SHRP-C-620

Evaluation of NORCURE Process
for Electrochemical Chloride Removal
from Steel-Reinforced Concrete Bridge Components

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Acknowledgments

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Abstract

The NORCURE™ process was tried on test slabs, and applied to a portion of the substructure of the Burlington Skyway in Burlington, Ontario. This report is an analysis of the rate and total amount of chloride removed, the corrosive state of the steel before and after the process, the effects on the concrete, and other aspects of the installations. Comparisons are made to slabs used in other SHRP research on electrochemical chloride removal and protection of concrete bridge components.

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Executive Summary

The NORCURE™ process uses a steel mesh anode, an electrolyte of wet cellulose fiber which is sprayed onto the structure surface, and relatively low current densities (< 100 mA/ft^2) and long treatment times (8-11 weeks). This report attempts to relate the NORCURE™ process to other work conducted for SHRP.

The NORCURE™ procedure was tested first on a section of Pier S-19 of the Burlington Skyway, Burlington, Ontario, in the summer of 1989. Because of the inhomogeneous nature of the chloride contamination and the difficulty of obtaining representative samples, it was difficult to make clear-cut conclusions regarding the chloride removed at Burlington. Chloride removed ranged from 8 to 25 g/ft^2 (27 to 60 percent of total chloride present) at a Faradaic current efficiency of 11 to 33 percent. Chloride at the level of the reinforcement was removed to a concentration below the corrosion threshold. Post-treatment corrosion data showed that corrosion of the reinforcement was effectively mitigated. Following treatment, 98 percent of half-cell potentials taken on treated faces were more positive than -200 mV vs CSE. Corrosion rate of the reinforcing steel, as measured by linear polarization, was reduced by a factor of 4 to 10.

Chloride removed by the NORCURE™ process was more easily defined on 2- x 2-ft slab specimens. The process removed 25 grams of chloride/ft^2 (41 percent of total chloride present) at a Faradaic current efficiency of 10 percent. Again, corrosion data show the steel reinforcement to be in a noncorrosive state after the process. Half-cell potentials were increased to > -200 mV vs CSE, the region characteristic of very little corrosion, and corrosion rate data were decreased by a factor of about 10.

The NORCURE™ process appeared to be simple and relatively easy to install. The wet cellulose mat was an effective electrolyte for the chloride removal process. Unsightly stains from the corrosion products of the steel anode were easily removed by subsequent grit blasting. The treatment process was completed without any evidence of mechanical or chemical distress to the concrete. Chloride removal efficiencies and post-treatment corrosion data were similar other slabs subjected to chloride removal, but under slightly different conditions. Long-term effectiveness of the process is not yet known.

1

Introduction

A major cause of the deterioration of reinforced concrete bridge decks and substructures is the corrosion of reinforcing steel due to the ingress of chloride ions from deicing salts or seawater. Chloride causes active corrosion by destroying the natural passivity of steel in the alkaline environment of concrete.

Once a structure has been contaminated by a sufficient amount of chloride, there are two possible electrochemical approaches to prevent the corrosion of steel components:

1. Apply cathodic protection, which is the only proven technique to stop corrosion in salt-contaminated concrete, or

2. Remove sufficient chloride from the structure to allow the steel to repassivate and then prevent the future ingress of chloride ion.

The second approach, removal of chloride ion, was the subject of two major studies conducted under a Federal Highway Administration (FHWA) contract in the 1970s: "Neutralization of Chloride in Concrete", Report No. FHWA-RD-76-60, September, 1965, by D. R. Lankard and others; and "Chloride Removal and Monomer Impregnation of Bridge Deck Concrete by Electro-Osmosis", Report No. FHWA-KS-RD. 74-1, December, 1975, by Garrette L. Morrison, et. al.

Both of these studies and follow-up reports have concluded that electrochemical migration was a promising technique for the removal of chloride ions from salt contaminated concrete.

ELTECH Research Corporation was awarded SHRP contract C-102A, Electrochemical Chloride Removal and Protection of Concrete Bridge Components, in May 1988. Subcontractors contributing to this effort include Corrpro Companies, Inc., Florida Atlantic University, Kenneth C. Clear, Inc., and Lankard Materials Laboratory, Inc.

Contract C-102A calls for the completion of four major tasks to confirm the feasibility of electrochemical chloride removal, develop techniques for protection against the return of corrosion, demonstrate the process with field validation trials, and complete an implementation package and final report. The feasibility of the process was confirmed in November of 1989, and work is presently continuing toward field validation.

After the start of SHRP contract C-102A, ELTECH Research Corporation and SHRP became aware of what is now known as the NORCURE™ process for chloride removal. The NORCURE™ process was developed in Norway in the mid-1980s, and has since been used on several structures worldwide. Since it was obvious that the existence of this process significantly impacted the C-102A contract, additional funding to study the process was authorized by SHRP in July of 1989.

The purpose of this supplemental study was principally twofold: 1) provide insight for the 18-month feasibility decision, and 2) provide technical input for direction of C-102A tasks. Data gathered to evaluate the NORCURE™ process were also used in direct comparison to other data accumulated under other tasks of the SHRP contract.

Specifically, the objectives of this work were: a) to apply the NORCURE™ chloride removal electrolyte and process to two steel reinforced concrete slabs, evaluate the effect of the removal process on the slabs, and compare results to the other SHRP slabs, and b) to observe a field demonstration on a substructure in Burlington, Ontario, of the NORCURE™ chloride removal process and evaluate technical data, including data gathered before treatment, during energization, and after treatment. The information gained from these two tasks helped establish the impact of the process on chloride removal rate, rebar bond strength, and concrete properties.

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Fairport Slab Studies

The NORCURE™ process was applied to two concrete slabs, No. 7 and No. 8, at the ELTECH laboratories in Fairport Harbor, Ohio on July 10, 1989 by CPS (Concrete Protection Services), the North American representative of Norwegian Concrete Technologies (NCT). These slabs were spare slabs from the SHRP C-102A contract and were used for comparison to the chloride removal from other slabs under that contract.

The Laboratory Slabs

These slabs were 24-in. (60 cm) x 24-in. (60 cm) x 8-in. (20 cm) thick and were constructed with Class C concrete conforming to Ohio Department of Transportation specifications. The concrete contained 612 lbs/yd³ of cement (363 kg/m³) and a water-to-cement ratio of 0.50. To simulate a corroding bridge deck that was exposed to a large amount of deicing salt, chloride in the form of NaCl was cast in the concrete at concentrations of 0.39 percent by weight of concrete in the top 1.5 in. (4 cm), 0.156 percent by weight of concrete in the next 3.25 in. (8 cm), and none in the bottom 3.25 in. (8 cm). There were two mats of reinforcing steel and these were made electrically continuous externally. The top mat was located 2 in. (5 cm) below the concrete surface. The surface area of the reinforcement, top and bottom mats combined, was 1.3 ft² per square foot of concrete. A drawing of the slab is shown in Figure 1.

Figure 1. ELTECH Slab for Chloride Removal
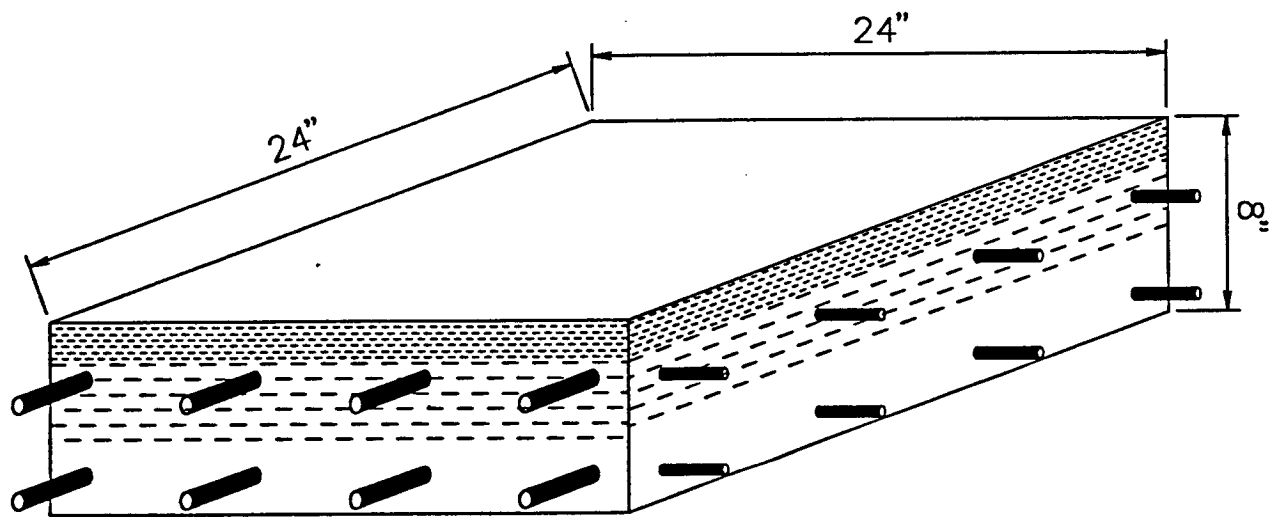
approx. 1.5" of 15 #Cl−/yd3 of concrete

approx. 3.25" of 6 #Cl−/yd3 of concrete

Installation and Operation

The NORCURE™ system was placed on Slab Number 8 with the treatment surface oriented in the vertical position to simulate the Burlington, Ontario substructure installation. Wooden battens, 3/4 in. (2 cm) thick, were installed vertically to space the mesh from the concrete surface. Since the slab surface of only 4 ft² (0.36 m²) is relatively small, it was not feasible to transport and set up the spraying equipment to apply the cellulose fiber. Instead, 920 grams of cellulose fiber was thoroughly mixed in a drum with 28 grams of calcium hydroxide and 6 liters of tap water. The surface of the concrete was wetted and the wet fiber mixture was applied a handful at a time until a layer was the thickness of the wooden battens. The steel mesh anode, 1/8 in. (0.3 cm) in diameter on 4 in. (10 cm) squares, was then attached to the battens with staples and another 1/4 in. (0.6 cm) of wet fiber was applied over the anode.

