MICHIGAN DEPARTMENT OF TRANSPORTATION
MDOT

ELECTROCHEMICAL CHLORIDE EXTRACTION

STEVE KAHL

KahlS@michigan.gov

**Testing and Research Section
Construction and Technology Division
Research Project 97 TI-1864
Research Report R-1384**

Lansing, February 2001

Technical Report Documentation Page

1. Report No. R-1384	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle ELECTROCHEMICAL CHLORIDE EXTRACTION	5. Report Date February 2001
7. Author(s) Steve Kahl	6. Performing Organization Code
9. Performing Organization Name and Address Michigan Department of Transportation Construction and Technology Division P.O. Box 30049 Lansing, MI 48909	8. Performing Org Report No.
12. Sponsoring Agency Name and Address Michigan Department of Transportation Construction and Technology Division P.O. Box 30049 Lansing, MI 48909	10. Work Unit No. (TRAIS)
	11. Contract/Grant No.
15. Supplementary Notes	13. Type of Report & Period Covered
	14. Sponsoring Agency Code 97 TI-1864

16. Abstract

Corrosion of steel reinforcement in concrete substructures causes premature deterioration, which must be repaired. Traditionally, repair has been mechanical removal of spalled and delaminated concrete. This chip and patch technique is effective in repairing the visual deterioration, but does nothing to the surrounding concrete. Steel reinforcement will therefore continue to corrode around the patched areas. At some point, the extent of delaminations and spalls is great enough to warrant substructure replacement. The continued expense of repairs followed by replacement can be significant. Mechanical removal is a treatment of symptoms only, whereas Electrochemical Chloride Extraction (ECE) deals with the cause of corrosion. By arresting the corrosion process, substructures gain extended service life at a reduced cost.

Electrochemical Chloride Extraction applies a temporary electric field between the reinforcement and the concrete surface, displacing chloride ions from the salt-contaminated substructure to a disposable cellulose electrolyte. Additionally, hydroxyl ions (OH^-) are generated at the level of reinforcement, restoring the passivity of the steel. The ECE process is reported to be effective in halting reinforcement corrosion.

The NORCURE™ electrochemical chloride extraction (ECE) process was used to rehabilitate part of the substructure carrying M-60 over I-94, Jackson, Michigan (pier four of bridge S02 of 38061). This project involved the treatment of one pier cap and four columns. The total surface area treated was 108 m^2.

This report is an analysis of the effectiveness of the ECE process as a substructure preventive maintenance technique for Michigan. A cooperative agreement work order for the ECE process was authorized by the U.S. Department of Transportation, Federal Highway Administration, Demonstration Projects Program, to be administered by the Michigan Department of Transportation (MDOT). Funding was supplied by the Federal Highway Administration.

17. Key Words	18. Distribution Statement No restrictions. This document is available to the public through the Michigan Department of Transportation.

19. Security Classification (report) Unclassified	20. Security Classification (Page) Unclassified	21. No of Pages	22. Price

ACKNOWLEDGMENTS

The author extends his appreciation to all Department personnel who helped in this project.

Mr. Roger D. Till, Supervising Engineer, Structural Research Unit, Testing & Research Section, developed the initial project specifications and coordinated project activities.

The valuable contribution of the University Region Special Crews is gratefully acknowledged, whose personnel provided traffic control, routine site inspection, water supply, and sealer application.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

A major cause of the premature deterioration of reinforced concrete bridge decks and substructures in Michigan is the corrosion of the reinforcing steel due to the ingress of chloride ions from deicing salts. Chloride ions cause this corrosion by destroying the passivity of steel in the alkaline environment of concrete. Formation of oxide by-products occupies several times the volume of the original steel, exerting tensile stresses greater than the tensile strength of the concrete. These stresses lead to crack formation and spalling, further accelerating the corrosion process. Continued damage to concrete from the corrosion process requires repair, and may eventually lead to replacement of the affected element.

The condition of substructure units in Michigan is evaluated during a biennial bridge inspection. If the bridge and substructure units do not have flaws affecting load carrying capacity, no rehabilitation activity is scheduled. If spalls are noted, this downgrades the condition rating of the structure, but spalls are not repaired until the bridge is scheduled for rehabilitation. Then the substructure units would be sounded to find the extent of spalls and delaminations, and repaired. Mechanical repair of substructures is completed by manual chip and patch techniques. Generally, minimal preventive maintenance is provided to substructures. One reason for minimal preventive maintenance may lie in the expense of patch repairs, and the lack of patch repair durability.

