

INTERIM REPORT

**PILOT APPLICATIONS  
OF ELECTROCHEMICAL  
CHLORIDE EXTRACTION  
ON CONCRETE PIERS  
IN VIRGINIA**

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**(The opinions, findings, and conclusions expressed in this  
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## ABSTRACT

Applying a temporary electric field between the concrete surface and the rebars can expel or remove chloride ions from salt-contaminated reinforced concrete, which will mitigate rebar corrosion. A new method for the permanent rehabilitation of concrete bridges, based on the technique of electrochemical chloride extraction (ECE), was applied to three concrete piers as part of pilot trials in Virginia, to demonstrate the practicality of the method on full-sized bridge elements and refine implementation techniques.

The ECE treatment involved placing a simple wet mesh-and-fiber anode system on the surface of the piers. A total electrical charge of 249 to 382 A-hr/m<sup>2</sup> (23.1 to 35.5 A-hr/ft<sup>2</sup>) was applied between the anode and the rebars underneath a total of 488 m<sup>2</sup> (5,253 ft<sup>2</sup>) of concrete for 72 to 77 days (a shorter treatment time would likely suffice). Approximately 27.2 to 59.9% and 12.9 to 52.7% of the initial chloride ions were removed from concrete at the depths of 0.6 to 1.9 cm (0.25 to 0.75 in) and 2.5 to 3.8 cm (1.0 to 1.5 in.), respectively. Some problems with the system were encountered during the treatment. All the problems were correctable. No discernible adverse effect on the concrete due to the treatment was observed. The project demonstrated that ECE treatment of full-sized concrete bridge piers can be conducted with reasonable success.

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## **INTRODUCTION**

Once the chloride ions from deicing salts have intruded into a concrete structure and started to damage the concrete, really effective permanent rehabilitation requires cathodic protection, after repair of the damaged concrete. In the absence of cathodic protection, many highway agencies still resort to replacing all contaminated concrete in permanent rehabilitation projects whether it is structurally sound or not, which can be wasteful and expensive. Technical difficulties prevent some of the contaminated concrete from being found. Therefore, microcells, or localized pockets of electrochemical imbalances, remain in the concrete and rebar corrosion and concrete damage begin again, making rehabilitation a temporary state of affairs.

Some state highway agencies have already adopted cathodic protection because it permanently halts rebar corrosion in salt-contaminated concrete structures, and because it makes it unnecessary to replace contaminated-but-sound concrete, which is very expensive, especially for load-bearing concrete piers. In practice, however, cathodic protection remains effective only as long as the system is inspected and maintained regularly. The maintenance is often relatively simple and inexpensive, but the idea of increasing the maintenance workload has discouraged

bridge engineers from using cathodic protection, especially with the work-force downsizing of many state highway agencies.

The failure of the excavation method and the maintenance demands of cathodic protection have prompted the search for an alternative way to remove chloride. One such method is based on the electrochemical principle that opposite charges attract and like charges repel. If an electrical field is created between the surface of a concrete structure and the embedded rebars by passing a direct current through it (as in cathodic protection), the concrete surface becomes positively charged and the rebars become negatively charged. The negatively-charged chloride ions (Cl<sup>-</sup>) that have accumulated in the concrete are then repelled by the rebars and drawn toward the surface of the concrete. The outward migration of the chloride ions accompanies the movement of other mobile ions in the concrete, each in the direction dictated by its electrical charge, contributing to the conduction of the electric current through the top layer of concrete.

This electrochemical process was studied in the mid-1970's, when the Kansas Department of Transportation and Battelle Columbus Laboratories confirmed the feasibility of electrochemical removal of chloride from concrete.<sup>1,2,3</sup> However, the levels of direct current used in those early studies -- with an average current density between 23-28 A/m<sup>2</sup> (2.3-2.8 A/ft<sup>2</sup>) and a constant voltage of 100 V in one study -- were unnecessarily high and led to adverse side-effects (increases in concrete permeability, decreases in the concrete-to-steel bond, and cracking in the concrete). The adverse side-effects discouraged further study of electrochemical chloride extraction (ECE) for several years. Consequently, bridge engineers still commonly try to replace all salt-contaminated concrete (as located by half-cell potential surveys and chloride tests of concrete samples) during permanent rehabilitation.

The recent Strategic Highway Research Program (SHRP) resumed the study of ECE in laboratory slabs and field trials on portions of some bridge elements.<sup>4,5,6</sup> SHRP studies concluded that levels of applied current below 5A/m<sup>2</sup> (0.5A/ft<sup>2</sup>) are unlikely to harm concrete. The various treatments removed 20 to 50% of the chloride ions present in the concrete and redistributed the remaining chloride well away from the rebars.

SHRP investigators also claimed that, as expected from known reaction of water molecules at a cathode, the treatment increased the concentration of hydroxide ions, [OH<sup>-</sup>], at the steel surface. This also helps arrest rebar corrosion in the concrete, which depends more on the

ratio of the concentration of chloride to the concentration of hydroxide,  $[Cl^-]/[OH^-]$ , than on chloride concentration,  $[Cl^-]$ , alone.

An independent study in Canada, where portions of a concrete pier column were treated, confirmed the partial removal of chloride in the concrete and the passivation of the rebars.<sup>7</sup>

We do not know how long ECE treatment continues to protect a concrete structure. Only the long-term monitoring of ECE-treated concrete can answer that question. The latest follow-up measurements of half-cell potential and corrosion rate made on the concrete slabs and components used in the SHRP and Canadian studies, some of which were treated six years ago, indicated that the rebars in those slabs and components are still passive.<sup>8,9</sup>

ECE can be accomplished with current levels considerably lower than those used in the earlier studies, avoiding adverse effects on the concrete. The elimination of the side-effects has rekindled considerable interest in ECE, since the process can be completed in 4 to 8 weeks (depending on the initial chloride content and the current density used) and requires no post-treatment maintenance of electrical components.

However, before ECE can become a routine rehabilitation process for salt-contaminated concrete structures, practical demonstrations on full-sized concrete bridge components are needed, to further refine the implementation techniques. Responding to this need, pilot ECE treatments were installed on three concrete piers in Charlottesville, Virginia, as described in this report. A companion report describes a similar treatment of concrete decks.<sup>9</sup>

## **ECE TREATMENT OF CONCRETE PIERS**

### **Description of the Concrete Piers**

The concrete piers of a 27-year-old bridge on 5th Street (Rt. 631) over Interstate Route 64 in Charlottesville, Virginia were used in this study (Figure 1). The bridge has three pairs of concrete piers, each pair divided by a joint into an east and a west section. The lengths of the caps on the selected piers, which have a rectangular cross section of 1.3 m by 1.5 m (4.3 ft. by

*Figure 1. The concrete piers of the 5th Street Bridge over Interstate Route 64, Albemarle County, Virginia.*



4.8 ft), vary from 13.9 to 16.1 m (45.5 to 53.0 ft). The circular columns have a diameter of 1.1 m (3.5 ft), and vary in height (above ground) from 5.6 to 6.5 m (18.5 to 21.3 ft).

To evaluate the long-term effect of the ECE treatment on the piers, only the west section of each of the three pairs of concrete piers was treated, using the east sections as controls (Table 1). As noted, a water-based silane sealer was applied over the treated concrete piers to provide a barrier against future ingress of water and chloride.