The horizontal Slab Number 7 was fitted with a ponding dam around the perimeter to hold the electrolyte. The steel anode mesh was placed in the pond and spaced from the concrete by 3/4 in. (2 cm) thick wooden battens. The steel anode was fixed to the battens with staples and weighted down to prevent the wood from floating. The pond was filled with 12 liters of tap water and saturated with calcium hydroxide. Since the electrolyte was contained by the ponding dam, it was unnecessary to use the cellulose fiber.

The two slabs were powered at 0.093 A/ft² (1.0 A/m²) of concrete. Operating data is shown in Table 1. The vertical slab required daily rewetting of the fiber. The steel anode for both slabs was consumed to a point where replacement was necessary on August 22, 1989. The use of thicker gauge steel mesh would have avoided this.

Operation of the slabs was halted on September 1, 1989, because the horizontal Slab Number 7 was drastically reducing in chloride removal rate as shown in Table 1. There was severe staining of the concrete surface with the horizontal slab without the fiber mat, and significant staining of the vertical slab. Both slabs required sandblasting. The slabs were restarted on September 25, 1989. After four more weeks of operation, the total chloride removed from each slab was analyzed to be similar. At this point, the voltage of the vertical Slab Number 8 escalated due to significant drying, of the cellulose fiber and a highly consumed anode. The tests were subsequently halted, accumulating a total of 13 weeks of treatment. Solution analyses show that chloride was removed at the same rate as with the SHRP slabs that used an inert DSA anode. This is shown in Figure 2 as a graph of grams Cl⁻ removed versus charge passed for the NORCURE™ Slab Numbers 7 and 8 along with the SHRP Slab Number 4 and 12.

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Results and Discussion

Concrete powder samples were collected from the slabs and analyzed for chloride content. Results of the analyses are shown in Table 2 and plotted in Figure 3 along with SHRP Slab Number 9 for comparison. Slab Number 9 was the only slab treated where the electrolyte was allowed to become acid. It was also for a total of 300 A-hr/ft^2 of total charge compared to 191 A-hr/ft^2 for the Norcure slabs, and this explains the lower chloride levels remaining above straight bars after treatment for SHRP Slab Number 9.

The slabs were retained in the ELTECH outdoor test yard for four months and then moved to the Kenneth C. Clear, Inc. outdoor test yard to be monitored for macrocell current between the top and bottom mats, static half-cell potentials, and 3-LP rate-of-corrosion (I$_{corr}$). Post-treatment data is summarized in Table 3.

The static half-cell potential measurement data show that the slabs required approximately 3 weeks for the steel to depolarize. Data taken nearly a year after the chloride removal treatment indicate that the corrosion of the steel rebar in the slabs has been halted and is consistent with the SHRP Slab Number 9.

Table 1. NORCURE™ Slabs Weekly Operating Data

Date	Days on Line	Cummulative A-hr/ft^2	Voltage Slab 7/8	Cummulative g Cl* removed from Horz. Slab 7	Vert. Slab 8
7-11	1	2.2	8.7/9.4	5.0	4.0
7-17	7	15.6	9.9/14.0	29.6	21.2
7-24	14	31.2	9.7/24.2	45.3	50.8
7-31	21	46.8	12.4/24.9	62.4	64.7
8-07	28	62.4	14.1/26.3	72.4	73.8
8-14	35	78.0	13.8/30.1	75.4	81.2
8-21	42	93.6	13.7/30.6	76.0	90.3
8-28	49	109.2	15.4/21.0	77.5	92.6
9-01	53	113.0	15.2/22.6	78.4	95.2
9-25	53	113.0	13.2/27.3	78.4	95.2
10-02	60	128.6	11.2/14.5	82.9	98.8
10-09	67	144.2	13.2/13.9	86.8	99.8
10-16	74	159.8	14.1/22.1	90.4	97.6
10-23	81	175.4	14.2/16.5	95.7	99.6
10-30	88	191.0	13.5/29.0	~100	~100

*Based on electrolyte analysis

**Figure 2. Slab Chloride Removal Rate**
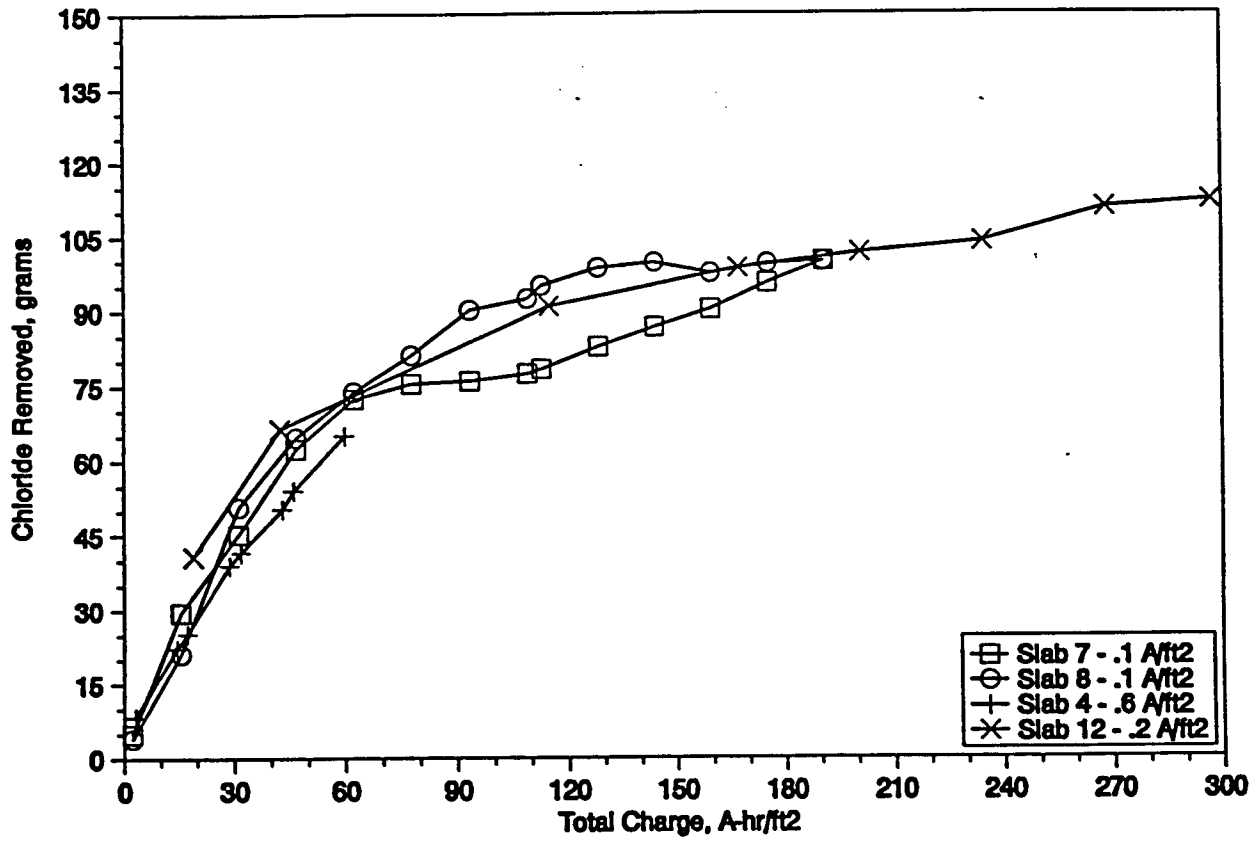
Table 2. Concrete Chloride Content

	% Cl⁻ by Weight of Concrete			
	Before Treatment	After Treatment		
	Slab 7, 8, and 9	Slab 7	Slab 8	Slab 9
Between Bars				
0-0.75 in.	~0.410	0.133	0.156	
0.75-1.5 in.	~0.410	0.158	0.146	0.161
1.5-3.125 in.	~0.180	0.138	0.146	0.125
3.125-4.75 in.	~0.180	0.158	0.107	0.120
4.75-6.375 in.	~0.015	0.082**	0.069**	
6.375-8 in.	~0.015	0.015	0.018	
Above Cross				
0-1 in.	~0.410	0.069	0.072	
1-2 in.	~0.353	0.046	0.049	
Above Straight Bar				
0-1 in.	~0.410	0.092	0.077	0.064
1-2 in.	~0.353	0.049	0.046	0.041