The premature deterioration of patch repairs can be attributed to the ongoing corrosion process. While the patch area is free of chlorides, the surrounding contaminated areas undergo accelerated corrosion. This accelerated corrosion is due to the creation of an electropotential difference between the patch area and the surrounding contaminated concrete. Steel reinforcement that was corroding has been cleaned and repassivated with the addition of fresh concrete. The surrounding steel reinforcement is exposed to a greater electropotential difference, accelerating corrosion, leading to spalls around the perimeter of the repair area. This can lead to failure of the patch (pop outs) as well. An effective preventive maintenance treatment would be to halt the corrosion process, for long-lasting repairs.

Electrochemical chloride extraction (ECE) was selected for evaluation as a potential tool in preventive maintenance of bridge substructures in Michigan. A work plan was written for the application of the ECE process to a bridge pier. The NORCURE™ ECE process was used to rehabilitate part of the substructure carrying M-60 over I-94, Jackson, Michigan (pier four of bridge S02 of 38061). Funding was supplied by the Federal Highway Administration.

Electrochemical chloride extraction is accomplished by applying an electric field between the reinforcing steel in concrete (cathode), and an externally mounted electrode mesh (anode). During treatment, the negatively charged chloride ions are displaced toward the positively charged anode, out of the concrete, and trapped in the electrolyte mixture. The treatment also increases the hydroxyl (OH^-) ion content at the steel reinforcement level, raising the pH of the concrete and restoring passivity to the reinforcing steel. The pier is then protected against further chloride ion ingress by the application of penetrating sealers after the ECE process is completed. This report will analyze

the effectiveness of the ECE treatment, and some aspects of the sealers used.

The acid-soluble chloride corrosion threshold is 0.71 kg/m^3 (1). Before ECE treatment, acid-soluble chloride at the level of the reinforcement (51-76 mm) ranged from less than 0.10 to 1.87 kg/m^3. Following treatment, total chloride removal at all levels ranged from 0.12 to 6.21 kg/m^3 (6.4 to 68 percent of total acid-soluble chloride present). Chloride levels at the reinforcement (51-76 mm), however, varied from complete chloride removal, to increases in chloride levels of 0.08 to 0.25 kg/m^3 (increases in chloride levels are explained in the report). Most chloride removal took place near the concrete surface, presumably where the concentration gradient was largest.

The corrosion state of the reinforcement was determined by half-cell potential readings. The steel reinforcement is considered passive if the half-cell potential readings are more positive than -200 mV versus Copper Sulfate Electrode (CSE). Eighty-one percent of half-cell potentials taken on treated faces were more positive than -200 mV, versus 37 percent before treatment. The ECE process has restored passivity to most of the reinforcing steel.

Penetrating sealers were applied after ECE, to prevent subsequent ingress of chloride ions from deicing salts. Power washing did not remove the unsightly stains from the concrete, but the stains were removed by subsequent sand blasting before application of the sealants. The sealants, however, highlighted small areas where epoxy was injected into cracks during the ECE installation. Masterseal GP from Master Builders, a two component epoxy based penetrating sealer, was used for the vertical surfaces. This product is believed to be an effective barrier to moisture carrying chlorides from deicing salts. AkaCote 700, a two component epoxy-polyamide based light grey colored penetrating sealer from Akemi, was used for the horizontal top portion of the pier cap.

The ECE process seemed simple to install, and was effective for chloride removal at levels near the concrete surface. Redistribution of chlorides, rather than removal, occurred at the level of reinforcement. At one location near the reinforcement, all chlorides were removed. The treatment process was completed without any evidence of mechanical distress to the concrete. ECE treatment, with the penetrating sealers, should extend the service life of the pier by at least ten years. However, the ECE treatment was not as effective as anticipated, especially at the level of reinforcement. Successful application of ECE in Michigan will depend upon more experience gained through additional field trials. Several more substructure units should be treated with ECE, and evaluated, before adoption as a standard alternative substructure rehabilitation method in Michigan.

ACTION PLAN

1. Engineering Operations Committee
    a. Approve Report R-1384, Electrochemical Chloride Extraction (ECE).

2. Design Division
    a. Identify up to four bridges with moderate corrosion damage to substructure units for ECE treatment. Work would be done in conjunction with a superstructure rehabilitation project and include ECE treatment in contract plans.

