges. It was adopted in 1977 as ASTM method C876. The method measures the electrochemical potential of reinforcement against a reference electrode placed on the concrete surface. The basic setup of this method is shown in Figure 2. Prior to testing, electrical continuity of reinforcement is checked by applying a potential difference across rebar at different sections of the structure. Normally a measured resistance of less than 1 ohm is used to indicate continuous electrical connection of reinforcement.

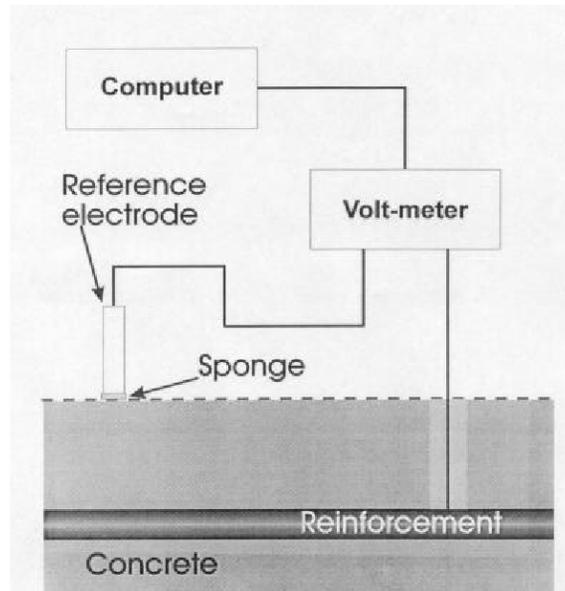


Figure 2 Basic Setup of Half-cell Method (Oskar, 1995)

In order to ensure a good contact with the reference electrode the concrete surface must be moist. A number of reference electrodes may be used, including copper/copper sulfate (CSE), silver/silver chloride or calomel (SCE). Potentials are measured with a high impedance voltmeter (>10 Mega ohm) to ensure low current conditions during testing. ASTM C876-87 provides a classification for assessing the results of the half-cell potential mapping as shown in Table 1.

Table 1 Half Cell Assessment Classification per ASTM C-876

Voltage	Probability of Corrosion
-200mv	< 5%
-200~-350mv	~50%
-350mv	>95%

The measured electrochemical potentials are affected by a number of factors and these should be considered in interpreting the results. One of the most important factors is the quality of the cover concrete, particularly its moisture condition and contamination by carbonation and/or chlorides. Also, access to oxygen strongly determines the potential values of passive steel in concrete. Low oxygen content results in decrease of the potential. In wet concrete, due to low oxygen admission, conditions may prevail resulting in a shift of the potential to comparably low values. Consequently, passive steel may show low potentials similar to those of corroding steel,

which could lead to the risk that passive areas under low aeration conditions will be classified as corroding areas.

Electrochemical Chloride Extraction (ECE) Technique

The concept of removing chloride ions from concrete by electrochemical migration was born in 1973 out of Kansas Department of Transportation (KDOT) experiments on electro-stabilization of clayey soils. Since then, numerous studies have shown it is possible to remove chlorides from concrete using electrochemical means. The benefit of removing the chloride ions electrochemically is that contaminated concrete that is still structurally sound would not require demolition after the application of the chloride removal process.

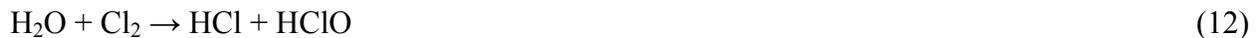
ECE technique produces hydroxyl ions at the cathode or the rebars, while water is decomposed at the anode. As shown in the following reactions, hydrogen gas can be produced at the cathode, and chlorine evolution and/or acidification of the electrolyte can occur at the anode during ECE. Two possible reactions at the cathode during ECE are:



At the anode, ECE can generate the following reactions:



In addition, the following chemical reaction can occur in the electrolyte:



As hydroxyl ions are produced at the cathode, the pH adjacent to the steel increases, which is beneficial for the rebar, but these electrochemical reactions can create adverse effects like hydrogen embrittlement or alkali aggregate reaction.

EXPERIMENTAL METHOD

Field Corrosion Test

In order to investigate the effectiveness of ECE technique, the properties of the bridge deck related to corrosion were examined. First, the half-cell potential technique was used for the determination of corrosion probability in the bridge deck. A beam at the Iowa Avenue Bridge in Iowa City, as shown in Figure 3, was selected to measure the corrosion. Values from 30 spots in the beam, as shown in Figure 4 and 5, were collected to improve the accuracy.