Table 1  
ECE Treatment of Concrete Piers of the 5th Street Bridge

Pier	Section	Option	Concrete Area (m <sup>2</sup> )
1	West	ECE and Silane Sealer	177
2	West	ECE and Silane Sealer	176
3	West	ECE and Silane Sealer	134
Total			488
1	East	Control	137
2	East	Control	136
3	East	Control	158
Total			431



Approximately four years ago, some delaminated and spalled concrete (with exposed rebars), mostly in the bottoms of pier caps and tops of columns, was repaired. During preparation for this ECE treatment, some 1.6 m<sup>2</sup> (17.3 ft<sup>2</sup>) of delaminated concrete, mostly at the bottoms of caps and tops of columns, was detected and repaired before the ECE treatment.

### **Installation of the Treatment**

During the installation of the ECE treatment system on the piers, which took only 6 to 7 days for all three piers, traffic control warning signs were set up beside the piers on the shoulders of I-64. Similar traffic warning signs were set up when the system was dismantled after the treatment. Traffic on the interstate and the 5th Street bridge was not interrupted during the project.

A suitable anode was attached to the surface of the concrete, as in cathodic protection. The only difference was that in ECE treatment the electrode is temporary, and was removed after treatment. To keep the ECE treatment as simple as possible, a Norcure™ licensed anode system, consisting of a mesh anode surrounded by wet cellulose fibers, was installed by Vector Construction Limited of Winnipeg, Canada. (A more elaborate Norcure-licensed anode system, which uses individual cassette shutters, is available from Martech Service Limited, England.) The installation proceeded as follows:

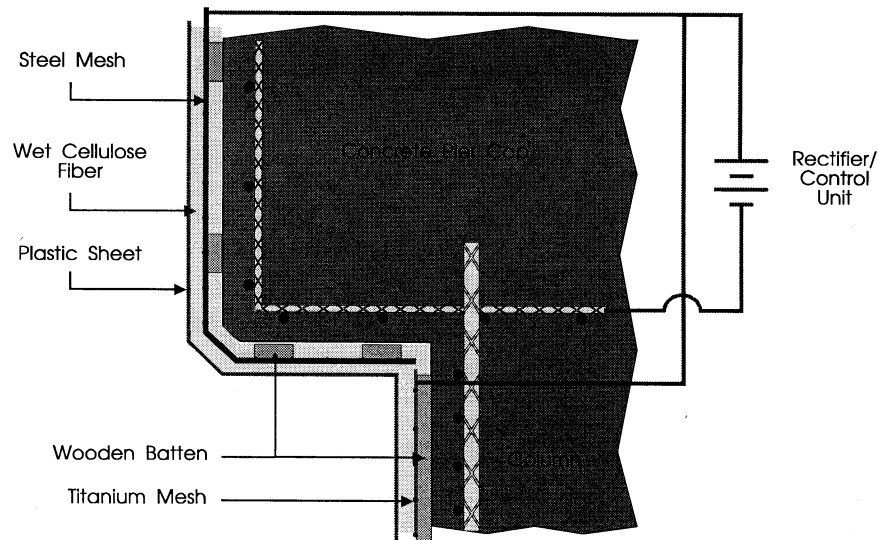
#### *Preparation of the Concrete Surface*

1. Removal and patching of all delaminated concrete in the piers.
2. Application of cement grout to cover any surface cracks on the concrete, to prevent electrical shorting. Failure to do this may jeopardize the treatment of an entire area.
3. Testing to ensure that the rebars in each pier are electrically continuous, followed by the establishment of three ground connections to the rebars across each pier.

### *Installation of the Anode System over the Concrete Piers*

The Norcure™ anode system is a mesh anode surrounded by wet cellulose fibers. As Figures 2 and 3 show, steel mesh was used as anode on the pier caps. Inert catalyzed titanium mesh, which is not as stiff as steel mesh, was used on the curved end of each cap and the columns. The installation of this anode system on each of the piers proceeded as follows:

1. Installation of at least two longitudinal 25 mm (1 in) thick wood spacers on each side (except the top side) of each pier cap, along the entire length of the cap. On the curved end of each cap, pieces of the same wood spacer were installed vertically along the entire height of this portion of a cap. To prevent any electrical short during the treatment, plastic anchor bolts were used to secure the wood spacers on the concrete.
2. Installation of a minimum of three vertical wood spacers on each column, from top to bottom.



*Figure 2. Cross section plan of the setup for the ECE treatment of the concrete piers.*

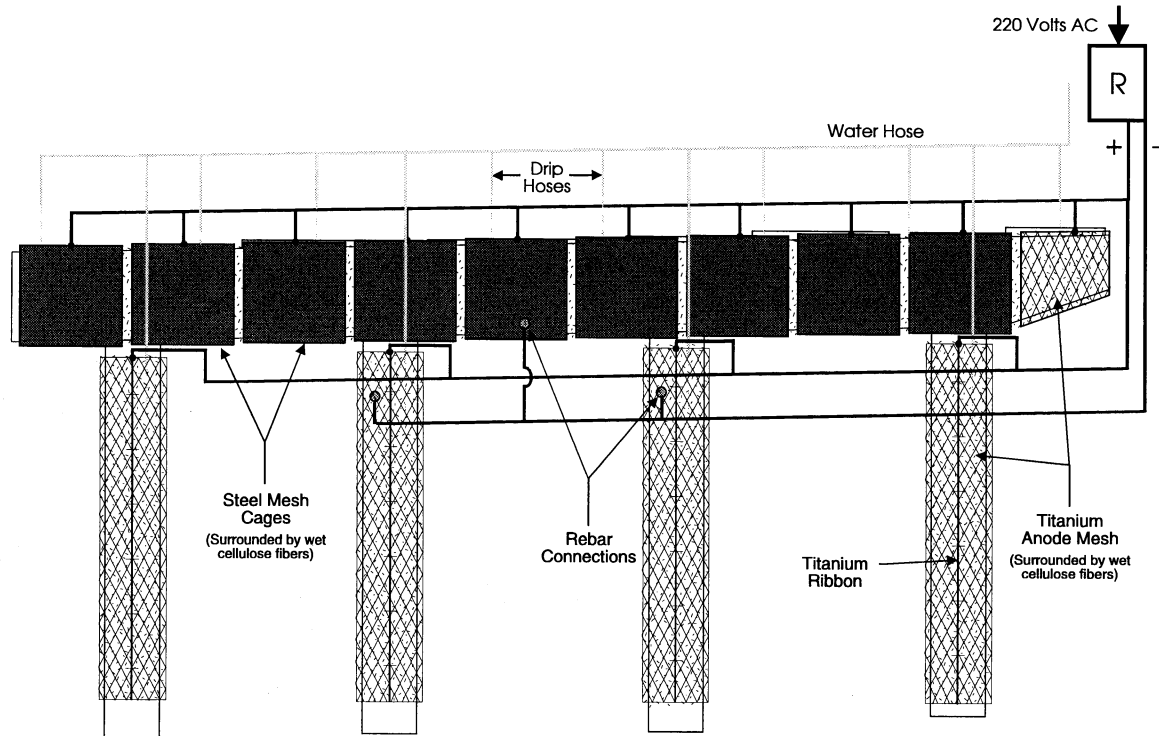


Figure 3. Plan view of the setup for ECE treatment of the concrete piers.

3. Placement of enough sections of 6 mm (0.25 in) thick steel mesh around each cap to cover everything except the curved end. (The mesh was pre-formed to fit over the wood spacers and around the caps.) All the mesh was secured around each cap with plastic ties, by running each tie underneath a wood spacer and over the mesh (Figure 4).