3. Structural Research Unit
    a. Assist in selection of candidate substructure units for ECE.
    b. Revise special provision for general use.
    c. Perform preliminary and post-ECE testing and evaluation as needed (chloride sampling, half-cell readings).
    d. Make final recommendation for ECE use as preventive maintenance, including cost estimates.
    e. Develop criteria for use.

4. Region
    a. Participate in the selection of test structures.
    b. Assist in the application and operation of ECE for the test structures.

INTRODUCTION

A major cause of the premature deterioration of reinforced concrete bridge decks and substructures in Michigan is the corrosion of the reinforcing steel due to the ingress of chloride ions from deicing salts. Chloride ions cause corrosion by destroying the passivity of steel in the alkaline environment of concrete. Formation of oxide by-products occupies several times the volume of the original steel, exerting tensile stresses greater than the tensile strength of the concrete. These stresses lead to crack formation and spalling, further accelerating the corrosion process. Extensive corrosion damage may warrant replacement of the substructure. Substructure repair or replacement can be a costly and time-consuming process.

The condition of substructure units in Michigan is evaluated during a biennial bridge inspection. The bridge is evaluated from a safety standpoint, for structural capacity. If the bridge and substructure units do not have flaws affecting load carrying capacity, no rehabilitation activity is scheduled. If spalls are noted, this downgrades the condition rating of the structure, but may not affect the structural capacity. The spalls are not repaired until the bridge is scheduled for rehabilitation. Then the substructure units would be sounded to find the extent of spalls and delaminations, and repaired. If the estimated repair area of an affected element is greater than 30 percent of the total area, the affected element is typically scheduled for replacement. Repair of substructures is done with manual chip and patch techniques. Generally, minimal preventive maintenance is provided to substructures. One reason for minimal preventive maintenance may lie in the expense of patch repairs, and the lack of patch repair durability.

The underlying reason behind the premature deterioration of patch repairs can be attributed to the ongoing corrosion process. While the patch area is free of chlorides, the surrounding contaminated areas undergo accelerated corrosion. This accelerated corrosion is due to the creation of an electropotential difference between the patch area and the surrounding contaminated concrete. Steel reinforcement that was corroding has been cleaned and repassivated with the addition of fresh concrete during the repair process. The surrounding steel reinforcement is exposed to a greater electropotential difference, accelerating corrosion, leading to spalls around the perimeter of the repair area. This can lead to failure of the patch (pop outs) as well. An effective preventive maintenance treatment would be to halt the corrosion process, for long-lasting repairs.

A study in the Strategic Highway Research Program (SHRP) explored the removal of chloride ions from concrete by electrochemical chloride extraction (ECE), a process that has been an effective alternate solution in some areas. This process applies an electric field over salt contaminated reinforced concrete, using a high current density to displace the chloride ions from around the steel reinforcement to the concrete surface. The study confirmed that ECE is feasible and that the steel reinforcement in the treated concrete becomes passive(2). No electrical components need to be maintained after the treatment is completed.

In August of 1997 a cooperative agreement work order for the ECE process was authorized by the U.S. Department of Transportation, Federal Highway Administration, Demonstration Projects

Program, to be administered by the Michigan Department of Transportation (MDOT). A special provision and work plan were developed before the work order, detailing the ECE process for the substructure discussed herein. The work order, work plan, and special provision can be found in Appendix A. Vector Construction, Inc. was the contractor for the ECE process.

The ultimate objective of this study is to add to the field experience on ECE in the United States, and contribute toward the application of this technology in Michigan, where the problem of steel reinforcement corrosion from deicing salts exists. The immediate objectives of this study are:

1. Apply the ECE process to a 40-year-old bridge pier in Michigan.
2. Monitor the effectiveness of the treatment.
3. Experiment with the application of concrete sealers on the pier after the ECE treatment.

BRIDGE S02 OF 38061 SUBSTRUCTURE, PIER FOUR

From April 7 to 15, 1999, the ECE system was installed on Pier 4 of S02 of 38061, carrying M-60 over I-94, in Jackson, Michigan. Vector Construction, Inc., Fargo, North Dakota, performed the ECE installation process. MDOT personnel provided traffic control, water supply, and routine site inspection during the 63-day operating period.

The structure was constructed in 1957 using Type I Portland cement. The concrete had a density of 2350 kg/m^3, a slump of 76 mm, and an estimated water-cement ratio of 0.44. The pier was reinforced concrete, with a concrete cover over the bars of 63.5 mm or more. The pre-treatment compressive strength was 46.9 MPa. The original mix design and concrete proportioning data are in Appendix B.