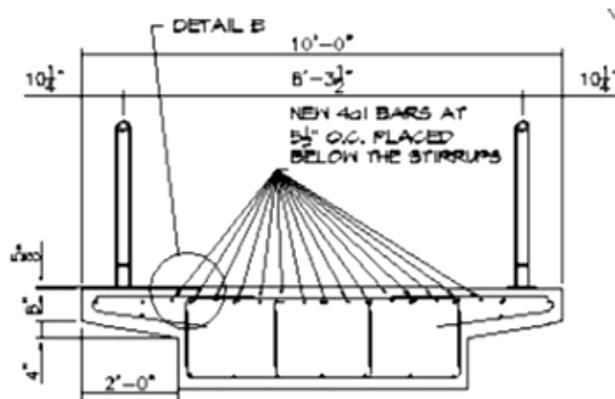


Figure 3 Cross Section of the Test Bridge Deck Near the Pier

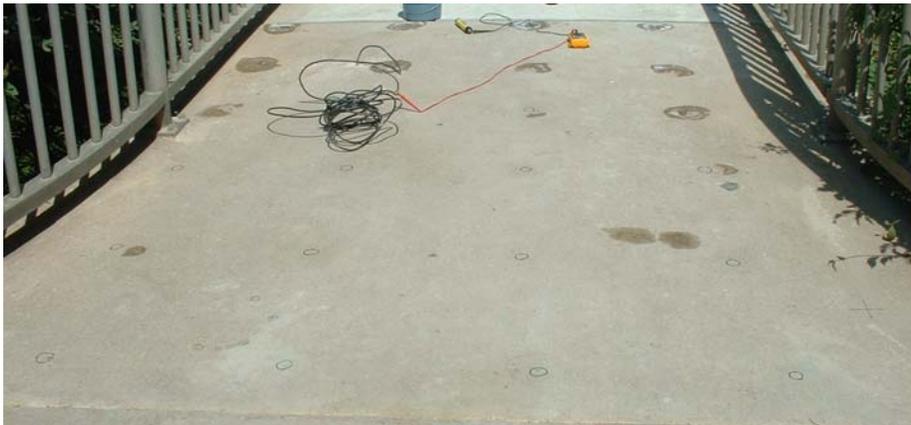


Figure 4 Half Cell Test Measurement Locations

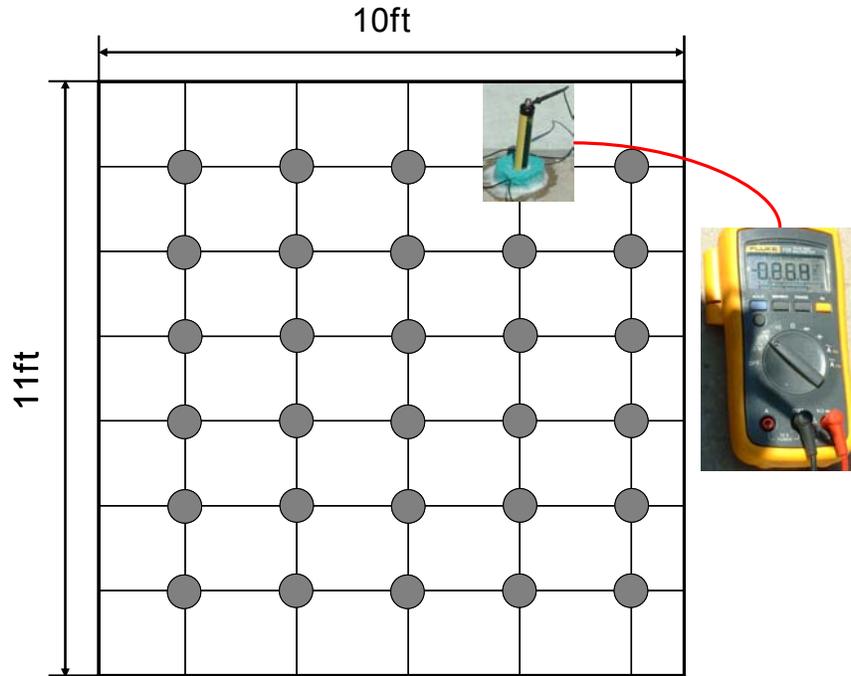


Figure 5 Half Cell Test Locations

Values of the potential were measured per the requirements of ASTM C-876. The testing pattern layout is shown in Figure 6. Detergent solution was used to improve conductivity between the concrete surface and the half cell, which was used vertically. When potential values were read, the temperature was also recorded for calibration. Each value of potential was collected four times in three days.



Figure 6 Measuring Potential with Half-cell Reference

Electrochemical Extraction Method

Electrochemical chloride extraction (ECE) works by setting up an electrical circuit between an anode placed on the surface of the deck (steel or titanium mesh), and the deck reinforcing steel (rebar), which is the cathode. The negatively charged chloride ions near the rebar migrate toward the positively charged anode mesh. The chloride is released as either chlorine gas or trapped in the electrolyte. The chemical reaction would be $\text{H}_2\text{O} + \text{Cl}_2 \rightarrow \text{HCl} + \text{HClO}$.

Even though the steel is less expensive, titanium mesh is preferred, because the steel is consumed during the ECE process. Potable water is most often used as the electrolyte, although calcium hydroxide solutions have been used. The calcium hydroxide reduces the chances that the water will become acidic and lessens the evolution of chlorine gas.