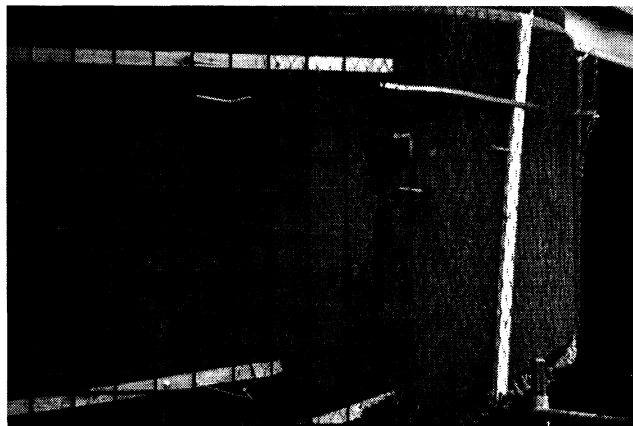


Figure 4. Construction workers securing a section of formed steel anode mesh around a pier cap.

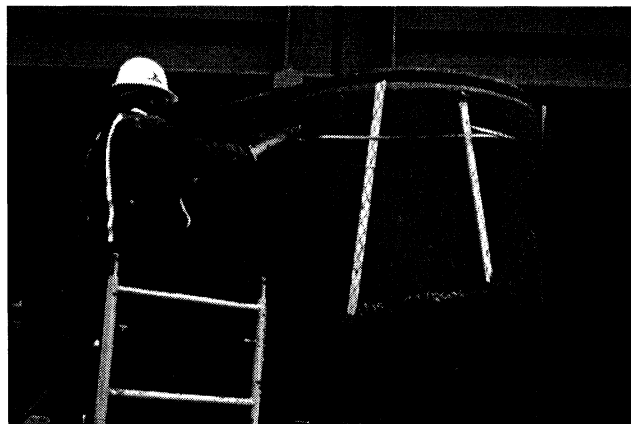
Cut sections of titanium mesh were similarly secured around the curved end of each cap (Figure 5).

4. Connecting an insulated copper lead wire, of adequate gage, to each of the ground connections. Each connection was then waterproofed with epoxy.
5. Covering the entire cap, except the bearing pads, with wet cellulose fibers, by spraying the wet fibers over the cap until the layer is at least 50 mm (2 in) thick (Figure 6).

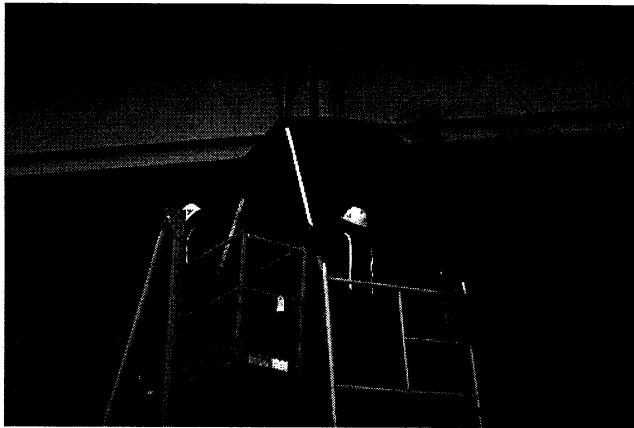
*Figure 5. Steel and titanium anode mesh secured around curved end of pier cap. Mesh secured to wood spacers with plastic cable ties.*



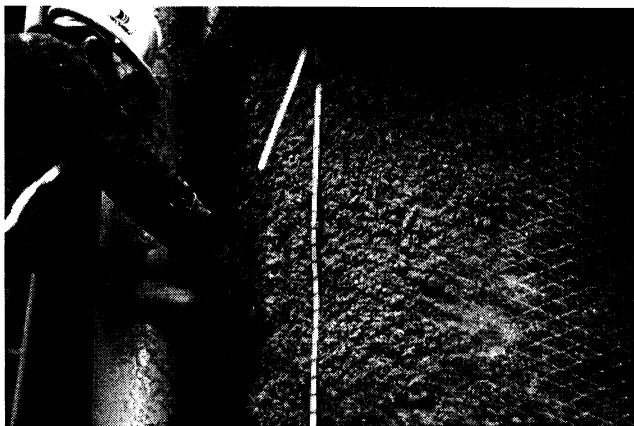
*Figure 6. Spraying wet cellulose fibers over the concrete pier cap.*



6. Wrapping the entire fiber-coated pier cap, from end to end, with a continuous sheet of black plastic to keep the fibers in place and minimize evaporation of the electrolyte. The plastic should be overlapped between turns. The plastic sheet is secured by banding with heavy plastic strapping (Figure 7).
7. Spraying a layer of wet cellulose fibers, approximately 25 mm (1 in.) thick, to cover each column from the top to about 0.15 m (6 in) above the ground or slope protection.
8. Installation of a layer of titanium mesh around each column and over the first layer of cellulose fibers (Figure 8). Before installation, a continuous piece of 12-mm (0.5-in) wide titanium ribbon was welded to the entire length of the mesh, to ensure adequate electrical connection of the mesh to the rectifiers.

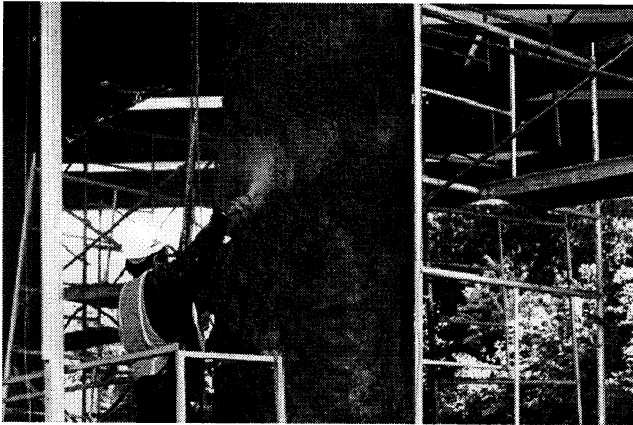


*Figure 7. Wrapping a pier with heavy plastic sheeting to protect the cellulose fibers.*



*Figure 8. Worker securing titanium mesh around a pier column coated with a layer of wet cellulose fibers. Note the titanium ribbon welded to the mesh.*

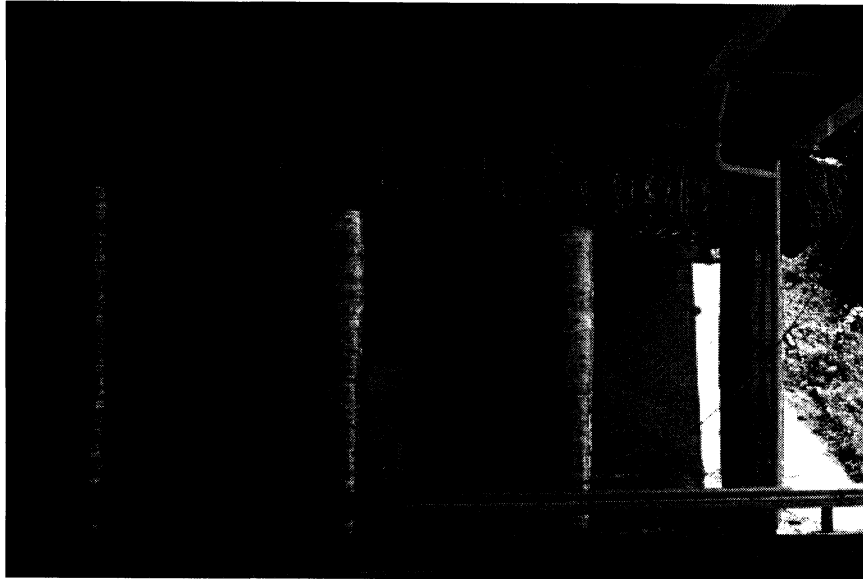
9. Application of a second layer of wet cellulose fibers over each column, to completely cover the titanium mesh (Figure 9). Including this layer, the fibers applied on each pier column totaled approximately 50 mm (2 in) thick.
10. Wrapping each column tightly, from top to bottom and allowing for considerable overlapping between turns, with a continuous piece of plastic film, such as Shrink Wrap (Figure 10). Figure 11 shows an entire pier completely wrapped.



