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Supplementary Notes				
<p>Abstract</p> <p>Electrochemical chloride extraction (ECE) is an electrochemical bridge restoration method for mitigating corrosion in reinforced concrete structures. ECE does this by moving chlorides away from the reinforcement and out of the concrete while simultaneously increasing the alkalinity of the electrolyte near the reinforcing steel. Despite its proven success, ECE is not used extensively in part because of an incomplete understanding of the following three issues:</p> <ol style="list-style-type: none"> 1. the time required for ECE with varying water-to-cement ratios (w/c) and cover depths 2. the cause of the decrease in current flow and, therefore, chloride removal rate during ECE 3. the additional service life that can be expected following ECE when the treated member is subjected to chlorides. <p>This study addressed the first two issues.</p> <p>Plain carbon steel reinforcing bars were embedded in portland cement concrete slabs of varying w/c and cover depths and then exposed to sodium chloride solutions. A fraction of the slabs contained sodium chloride as an admixture. All slabs were subjected to cyclical ponding with a saturated solution of sodium chloride. ECE was then used to remove the chlorides from the slabs while electrical measurements were made in the different layers between the reinforcing bar (cathode) and the titanium mat (anode) to follow the progress of the ECE process.</p> <p>The resistance of the outer concrete surface layer increased during ECE, inevitably restricting current flow, and the resistance of the underlying concrete either decreased or remained constant. During ECE, a white residue, or surface film, formed on the surface of the concrete. The residue contained calcium carbonate, calcium chloride, and other yet unidentified minor components when calcium hydroxide was used as the electrolyte. The surface film can be removed mechanically or, to some extent, inhibited chemically. There was no obvious relationship among cover depth, w/c, and chloride extraction efficiency, although cover depth did influence the current density.</p> <p>The investigators recommend that the Virginia Department of Transportation's Structure & Bridge Division (1) require that contractors mechanically remove the latent surface layer of concrete prior to treatment using ECE and (2) discuss with corrosion consultants the potential for using a scale inhibitor during ECE to increase the efficiency of chloride removal.</p> <p>The benefits and costs assessment of treating a structure using ECE can not currently be determined, but research currently underway will provide the necessary information for the assessment.</p>				

FINAL REPORT

**FACTORS THAT INFLUENCE THE EFFICIENCY OF ELECTROCHEMICAL
CHLORIDE EXTRACTION DURING CORROSION MITIGATION IN REINFORCED
CONCRETE STRUCTURES**

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ABSTRACT

Electrochemical chloride extraction (ECE) is an electrochemical bridge restoration method for mitigating corrosion in reinforced concrete structures. ECE does this by moving chlorides away from the reinforcement and out of the concrete while simultaneously increasing the alkalinity of the electrolyte near the reinforcing steel. Despite its proven success, ECE is not used extensively in part because of an incomplete understanding of the following three issues:

1. the time required for ECE with varying water-to-cement ratios (w/c) and cover depths
2. the cause of the decrease in current flow and, therefore, chloride removal rate during ECE
3. the additional service life that can be expected following ECE when the treated member is subjected to chlorides.

This study addressed the first two issues.

In this study, plain carbon steel reinforcing bars were embedded in portland cement concrete slabs of varying w/c and cover depths and then exposed to sodium chloride solutions. A fraction of the slabs contained sodium chloride as an admixture. All slabs were subjected to cyclical ponding with a saturated solution of sodium chloride. ECE was then used to remove the chlorides from the slabs while electrical measurements were made in the different layers between the reinforcing bar (cathode) and the titanium mat (anode) to follow the progress of the ECE process.

The resistance of the outer concrete surface layer increased during ECE, inevitably restricting current flow, and the resistance of the underlying concrete either decreased or remained constant. During ECE, a white residue, or surface film, formed on the surface of the concrete. The residue contained calcium carbonate, calcium chloride, and other yet unidentified minor components when calcium hydroxide was used as the electrolyte. The surface film can be removed mechanically or, to some extent, inhibited chemically. There was no obvious relationship among cover depth, w/c, and chloride extraction efficiency, although cover depth did influence the current density.

The investigators recommend that the Virginia Department of Transportation's Structure & Bridge Division (1) require that contractors mechanically remove the latent surface layer of concrete prior to treatment using ECE and (2) discuss with corrosion consultants the potential for using a scale inhibitor during ECE to increase the efficiency of chloride removal.

The benefits and costs assessment of treating a structure using ECE cannot currently be determined, but research currently underway will provide the necessary information for the assessment.

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INTRODUCTION

Corrosion of reinforced concrete structures has created an economic burden for many transportation agencies. This cost has become so significant that studies have been initiated to develop a fuller understanding of corrosion of the infrastructure and ways of mitigating the problem.¹ For new construction, this has resulted in improved concretes with lower slump, increased cover thickness, reduced permeability through the use of a lower water-to-cement ratio (w/c) and the addition of pozzolans, and the replacement of conventional carbon steel reinforcing bar (rebar) with epoxy-coated or galvanized rebar. Moreover, alternative metallic bars have emerged, which include solid stainless steel, stainless steel clad, and other types of metallic bars.¹⁻³ For older structures, several rehabilitation techniques exist including patching and various types of overlays, shotcrete repairs with high-resistivity concrete, cathodic protection, and electrochemical chloride extraction (ECE).

ECE is used for rehabilitating reinforced concrete structures that are succumbing to chloride-induced corrosion. A schematic of the treatment process is shown in Figure 1, which illustrates how a corroding reinforced concrete bridge structure can be revitalized through the temporary application of ECE to the structure. During treatment, ECE removes chloride ions from the concrete while simultaneously increasing the alkalinity near the reinforcing steel; both the chloride removal and the increase in alkalinity increase the corrosion threshold.⁵⁻⁷ The ECE process operates under either a constant voltage or a constant current condition. The constant current or voltage operating condition is controlled by limiting the maximum output for the current and voltage and then allowing the rectifier to respond accordingly. Once the chloride ions have been removed below the threshold level for corrosion, ECE is terminated. The ECE equipment is then removed and often a sealer is applied to reduce the future intrusion of chloride ions.

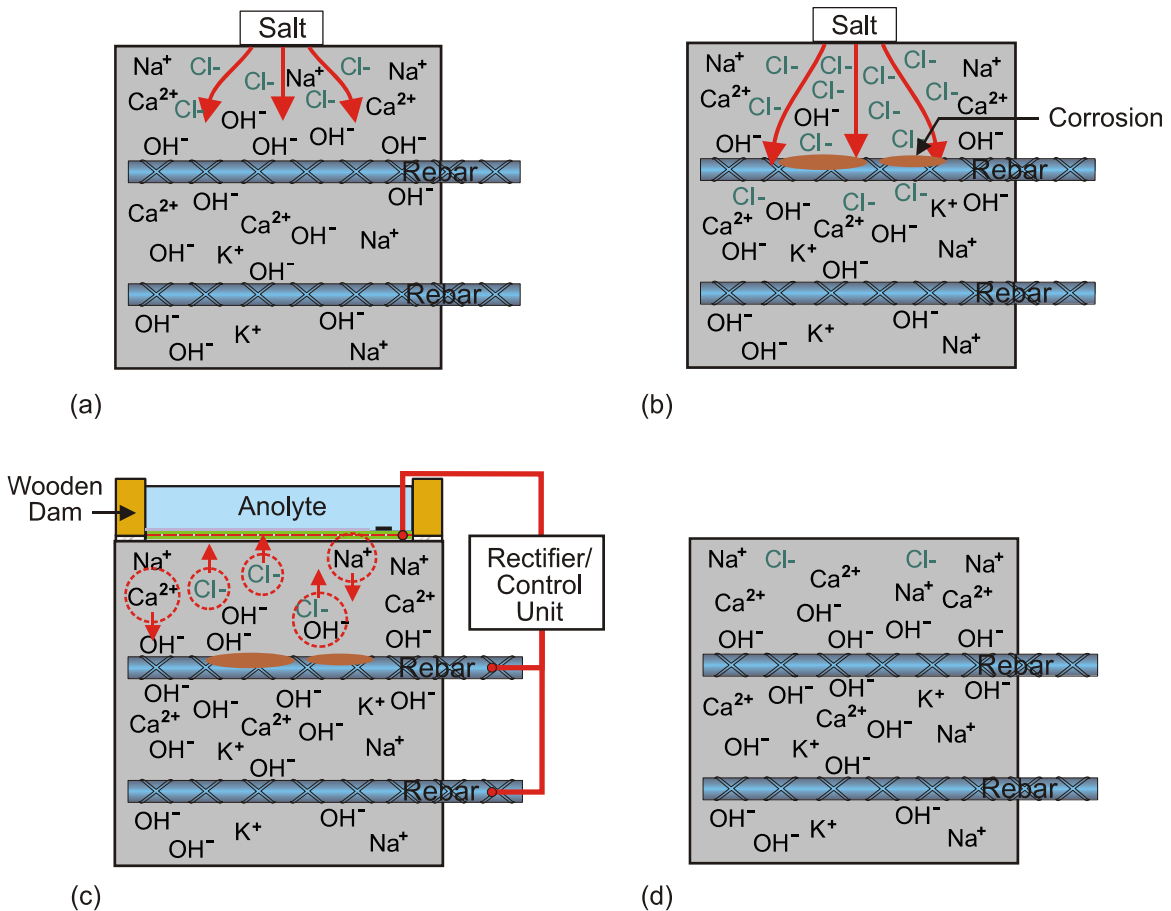


Figure 1. Illustration showing the corrosion and treatment cycle: (a) chlorides are introduced into the concrete, (b) chlorides migrate to the steel and initiate corrosion, (c) ECE removes chloride ions from the concrete while simultaneously increasing the alkalinity (due to the migration of sodium and other cations and the production of hydroxide ions) at the reinforcing steel, and (d) after the structure is revitalized, ECE is terminated and the equipment removed.

It is commonly accepted that ECE not only removes chlorides from the structure while increasing the alkalinity near the steel but can also change the characteristics of the concrete. Research has shown that current flow through concrete can alter the voids within the concrete as well as the outer concrete surface.