During the ECE process it is important to maintain good contact between the electrolyte and the concrete surface. The felt landscaping mats were used for this purpose. The electrical circuits were set up in 4 zones, using 4 rectifiers, 40V maximum. Each rectifier served 900 sf to 1000 sf of deck. Connections to the rebar were made at 2 to 4 locations per zone. A 480 Volt line was run from the University of Iowa campus near Hillcrest Dormitory.

The extraction was done over a period of 8 weeks during the summer of 2003, and cost approximately \$88,000, which is about \$25 per square foot of bridge deck. Keith Stewart, with Vector Construction, Inc., coordinated the ECE process.

The process of chloride extraction in the field for this study involved a number of steps. (1) A layer of lime was placed on the deck. (2) Then a layer of felt (landscaping mat) was placed on the lime. See Figure 7 below.



Figure 7 Felt Mat Placed on the Deck

(3) Next, the titanium mesh was placed. Steel mats were used on the spiral ramps to the deck, in lieu of the titanium, so the expensive rolls of titanium would not need to be cut. See Figures 8 & 9 next page.



Figure 8 Titanium Mesh Placed on the Deck



Figure 9 Steel Mats Placed on the Spiral Ramps to the Deck

(4) Another layer of felt was placed on top of the steel and titanium mesh (anode). (5) Then a soaker hose was snaked across the deck, and a final layer of 6 mil plastic sheets put in place. The concrete surface was kept wet during the extraction. Hoses were connected over a long distance to bring water to the pedestrian bridge. A 2 x 2 silicone strip was placed at the edges of the deck over the traffic lanes to minimize water on cars.



Figure 10 Soaker Hoses & Plastic Sheets Placed on the Felt

The electric lines and rectifiers were put in place. To ensure a consistent voltage, there were four zones (4 rectifiers) which were 40 Volt maximum. Each rectifier serves 900 to 1000 square feet of deck. Connections to the rebar were made at 2 to 4 locations per zone. For power, a 480 Volt electric line was run from the University of Iowa campus. A direct current of around 1 A/m² of surface area was maintained. The ECE system was left in place for a period of 8 weeks.



Figure 11 Electrical Connections to the Deck Rebar



Figure 12 ECE System in Place

Following the extraction, reference cells were embedded in the deck to monitor the long term effects of the extraction. To protect the deck surface, a urethane membrane was applied by roller on the deck surface and sides. Sand was spread on the wet membrane to provide traction.

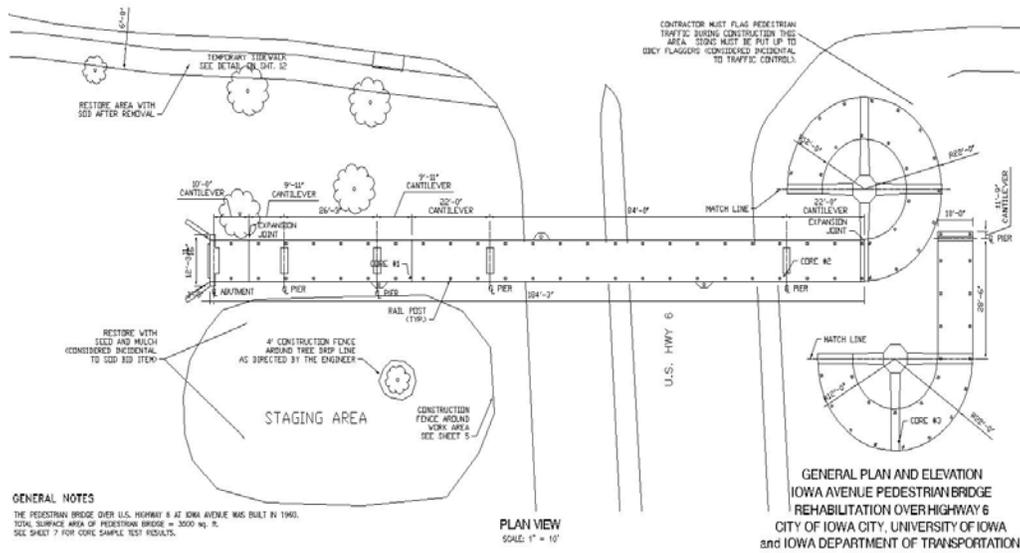


Figure 13 Plan View of Bridge

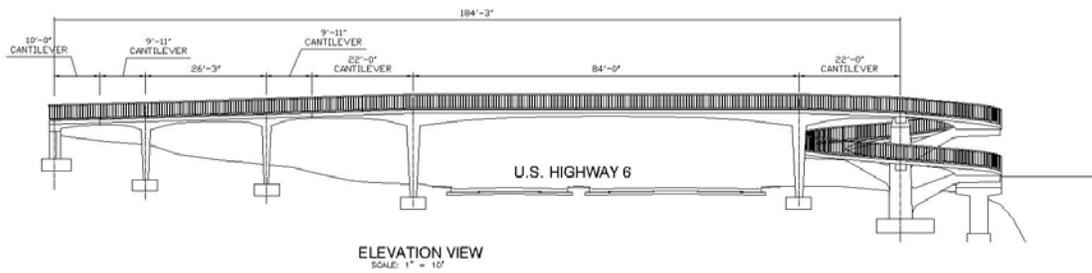


Figure 14 Elevation View of Bridge

Laboratory Corrosion Test

In order to evaluate the effectiveness of ECE in the laboratory, concrete beam and slab specimens were made with a typical concrete mix design used for a bridge deck as follows:

Table 2 Concrete Mix Design (A Batch, 2 ft³)

	Weight (lbs)
Cement, ASTM C-150	44.2
Fine aggregates (S.G. 2.60)	112.6
Coarse aggregates (S.G. 2.55)	107.8
Water	26.8
TOTAL	291.4
Water/Cement Ratio	0.57
Slump (in.)	2.5 in.