The dimensions of the treated surfaces of pier four were taken from plan details. The average height of the columns was 4.00 meters. Column thickness was 0.915 meters, and width was 1.22 meters for the outer columns and 0.915 meters for the inner columns. The cap was 15.1 meters in length, 0.915 meters wide, and 1.07 meters tall. The total surface area to be treated was approximately 108 m^2. The pier was showing signs of deterioration, evidenced by cracking at the top of the south face, and several areas of delaminations and spalling near the top and sides of the columns. These areas needed to be repaired before the ECE treatment could be applied.

Roadway drainage, which contained deicing salts in the winter season, flowed through an open deck joint above the pier, causing high chloride levels in the pier cap and corrosion of the reinforcement. Acid-soluble chloride analysis results (per AASHTO T260-94) of drill samples taken from several pier locations are reported in Appendix D. Acid-soluble chloride ion concentration at the level of the reinforcement ranged from less than 0.10 kg/m^3 to 1.87 kg/m^3, with the highest levels at the top of the pier cap, under the deck joint. The results are summarized in Table 1.

Half-cell corrosion potential measurements (-mV versus copper sulfate electrode, ASTM C876) were taken before treatment, and indicated active corrosion occurring at the locations where chloride levels at the reinforcement exceeded the corrosion threshold of 0.71 kg/m^3 . The initial half-cell potential measurements are shown in Table 2. Visual inspection of the pier confirmed the presence of corrosion on the reinforcing steel (Figure 1).

***Figure 1** Effects of corrosion upon the substructure (Jackson, Michigan).*

Location	Depth (mm)	Acid-soluble Chloride Results	
		Percent, %	kg/m^3
East Column	0-25	0.229	5.09
	25-51	0.126	2.86
	51-76	0.052	1.18
Middle Column	0-25	0.098	2.22
	25-51	0.021	0.47
	51-76	0.008	0.19
West Middle Column	0-25	0.119	2.69
	25-51	0.017	0.38
	51-76	<0.005	<0.10
Pier Cap, Top South	0-25	0.404	9.14
	25-51	0.183	4.15
	51-76	0.083	1.87
Pier Cap, Top Northwest Corner	0-25	0.231	5.24
	25-51	0.092	2.07
	51-76	0.034	0.76

Table 1: Pre-treatment Acid-soluble Chloride (Cl^-) Results (AASHTO T260-94).

Location	Number of Measurements		
	> -200 mV (passive)	-200 mV to -350 mV (uncertain)	< -350 mV (active)
East Column	1	4	4
Middle Column	5	4	0
West Middle Column	3	4	0
Pier Cap, Top South	0	7	2
Pier Cap, Top Northwest Corner	2	2	6

Table 2: Pre-Treatment Half-Cell Potential Measurements (-mV versus CSE, ASTM C876).

INSTALLATION

Column repair and installation of the ECE chloride removal system were conducted on April 7-15, 1999. The steps in the installation process are detailed in a report furnished by the contractor, which is referenced here and can be found in Appendix C.

In 1998, the Michigan Department of Transportation personnel had repaired the substructure in anticipation of the ECE installation. After a year had passed, however, the substructure had deteriorated further. The deterioration underscored the problem of ongoing corrosion in achieving durable patch repairs. Three percent of the total surface area, 3.1 m^2, was repaired on April 7-8, 1999, by hand placing and finishing with Master Builders EMACO S88-CA rheoplastic fiber reinforced, shrinkage compensated structural repair mortar. The contractor's report contains site drawings showing the size and location of repairs. All cracks were then sealed with epoxy paste to prevent contact between the electrolyte and the reinforcement, reducing the possibility of an electrical short.

After repairs, the ECE installation began. Cathode connections were established with the steel reinforcement. The sacrificial steel mesh (anode) was secured to wooden battens, and connected to the ECE system. The mesh installation is shown in Figure 2. Cellulose fiber was then wet sprayed onto the mesh to a depth of about 38 mm. The fiber was air blown out of the center of a nozzle, and wetted by water sprayed through jets mounted around the perimeter of the nozzle (Figure 3). Spraying of the fiber took approximately eight hours for the entire pier. Hydrated lime, 2.5 liters per bail of cellulose fibers, was added (ASTM C206, Type S), which resulted in approximately 10 percent by weight of lime incorporated into the fibers. The lime was added to keep the system pH above nine, to prevent concrete etching because of possible acidic conditions generated at the anode.