*Figure 9. A final layer of wet cellulose fibers sprayed on a column, completely covering the titanium anode mesh.*

*Figure 10. A column completely coated with cellulose fibers being wrapped from top to bottom with a plastic film.*





*Figure 11. A pier completely covered with plastic sheet and film, after installation of the anode system.*

11. Connecting all sections of anode mesh that surrounding each pier cap to the positive terminal of a rectifier designated for the pier, using insulated electrical wires of a sufficient gage. Similarly, all titanium mesh on the columns is connected to the same rectifier (Figure 3), with a maximum output rating of 150 A at 40 V requiring a single phase 220 V AC line.
12. Connecting all ground lead wires to the negative terminal of the same rectifier.
13. Installing a system of drip hoses on top of the cap, connected through a main hose to a central water source or faucet, to keep the cellulose fibers on the cap and the columns wet throughout the treatment. To add lime to the water, if it becomes necessary to neutralize any excessive acid generated by the titanium mesh, a mixing tank (converted from a water heater) is connected between the central water source and the main hose.

### *Startup of the Treatment*

1. Turning on the central water source to allow water to flow very slowly but continuously over each pier, keeping the fibers constantly wet. The water drains onto the ground.
2. Switching on the rectifiers. Each pier is connected to a rectifier, operated in the constant-voltage mode, with the DC output set at as high as possible but not to exceed 40 V and 1 A/m<sup>2</sup> (or 100 mA/ft<sup>2</sup>) of concrete.

### *Monitoring the Treatment*

The ECE treatment of the piers was planned for 6 to 8 weeks, a convenient length. During the treatment, the condition of the wrapped anode system on each pier, the flow of water to each pier, the output voltage and current of each rectifier, the current passing through each of all the positive and negative (ground) lead wires and the pH of the electrolytes were checked at least once every week. When the electrolyte on a pier became acidic, lime was added to the water in the converted water heater to raise the pH.

### **Pre-Treatment and Post-Treatment Tests**

To assess the extent of chloride removal, pulverized concrete samples were taken from several designated sampling points on the cap and the columns of each pier, before and after treatment, for chloride analyses. At each sampling point, separate concrete samples were taken at two depths from the surface: 0.6 to 1.9 cm (0.25 to 0.75 in), and 2.5 to 3.8 cm (1.00 to 1.50 in). At a few locations on pier 1, a third sample was taken at 4.4 to 5.7 cm (1.75 to 2.25 in). To minimize the effect of the natural inhomogeneity in the composition and physical characteristics of concrete on the results, the pre- and post-treatment samples from each sampling point were taken at spots within 1 cm (0.5 in) of each other. A potentiometric titration procedure, described elsewhere,<sup>10</sup> was used to determine the total chloride contents of all concrete samples.

A Digischmidt rebound hammer was used to measure the surface hardness of the concrete in each pier, before and after the treatment, to determine if there was any adverse effect on the



concrete surface. A permanent reference cell was embedded in each of the six concrete piers, including the untreated ones, for long-term monitoring.

## RESULTS AND DISCUSSION

At the beginning of the treatment, the output voltage of each rectifier was adjusted so the total current passing through the corresponding pier was less than  $1 \text{ A/m}^2$  ( $100 \text{ mA/ft}^2$ ). Then the rectifiers were operated in constant-voltage mode, in which the output voltages were maintained to within 2% of the mean -- except for the rectifier for pier 3, where voltage fluctuated by as much as 14.3%.

A short was encountered by the contractor on a circuit connected to the mesh on one section of the cap of pier 3, during treatment startup. Because it was impossible to locate the short once the entire pier was covered and wrapped up, that section of mesh was disconnected from the system. This could have affected chloride removal in a portion of pier 3, which (as discussed later) showed the lowest removal efficiency. Because electrical shorts cannot be located after the pier is completely wrapped, there needs to be a procedure to detect shorts during the spraying of the wet fibers. Perhaps the procedures used during the application of conductive anodes in the cathodic protection of concrete piers can be adapted for this purpose.

Figures 12 to 14 show the change in the density of direct current passing through each pier during treatment, which lasted from 72 to 77 days. The current passing through each pier, in general, decreased exponentially as treatment time increased. For example, in pier 1 the current started at  $300 \text{ mA/m}^2$  ( $27.9 \text{ mA/ft}^2$ ) and ended at  $117 \text{ mA/m}^2$  ( $10.9 \text{ mA/ft}^2$ ). This trend is commonly observed in the first several months of operation of cathodic protection systems, and is the result of a net increase in the electrical resistance of the concrete, which arises from the redistribution of different ions in the concrete. Table 2 summarizes various electrical parameters recorded for all piers during their treatment.

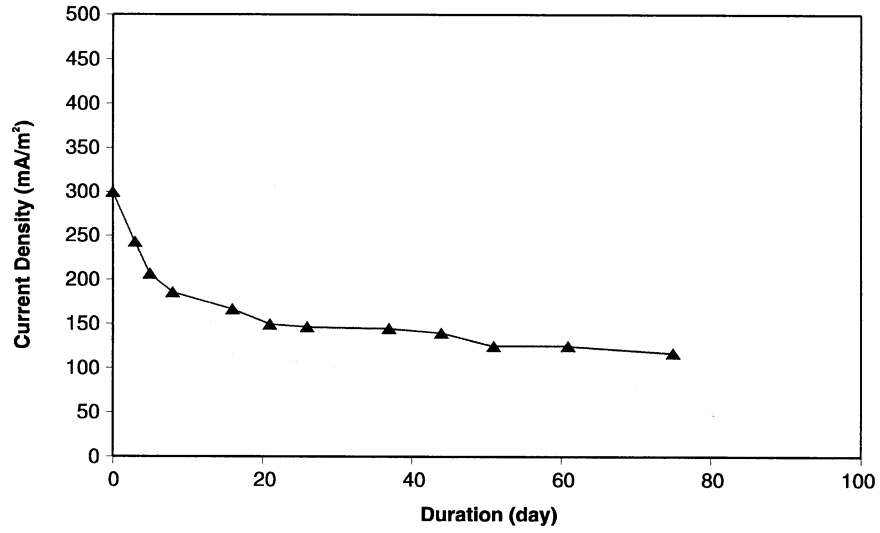


Figure 12. The treatment current passing through pier 1 under a constant voltage that averaged 38.5 volts.