The size of beam specimens was 21.5" x 6" x 6" (= 0.5ft³). See Figure 15. Slab specimens were 21" x 21" x 7" (= 2ft³). Steel reinforcing bars (35/30 in. long) were placed in the center of the slab thickness as shown in Figures 16 and 18. Rebars were sandblasted and each concrete specimen had a 21.5" long crack in the center, which was artificially created by using a 1/32" thick aluminum sheet as shown in Figures 17 and 18.

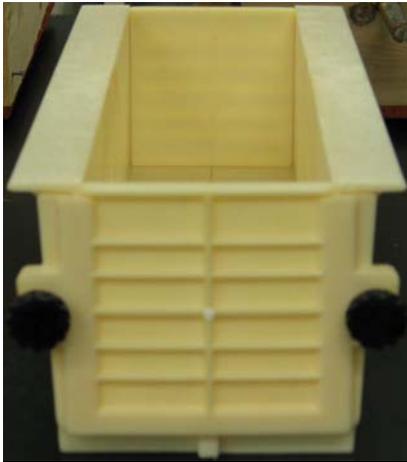


Figure 15 Beam Specimen



Figure 16 Slab Specimen



Figure 17 Beam Specimen Cracked



Figure 18 Slab Specimen Cracked

As shown in Table 3 and Figure 19, a total of 12 beams and 2 slab specimens were prepared. Beam specimens were separated into four testing groups: 1) Crack, salt supply, ECE supply, 2) Crack, salt supply, no ECE supply, 3) No crack, salt supply, no ECE supply, and 4) No crack, water supply, no ECE supply. Two slab specimens were used to test the following conditions: 1) Crack, salt supply, ECE supply and 2) Crack, water supply, no ECE supply.

Table 3 Type of Specimen in Corrosion Test

	Reference	Salt	Total
Slab	1	1	2
Beam with Big Rebar	3	3	6
Beam with Small Rebar	3	3	6
TOTAL	7	7	14