Clemeña and McGheehan studied the filling of cracks using electrochemical accretion of seawater minerals.⁸ Accretion current densities around 0.1 A/ft^2 were used to create mineral deposits inside cracks. More recently, Ryu and Otsuki used electrodeposition to close cracks.⁹ Their study showed that the electrodeposition of ZnO precipitates inside the crack and along the concrete surface (ranging from 0.02 and 0.08 in thick) resulted when an anolyte containing ZnSO_4 was used. In addition, their permeability measurements indicated a decrease in permeability. Except for the crack studies, most of the electrochemical effects on concrete and the concrete/rebar interface appear to be insignificant at the recommended lower operating current densities. However, these studies support not only some of the findings in the current study, but also the idea that the electrodeposition of cations causes the reduction in current during ECE.

PURPOSE AND SCOPE

Although it is accepted that ECE moves chloride ions away from the reinforcement and out of the concrete while increasing the pH near the reinforcing steel, its use is not widespread. This has been attributed in part to various crucial issues, including the following three:

1. the time required for ECE with varying w/c and cover depths
2. the cause of the decrease in current flow and, therefore, chloride removal rate during ECE
3. the additional service life that can be expected following ECE when the treated member is again subjected to chlorides.

This report focuses on the first two issues. After the initial tasks were completed, an attempt was made to determine a method for improving the efficiency of this process. An investigation of the third issue is currently underway.

All of the research performed during this project used reinforced concrete laboratory slabs.

METHODS

Overview

Three types of test slabs were used, as described later. Three tasks were carried out to achieve the objectives of the study.

1. *Identify the cause of the decrease in chloride removal efficiency during ECE.* This task included casting concrete slabs, ponding them with saturated sodium chloride (NaCl) solution, determining when the slabs were ready for ECE based on chloride penetration into the concrete, and monitoring the progress of ECE while it was applied using calcium hydroxide ($\text{Ca}(\text{OH})_2$) as the electrolyte. To accomplish this task, testing included monitoring for changes in half-cell potential, corrosion rate, regional temperature, and the resistivity and total chloride concentration of the concrete. Current and voltage measurements were made during ECE.
2. *Develop a method for improving the chloride removal efficiency during ECE.* This task included casting concrete slabs, ponding them with saturated NaCl solution, determining when the slabs were ready for ECE, and monitoring ECE while it was applied. Unlike in Task 1, during Task 2 the region of inefficiency for chloride removal was altered by either mechanical or chemical means. To monitor the increase in chloride removal efficiency, testing included again monitoring for changes in half-cell potential, corrosion rate, regional temperature, and the resistivity and total chloride concentration of the concrete. Current and voltage measurements were made

during ECE. The mechanical and chemical methods of altering the region of inefficiency included sandblasting, milling, and using a particular chemical designed to inhibit the formation of calcium carbonate and magnesium carbonate, as well as other types of calcium and iron scales.

3. *Determine the influence of w/c and cover depth on ECE.* This task was conducted simultaneously with Task 1. Testing included monitoring changes in concrete resistivity, half-cell potential, corrosion rate, regional temperature, and total chloride concentration. Current and voltage measurements were made during ECE.

Electrochemical Chloride Extraction

Chlorides were extracted following the methods described in a previous report.⁴ The concrete surface area and the reinforcing steel area were different for each type of test slab, as indicated in Table 1. Further, the concrete and rebar surface areas were different for a given type of test slab. Therefore, to determine the maximum operating current, the calculation of the treatment area was based on the surface area of the concrete, which is consistent with the practice recommended by the National Associate of Corrosion Engineers.¹⁰ After the size of the treatment area was determined, the maximum allowable current was calculated for each type of slab using a maximum current density of 0.1 A/ft².

To treat a reinforced concrete structure, the positive lead from the DC power supply was attached to the anode and the negative lead to the reinforcing steel mat. The power supply was then set to operate in constant current mode until it reached the maximum voltage output, at which time it would switch from constant current to constant voltage mode. The maximum voltage setting was dependent on the power supply. For 24 of the 36 Type I slabs, the maximum obtainable voltage for the power supplies used was between 9 V and 15 V. After higher output power supplies were obtained, all of the remaining slabs were subjected to a maximum voltage of 40 V. The ECE parameters/materials used are listed in Table 2.

Table 1. ECE Comparison Among the Three Types of Slabs

Description	Type I	Type II	Type III
Treated concrete surface area	38.4 in ²	131 in ²	47 in ²
Rebar surface area	20.2 in ²	181 in ²	76 in ²
Number of mats	1 (single bar)	2	2

Note: The surface area was based on the interior dimensions of the dam.

Table 2. ECE Parameters/Materials

Description	Selection
Anode material	Titanium mat
Anode contact material	Two felt layers: 1 above and 1 below anode mat
Electrolyte	Saturated calcium hydroxide solution
Maximum current density (based on concrete surface area)	0.1 A/ft ²

The materials used for ECE were also based on those used to treat a structure in the field. A titanium anode and two pieces of felt were cut to fit the inside dimensions of the dam. A piece of felt was placed on the surface of the concrete inside the dam, followed by the titanium anode mat, and the titanium mat was covered by a second piece of felt. The sandwiching of the titanium between the felt ensured the complete wetting of the titanium anode mat. The anolyte was carefully added until the solution level inside the dam completely covered the upper felt mat. A saturated calcium hydroxide solution was selected as the anolyte during ECE. Calcium hydroxide was also added as needed to ensure the solution did not become acidic, which could result in etching of the concrete or the evolution of chlorine during ECE.

Test Slab Design

Three types of laboratory test slabs were fabricated using plain carbon steel rebar, which complied with the requirements of ASTM A615, and Type I/II cement, which complied with the requirements of ASTM C150.

The slab designs were similar and are provided in Table 3. The most significant difference was the size of the slab. These three slab designs were an attempt to maximize the amount of reinforcing steel while simultaneously minimizing the weight. Some of the slabs had additional measurement points to aid in the investigation. A description of each set of measurement points is provided in Table 4, and an example of the positioning is shown in Figure 2. In every case, however, after the slabs had cured, a dam was affixed to the top of each slab to hold the appropriate solutions.

Table 3. Description of Types I, II, and III Concrete Test Slabs

Slab Type	Chloride Exposure Method	Width x Length	Cover Thickness	W/C	No. of Slabs Tested
Type I	Admixed and Ponding	12.0 in x 5.0 in	1.75 in	0.40	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	1.75 in	0.45	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	1.75 in	0.50	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	1.75 in	0.55	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	2.25 in	0.40	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	2.25 in	0.45	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	2.25 in	0.50	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	2.25 in	0.55	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	2.75 in	0.40	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	2.75 in	0.45	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	2.75 in	0.50	3
Type I	Admixed and Ponding	12.0 in x 5.0 in	2.75 in	0.55	3
Type II	Admixed and Ponding	14.0 in x 12.0 in	2.0 in	0.47	8
Type III	Ponding	12.0 in x 6.0 in	1.75 in	0.50	12

Table 4. Description of Contact Points Used to Make Measurements in Types I, II, and III Concrete Test Slabs

Item No.	Region Studied	Description
1	Anode/anolyte ti strip	Measurement contact points are anode mat and titanium strip located in anolyte
2	Anode/rebar	Measurement contact points are anode mat and reinforcing steel mat
3	Anolyte ti strip/ upper ti rod	Measurement contact points are titanium strip in anolyte and titanium rod in top row of embedded titanium rods
4	Bottom row	Measurements made using bottom row of embedded titanium rods
5	Lower ti rod/rebar	Measurement contact points are titanium rod in bottom row of embedded titanium rods and reinforcing steel mat
6	Top row	Measurements made using top row of embedded titanium rods
7	Upper/lower ti rod	Measurement contact points are titanium rod in top row and titanium rod directly below it in bottom row of embedded titanium rods

Type I Test Slabs

These test slabs provided insight into the changes occurring in different regions between the anode and cathode during ECE. In addition, some of the initial surface analysis was performed on material removed from these slabs following ECE. The regions studied are listed in Table 4. Table 5 gives the mix designs for the slabs. Illustrations of the Type I test slab, including a cross section illustration of the regions listed in Table 4, are shown in Figure 2.

Two rows, each containing four activated titanium rods, were embedded at different depths in the Type I slabs. The rods were placed in horizontal rows either 1 cm below the concrete surface or 1 cm above the reinforcing steel. Resistivity measurements were made using the rods in accordance with the guidelines in ASTM Standard G 57. The titanium rods were used to measure the voltage difference between selected points.

The Type I slabs were kept in a controlled laboratory environment during ponding and while routine measurements were made. The temperature inside the laboratory is on average 75 F. Saturated sodium chloride solution was used to pond the slabs. Ponding was performed in cycles: 1 week ponding, then 1 week dry.

Type II Test Slabs

Similar to the Type I test slabs, these slabs were designed so that changes occurring in different regions between the anode and cathode during ECE could be observed. The regions studied are listed in Table 4. Some of the basic features of this slab design are listed in Table 3. Table 6 lists the mix design, which was based on the Virginia Department of Transportation's 1970 *Road and Bridge Specifications*.¹¹ Illustrations of the Type II slab are shown in Figure 3.

The slabs were cast and cured outside (but covered during the initial curing period) and then remained outside during ponding and while routine measurements were made. The ponding solution was saturated sodium chloride solution. Ponding was performed in cycles: 1 week ponded, then 1 week dry. The slabs were exposed to temperatures (in Fahrenheit) ranging from the mid 20s in January (coldest month) to the mid 80s in July (warmest month).