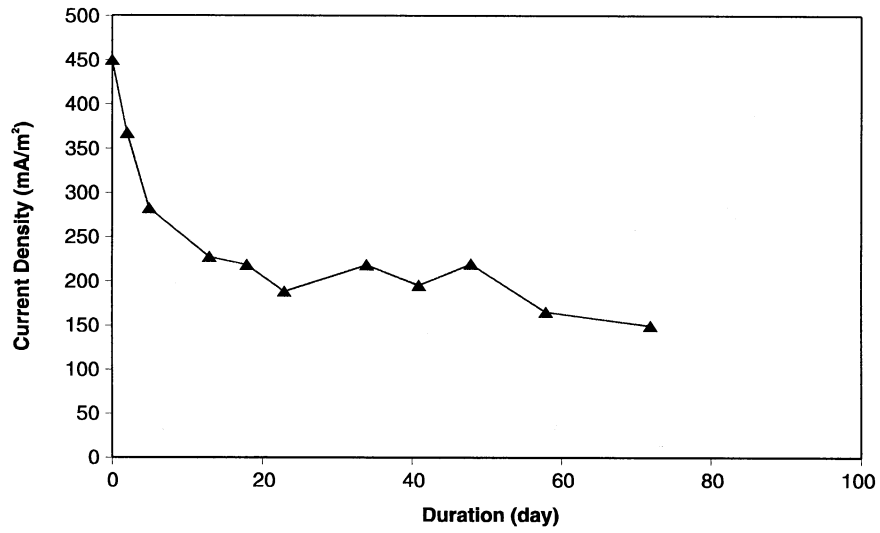


Figure 13. Current passing through pier 2 during treatment, under a constant voltage that averaged 40.1 volts.

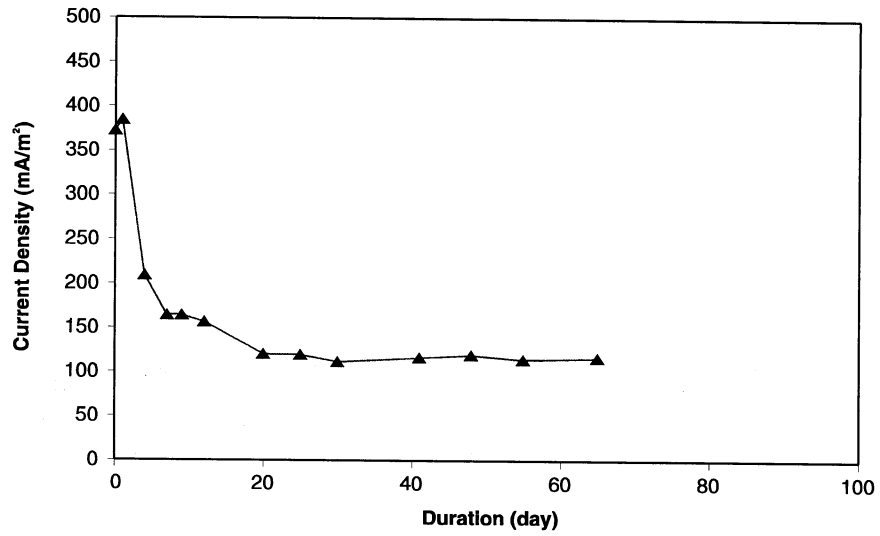


Figure 14. Current passing through pier 3 during treatment, under a constant voltage that averaged 41.2 volts.

Table 2  
Various Electrical Parameters Recorded During the  
ECE Treatment of the Concrete Piers

Pier	1	2	3
Treatment Duration (day)	77	74	72
Average Voltage (volt)	38.5	40.1	41.2
Initial Current (mA/m <sup>2</sup> )	300	450	373
Final Current (mA/m <sup>2</sup> )	117	150	117
Average Resistance (mohm/m <sup>2</sup> )	7.8	5.8	15.5
Total Charge (A-hr/m <sup>2</sup> )	276	382	249

Figures 15 to 17 show the estimated total electrical charge applied on each pier at different stages of the treatment. At the end of the treatment, the accumulated charge ranged from a low of 249 A-hr/m<sup>2</sup> (23.1 A-hr/ft<sup>2</sup>) for pier 3, to a high of 382 A-hr/m<sup>2</sup> (35.5 A-hr/ft<sup>2</sup>) for pier 2 (Table 2). This range is less than the 600 to 1500 A-hr/m<sup>2</sup> (60 to 150 A-hr/ft<sup>2</sup>) suggested as typical in the SHRP Implementation Guideline.<sup>11</sup> This is perhaps due to the relatively thicker concrete cover over the rebars in these piers and the relatively high electrical resistances of the concrete, due to the quality of the concrete in these piers.

Measurement of the pH of the electrolyte at various stages of the treatment indicated that it started to become slightly acidic, but never lower than 6.5, after the first several days of treatment. This required the addition of lime into the converted mixing tank. During this period, some yellowish staining of the wet cellulose fibers was observed at the bottom portions of some of the columns through the transparent plastic film wrap. This was attributed to formation of acid and a minute amount of chlorine on the titanium anode mesh used on the columns, which operates at anodic potentials that favor such evolution.

If the electrolyte becomes too acidic for too long, etching and consequent softening of the concrete surface may result. A comparison of the average surface hardness of the concrete before and after treatment indicated changes in surface hardness ranging from -3.5 to +5.7%. The concrete in pier 1 showed a slight increase (Table 3). However, based on the standard deviations observed among the individual surface hardnesses measured across each of the piers, the differences appeared not to be statistically significant. Examination of concrete cores taken from the piers after the treatment revealed that the concrete is generally in good condition.

The steel mesh appeared to be a satisfactory anode for use around the pier caps. Examination of the mesh after the treatment did not show that the expected corrosion on the mesh led to any discernible loss of cross-section. However, the steel-mesh anode left rust stains on the concrete surface after the treatment. Fortunately, the stain was removed easily by a strong water jet.

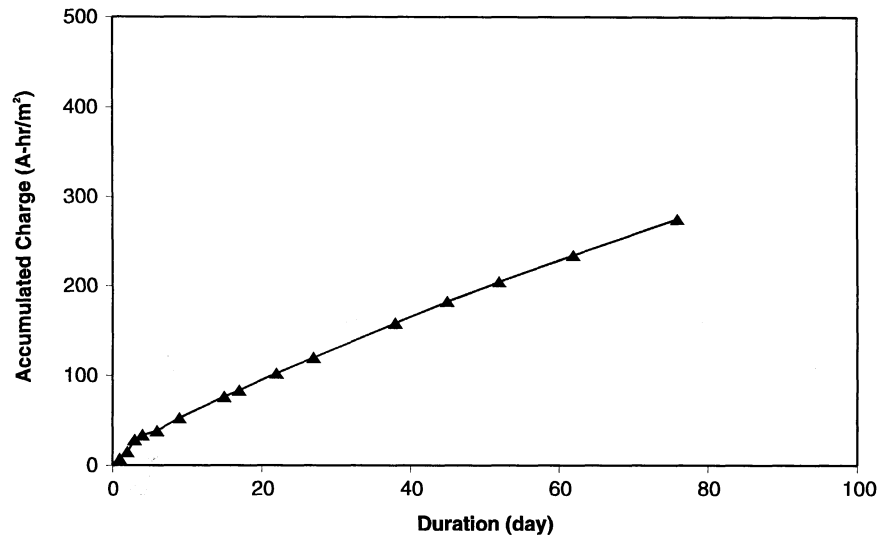


Figure 15. Total charge passing through pier 1.

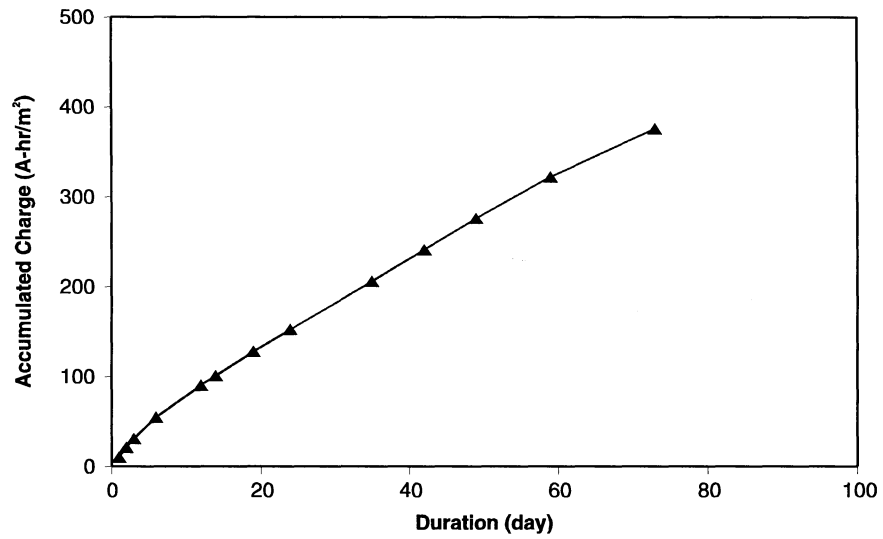


Figure 16. Total charge passing through pier 2.