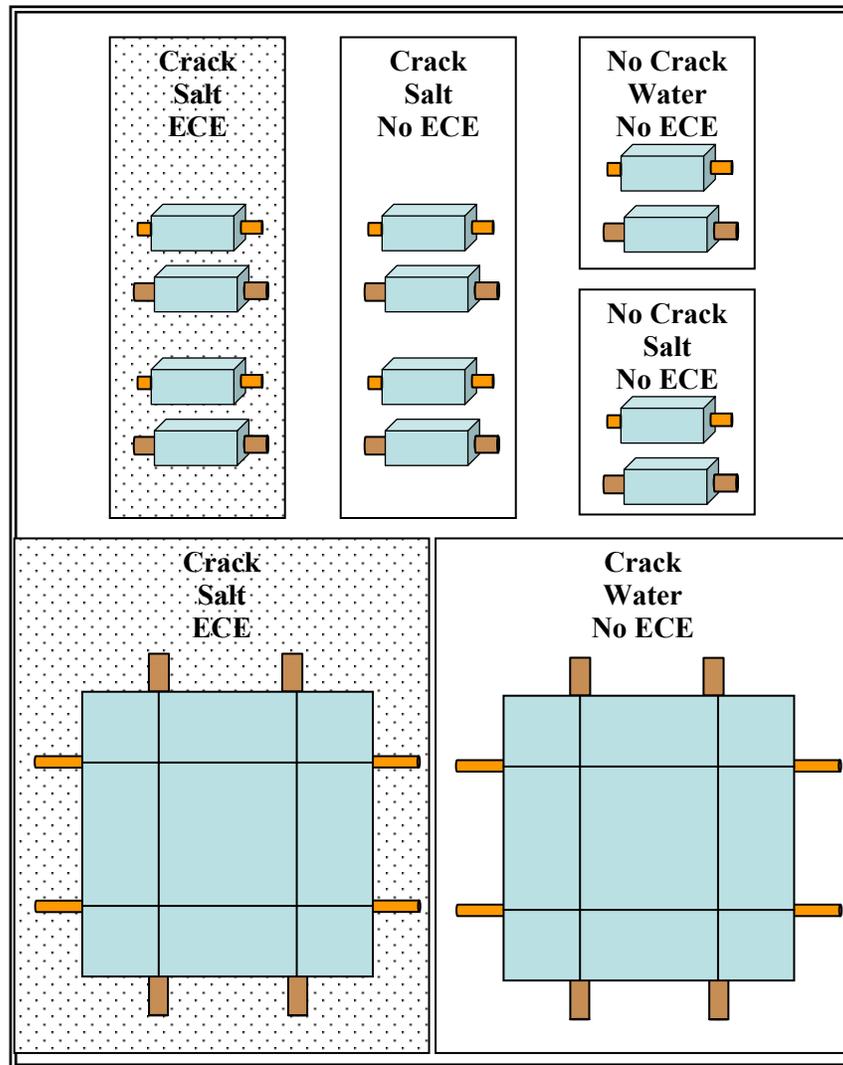


Figure 19 Combination of Specimens

After one week of curing, corrosion was monitored using half cell and voltmeter. Potential data were collected from 21 spots on the surface of the slab specimens as described in Figure 20. One potential measurement was made from the center of the beam specimen. When the potential data became stabilized, 20 ml of deicer solution was added to the specimens. Following ASTM G109, deicer solution was used with a 3% concentration, which would provide the most aggressive concentration. The corrosiveness of salt solutions to steel reaches a maximum at 3% and then begins to fall off due to decreasing oxygen solubility (Uhlig, 1963). The corrosion data was recorded in 12 hours after salt solution is added everyday until the potential values show that the specimens are corroded with 95% probability. After the test specimens reached 95% corrosion probability, the salt solution was discontinued and the ECE was provided.

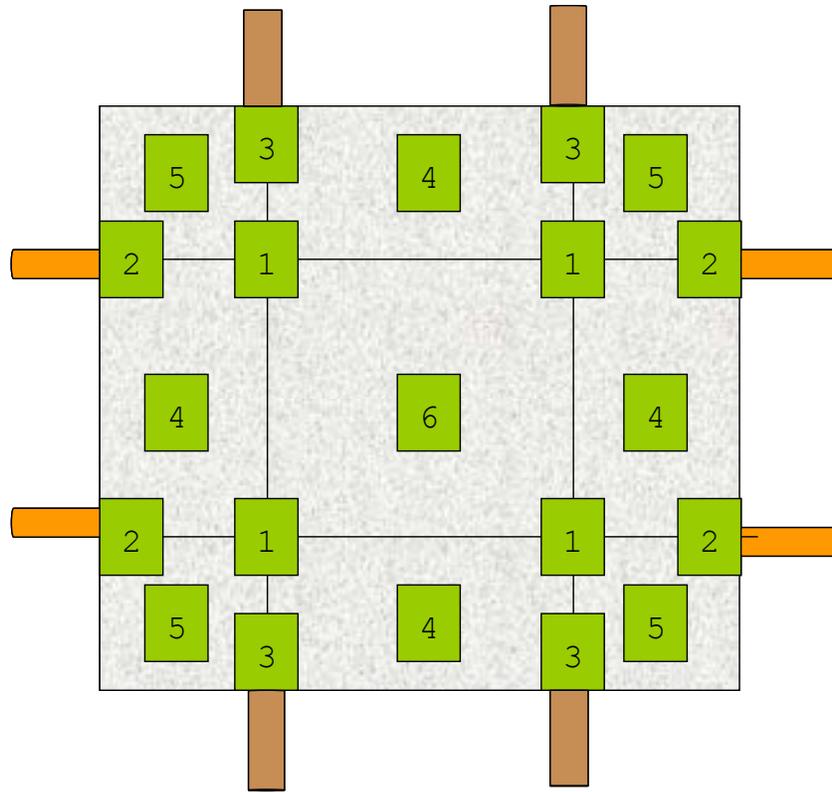


Figure 20 Group for Measurement in Slab Specimens

RESULTS AND DISCUSSION

Field Corrosion Test

Table 4 summarizes the potentials measured from 30 spots in the bridge deck. As shown in Figure 21, 2 spots appeared to have a probability of corrosion of less than 5%, 5 spots with a probability of corrosion of 95%. Since the rest of the spots are located in the indecisive range of corrosion, this bridge deck would have tended to continue to corrode.

Table 4 Potential Data of Bridge Deck

Y axis	Trial	X axis				
		A	B	C	D	E
1	A	245	233	214	213	144
	B	247	242	218	209	142
	C	257	242	221	213	144
	D	251	246	224	209	136
	Average	250	241	219	211	142

2	A	211	289	225	204	183
	B	204	262	226	206	174
	C	212	273	223	205	176
	C	206	263	223	199	167
	Average	208	272	224	204	175
3	A	258	226	244	313	238
	B	247	229	243	299	230
	C	255	226	255	324	243
	D	253	224	245	294	215
	Average	253	226	247	308	232
4	A	262	262	268	243	212
	B	251	253	267	240	203
	C	250	266	277	247	213
	C	243	257	274	246	192
	Average	252	260	272	244	205
5	A	278	311	376	290	213
	B	276	312	362	288	206
	C	276	311	385	294	267
	D	279	313	375	296	234
	Average	277	312	375	292	230
6	A	408	384	355	364	308
	B	276	312	362	288	206
	C	414	395	368	375	309
	D	418	390	372	372	303
	Average	379	370	364	350	282