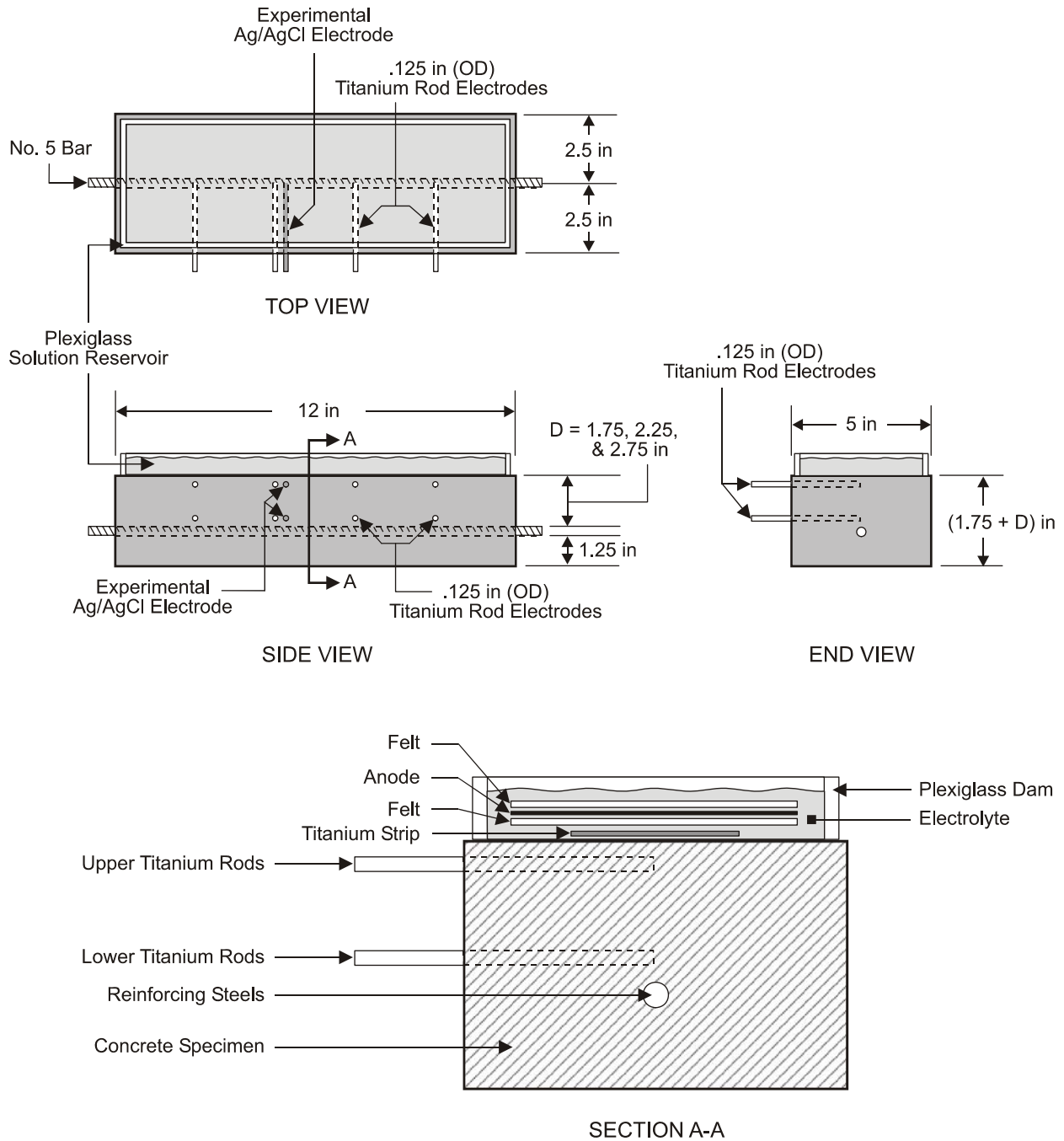


Figure 2. Type I Test Slab

Table 5. Mix Designs for Type I Concrete Slabs

W/C	0.40	0.45	0.50	0.55
Cement (Type I/II), lb/yd ³	635	622	616	603
Water, lb/yd ³	255	279	308	333
Coarse aggregate, lb/yd ³	1514	1484	1469	1438
Fine aggregate, lb/yd ³	1493	1463	1448	1418
NaCl added, lb/yd ³	10	10	10	10

Table 6. Mix Design for Type II Concrete Slabs

W/C	0.47
Cement (Lehigh Type I/II), lb/yd ³	681
Coarse aggregate, ^a lb/yd ³	1869
Fine aggregate, lb/yd ³	982
Water, lb/yd ³	320
Air entrainment, oz	As required
Set retarder, oz	As required
NaCl, lb/yd ³	15

^a #57 Stone (3/4 in) 100% passing 1-in sieve.

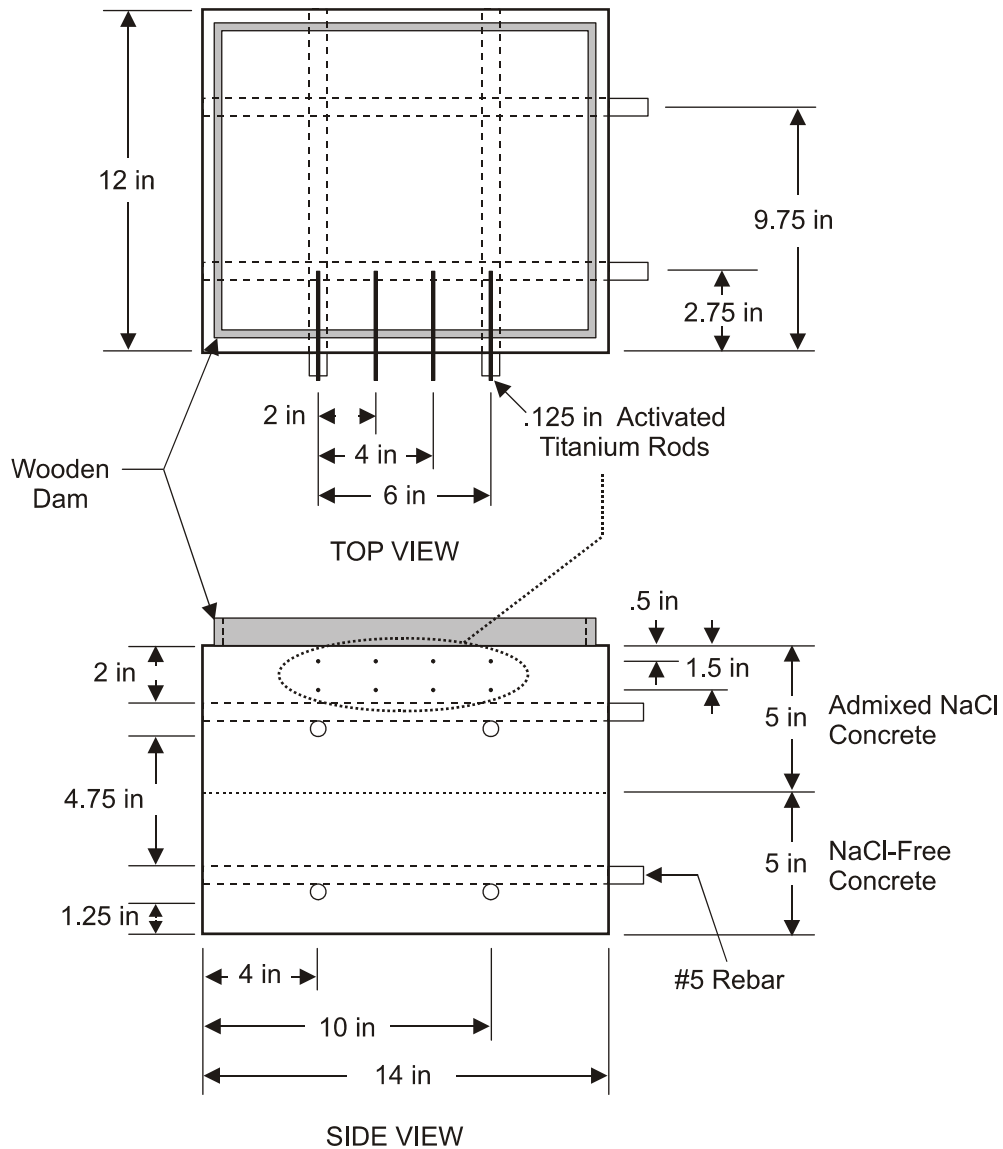


Figure 3. Type II Slabs

Type III Test Slabs

The Type III and Type II test slabs have numerous similarities. However, by comparison the Type III slab's concrete surface area is smaller. Like the other test slabs, these slabs also included the ability to evaluate different layers between the anode and cathode.

The various regions studied with the Type III test slabs are listed in Table 4. Table 3 describes some of the features, and Table 7 provides the mix design used. Figure 4 is an illustration of the slabs.

Table 7. Mix Design for Type III Concrete Slabs

W/C	0.50
Cement (Lehigh Type I/II), lb/yd ³	558
Coarse aggregate, ^a lb/yd ³	1788
Fine aggregate, lb/yd ³	1292
Water, lb/yd ³	280
Air entrainment, oz	As required
Set retarder, oz	As required

^a #57 Stone (3/4 in) 100% passing 1-in sieve.

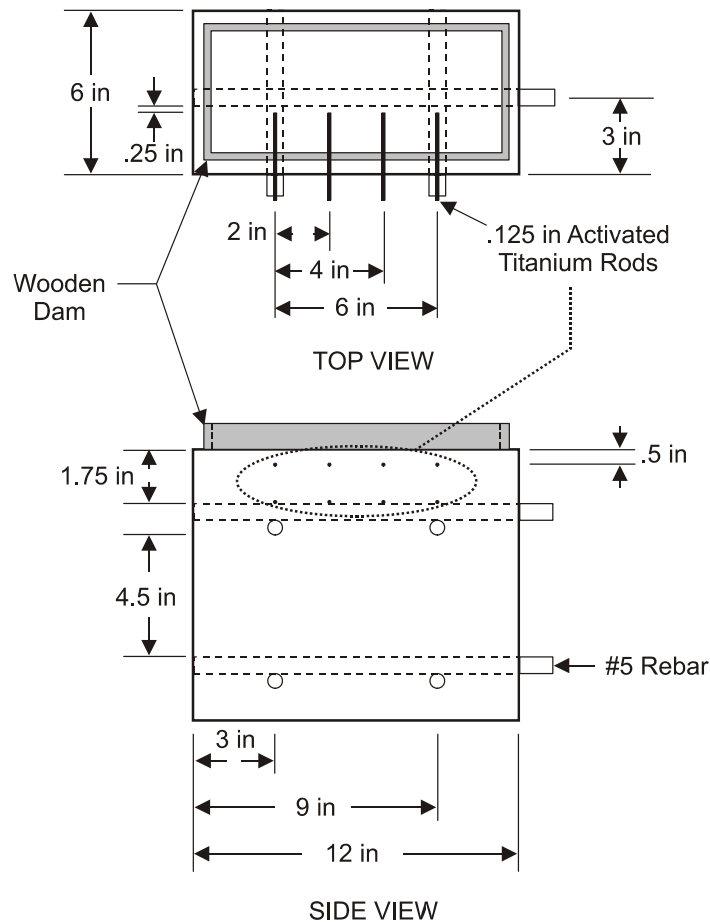


Figure 4. Type III Slabs

These slabs were cast, covered with plastic, and cured indoors. The slabs were then moved outside during ponding and while routine measurements were made. A saturated sodium chloride solution was used to pond the slabs, with the slabs subjected to ponding cycles of 1 week ponded, then 1 week dry.