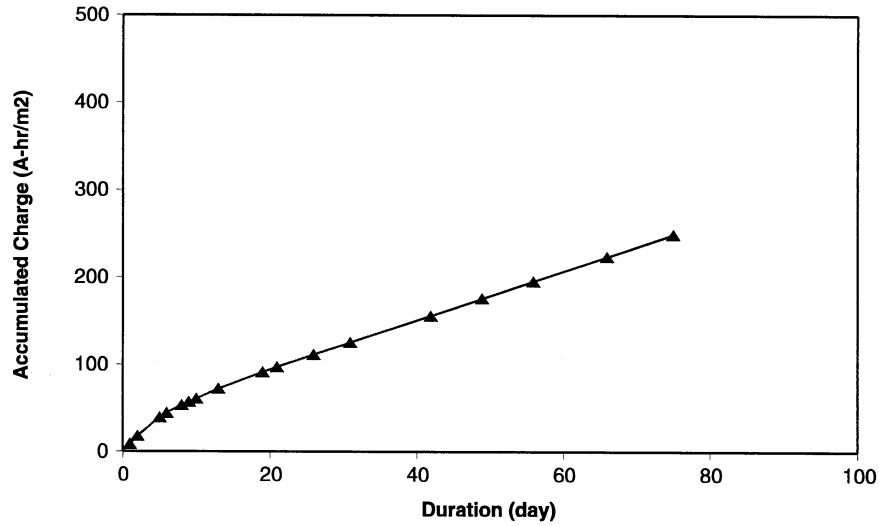


Figure 17. Total charge passing through pier 3.

Table 3

The Relative Surface Hardness of the Concrete, Before and After ECE Treatment

Pier	Relative Surface Hardness (N/mm <sup>2</sup> )				
	Before ECE		After ECE		Change (%)
	Mean	SD (%)	Mean	SD (%)	
1	53	6.0	56	6.1	+5.7
2	55	6.9	54	5.0	-1.8
3	57	5.6	55	3.9	-3.5

Comparison of the chloride contents in the concrete before and after the ECE treatment showed that the treatment led to a decrease in the concentration of chloride in all piers. Figures 18 to 20 show a shift in the distribution in chloride concentrations toward lower values among the concrete samples taken from each pier (at both sampling depths) after the treatment.

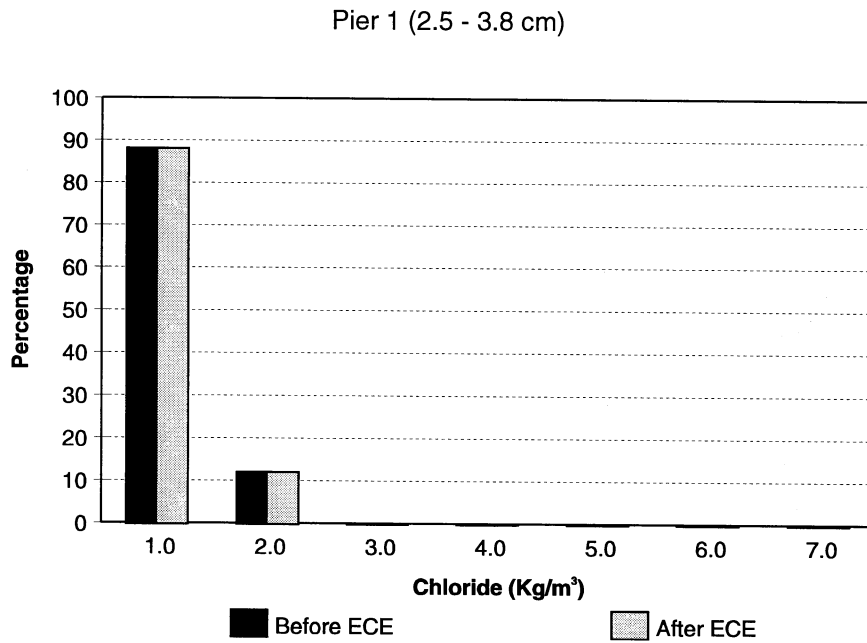
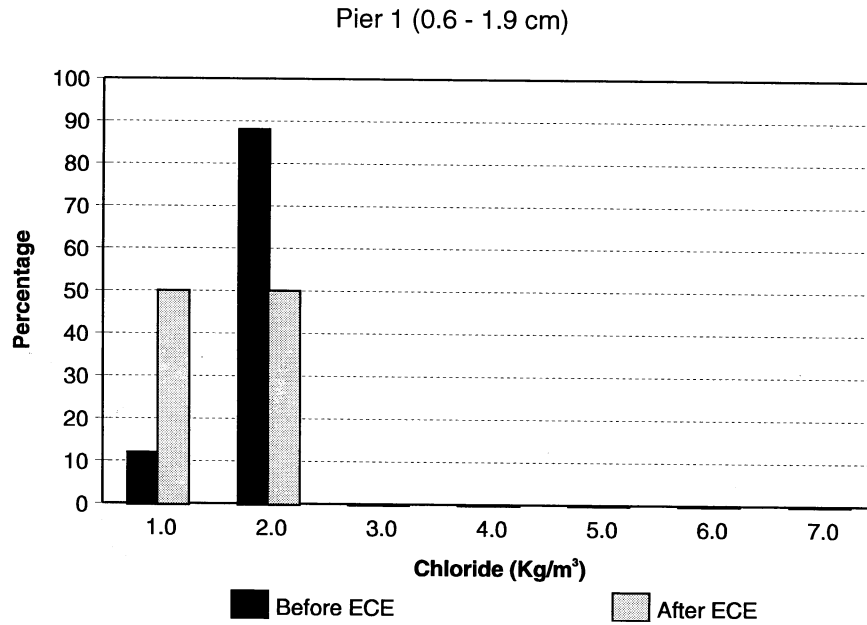
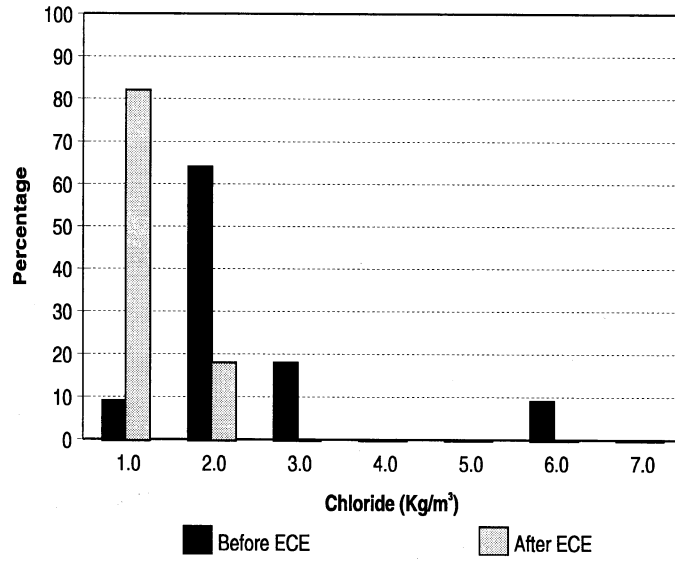


Figure 18. Change in the sample population distribution for chloride concentrations in pier 1, at two different depths, after ECE treatment.