** - contamination from adjacent level may have occurred
due to migration after casting.

Table 3. Post-Treatment Corrosion Data

Days After Removal Terminated	Macrocell Current, mA		Static Potential mV vs. Cu/CuSO₄		3-LP I_corr mA/ft²	
	Slab 7	Slab 8	Slab 7	Slab 8	Slab 7	Slab 8
3	5.2	4.4	-826	-846	7.4	10.0
8	0.8	0.4	-280	-310	0.1	2.5
15	0.0	0.0	- 35	- 79	0.3	2.2
22	0.0	0.0	10	12	0.2	1.5
36	0.0	0.0	- 17	16	0.3	3.1
64	0.0	0.0	30	- 37	0.5	4.2
79	0.0	0.0	20	- 17	0.6	2.4
107	0.0	0.0	65	40	0.4	1.4
135	0.012	0.010	26	1	0.5	1.9
162	0.008	0.002	- 85	2	0.2	0.7
272	0.010	0.010	53	26	0.3	0.8
345	0.000	0.010	94	41	0.3	0.1

Figure 3. Concrete Chloride Content After Removal Treatment
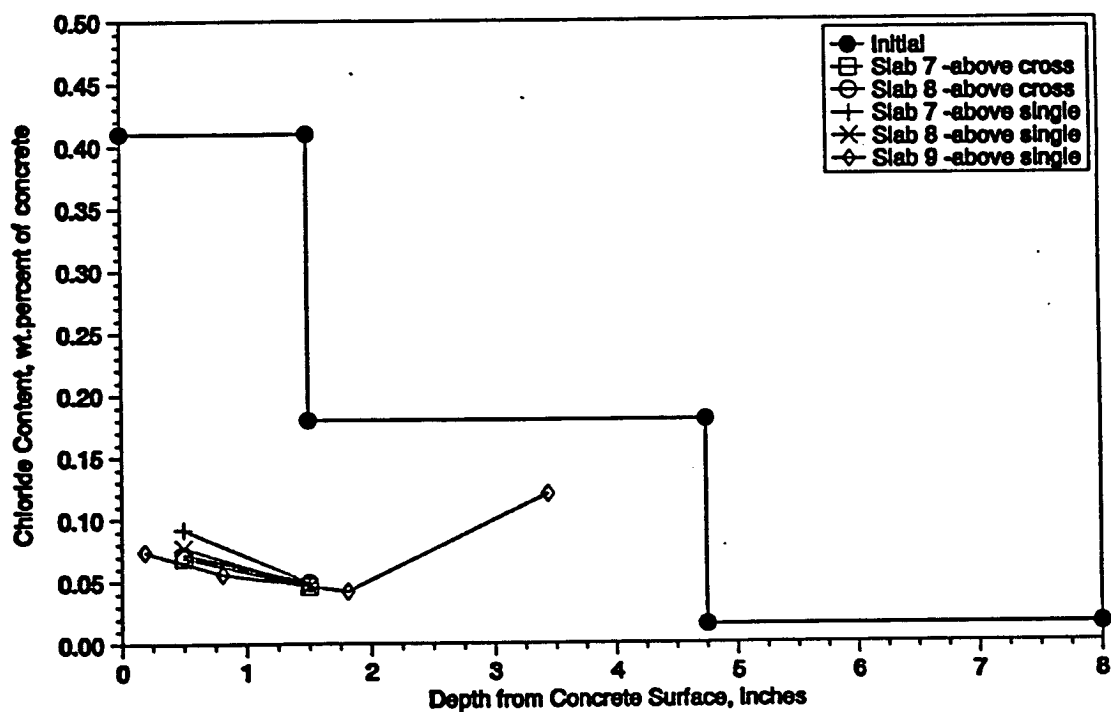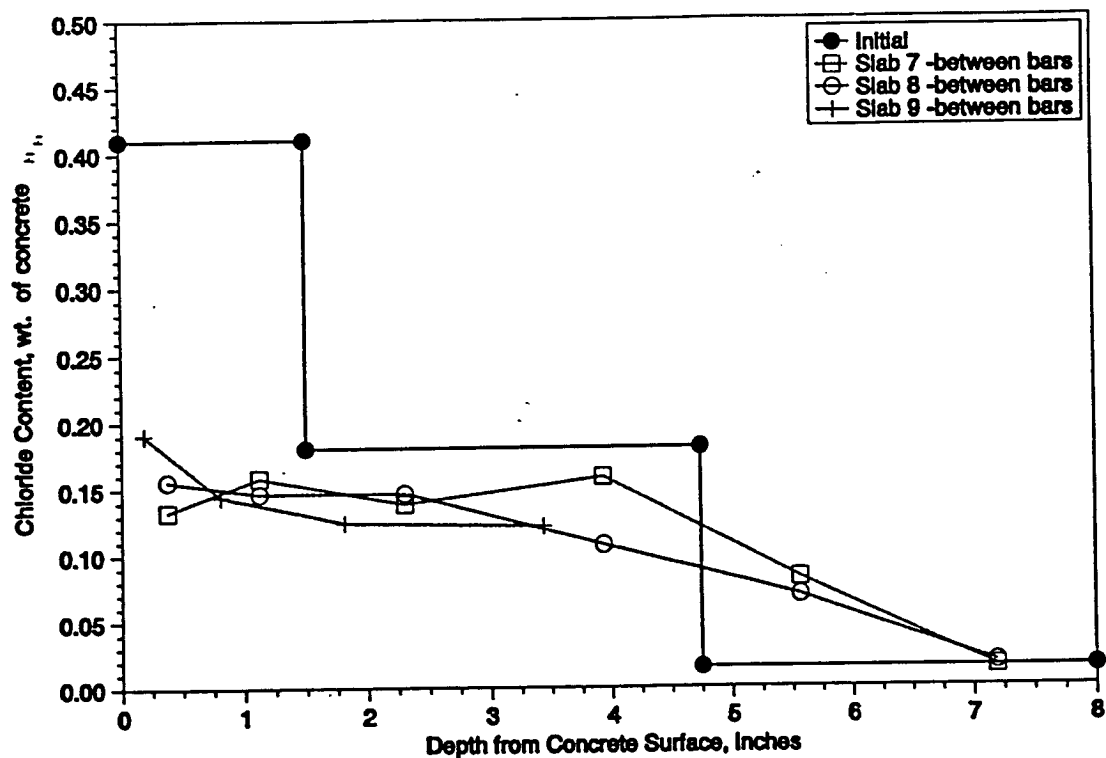
reinforcement at 2 and 7 inch depths

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Burlington Skyway Trial

A chloride removal trial was conducted during the summer of 1989 on a section of Pier S-19 of the Burlington Skyway, Burlington, Ontario. The chloride removal process, known commercially as NORCURE™, was funded by the Ontario Ministry of Transportation, but since it was the first application of this technology in North America, ELTECH Research Corporation was invited to audit the trial.

The Trial Structure

The piers of the Burlington Skyway were constructed in 1955 using Type I portland cement at about 560 lbs/yd³ (330 kg/m³). The specified compressive strength was 3500 psi (28 days) with a slump range of 2.5 to 3.5 inches (6.35 to 8.90 cm), and it is estimated that the water-cement ratio was about 0.45. The coarse aggregate was a dolomitic limestone which contained up to 0.12 weight percent of acid soluble chloride ion. Since it is believed that this chloride is unavailable for either corrosion or removal, the corrosion threshold value for the concrete in Pier S-19 can be calculated to be 0.07 percent by weight of concrete, or about 2.7 lbs/yd³.

The plan dimensions of the west column of Pier S-19 were approximately 5.6- x 9.8-feet (1.7- x 3.0-m) and the column was treated to a height of 13.1 feet (4.0 m). The north face of the column was left untreated as a control area, and the east, west and south faces were treated to provide a total trial area of 330 ft² (30.8 m²). The column was lightly reinforced, the reinforcement surface area being about 0.55 ft²/ft² of concrete for the east and west faces, and about 0.79 ft²/ft² of concrete for the north and south faces. Distance between reinforcement bars measured as great as 15 in. (38 cm). Concrete cover over the bars was three inches (75 mm) or more.

Roadway drainage, which contained deicing salt in the winter months, flowed through an open deck joint above the Pier causing corrosion of the reinforcement, in spite of the high concrete cover. The chloride analysis of cores taken from each face is detailed in Table 4.

Chloride ion concentration at the level of the reinforcement averaged 4.09 lb/yd³ (0.106 percent by weight of concrete); well above the threshold for corrosion. In spite of this, however, the pier was in relatively good condition. The concrete was uncracked with no delaminations, and reinforcement continuity was good.