Current and Voltage Measurements

Voltage and current measurements were made with either a Tektronix digital multimeter or an IO Tech Logbook data acquisition system. With both instruments, voltage measurements were made directly. The current was determined by measuring the voltage across a resistor of known resistance and then calculating the current using Ohm's law.

As discussed earlier, the Type I test slabs were designed with the intention of making resistivity measurements during ECE. This was performed using a Nilsson Soil Resistance Meter, Model 400, in accordance with ASTM G57.¹² This meter induces an AC signal between two outer test points while the voltage drop is measured between two inner test points.¹² The resistance is then measured and converted to resistivity using a calibration cell or equations that are based on the configuration of the test points.¹²

Surface Removal

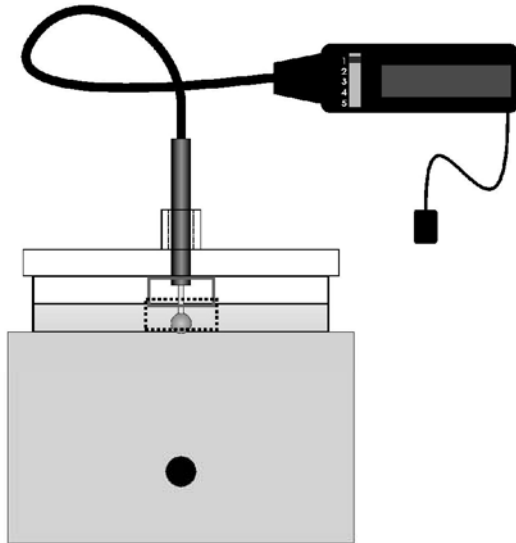
In-Situ Surface Milling

In-situ surface milling was performed after the anode mat and felt were removed and the anolyte left in place. This required the creation of a device that could be submerged in an alkaline solution without causing the solution to spray uncontrollably during the milling operation.

After several options were investigated, the Dremel Tool[®] was selected for this task. It was able to provide rotary motion through a flexible driveshaft to a diamond-impregnated cutting head. This cutting head was then placed in the alkaline solution, and the surface milled. An initial sketch of the idea, photographs showing the actual device, and the result of milling a test surface are shown in Figure 5.

Sandblasting

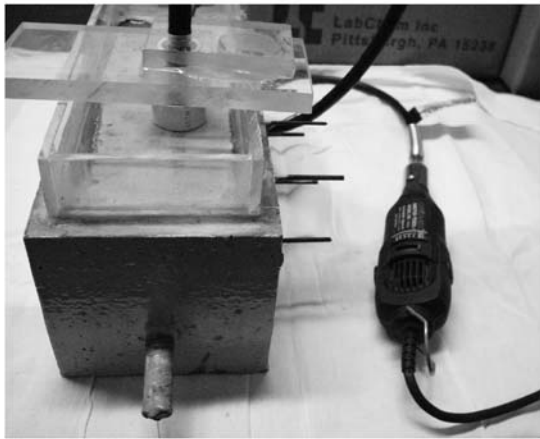
A sandblasting cabinet was used for removing the surface layer on the Type II test slabs. The blast medium was black beauty slag, which is similar to the type of blast medium used for sandblasting concrete bridge structures. The slabs were divided into three groups, with the group number indicating the number of times the slabs were sandblasted. Group 0 contained two control slabs that were not sandblasted but were treated using ECE. Group 1 contained three slabs that were sandblasted once before ECE. Group 2 contained three slabs that were sandblasted twice, once before ECE and once midway through treatment. The surfaces of the sandblasted slabs were abraded until it became visually apparent that the latent surface layer was removed. The difference between an as-cast surface and abraded surface is shown in Figure 6.



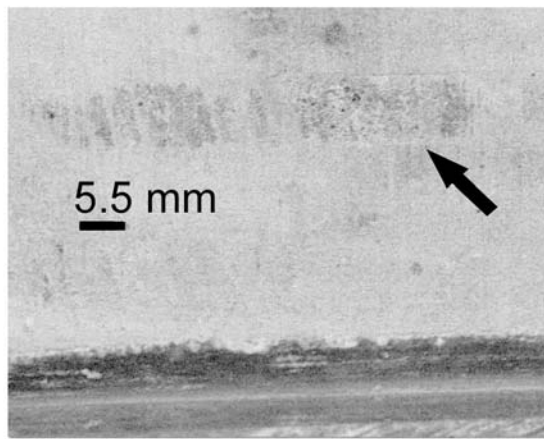
(a)



(b)

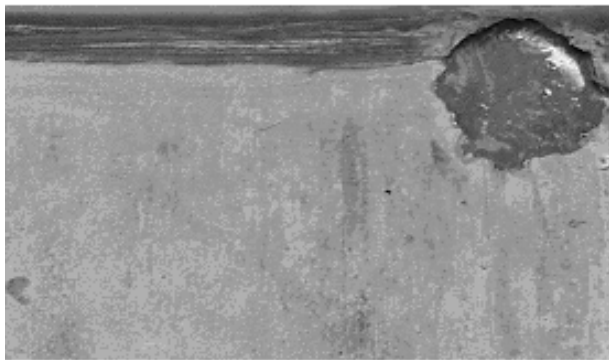


(c)

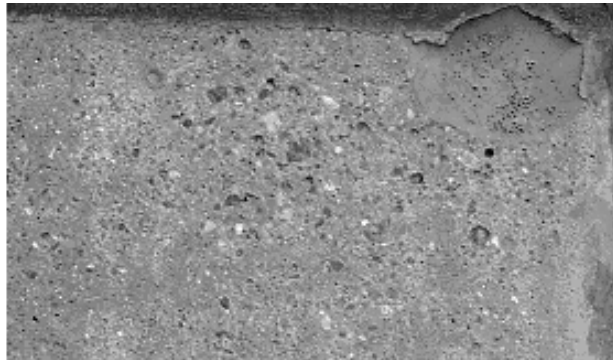


(d)

Figure 5. In-situ Surface Milling Device: (a) sketch of idea, (b) actual milling device showing grinding blade, (c) dry run on test slab, and (d) image of milled surface after one pass with device



(a)



(b)

Figure 6. Example of Different Surfaces: (a) as-cast surface and (b) sandblasted surface

Scale Inhibitor

A proprietary scale inhibitor, Alpha 2771, manufactured by Clearwater, Houston, Texas, was tested on eight Type III test slabs. These scale inhibitors are commonly used in the petroleum industry to minimize the formation of mineral deposits. During this study, the surfaces were treated with the inhibitor at two times during the ECE treatment. The first set of slabs was treated before ECE, and the second set was treated midway through the treatment. The details on the application of the scale inhibitor solution for the 12 slabs are given in Table 8. The composition of the solution applied to each slab is provided in Table 9. Every time the scale inhibitor was applied to the slabs, the pH of the anolyte decreased to a value of 3. Therefore, to increase the pH, calcium hydroxide was added until the pH had increased to approximately 12.

Table 8. Chemical Treatment of Type III Slabs with Alpha 2771

No. of Slabs	Initial Electrolyte	Scale Inhibitor Solution	Charge Passed Before Addition of Inhibitor (A-hr/ft ²)
4	Sat Ca(OH) ₂	None	N/A
4	Sat Ca(OH) ₂	Alpha 2771	0
4	Sat Ca(OH) ₂	Alpha 2771	47.8

Table 9. Scale Inhibitor Composition

Ingredient	Quantity (tbsp)
Distilled water	10
Alpha 2771	0.40

Sample Analysis

Collection of Concrete Samples at Various Depths Above Steel

Concrete samples for chloride analysis were collected starting on the outer perimeter of a slab and working inward. This was done to keep from interfering with the subsequent current flow. The sampling depths before and after ECE were from the surface to ¼ in, ¼ in to ¾ in, ¾ in to 1¼ in, and 1¼ in to 1⁵/₈ in. All depths were above the top reinforcing steel mat.

Calculation of Chloride Extraction Efficiency

The chloride extraction efficiency was calculated using the chloride concentration values and the daily current measurements. The concentrations of chlorides in the concrete slabs before and after ECE were determined in accordance with AASHTO T260.¹³ With the assumption that the reduction in chloride content was the same over the entire treated area, the amount of charge carried by the chloride ion was calculated using Equation 1.

$$Q_j = \frac{|Z_j| F (\Delta W_j)}{(A_j)} \quad [\text{Eq. 1}]$$

Q_j = charge carried by species j

Z_j = charge on species j

F = Faraday constant

ΔW_j = change in measured mass of species j in concrete sample (before versus after ECE)

A_j = atomic weight of species j.

Then, using the daily current measurements, the amount of total charge passed during the treatment was calculated using Equation 2.

$$Q_{Total} = \int Idt \quad [\text{Eq. 2}]$$

Q_{Total} = total charge passed

I = measured current

t = treatment time.

The chloride extraction efficiency was then calculated by dividing the amount of charge carried by the chloride ion (Q_j) by the total charge passed (Q_{Total}) and multiplying that value by 100. An example of the chloride extraction efficiency calculation follows:

If species j is the chloride ion,

Z_j = -1 eq/mol

F = 96500 C/eq

ΔW_j = 0.511 g

A_j = 35.45 g/mol

Based on Equation 1, the total amount of charge carried by the chloride ion is

Q_j = 1390 C.

If the total charge passed during ECE is 5160 C (and it is known that the chloride ion carried 1390 C of charge), the calculated efficiency is 26.9 percent.

RESULTS AND DISCUSSION

Influence of W/C and Cover Thickness on ECE

As discussed previously, Type I slabs were used to examine the influence of w/c and cover thickness on ECE. The slabs were treated initially at constant voltage (varying current

density) until the maximum allowable current density was reached. Then, they were treated under constant current conditions.