Pier 2 (0.6 - 1.9 cm)



Pier 2 (2.5 - 3.8 cm)

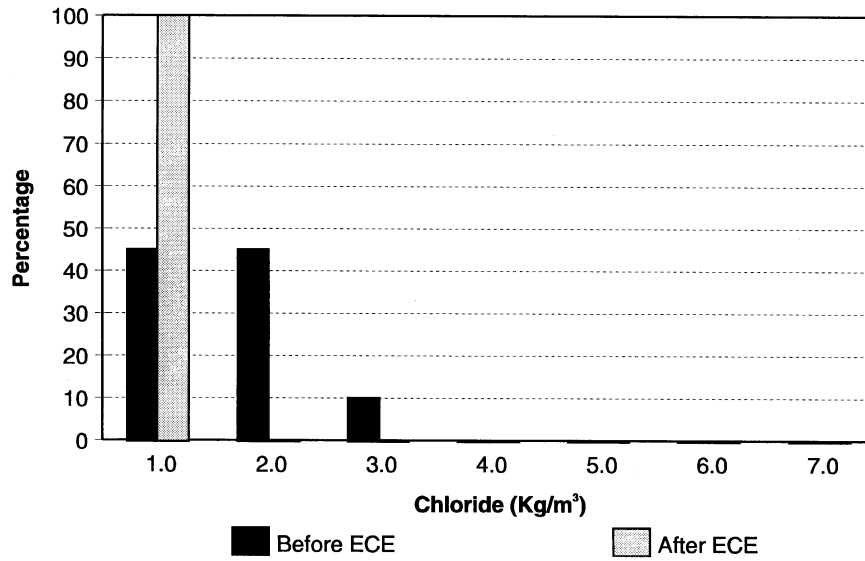
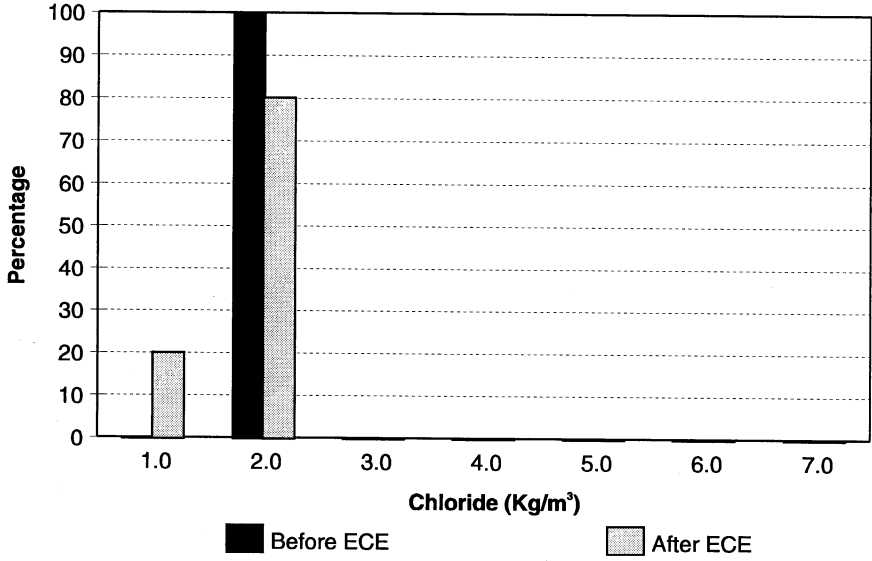


Figure 19. Change in the sample population distribution for chloride concentrations in pier 2, at two different depths, after ECE treatment.



Pier 3 (0.6 - 1.9 cm)



Pier 3 (2.5 - 3.8 cm)

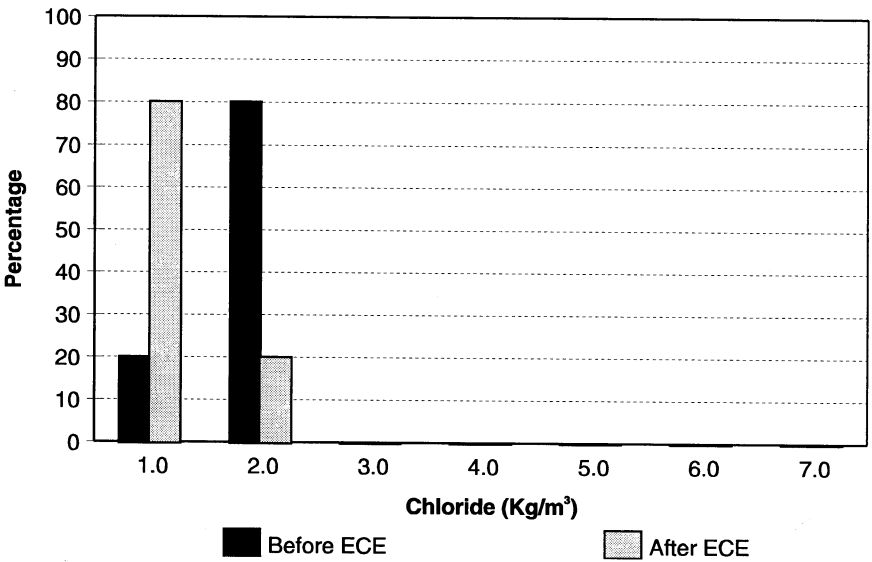


Figure 20. Change in the sample population distribution for chloride concentrations in pier 3, at two different depths, after ECE treatment.

Table 4 shows that, at the depth of 0.6 to 1.9 cm (0.25 to 0.75 in), the decrease in the average chloride concentrations ranged from 27.2 to 59.7%. At the depth of 2.5 to 3.8 cm, the decrease was between 12.6 to 52.9%. The amount of chloride ions removed from each pier was translated into current efficiency, defined as the fraction of total current or charge used that was carried by the amount of chloride ions removed. Current efficiency (Table 5) ranged between 8.6% (for pier 3) to 27.0% (for pier 2). This range is more varied than the range of 11.2 to 15.0% efficiency observed in the trial treatment of bridge decks in Virginia.<sup>9</sup> However, the average efficiency of 16.0% for the piers is comparable to the average of 13.0% for the bridge decks and to the approximately 20% mentioned in one of the SHRP reports.<sup>4</sup> Plainly, current efficiency can vary between structures and treatments, depending on the presence of other mobile ions in the concrete, concrete cover, the amount of steel, the electrolyte used, treatment time, etc.