Both potential measurements and linear polarization data indicated that the steel was corroding prior to treatment. Ninety (90) percent of the potential readings taken on Pier S-19 ranged from -200 to -350 mV (vs $Cu/CuSO_4$), and 10 percent were more negative than -350 mV. Rates-of-corrosion averaged 0.97 mA/ft² (1.04 micro-A/cm²), as measured by a commercial linear polarization resistance (3 LP) device. Potential and rate-of-corrosion measurements are further detailed in Tables 5 and 6. Petrographic examination of cores confirmed the presence of light corrosion on the reinforcing steel.

Installation

Installation of the NORCURE™ chloride removal system was conducted on July 4-5, 1989. Reference electrodes were installed in each face, and thermocouples were installed in the north and south faces at the depth of the reinforcement. Wooden battens, approximately 1.5 in. wide by 0.75 in. thick (40-mm x 20-mm), were fastened vertically to the concrete using insulated anchor screws. A schematic of the installation as applied to the east and south faces is shown by Figure 4.

Cellulose fiber (from recycled newspaper) was then wet sprayed on the east, south and west faces to a depth of about one inch (2.5 cm). The fiber is air blown out the center of an application nozzle and is wetted by lime water sprayed through six jets mounted around the perimeter of the nozzle. The equipment for handling and spraying the fiber was contained in an enclosed trailer manufactured by Krendl Machine Co. Inc., Delphos, Ohio. Spraying of fiber on the east and west faces took about 10 minutes and the south side took about 5 minutes.

Following the first application of fiber, steel construction mesh was stapled onto the wooden battens to serve as an anode. The steel mesh consisted of strands 3/16 inch (5 mm) in diameter welded on 4-inch (100 mm) centers.
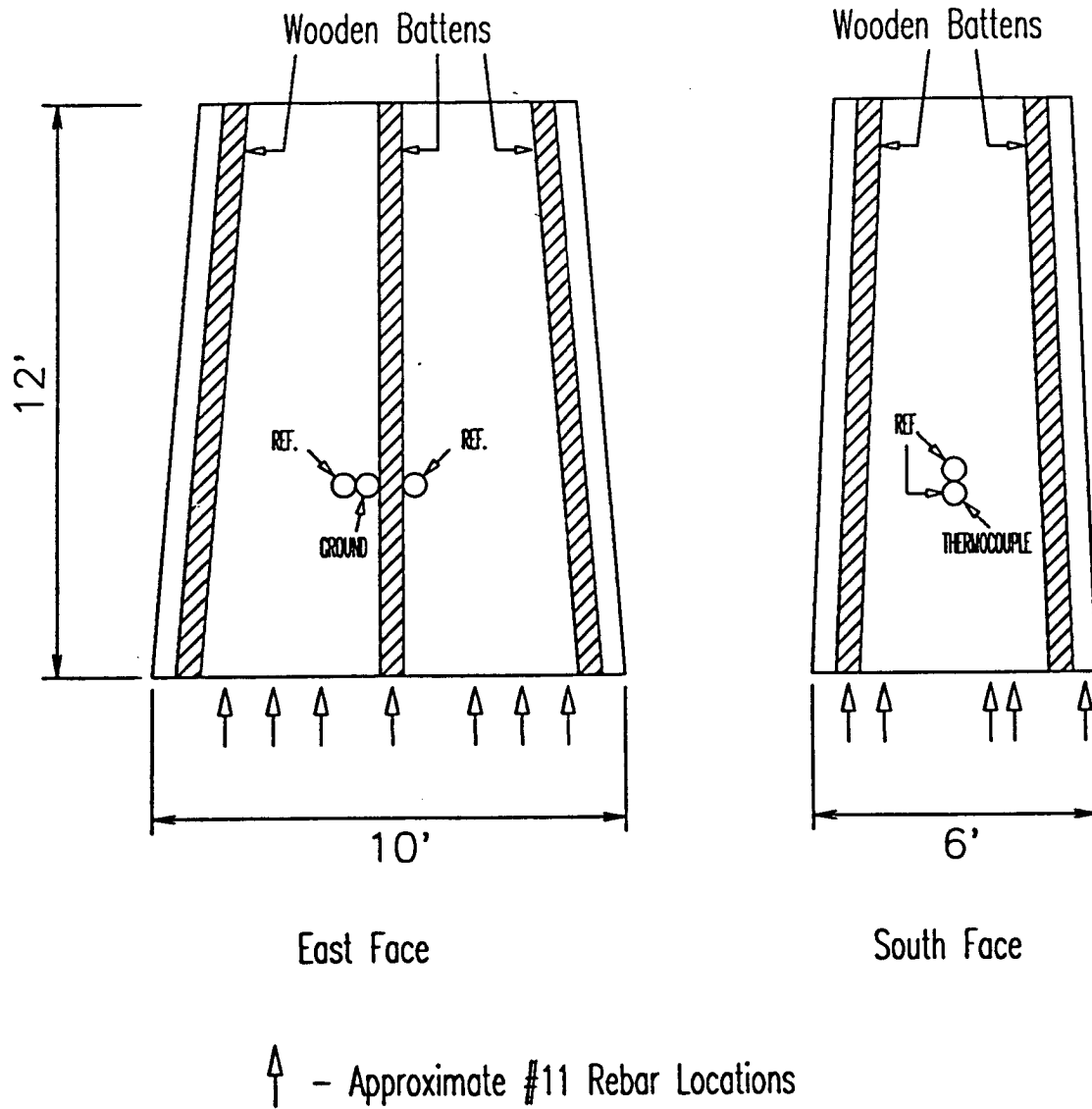
Table 4. Initial Chloride Content of Pier S-19

Depth from Surface (in.)	Chloride Content, #Cl⁻/yd³ Concrete East	West	South	North
0-0.39	5.09	5.99	4.19	5.76
0.39-0.79	11.82	13.31	14.99	16.87
0.79-1.18	10.30	15.03	16.25	17.62
1.18-1.57	7.52	12.14	11.67	14.17
1.57-1.97	6.54	10.02	10.49	10.65
1.97-2.36	4.50	7.09	8.30	8.73
2.36-2.76	3.05	6.66	6.15	6.22
2.76-3.15	2.51	5.05	4.74	4.54
3.15-3.54	1.88	3.76	3.72	3.09
3.54-3.94	2.04	2.98	2.74	2.90
3.94-4.33	2.23		2.58	2.39
4.33-4.72	1.88			2.11
4.72-5.12	1.61			1.68

Table 5. Corrosion Potential Measurements

Corrosion Potentials (-mV vs Cu/CuSO₄)

	North ≤ 200	North 200 to 350	North ≥ 350	West ≤ 200	West 200 to 350	West ≥ 350	South ≤ 200	South 200 to 350	South ≥ 350	East ≤ 200	East 200 to 350	East ≥ 350
Original	0	85	15	0	96	4	0	96	4	0	84	16
Six weeks after treatment	0	81	19	38	42	20	22	33	45	29	31	40
Six mos. after treatment	63	37	0	96	4	0	100	0	0	98	2	0
10 mos. after treatment	30	70	0	96	4	0	100	0	0	98	2	0

Figure 4. Layout of Burlington Skyway Bent S-19

Wooden Battens

Wooden Battens

REF.   REF.

GROUND

12'

10'

East Face

REF.

THERMOCOUPLE

6'

South Face

⇧ — Approximate #11 Rebar Locations

Table 6. Rate-of-Corrosion Measurements

	North	West	South	East
Before	1.15	0.66	0.56	1.50
Six weeks after treatment	0.84	0.14	0.10	0.15
Six months after treatment	0.75	0.20	0.09	0.16
Thirteen months after treatment	1.15	0.14	0.09	0.17

Average Rates-of-Corrosion in mA/ft^2

After installation of the steel mesh anode, a second layer of fiber was sprayed over the mesh to a depth of about one inch (2.5 cm). For this application, the west face was completed in 7 minutes and the east face in 8 minutes. This represents an application rate of about 1000 ft^2 (100 m^2) per hour. The equipment manufacturer stated that an application rate of 2000 ft^2 (200 m^2) per hour should be possible at this thickness of fiber.

A separate electrical connection was then made to each section of anode mesh, and these were wired to the positive pole of the power supply. A wire connected to the steel reinforcement was wired to the negative pole of the power supply.

Installation of the system is shown on Figures 5 and 6.

Energizing and Operation

The system was energized July 5, 1989 at 15 amps, 23 volts. After a few hours, current was increased to 20 amps, 34 volts. A complete current and voltage profile over the operating life of the system is shown by Figures 7 and 8. The voltage required by this trial was somewhat high for the level of current used. This is apparently a result of both the high concrete cover and wide spacing of the reinforcing steel. Voltage was maintained at or below 40 volts for safety reasons and, as a result, current decreased over the course of the test to about one-third its original value.