Based on previous research, ECE performance appears to be governed by multiple factors. For example, Arya et al. investigated the relationship between the initial chloride content and duration required for ECE to reduce the chloride level at the rebar to a concentration below the threshold level.¹⁴ Their study indicated that the greater the initial chloride concentration, the greater the concentration of chlorides removed.¹⁴ However, the study also indicated that the initial concentration before treatment and the remaining chloride concentration after treatment are independent.¹⁴

In the current study, the initial chloride content at the rebar was different for each Type I slab because the slabs had varying w/c and concrete covers, which influenced the diffusion of chlorides into the concrete during ponding cycles. Consequently, chloride removal by ECE could be affected the same way as chloride penetration because of the varying w/c and concrete cover. The chloride removal efficiency data, which are a function of the quantity of chlorides removed for a given amount of charge passed, were used to evaluate the different w/c and depths of concrete cover.

Influence of W/C on ECE

Initially, the w/c was found to have very little influence on current densities, except for the slabs with a w/c of 0.55 (0.55 w/c slabs). This is evident in Figure 7 through Figure 9. The difference with the 0.55 w/c slabs could be due to a more continuous pores system within the concrete.

More significant, the w/c did not influence the chloride removal efficiency as no clear relationship between chloride removal efficiency and w/c was observed. It is evident in Figure 10 that increasing the w/c usually resulted in an increase in chloride removal efficiency, but this was not always true. For instance, the 0.50 w/c slabs had a higher average efficiency than did the 0.55 w/c slabs. Therefore, other factors might have a stronger influence on the chloride extraction rate, such as concrete surface finish, cement type, and initial chloride content.

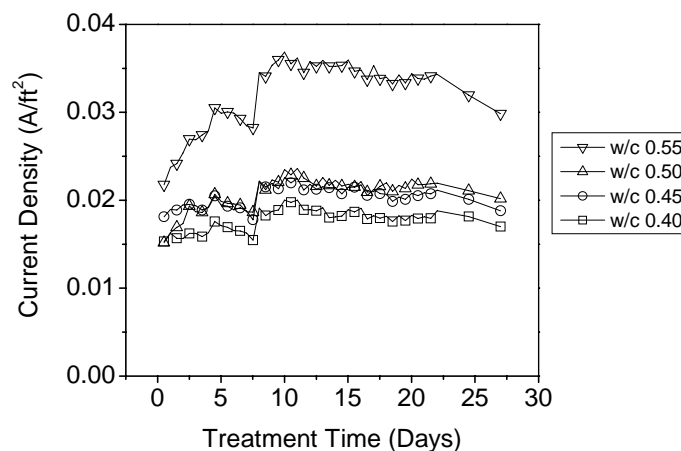


Figure 7. Average Current Density for Type I Slabs with 1.75-in Cover Thickness

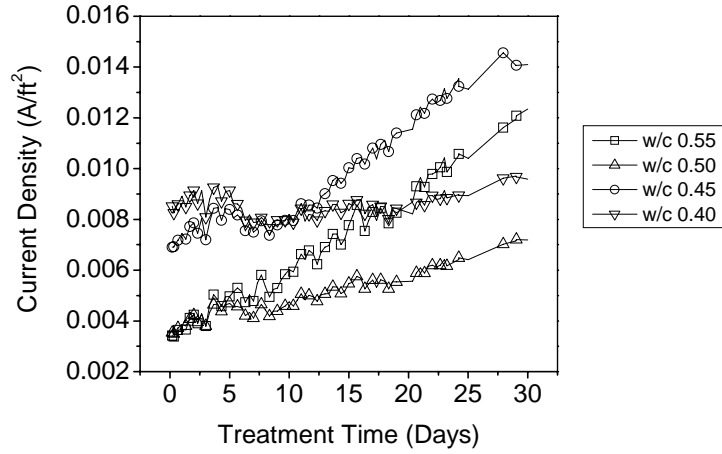


Figure 8. Average Current Density for Type I Slabs with 2.25-in Cover Thickness

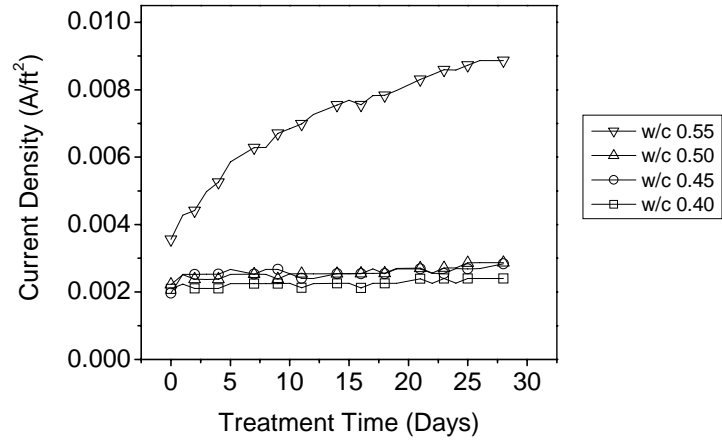


Figure 9. Average Current Density for Type I Slabs with 2.75-in Cover Thickness

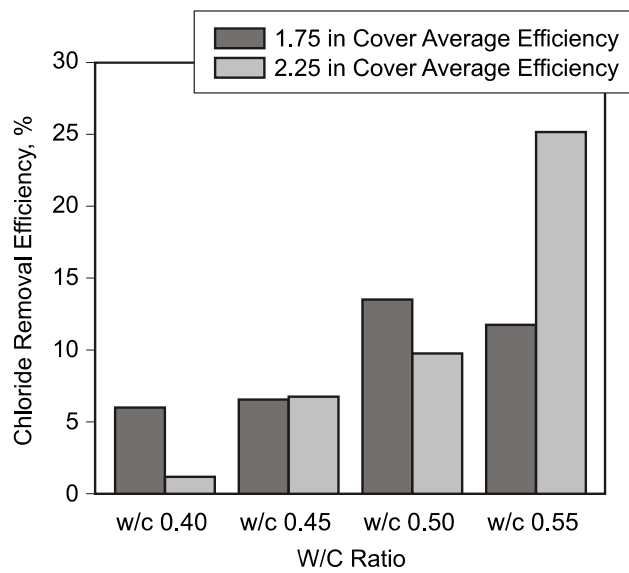


Figure 10. Influence of w/c on Chloride Removal Efficiency

Influence of Cover Depth on ECE

A clear relationship between cover depth and average current density was observed: the greater the depth, the lower the average current density. This trend can be seen in Figure 11 through Figure 14. This finding was not surprising because the resistance between the anode and cathode is being increased. Bennett et al. also demonstrated this relationship although their tests were of much shorter duration.¹⁵ However, as indicated in Figure 10, there was no relationship between chloride removal efficiency and cover depth. It is expected that a lower current density will also reduce the amount of chlorides being removed. However, as mentioned earlier, other factors will also influence the chloride removal rate.