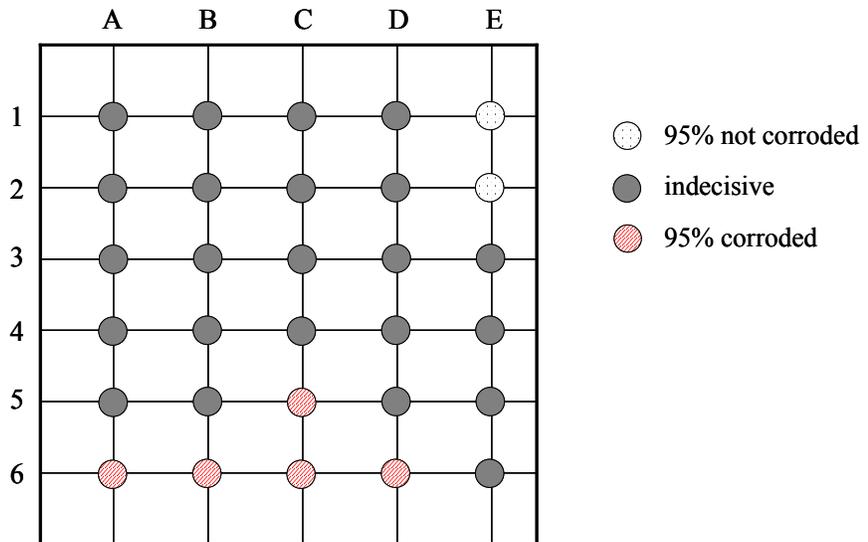


Figure 21 Status of Corrosion in Bridge Deck

Table 5 summarizes the compressive strength data of the cores collected from the bridge deck while undergoing the ECE technique. Based on the compressive strength data collected over a period of 8 weeks, the concrete strength was not negatively affected by the ECE technique.

Table 5 Compressive Strength

Day	No. of Sample	Strength (psi)
0 week	4	5,893
4 week	4	6,468
8 week	3	6,520

Table 6 summarizes the chloride concentration in the deck under the ECE process following AASHTO T 260. At the concrete surface to 1/2" down, chloride content had reached up to 25 lb/cy before the ECE technique was applied. While applying the ECE technique, the chloride content near the deck surface decreased to 4.96 lb/cy in 8 weeks.

Table 6 Concentration of Chloride (lb/cy)

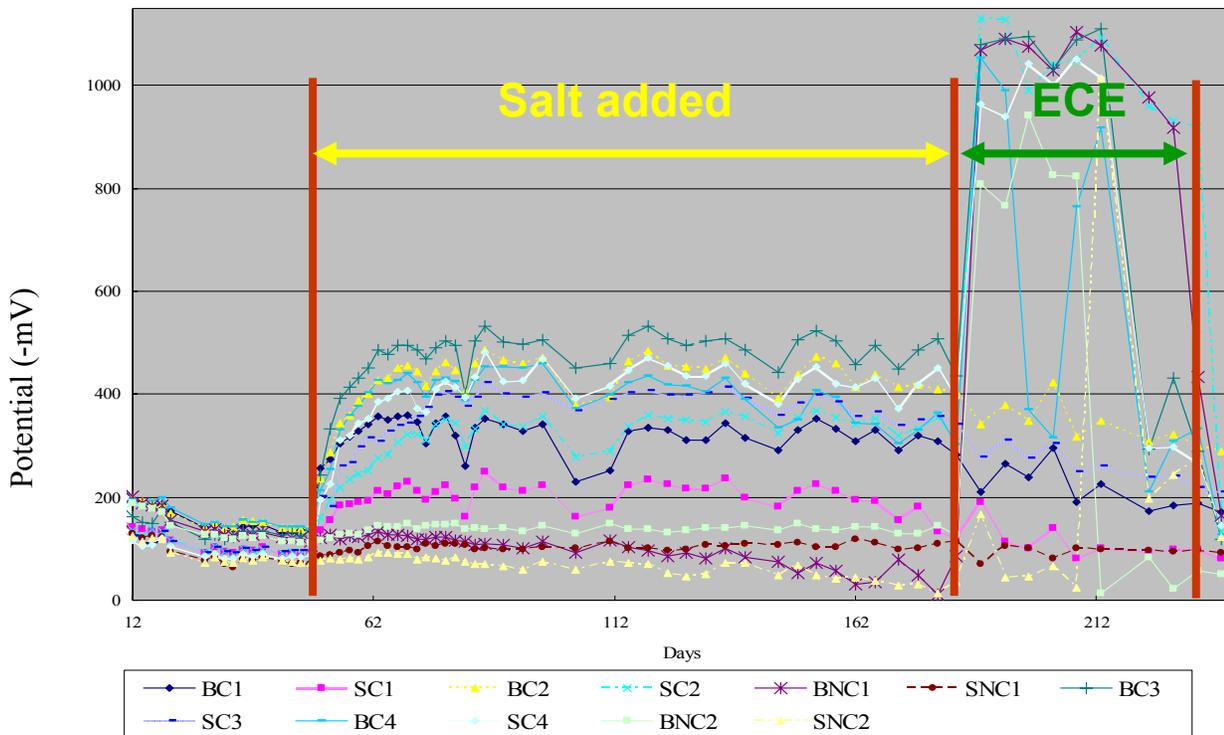
	No. of Sample	1/2-inch	1-inch	1 1/2-inch	2 1/2-inch
Design Phase	3	24.58	11.14	7.76	1.64
2 Week	2	12.92	7.81	4.74	0.59
4 Week	1	6.71	5.29	2.59	0.42
6 Week	2	7.04	4.50	3.84	0.90
8 Week	2	4.96	2.80	2.78	0.32