Because of the considerable decrease in current, and because it was perceived that anode corrosion was especially high on the east face, the anode mesh and outer fiber layer were replaced on the east face after a few weeks of operation. This had no noticeable affect on the operation of the system, however.
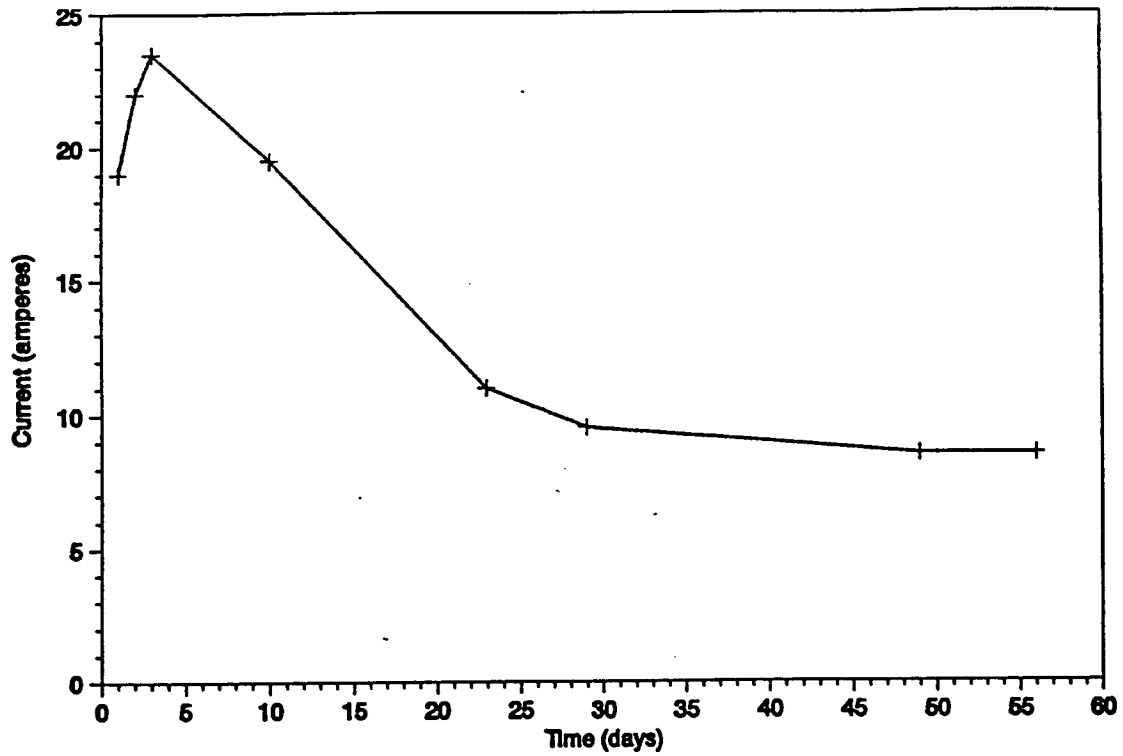
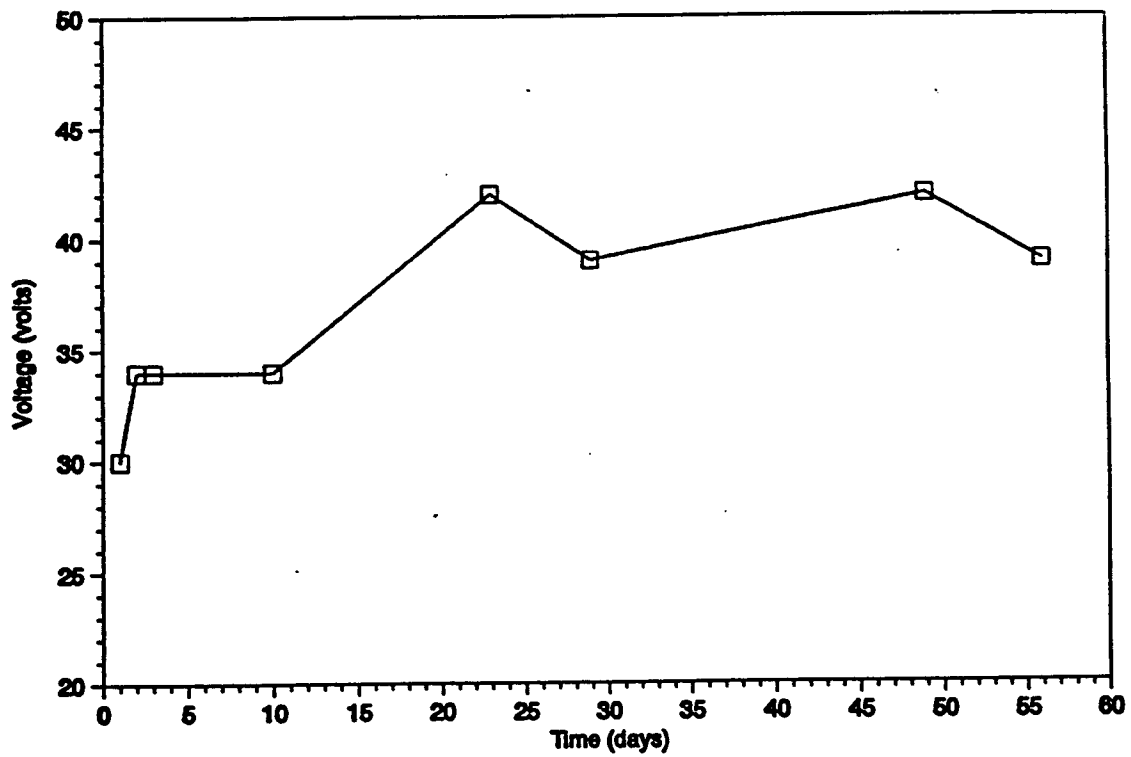**Figure 5.** Application of First Layer of Cellulose Fiber

Figure 6. Application of Cellulose Fiber Over Anode and First Layer of Cellulose Fiber
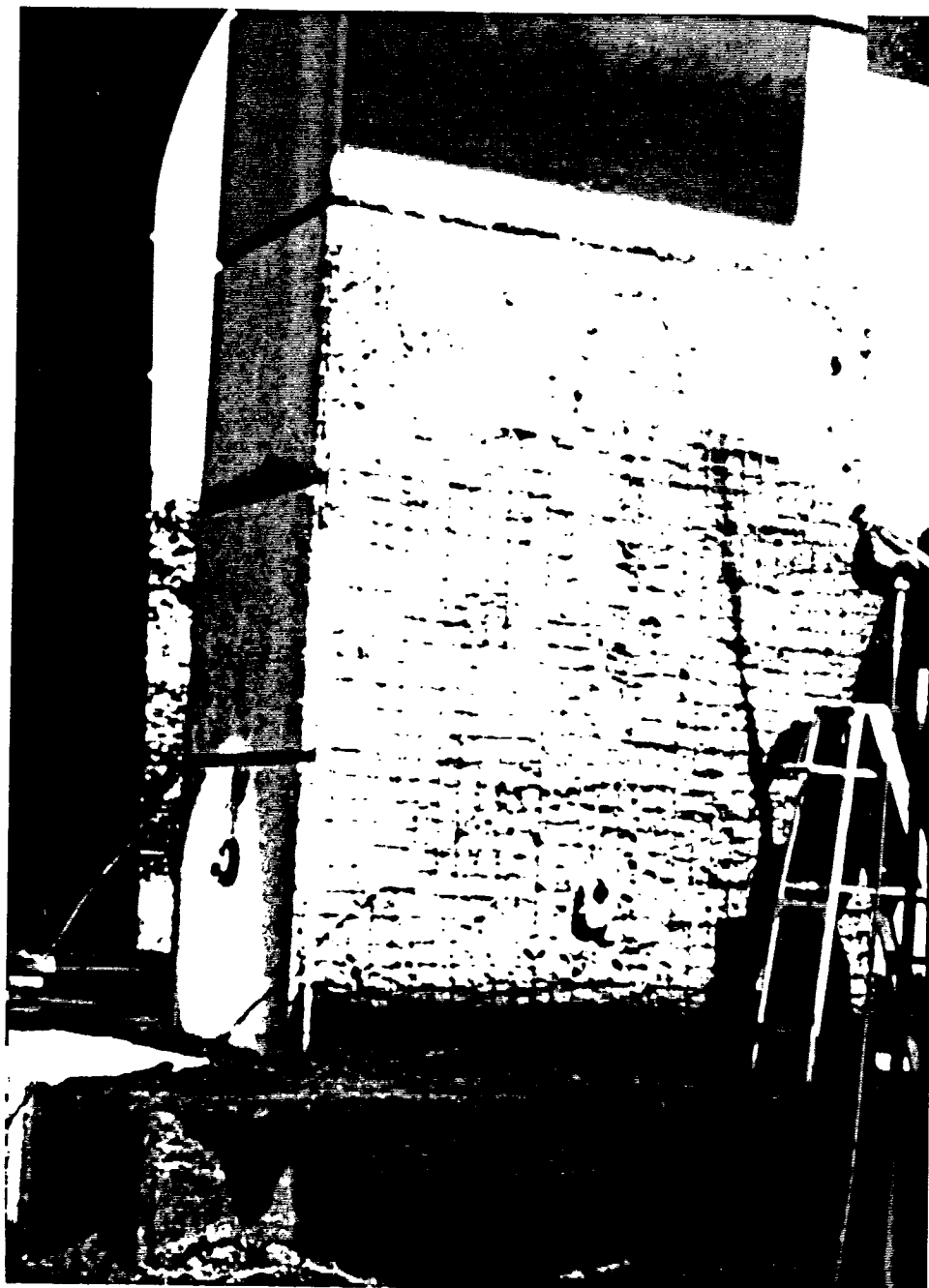
Figure 7. Burlington Current Profile

Figure 8. Burlington Voltage Profile

The total charge passed was approximately 56.7 A-hr/ft^2 of concrete (610 A-hr/m^2). If the current efficiency for the process were 100 percent, the total amount of chloride removed would have been 75.1 g/ft^2 (theoretical). Power consumption for the total process was about 730 KWH or 2.2 KWH/ft^2 (23.8 KWH/m^2). The power level was not sufficient to produce any measurable difference in temperature between the treated and untreated faces.