Figure 2 *Installation of the Anode Mesh*

After application of the cellulose fiber mixture, the column was wrapped in 0.15 mm plastic sheeting (Figure 4). Column wrapping was done to reduce water evaporation. Drip hoses were then installed on top of the pier cap, to keep the cellulose fibers (electrolyte) wet during the process. These hoses were connected in series to a main metering pump. The water was supplied by a 3,800 liter tank. The tank was installed along the south embankment by MDOT personnel before the installation process, and removed after the ECE treatment. During treatment, the 3,800 liter tank was filled by MDOT personnel every three to five days. This limited water consumption to 760 liters per day.

The main power was supplied by an AC electrical conduit running to a utility pole. MDOT electricians had installed the AC conduit along the superstructure barrier wall in February 1999. After all anode and cathode connections were made, the ECE power supply line was connected to the fuse box on the abutment wall. The utility company was responsible for the meter socket hookup.

To complete the installation process, the water pump was turned on to wet the fibers, and on April 15, 1999, the system was switched on. The system was set for 40 volts, in the constant voltage mode, and set for 2.0 Amps/m^2 current. The voltage was kept at or below 41 volts for safety concerns. The system ran for 63 days, during which time the current and voltage were monitored and recorded by Vector Construction, Inc. via cellular phone modem. The system also was inspected at least once a week by MDOT personnel during filling of the water reservoir.

Figure 3 *Application of Cellulose Fiber Mix.*

Figure 4 *Plastic Wrap to keep cellulose fibers moist.*

INSTALLATION ISSUES

During installation, traffic control was needed for a twelve-day period. Two shoulder closures were needed, on eastbound I-94 and northbound M-60. Because of the high traffic volume on the I-94 corridor, lane closure was not advisable. The vehicles and equipment were placed near the bridge superstructure (M-60), allowing more room for the scaffolding below.

The installation was delayed one and one-half days, due to the extent of delaminations and spalls that have occurred since the pier was repaired in 1998.

Water consumption averaged 760 liters per day, except the first four weeks, where the process used 2,500 liters daily. The additional water consumption was attributed to the lack of a check valve, and that the tank was mounted above the pier, allowing for gravity feed after the pump was shut off. After correction of this problem, consumption of water dropped to 760 liters per day. The water supply was limited to one tank fill (3,785 liters) per three to five days due to the difficulties involved in transporting water to the remote site.

The electrical conduit running from the utility pole to the abutment wall was installed in 1998 by MDOT personnel. During the ECE installation, it was noticed that the meter socket hookup by the utility company had not yet been completed (Figure 5). This was scheduled to take place before the ECE installation. Several attempts were made to contact the utility company to arrange for the meter socket hookup. Because of the lack of electrical power during the installation period, generators were needed to operate the tools. The contractor ran two of their own gasoline-powered generators during the installation. The electrical hookup from the conduit to the ECE power distribution system was completed on April 14, 1999 by a licensed MDOT electrician. The meter socket was connected by the utility company on April 15, 1999.