Table 4  
Average Concentrations of Chloride Ions at Various Depths  
in the Concrete Piers -- Before and After ECE Treatment

Pier	At 0.6 - 1.9 cm			At 2.5 - 3.8 cm		
	[Cl <sup>-</sup> ] (kg/m <sup>3</sup> )		Change (%)	[Cl <sup>-</sup> ] (Kg/m <sup>3</sup> )		Change (%)
	Before	After		Before	After	
1	1.35	0.88	-34.6	0.85	0.74	-12.9
2	1.97	0.79	-59.9	1.10	0.52	-52.7
3	1.47	1.07	-27.2	1.12	0.73	-34.8

Table 5  
Estimated Current Efficiency of ECE Treatment of the Concrete Piers

Pier	1	2	3
Current Efficiency	12.3%	27.0%	8.6%

As mentioned earlier, an electrical short was detected on one of the circuits for pier 3, and since the source of short could not be pinpointed (because of the fibers and wrapping on the pier), the circuit was disconnected at the start of the treatment. This may have contributed to the relatively low efficiency for that pier. Interestingly, the increasing order of the observed efficiencies (pier 3 < pier 1 < pier 2) coincided with the sequence in which the anode system was installed on these piers (pier 3 first, then pier 1, and finally pier 2). This coincidence suggests that the treatment efficiency for concrete piers may very well be affected by the contractor's familiarity or experience with the installation of a specific anode system over piers with a particular geometry. In contrast to bridge decks, which have only horizontal surfaces, piers have mostly vertical and bottom surfaces, which are relatively more difficult to work with, especially in terms of keeping the cellulose fibers uniformly wet and in good contact with the concrete surface.

The treatment did not completely remove all the chloride ions from the concrete, and should not be expected to, particularly within the typical treatment duration. As Table 6 shows, 12.5, 9.1, and 60.0% of the concrete samples taken after the treatment from pier 1, 2, and 3 at the depth of 2.5 to 3.8 cm (1.0 to 1.5 in) still contained chloride exceeding 0.77 kg/m<sup>3</sup> (1.3 lb/yd<sup>3</sup>), which is generally accepted to be the corrosion threshold value. The limited number of samples taken from pier 1 between the depth of 4.4 to 5.7 cm (1.75 to 2.25 in) showed chloride ranging between 0.3 to 0.5 kg/m<sup>3</sup> (0.5 to 0.8 lb/yd<sup>3</sup>), all below the corrosion threshold. If additional samples were also taken from piers 2 and 3 at that depth, probably all samples from pier 2 would show chloride levels below the corrosion threshold; but the chloride levels in some of the samples from pier 3 would still exceed the corrosion threshold.

Table 6  
Percentage of Concrete Samples with Chloride Concentration  
Exceeding Corrosion Threshold - Before and After Treatment

Pier	at 0.6-1.9 cm		at 2.5-3.8 cm	
	Before	After	Before	After
1	100.0%	75.0%	75.0%	12.5%
2	100.0%	45.5%	63.6%	9.1%
3	100.0%	80.0%	80.0%	60.0%

This does not imply that ECE treatment is not beneficial. It reduced the  $[Cl^-]/[OH^-]$  ratio by reducing the chloride concentration considerably and simultaneously producing some hydroxide at the surface of the rebars (as a result of the reduction of water molecules). In addition, the chloride ions which remain in the concrete would be distributed well away from the rebars, and would require a long time to remigrate back to the rebars, if at all.

Sagging of the black plastic wrapping around some sections of some pier caps was a problem during the treatment. The sagging resulted from the accumulation of rainwater inside the plastic, particularly near the west end of the pier caps where there was no sheltering deck overhang. Since the layer of cellulose fibers can become detached from the concrete surface if it becomes too wet and is not wrapped tightly, the sagging caused some concern. Because the plastic wrappings were not transparent, it was impossible to determine the extent to which cellulose fibers were becoming detached, or to apply corrective measures.

Another problem was the leaking of electrolyte water around the connectors between some drip hoses and the feeder hose over pier 1. Because of the bad connectors, these leaks could not be completely stopped during the treatment. This may have allowed some of the concrete on the cap to become dry, which may help account for the relatively low removal efficiency observed for that pier.

In addition to these problems, the simple anode system used on these piers will be inadequate if a special electrolyte such as lithium borate has to be used (to prevent an alkali-silica reaction). For those situations, an electrolyte collection and recirculation system will be required to keep from discharging electrolyte into the environment. The more elaborate cassette-shutter anode system, mentioned earlier, may be suitable.

As expected, the steel mesh was an adequate anode. With a sufficient gage, the material loss on the mesh (due to corrosion during the treatment) was not noticeable. The only undesirable aspect of the steel mesh was rust stains left on the surface of the concrete. The stains, and a small amount of cellulose fibers tightly bonded to the surface layer of concrete, required blast cleaning after the treatment. Blast cleaning fits perfectly in the project, since it is the recommended surface preparation method for the silane sealer, which was applied on the piers after the ECE treatment.

The total cost of the treatment was \$63,932.39 (Table 7). In terms of unit concrete area, this cost comes to \$131.01/m<sup>2</sup> (\$12.17/ft<sup>2</sup>) of concrete. Based on the labor, equipment, materials, etc., required, this price was thought to be somewhat high. Possibly the price will come down as the amount of ECE work increases in the future. Many potential users think a unit cost of no more than \$110/m<sup>2</sup> (\$10/ft<sup>2</sup>) would be more desirable. Since ECE technology is new, experienced or qualified contractors are rare, and this probably contributed to the high cost. When arrangements were being made for the treatment, Vector Construction, previously involved in the Canadian trial, was the only contractor in North America known to have experience with the process.

Worse, Vector Construction is based in Winnipeg, Canada. This meant that personnel of the Virginia Department of Transportation's Research Council had to be involved in checking the system and correcting every problem that surfaced during the entire treatment. This posed a manpower problem for the agency, and would be a problem to other shorthanded transportation agencies.

Table 7  
Costs Associated with the ECE Treatment of the Concrete Piers

Item	Cost
Mobilization	\$ 6,442.50
ECE Treatment (Including Silane Sealer)	55,840.00
Traffic Control	1,187.89
Repair of Concrete	462.00
Total	\$63,932.39

Clearly, more contractors need to get involved in this new technology to minimize such logistic problems and make the cost more reasonable. This is a very good opportunity for the corrosion engineering firms that are already providing cathodic protection of concrete bridges to expand their market, since cathodic protection is similar to ECE treatment in many respects.

## CONCLUSIONS

The following conclusions are based on the observations made in this trial treatment of three concrete piers.

1. ECE treatment appeared to be a practical method for the permanent rehabilitation of full-sized concrete piers (at least for the types of piers used in this pilot trial) that are being damaged by salt-induced rebar corrosion. At the current densities used, the treatment appeared to have no adverse effects on the concrete.
2. The installation and the treatment process require monitoring and inspection, especially during the first weeks.
3. A way to check for electrical shorts during the spraying of the wet cellulose fibers across the pier should be devised for use with the mesh-and-fiber anode system.
4. The wetting system used with the anode system in this trial needs improvements to ensure the constant and uniform wetting of the concrete, and the uniform mixing of lime in the electrolyte if that becomes necessary.
5. The plastic wrapping system used to keep the wet mesh-and-fiber anode system in place around the concrete needs to be modified to keep rainwater from penetrating the wrapping, which can cause the fibers to become too wet and then drop off the concrete surface.
6. A treatment of typical duration cannot be expected to remove all the chloride from a structure. The treatment, however, offers other important beneficial effects that contribute to arresting rebar corrosion, including redistributing the remaining chloride away from the rebars, decreasing the  $[Cl^-]/[OH^-]$ , and cathodically polarizing the rebars.

## RECOMMENDATIONS

Even though some minor improvements in the ECE treatment system are necessary, this pilot trial demonstrated beyond any doubt the feasibility of the technique for full-sized concrete piers. VDOT should consider ECE treatment as an alternative method for the permanent rehabilitation of existing inland concrete piers. The improvements or modifications mentioned above should be incorporated before the mesh-and-fiber anode system is used. For concrete piers situated over sensitive bodies of water, or containing ASR-susceptible aggregates for which the use of lithium electrolyte is recommended, an anode system with adequate electrolyte collection, circulation, and draining provisions would be necessary.

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