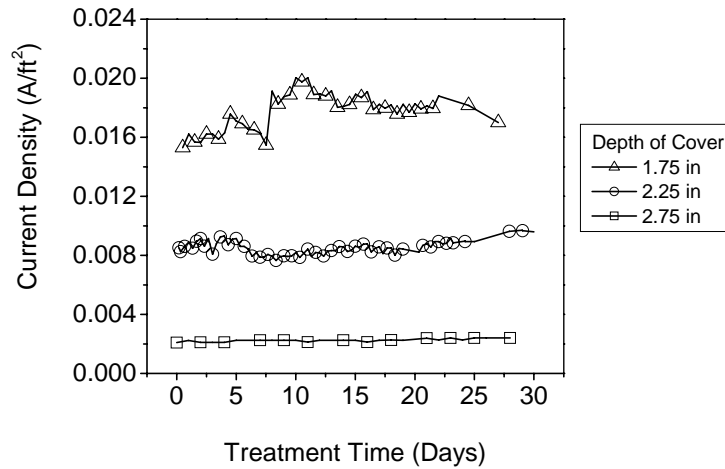


Figure 11. Average Current Density for Type I Slabs with w/c of 0.40

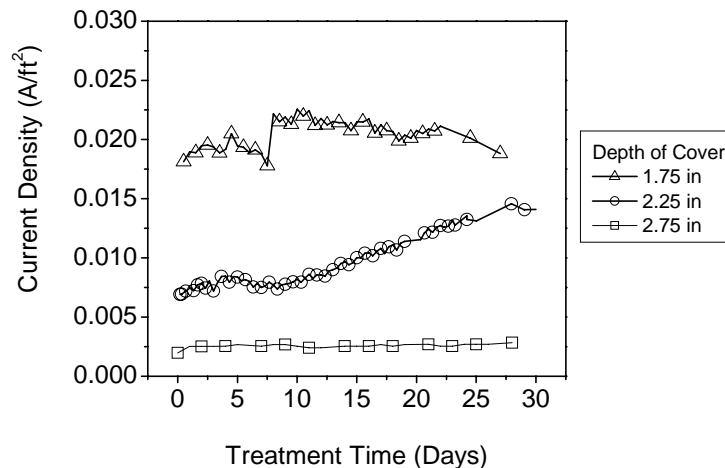


Figure 12. Average Current Density for Type I Slabs with w/c of 0.45

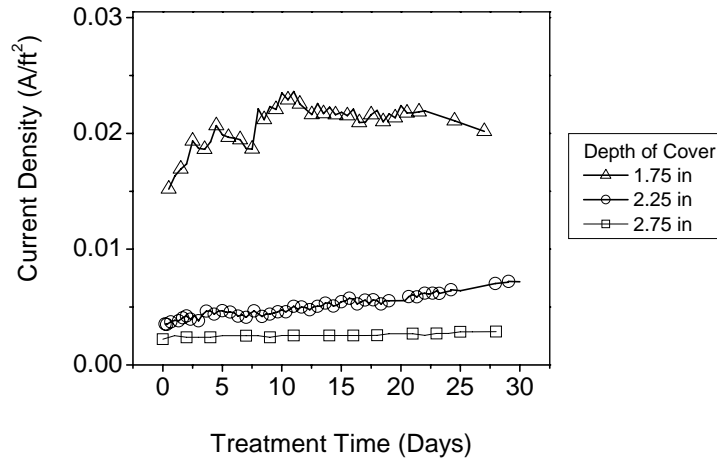


Figure 13. Average Current Density for Type I Slabs with w/c of 0.50

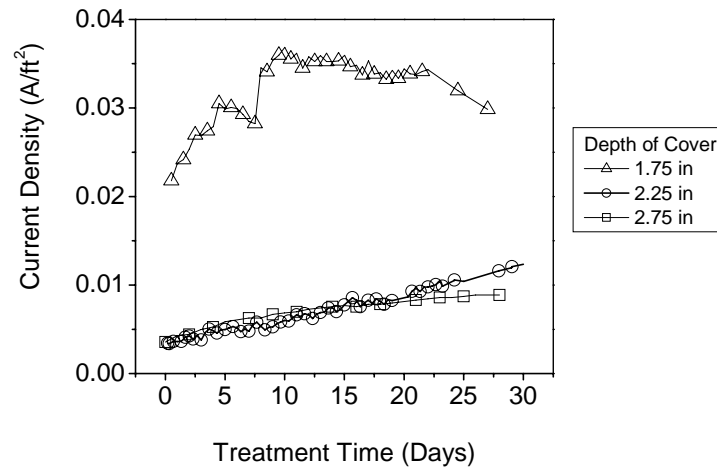


Figure 14. Average Current Density for Type I Slabs with w/c of 0.55

Methods for Improving Chloride Removal Efficiency

Earlier work demonstrated that a tightly adherent surface layer on the concrete causes an increase in the resistance during ECE.⁴ Therefore, three different for removing the surface layer were investigated: in-situ surface milling, sandblasting, and the addition of a scale inhibitor.

In-situ Surface Milling

In-situ surface milling was performed 3 times on four of the Type I slabs near the end of the treatment. The influence of milling the concrete surface was evident in the 4-pin resistivity measurements of the concrete. This was done using contact point items 4 and 6 (the four upper titanium rods and then the four lower titanium rods) as described in Table 4. The results are shown in Figure 15 for 0.40 and 0.50 w/c slabs. It is clear from this figure that the milling had a stronger influence on the top row of titanium rods than on the bottom row. It is also clear that some attempts at removing the surface had a much stronger influence on the resistivity than did others. This is probably due to difficulties in removing the surface material evenly, which is evident in Figure 16.

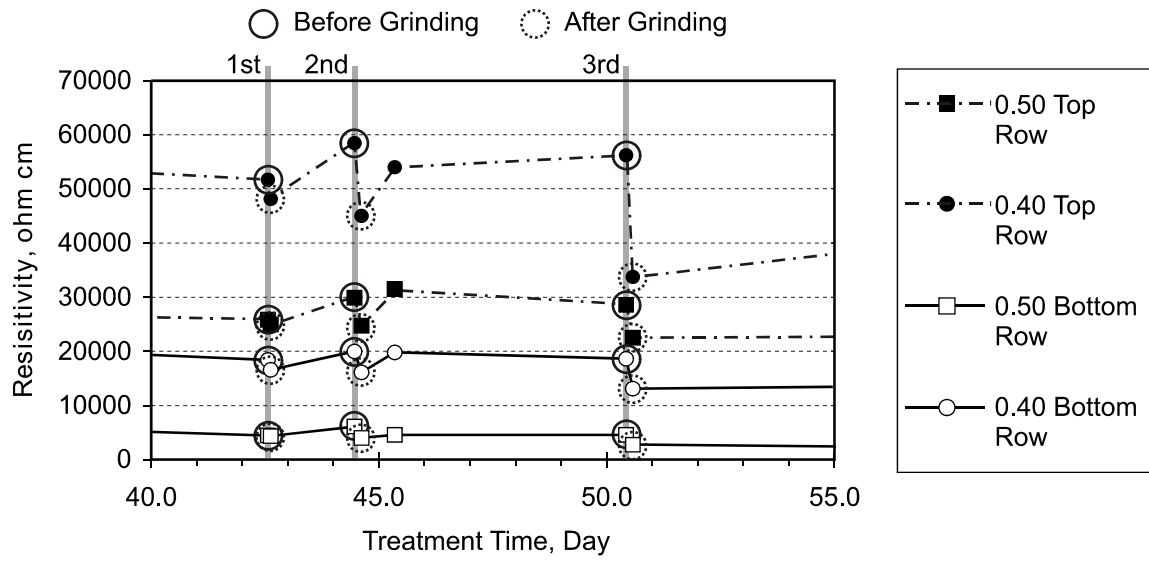


Figure 15. Change in Resistivity Attributable to In-situ Milling

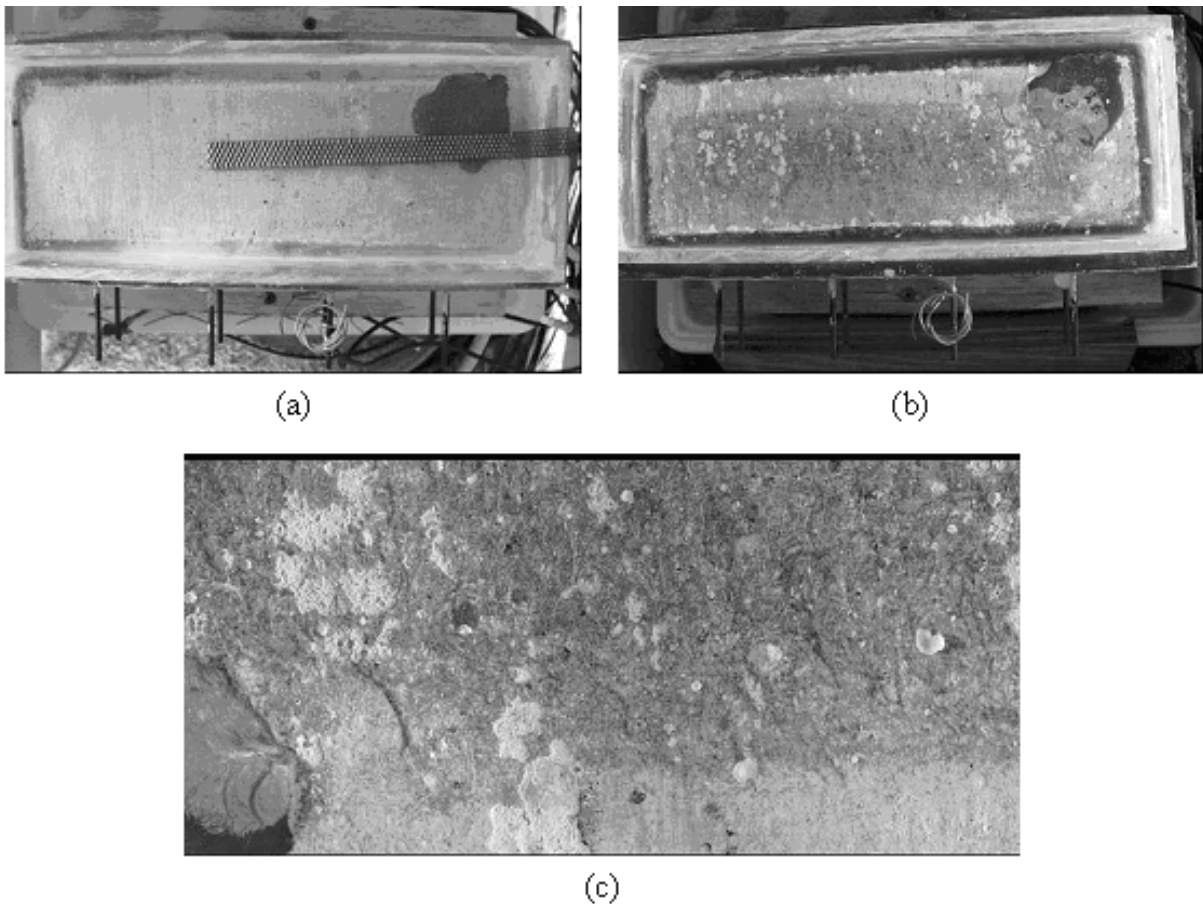


Figure 16. Visual Results of In-situ Surface Milling: (a) surface before milling, (b) surface after milling, (c) close-up of surface after milling

Sandblasting

Tests were conducted on the eight Type II test slabs, described in Table 3, to evaluate the influence of sandblasting the surface both before and during ECE. For Group 1 and 2 slabs, the complete surface was abraded before ECE. When the treatment had reached the midpoint, Group 2 slabs were sandblasted for a second time. The measurements of accumulated charge, which occurred over 26 days, before the second sandblasting of Group 2 are given in Table 10.

Before Group 2 was sandblasted for the second time, the data from Group 1 and Group 2 can be combined for analysis because the groups were treated equivalently. When comparing the sandblasted (Group 1 and 2) and control samples (Group 0) using a two-sample independent t test, it is evident that at the 0.05 level, the difference of the means of the populations is not significantly different than the test difference. A summary of the statistics is given in Table 11. It is clear that although there is a difference in the average charge passed for some of the blocks, statistically there is no significant difference between the means. However, the sample size was small (in general, two or three samples per group), which can strongly influence the magnitude of the standard deviation.

After ECE, the amount of charge passed during ECE was again determined for each test condition, as shown in Table 12. Table 13 and Table 14 provide a summary of the statistical comparison between the means of the sandblasted and control test blocks. Again, using a two-sample independent t test, the difference of the population means when the Group 1 or 2 specimens were compared to the Group 0 specimens was not significantly different than the test difference at the 0.05 significance level.