Laboratory Corrosion Test

Half-cell potential measurements were made every other day for six months. Because the laboratory temperature was in the range of $22.2 \pm 5.5^\circ\text{C}$, there was no need for temperature calibration.

Beam specimens

Figure 22 illustrates the potential values of beam specimens for six months. Until the salt is added on the 48th day, half-cell potential has decreased from -200 mV to -100 mV. Upon introduction of 3% salt solution, the potential reached up to -500 mV. In general, the larger the rebar diameter we observed the higher potential. As shown in Figure 22, when the salt solution was added into the cracked specimens, the potential values jumped up to -300mV in one week. This was not the case for Non-Cracked specimens (BNC, SNC) and Small Cracked specimen (SC1). As expected, the cracked specimens produced the higher potential values than non-cracked ones.



Note B: Big Rebar, S: Small Rebar, C: Cracked Beam, NC: Non-Cracked Beam

Figure 22 Potential Measurement Values from Beam Specimens for 6 Months

Slab specimens

Figures 23 and 24 present potential values for a slab with salt added and the other without salt, respectively. Measurements were made every other day for six months. The slab with a smaller initial potential value was chosen for the application of salt solution. It should be noted that Measurement Set 1, measured at the intersection of rebar, consistently produced the highest potential value among 6 groups. As expected, after salt was added, the potential values of the slab jumped up to -400mV , whereas the slab without salt stayed lower than -250mV .