Immediately after installation, the cellulose fiber was grey to light brown in color as shown in Figure 9. After 24 hours, a rust-stained outline of the mesh was visible, confirming that all anode sections were active. After three weeks of operation, the cellulose had a dark red-brown appearance as a result of corrosion of the steel mesh, as shown in Figure 10. After eight weeks of treatment, the surface of the column and column plinth were heavily stained by rust. This staining was removed by blast cleaning.

Results and Discussion

Chloride ion contents as a function of depth are shown for each treated face in Figures 11, 12, 13 and 14. These profiles were established by taking 4-in. (100 mm) diameter cores, cutting cores into 0.4-in. (10 mm) thick slices, and measuring the acid-soluble chloride ion content. Since the flow of drainage water over the column was uneven, chloride ion content can be expected to vary considerably over each face. In an effort to minimize these variations, cores taken at various stages of treatment were taken vertically below each other on the face.

Chloride ion removal was relatively rapid during the first three weeks of operation, but the rate of removal decreased with time. All faces showed very little difference in analyses between seven and eight weeks of operation. These are illustrated by the data shown on Figures 11, 12, 13 and 14. Performance is also summarized by Table 7, which shows the total grams of chloride removed (from concrete analysis), percentage of chloride removed, and current efficiency for the process. Current efficiency is here defined as the amount of chloride removed relative to the theoretical amount which could have been removed if 100 percent of the current was carried by the movement of chloride ions.

One obvious discrepancy presented by Table 7 is the difference in current efficiency and chloride ion removed between the east face, and the west and south faces. Current efficiency was calculated at 11 percent for the east face, and about 30 percent and 32 percent for the south and west faces, respectively. There is no obvious explanation for this large discrepancy. Poor distribution of current could account for this difference, but current distribution was measured during the process and was reported to be good to all faces. As judged by other work done under contract C-102A, one could expect a current efficiency, for this amount of chloride ion concentration and total charge passed, to be about 20 percent. It therefore appears that the efficiency calculated for the east face is too low, while the efficiencies reported for the south and west faces are too high. It may be that this is simply a consequence of the inhomogeneous nature of the chloride ion concentration within the column, and that a more accurate calculation is not possible without taking a much larger number of samples.

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Figure 9. Cellulose Fiber Immediately After Installation
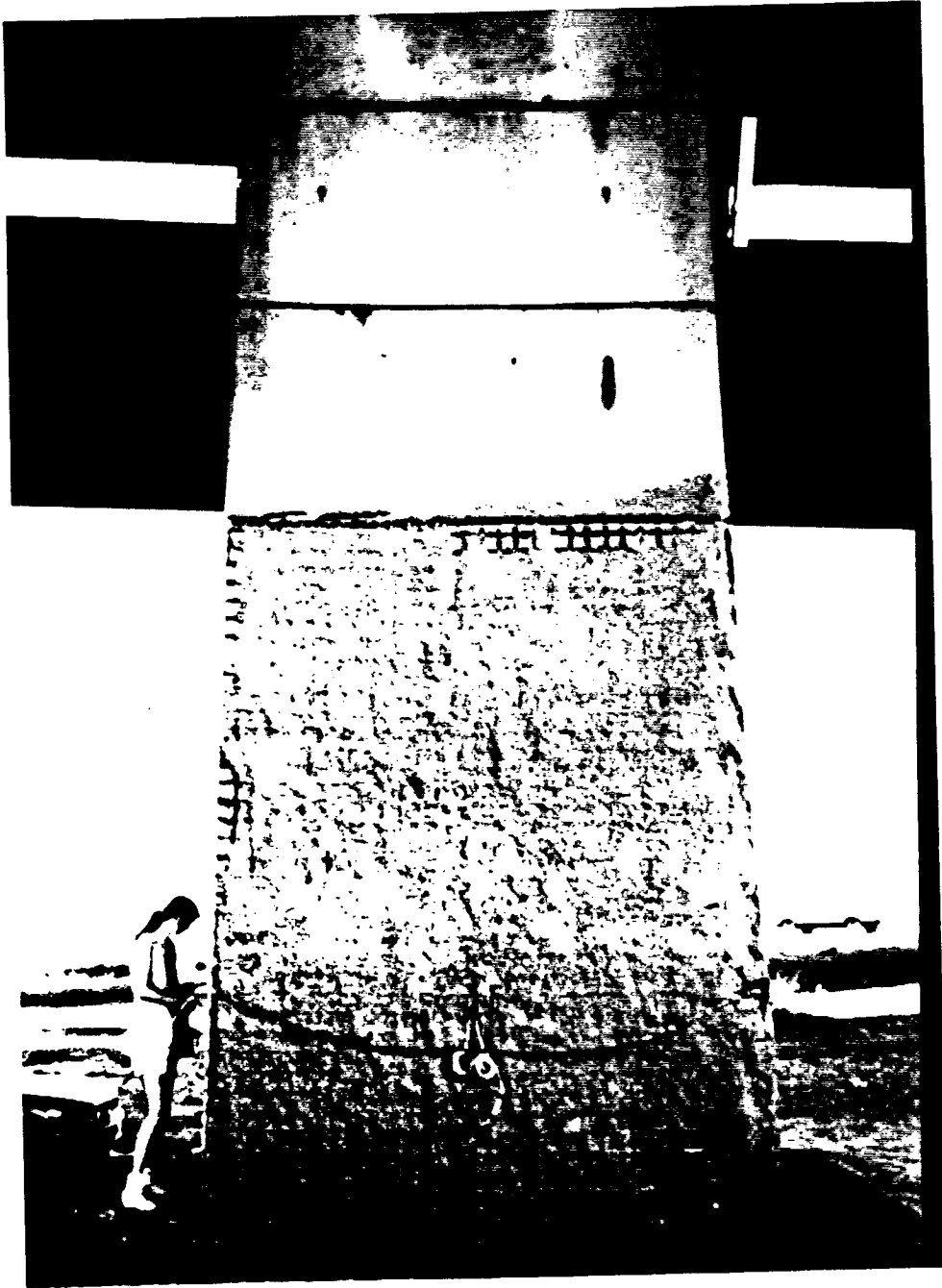
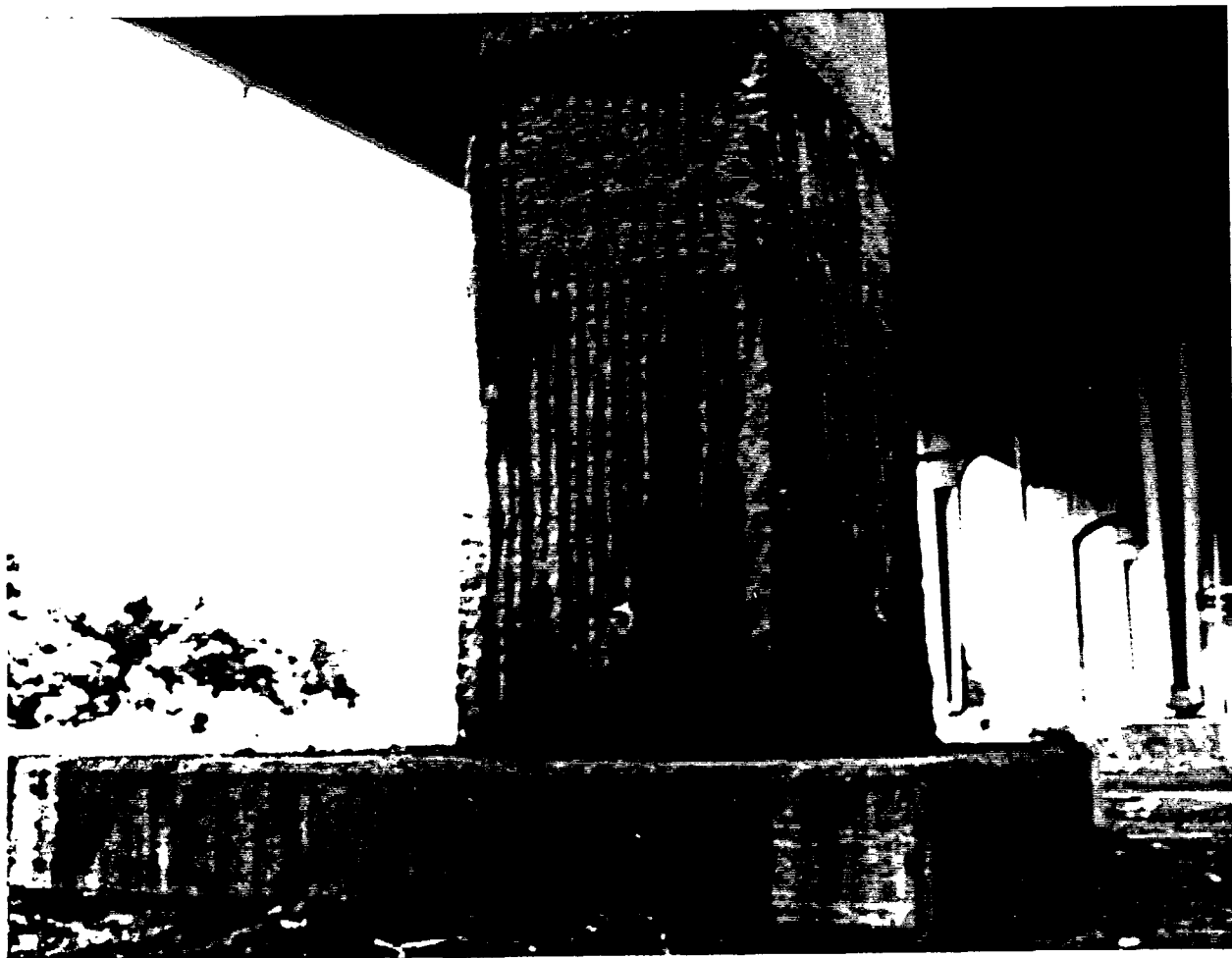**Figure 10. Cellulose Fiber After Three Weeks of Operation**
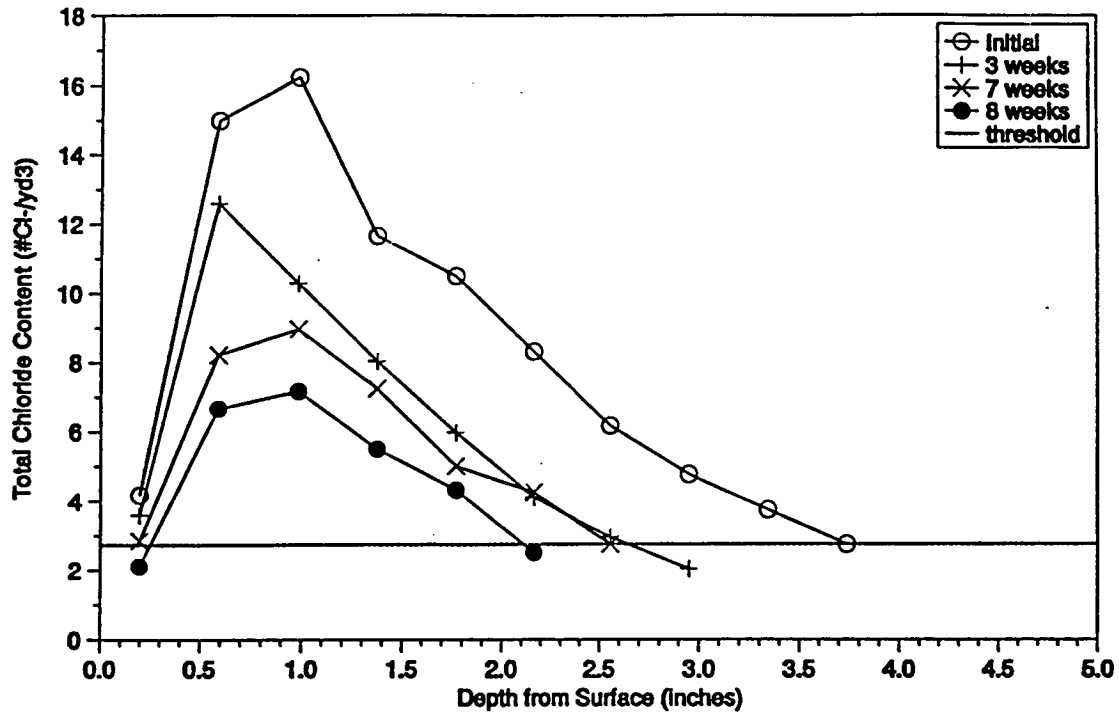
Figure 11. Burlington Chloride Profile: South Face, Between Bars