Table 10. Summary of Charge (in Coulombs) That Passed Through Slabs After Partial ECE Treatment But Before Sandblasting Slabs 17-19 Again and Restarting Treatment on All Slabs

Group 2		Group 1		Group 0	
Slab No.	Charge Passed	Slab No.	Charge Passed	Slab No.	Charge Passed
17	145911	20	169846		
18	181507	21	155140	23	160320
19	163818	22	166687	24	160929

Table 11. Statistical Comparison Using Independent t Test of Data in Table 10 Between Slabs Sandblasted Before ECE and Control Slabs

Null Hypothesis: Mean (Group 1 and 2) – Mean (Group 0) = 0				
Alternative Hypothesis: Mean (Group 1 and 2) – Mean (Group 0) \neq 0				
Sample	N	Average Charge Passed, C	Standard Deviation	Standard Error
Sandblasted prior to ECE (Groups 1 and 2)	6	163818	12275	5011
Control (Group 0)	2	160624	431	305
Difference of means = 3194				
T = 0.349				
Degrees of freedom = 6				
P value = 0.73901				

Table 12. Summary of Charge (Coulombs) That Passed through Slabs After ECE

Group 2		Group 1		Group 0	
Slab No.	Charge Passed	Slab No.	Charge Passed	Slab No.	Charge Passed
17	386705	20	448405		
18	482892	21	438561	23	406825
19	439322	22	446701	24	495864

Table 13. Statistical Comparison Using Independent *t* Test on Data in Table 12 Between Slabs Sandblasted Twice and Control Slabs

Null Hypothesis: Mean (Group 2) – Mean (Group 0) = 0				
Alternative Hypothesis: Mean (Group 2) – Mean (Group 0) < 0				
Sample	N	Average Charge Passed, C	Standard Deviation	Standard Error
Sandblasted before and during ECE (Group 2)	3	436306	48164	27808
Control (Group 0)	2	451344	62960	44520
Difference of means: -15038				
T = -0.30761				
Degrees of freedom = 3				
P value = 0.77850				

Table 14. Statistical Comparison Using Independent *t* Test on Data in Table 12 Between Slabs Sandblasted Once and Control Slabs

Null Hypothesis: Mean (Group 1) – Mean (Group 0) = 0				
Alternative Hypothesis: Mean (Group 1) – Mean (Group 0) < 0				
Sample	N	Average Charge Passed, C	Standard Deviation	Standard Error
Sandblasted before ECE (Group 1)	3	444555	5261	3037
Control (Group 0)	2	451344	62960	44520
Difference of means = -6789				
T = -0.20318				
Degrees of freedom = 3				
P value = 0.85200				

However, in Figure 17 through Figure 20, the influence on the treatment process on the surface is evident. A white film covers the surface of the slabs that were never sandblast, as seen in Figure 17. The surface of the slabs sandblasted before treatment have surface pores filled with residue, as seen in Figure 18, in addition to a unusual pattern across the top surface. The spots are similar in size and shape to the coarse aggregate used in the slabs. As seen in Figure 19, most of the surface film is gone, but some is evident. Even though the black beauty slag blast medium is very aggressive and is intended for use on concrete, it cannot penetrate small crevices and cracks in the concrete. Clearly though, as seen in Figure 20, sandblasting the surface removes a significant amount of this residue and reopens the larger surface pores. However, as evident in Figure 15, the resistivity begins to increase again following removal of the surface. This is consistent with the findings of Clemeña and McGeehan, who studied the electrochemical accretion of minerals from seawater. In their study, applying a current density of 0.1 A/ft² resulted in the formation of mineral deposits in cracks in approximately 3 days.⁸ Further, in 1 week, the deposit had extended past the surface plane of the test specimen into the anolyte.⁸ Therefore, during ECE, it is expected that deposits will form again in the cracks and pores reopened using sandblasting.



Figure 17. Concrete Surface Never Sandblasted

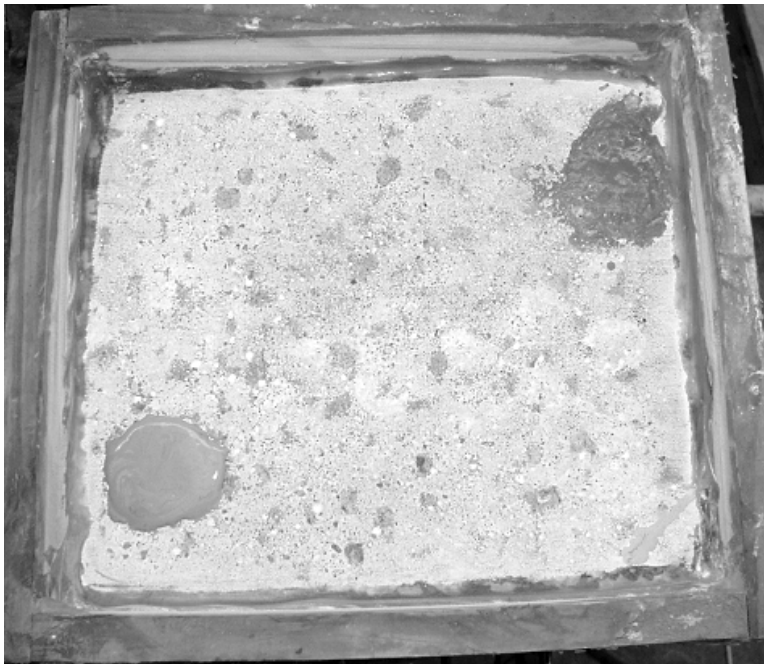


Figure 18. Concrete Surface Sandblasted Only Once, Prior to ECE

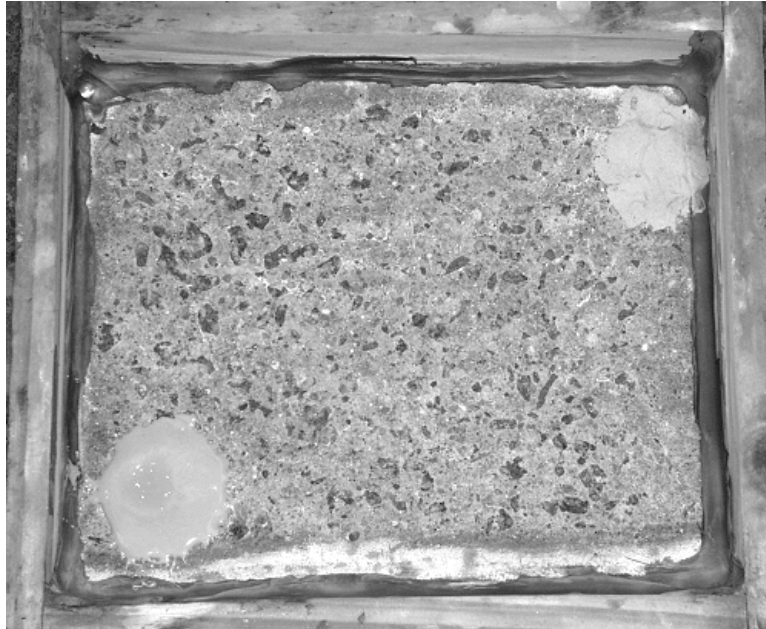


Figure 19. Concrete Surface after Sandblasted a Second Time Midway Through ECE

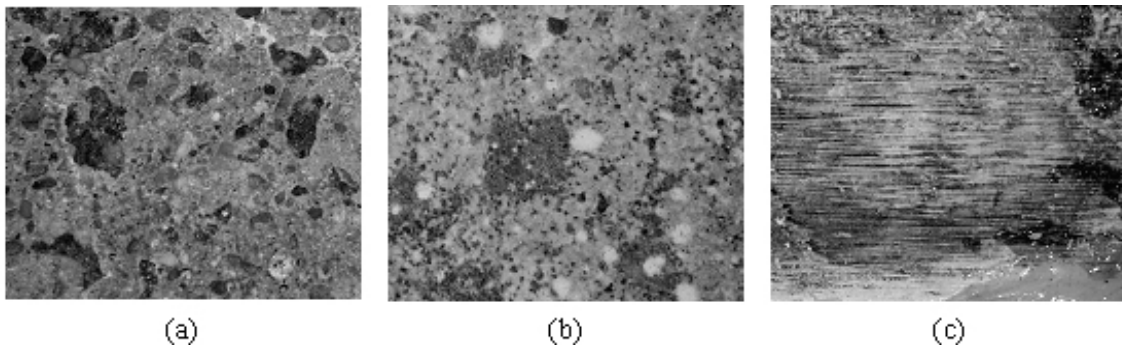


Figure 20. Close-up of the Three Surfaces Midway through ECE: (a) from Group 2, sandblasted, (b) from Group 1, sandblasted, (c) from Group 0, not sandblasted

The voltage and current density measurements made during sandblasting are shown in Figure 21. Initial observations indicate that removing the surface layer was beneficial for ECE. Initially, Group 1 and 2 slabs were sandblasted, and Group 0 slabs were not. All specimens were then treated simultaneously using ECE. Then, after approximately 26 days, the electrolyte was removed from all the slabs, concrete samples were gathered for chloride analysis, and the slabs in Group 2 were sandblasted a second time. All slabs in Group 2 showed a substantial change in voltage across the top surface of the concrete and a decrease in the overall voltage. As shown in these figures, the Group 2 slabs underwent nearly a 77 percent drop in voltage in the surface region following sandblasting, whereas the other slabs show very little change.