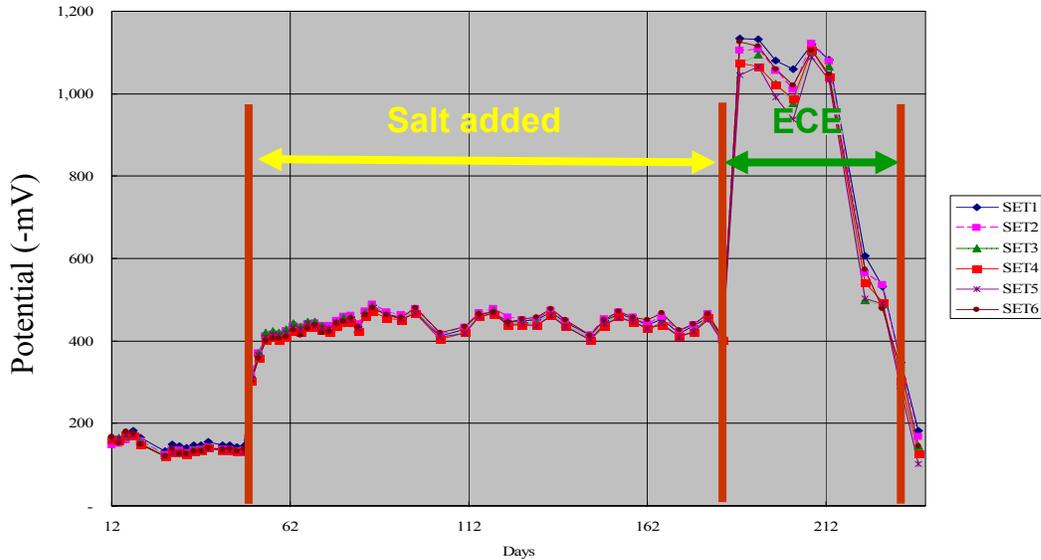


Figure 23 Potential Values of Slab with Salt

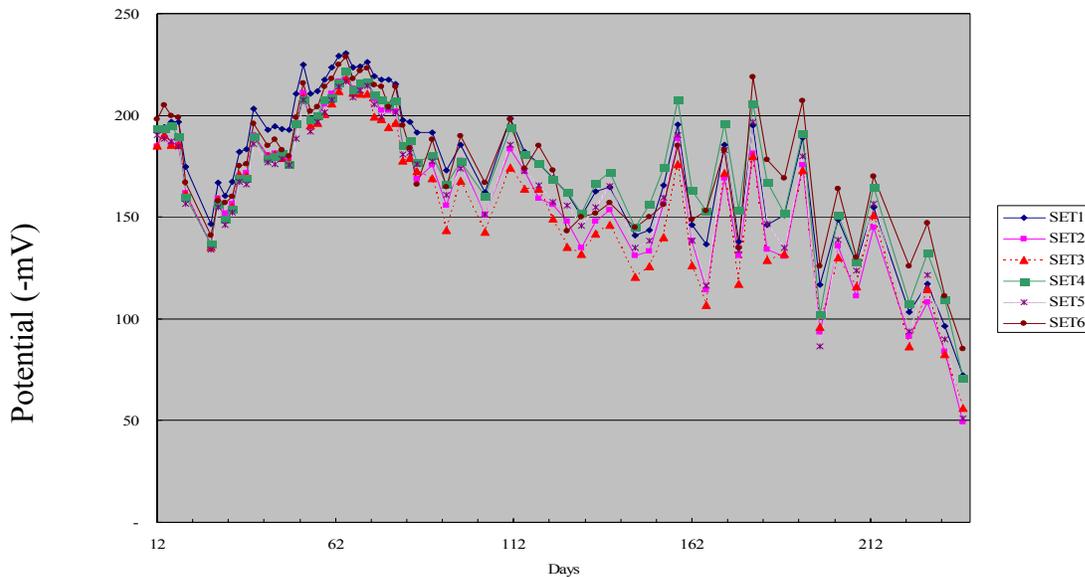


Figure 24 Potential Values of Slab Without Salt

Table 7 shows the chloride concentrations from the specimens following AASHTO T 260. Dust samples collected at the depth of 2 inches were used to measure the chloride concentrations. As shown in Table 7, chloride concentration of specimens to which salt solution was not added stayed below 0.52 lb/cy while the others, with salt applied, had reached up to 13.18 lb/cy. The values for the “water only” slabs (no salt added), 2E & 3B, show a slight increase in the concentration of chloride following the ECE process. These concentrations are very small numbers and the difference is within the margin of error.

Table 7 Concentration of Chloride, %Cl⁻ (lb/cy)

	2A Salt Crack Big Rebar	2C Salt Crack Big Rebar	1D Salt Crack Small Rebar	2D Salt Crack Small Rebar	1E Salt NC Big Rebar	2E Water NC Big Rebar	3A Salt Crack Slab	3B Water Crack Slab
Before	0.220 (8.61)	0.313 (12.27)	0.253 (9.92)	0.293 (11.48)	0.220 (8.61)	0.013 (.52)	0.337 (13.18)	0.007 (0.26)
After	0.120 (4.70)	0.160 (6.26)	0.102 (3.99)	0.120 (4.70)	0.023 (0.90)	0.063 (2.47)	0.107 (4.19)	0.028 (1.10)

CONCLUSION

For the laboratory tests, in order to simulate the corrosion in the bridge deck, two reinforced slabs and twelve reinforced beams were prepared. First, the half-cell potentials were measured from the test specimens and they ranged below -200 mV. However, upon introduction of 3% salt solution, the potential reached up to -500 mV and this level was maintained while salt solution was being added for six months.

The ECE technique was applied to the test specimens in order to remove the chloride from them. It took approximately three months to remove the chloride from the test specimens in the laboratory. Half-cell potential was then measured. The ECE technique had reduced the level of corrosion in the reinforcing steel significantly. See Table 7.

The half-cell potential values were measured from the bridge deck in Iowa City and most of them were in the indecisive range of corrosion (between -200 mV and -350 mV). To minimize future corrosion, the ECE technique was applied to remove the chloride from the deck. Based on the compressive strengths measured from the cores, it was concluded that the concrete strength

was not negatively affected by the ECE technique. The chloride content in the top of the deck was significantly reduced from 25 lb/cy to 4.96 lb/cy in 8 weeks. At the rebar level, the chloride content was reduced from 4.7 lb/cy to 1.55 lb/cy due to the ECE process.

More than 50% of the chloride was removed from both the laboratory specimens and from the Highway 6 pedestrian bridge in Iowa City. The chloride content of the laboratory beams (with salt added) was reduced 59.6% with ECE. The laboratory slab (with salt added) chloride content was reduced 68.2%. The chloride test results before and after ECE at 1½” and 2½” slab depths (averaged) for the Highway 6 pedestrian bridge show that the reduction was 72.3%.

FUTURE WORK

Roadway bridge decks in Iowa are typically constructed with a dense concrete overlay around 1½ inches thick. This effectively reduces the potential for corrosion to the point that ECE on bridge decks will not generally be required. The exception would be on older bridges that are marginally adequate structurally, and a concrete overlay is not feasible due to the additional weight. There are many instances, however, where concrete barrier rails and sidewalks have significant potential for deterioration due to corrosion. ECE may be the best choice, in these instances, for prolonging the useful life of the structures. More research is necessary to determine the extent of the corrosion problem at barrier rails, and the effectiveness of the ECE process applied to these structures.

It is recommended that a follow-up Phase II study be completed to explore the effectiveness of the ECE process on barrier rails in Iowa. It would also be beneficial to use the embedded cells in the Iowa Avenue Pedestrian Bridge deck to monitor the effectiveness of the ECE process over a period of years.

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