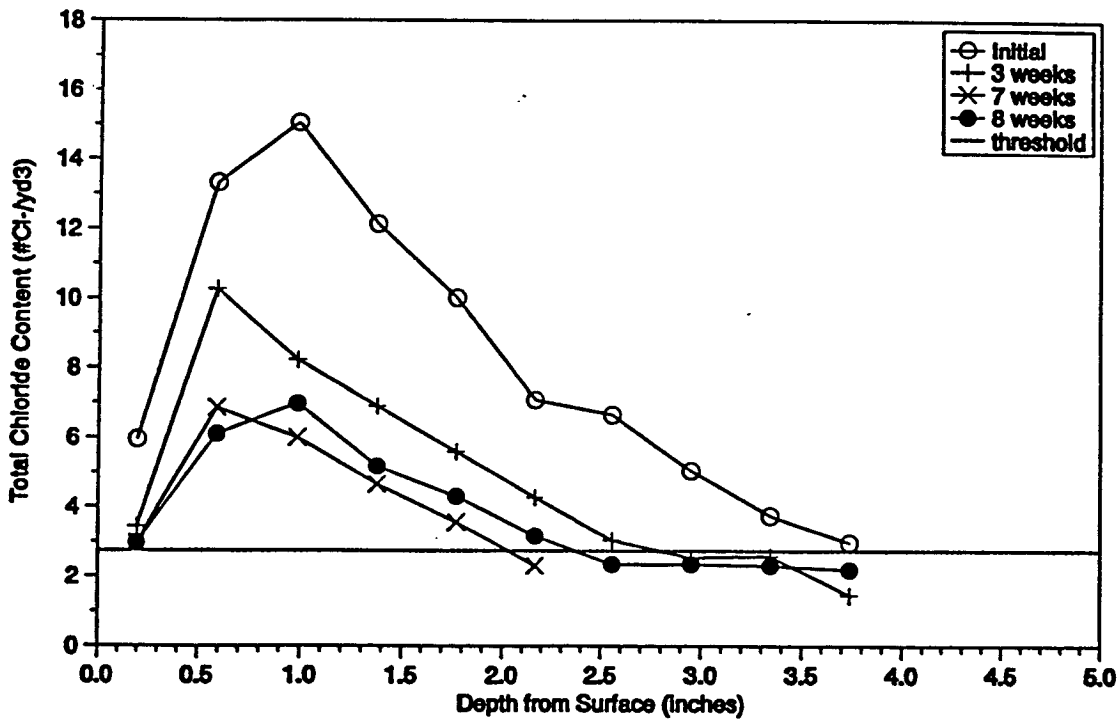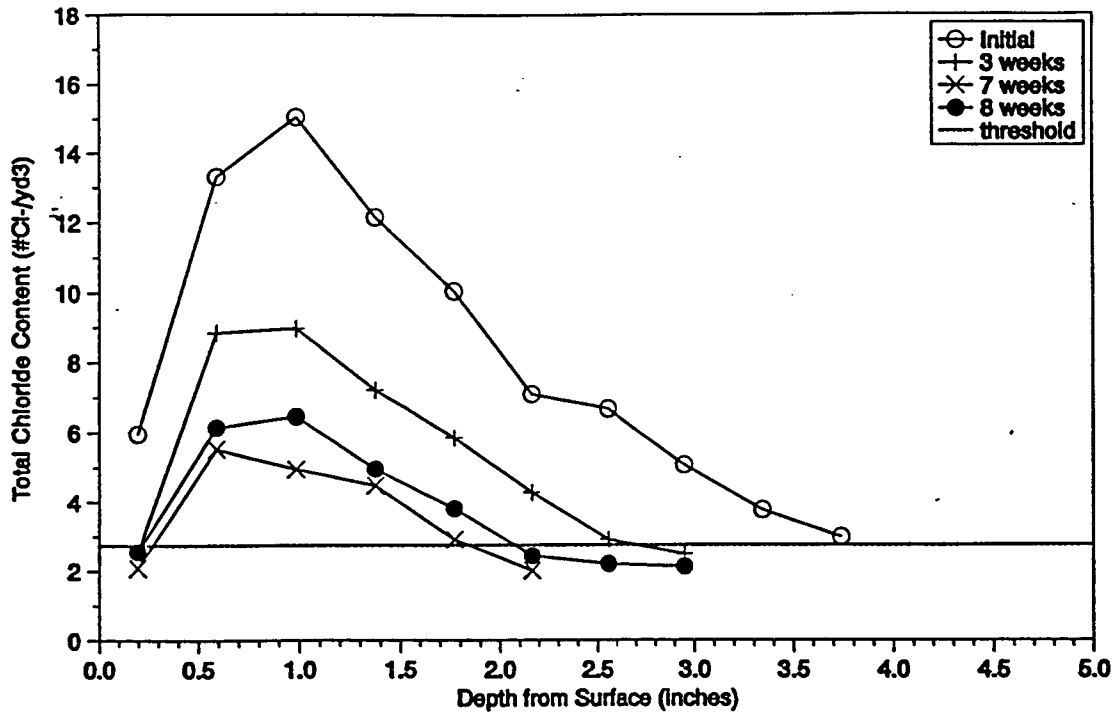based on 3915 #/yd3 concrete mass