After ECE, the impact of sandblasting the Group 2 slabs can be seen in Figure 21. The voltage difference between the titanium strip and the titanium rod, as well as the voltage difference between the anode and rebar (the total applied voltage), remained lower than those of the Group 1 and Group 0 test slabs. It is known that the flux of a species is directly proportional to the difference in potential over a given distance. Therefore, if the voltage difference in one region of the concrete increases at the expense of another and all other factors remain constant,

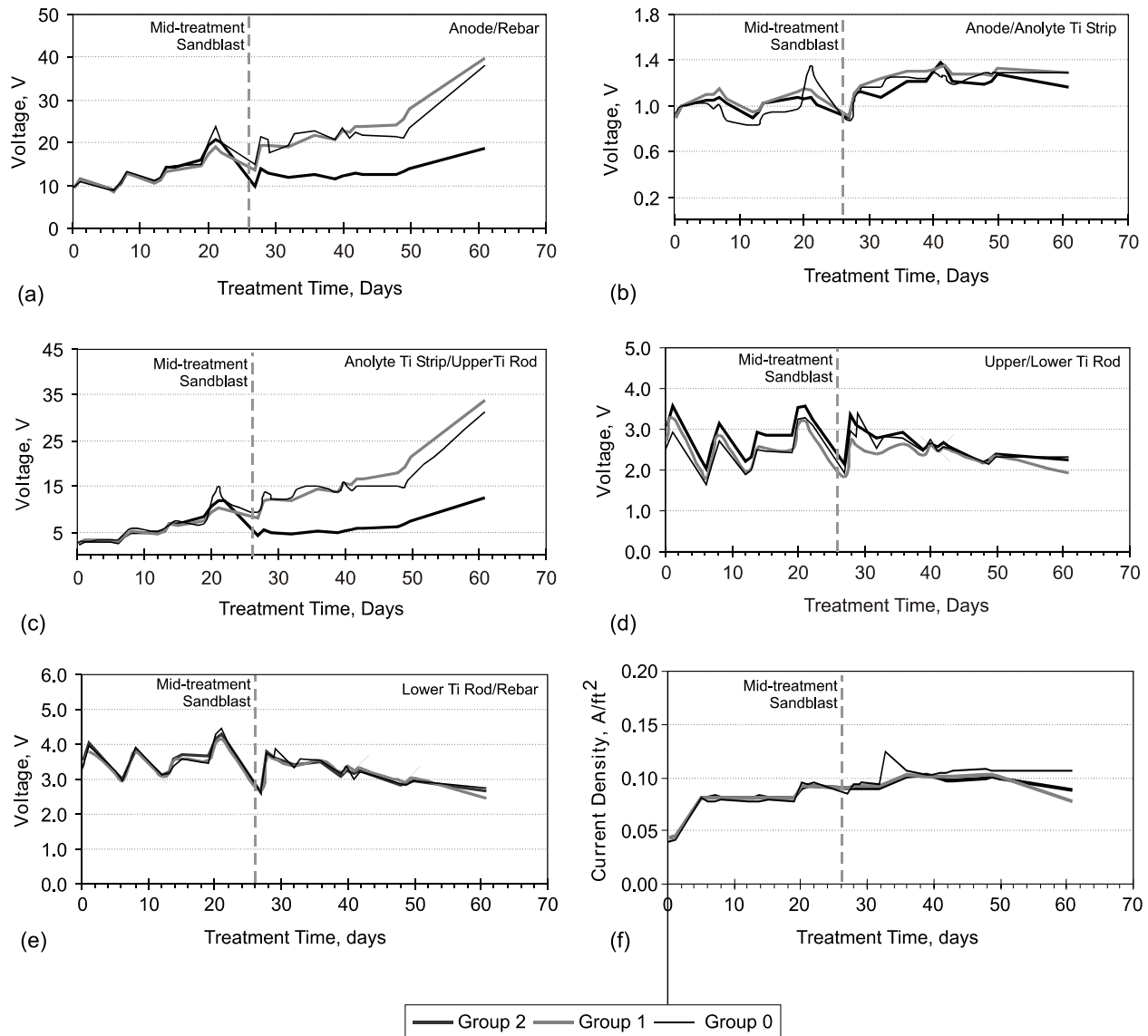


Figure 21. Influence of Sandblasting on Voltage and Current: (a) voltage between anode and rebar, (b) voltage between anode and titanium strip, (c) voltage between titanium strip and upper titanium rods, (d) voltage between upper and lower titanium rods, (e) voltage between lower titanium rod and rebar, (f) current density during treatment.

the flux in the region will be greater. Although research has shown that chloride movement in concrete is time dependent during ECE, and therefore the assumption that only the potential is changing is not valid, a larger potential difference near the steel is desirable. However, previous work has shown that during ECE the largest voltage difference occurs at the concrete surface.⁴ Further, the increase in voltage at the surface becomes more significant during ECE because the total applied voltage cannot exceed a preset maximum because of public safety concerns. In the field, this results in the voltage across the concrete surface continuing to increase until it reaches the maximum voltage setting for the system, which then causes the current density to decrease.

Another way of evaluating the influence of the surface film and the effect of removing it is to consider the measured current density versus the ideal current density. As can be seen in Figure 22, the measured current density begins to decrease once the voltage has reached the maximum value. Therefore, if the system voltage is kept below the preset maximum throughout the treatment, the current density operates at the preset maximum. For a given current density, the ionic flux is maximized. According to data for a Type I test slab, allowing the system to operate at the ideal current density (ideal being the maximum current density that will not result in damage to the concrete or steel, which in Figure 22 would be 0.1 A/ft²) would result in a 5 percent increase in charge passed. In addition, it is expected that this value would actually be higher since the total treatment time was less than 60 days. Unfortunately, during the sandblasting portion of the study, the current densities remained at the maximum settings during the entire duration of the treatment, so the expected benefit could not be proven.

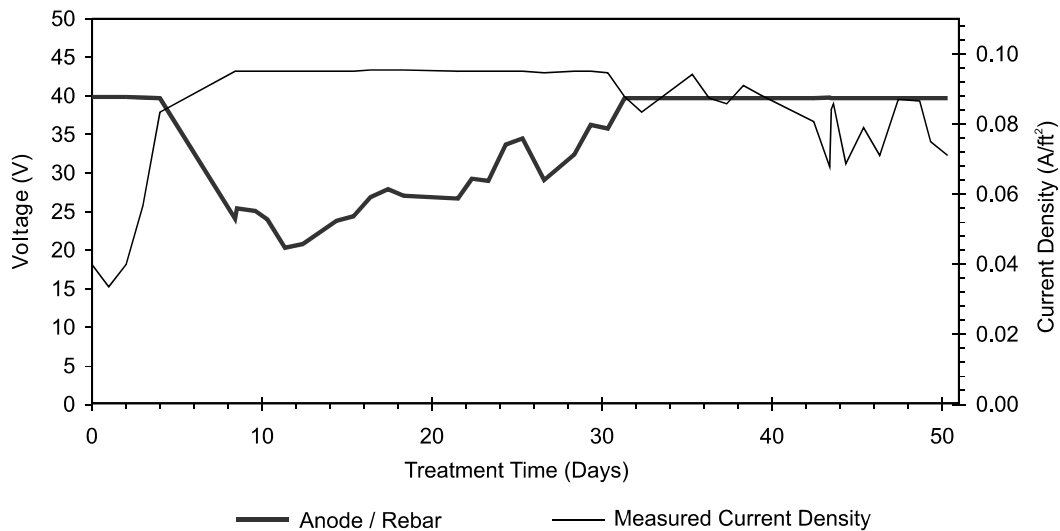


Figure 22. Measured Current Density versus Ideal Current Density

Scaling Inhibitor Solution Addition

Type III test slabs were used to evaluate the influence of a scaling inhibitor on the surface layer that forms during chloride extraction and on the chloride removal efficiency. The chloride removal efficiency was evaluated based on chloride sampling depth, which is shown in Figure 23. The chloride removal efficiency is defined by Bennett et al. as the percent difference between the actual amount of chloride removed and the ideal amount if the chloride ion carried 100 percent current.¹⁵

Since the scale inhibitor was added to the ponding area, it was important to determine if the inhibitor influenced the chloride removal efficiency at the reinforcing steel. As is evident in Figure 23, when the scale inhibitor is added before treatment it appears to have the strongest influence near the surface. This was expected since it is known that Alpha 2771 will bind with calcium.

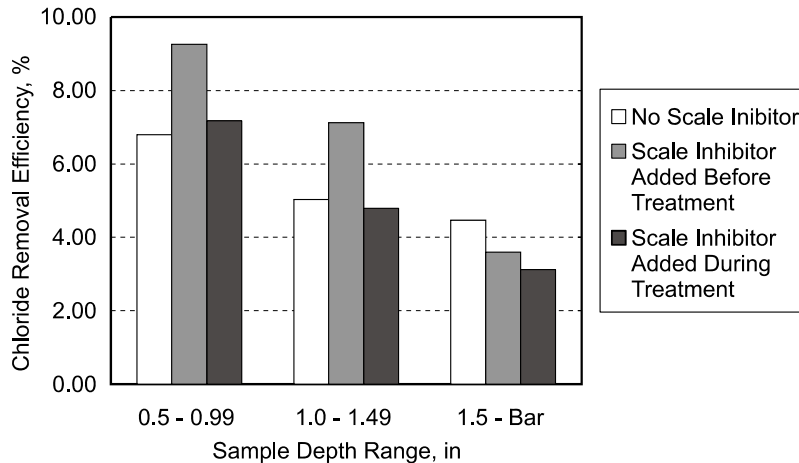


Figure 23. Influence of Scale Inhibitor Treatment on Average Chloride Removal Efficiency

CONCLUSIONS

- The cover depth did not decisively influence the chloride removal efficiency during ECE.
- The w/c did not clearly influence the chloride removal efficiency during ECE.
- Increasing the cover depth increases the resistance between the anode and cathode.
- In general, sandblasting and in-situ surface milling improve the chloride removal efficiency of ECE.
- Scaling inhibitor solutions have the potential to increase the removal of chloride, especially adjacent to the concrete surface.

RECOMMENDATIONS

1. VDOT's Structure & Bridge Division should require that contractors mechanically remove the latent surface layer of concrete prior to applying ECE.
2. VDOT's Structure & Bridge Division should discuss with corrosion consultants the potential for using a scale inhibitor during ECE to increase the efficiency of chloride removal.

BENEFITS AND COSTS ASSESSMENT

Research currently underway is investigating the increase in service life that will result from treating a structure with ECE. This will be done using laboratory slabs and concrete piers that are being constructed for testing. A designated section on the vertical face of the piers will

be exposed to cyclic ponding cycles. Similar to the slabs, a portion of the piers will be treated and the other left untreated. To accomplish these tasks, comparisons will be made among the controls, treated, and untreated slabs. Monitoring will include changes in permeability, resistance, half-cell potential, corrosion rate, regional temperature, current and voltage measurements, and total chloride concentration. The data will be analyzed to determine the benefit of ECE treatment, and a life cycle cost analysis will be performed. The life cycle cost analysis will provide a comparison of minimal restoration versus ECE.

Additional work with scaling inhibitor solutions should also be pursued. From this research work, it is evident they have the potential to increase the chloride removal efficiency. Further, this approach can most likely be done in the field without significantly increasing the overall treatment cost. Finally, it would be interesting to see the combined effects of sandblasting before ECE to open the pathways of the concrete and then using a scaling inhibitor to keep these pathways open during ECE. Most likely, this would not significantly increase the cost of treating an actual structure and could even reduce the overall cost by increasing the efficiency of the treatment process, which would lead to a reduction in the required treatment time.

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