Figure 12. Burlington Chloride Profile: West Face, Between Bars
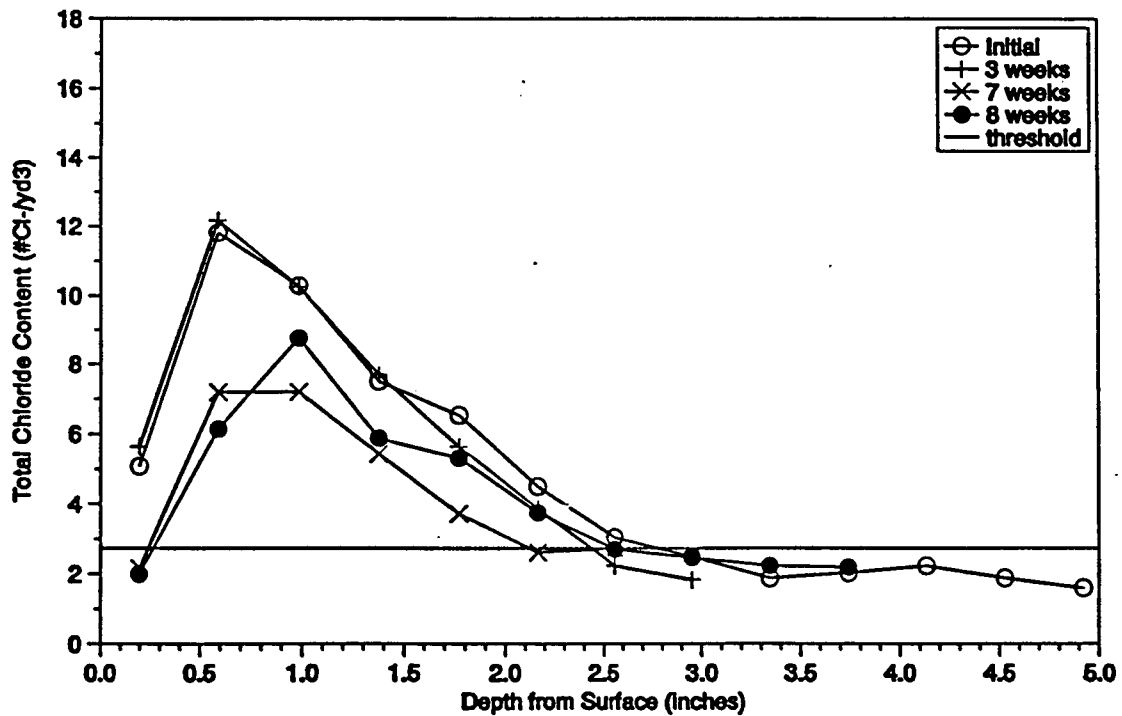

based on 3915 #/yd3 concrete mass

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Figure 13. Burlington Chloride Profile: West Face, Over Bars

based on 3915 #/yd3 concrete mass

Figure 14. Burlington Chloride Profile: East Face, Over Bars

based on 3915 #/yd3 concrete mass

Table 7. Post-Treatment Chloride Removal Summary

Face	Cl Removed g/ft²	(%) of Total Cl Removed	(%) of Cl Removed Above Corr. Threshold	Current Efficiency %
East (Over Rebar)	7.88	26.8%	48.8%	11.0%
West (Over Rebar)	24.59	59.5%	82.2%	32.7%
West (Between Rebar)	24.25	58.7%	81.0%	32.3%
South (Between Rebar)	22.61	57.0%	74.8%	30.1%

Another difficulty is the identical current efficiencies reported over rebar and between rebar on the west face. From other work done under SHRP contract C-102A, one would expect to see a significantly higher efficiency over the rebar. This is especially true of Pier S-19 since the steel is widely spaced. Again, there seems to be no convenient explanation for this result. Perhaps the inhomogeneous nature of the chloride ion within the pier is again responsible for this discrepancy.

Corrosion potential measurements for the pier are summarized on Table 5. Ninety percent of the potentials before treatment were in the range from -200 to -350 mV versus CSE, indicating a mild state of corrosion. Potentials taken six weeks after treatment were strongly negative, but these data are not considered meaningful since the steel was still polarized at this time. Six months after treatment, 98 percent of the potentials on the treated faces had shifted less negative than -200 mV, indicating a nearly complete lack of corrosion. The north face was also relatively non-corrosive at this time since the temperature at the time of measurement was only 15°C. Ten months after treatment, 98 percent of the potentials on the treated faces were still non-corrosive, even though temperature had risen to 27°C and corrosive readings had returned to the untreated north face. These data indicate a dramatic reduction in corrosion activity as a result of the chloride removal treatment.

Corrosion currents were measured before and after treatment using a commercial three-electrode linear polarization device, and these are shown on Table 6. The data indicate that rate-of-corrosion was reduced by the chloride removal process. Other work within the SHRP C-102A contract suggest that this may not be quantitatively true, however. The only conclusion which can be made from these data is that the rate of corrosion of steel within the treated faces has been substantially reduced.

Following treatment, two 4-3/4 in. (120 mm) diameter cores were removed from the structure, one from the treated east face and one from the untreated north face of the column. These cores were sent to Lankard Materials Laboratory, Inc. for examination in order to apply the same techniques as developed for use in the SHRP C-102A contract. Both cores contained a Number 11 rebar about 4 in. (100 mm) from the surface. Cores were subjected to petrographic examinations (optical microscopy), scanning electron microscope (SEM) examinations, chemical characterization using energy-dispersive x-ray spectroscopy (EDS), and porosity measurements using mercury porosimetry.

The concrete was judged to be of good quality from the point of view of water-cement ratio, quality of materials, maturity and consolidation. Examinations of samples removed from the top 3 inches (75 mm) of the cores indicate that the electrochemical treatment had no significant effect on the concrete chemistry or microstructure other than the intended purpose of reducing chloride ion concentration.

Examination of samples removed from areas close to the reinforcing steel did show some differences between the treated specimen and the control, however. The porosity of the cement paste phase was 25 to 30 percent higher in the electrochemically treated concrete. This increased porosity is principally within the pore size range from 0.001 to 1.0 micron, and as such, is not expected to have a significant effect on overall concrete permeability.

In addition to the migration of chloride ion during treatment, a redistribution of potassium ion also occurred in the treated concrete. Relatively high levels of potassium were found in isolated pockets of mortar adjacent to the top reinforcing steel. This is consistent with other samples examined in the C-102A contract, and has not had any adverse effect on the quality of the cement paste or aggregates to date. These increased concentrations of alkali metal cations should be considered with regard to their effect on alkali-silica reactivity-prone aggregates (no such aggregates were identified in this concrete). The only other effect noted was a slight "wet" or "oily" appearance in the concrete adjacent to the reinforcing steel. This appearance has, in previous work, been associated with high levels of alkali metal cations and high Ph levels. Despite this different appearance, however, neither the cement past nor aggregate show any evidence of chemical attack.

In summary, no features of mechanical or chemical distress could be attributed to the electrochemical chloride removal treatment. No unique features of the cores from Pier S-19 were identified which distinguish them from other cores examined under the C-102A SHRP contract.

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Conclusions

The NORCURE™ system, as applied at both Burlington, Ontario and Fairport Harbor, Ohio in 1989, is simple and relatively easy to install. The wet cellulose fiber mat provides an effective electrolyte for the chloride removal process. The need for daily wetting and the increasing resistance of the system with time were bothersome, however. Staining from corrosion products of the steel anode are unsightly in the latter stages of the process, but this is easily removed following treatment by grit blasting.

The level of current and time required for the NORCURE™ process, about 4-8 weeks, are roughly equivalent to that used for other work done under the SHRP C-102A contract. Chloride extracted and current efficiency for the process are also equivalent to previous work done under the contract. Apparent discrepancies in efficiency observed at Burlington were likely an artifact due to difficulty of sampling and the inhomogeneous nature of chloride concentration within the column.

The state of the steel following the NORCURE™ treatment, as judged from potential and rate-of-corrosion data, was very noncorrosive. Again, this is consistent with other chloride removal trials.

The treatment process was completed without any evidence of mechanical or chemical distress to the concrete.

The long-term effectiveness of the treatment is unknown at this time.