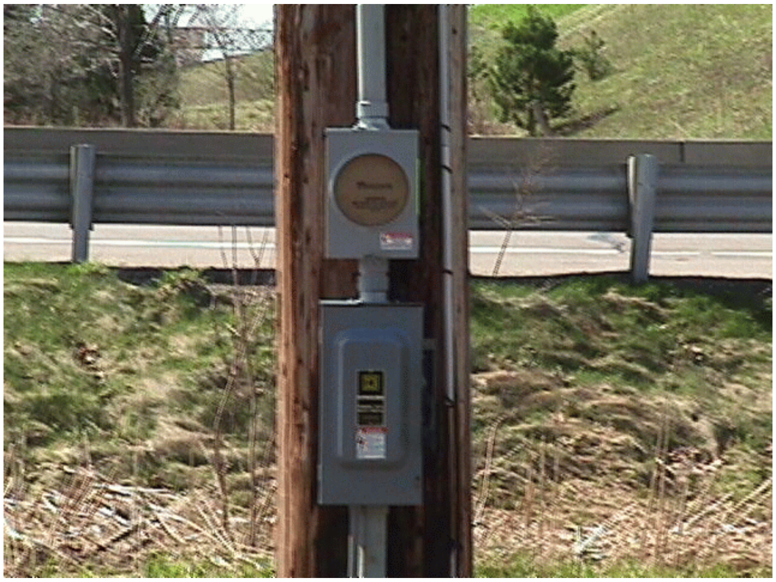

Figure 5 *Meter Socket not installed until 4/15/99.*

RESULTS AND DISCUSSION

The system was initially energized April 15, 1999 at 46.3 amps, 40 volts. The voltage was maintained at or below 41 volts for safety reasons. The total applied current remained constant at 43.8 ± 10 amps for the 63-day period. Data from other ECE projects has shown the applied current starting high, typically 80-100 amps, then decreasing over time. One reason for the low current draw is that the moisture content of the electrolyte media and concrete was limited by the water supply. Since the water tank could only be filled every three to five days, the water supply was limited to 760 liters per day. This is an obvious drawback for ECE in remote locations. In other ECE projects, water was supplied by direct hookup to a water main, which provided more water to keep the fibers and concrete saturated. The water supply limitation of 760 liters per day was exceeded for the first fifteen days of the treatment because of a gravity feed problem. In addition, there were problems setting the timer on the watering pump, which allowed for half the pier to nearly dry out. As the fiber dried out, the resistance increased and the current drawn went down. When the pump started wetting the fibers, the current would increase. During this 15-day period, the other half would remain wet because of the gravity feed and lack of a check valve. These problems were corrected, and the water consumption dropped back to 760 liters per day. The ECE system ran until June 16, 1999, for a total of 63 days. The total charge passed was 612 A-hr/m^2, the low side of the recommended range (600 to 1500 A-hr/m^2)$^{(3)}$. Power consumption for the total process was about 4510 KWH or 41.8 KWH/m^2. At the beginning of the treatment, the cellulose fiber was grey to light brown in color. After several weeks of operation, the cellulose fiber had a dark brown appearance, from the corrosion of the steel mesh. After the treatment, the surface of the pier was heavily stained by rust. This rust staining was removed by blast cleaning before application of the sealer.

Dust samples for chloride analysis before and after the ECE process were taken with a rotary impact drill, collected, and tested. Three sample depths at five different locations were drilled, and post treatment samples were taken at the same elevations as pretreatment samples. Initially, water-soluble chloride analysis was performed per ASTM C1218 (specified in MDOT special provision, Appendix A), by Vector Construction on pre- and post treatment powdered samples, and selected split samples were tested by MDOT for verification. Results are shown in Appendix D. Vector's test results on average were lower than MDOT results by 0.36 kg/m^3 at the 0-25 mm depth, but came to close agreement with MDOT results at the level of reinforcement, within 0.02 kg/m^3. According to ASTM C1218, results of two properly conducted tests from two different laboratories on samples of the same material should not differ by more than 0.0106 percent.$^{(4)}$ Overall, the average difference was 0.009 percent. It can be concluded that Vector's test results for water-soluble chloride analysis were valid.

During preparation of the application report by Vector Construction, it became apparent that meaningful comparison to literature values would preclude water-soluble chloride analysis. Therefore, acid-soluble chloride analysis was performed on all samples to measure against the acid-soluble corrosion threshold of 0.71 kg/m^3. Results are summarized in Table 3, showing the total acid-soluble chloride per cubic meter removed, and percentage of chloride removed. Acid-soluble chloride ion concentrations versus depth are shown in Figure 8. Acid-soluble chloride testing for pre- and post treatment samples (AASHTO T260-94) was performed by the author. Because the special provision specified water-soluble chloride analysis, the contractor was not held liable for the additional testing.

Location	Depth (mm)	Pre Treatment Results	Post Treatment Results	Percent Chloride Removed
		Acid-soluble Cl^- (kg/m^3)	Acid-soluble Cl^- (kg/m^3)	Acid-soluble Cl^- (%)
East Column	0-25	5.09	1.74	65.8
	25-51	2.86	1.05	63.3
	51-76	1.18	< 0.10	91.5
Middle Column	0-25	2.22	1.52	31.5
	25-51	0.47	1.11	-136.2
	51-76	0.19	0.44	-131.6
West Middle Column	0-25	2.69	1.29	52.0
	25-51	0.38	0.49	-28.9
	51-76	< 0.10	0.29	-190.0
Pier Cap, Top South	0-25	9.14	2.93	67.9
	25-51	4.15	2.71	34.7
	51-76	1.87	1.75	6.4
Pier Cap, Top Northwest Corner	0-25	5.24	2.64	49.6
	25-51	2.07	1.64	20.8
	51-76	0.76	0.84	-10.5

Table 3: Summary of Acid-Soluble Chloride (Cl^-) Results by AASHTO T260-94.

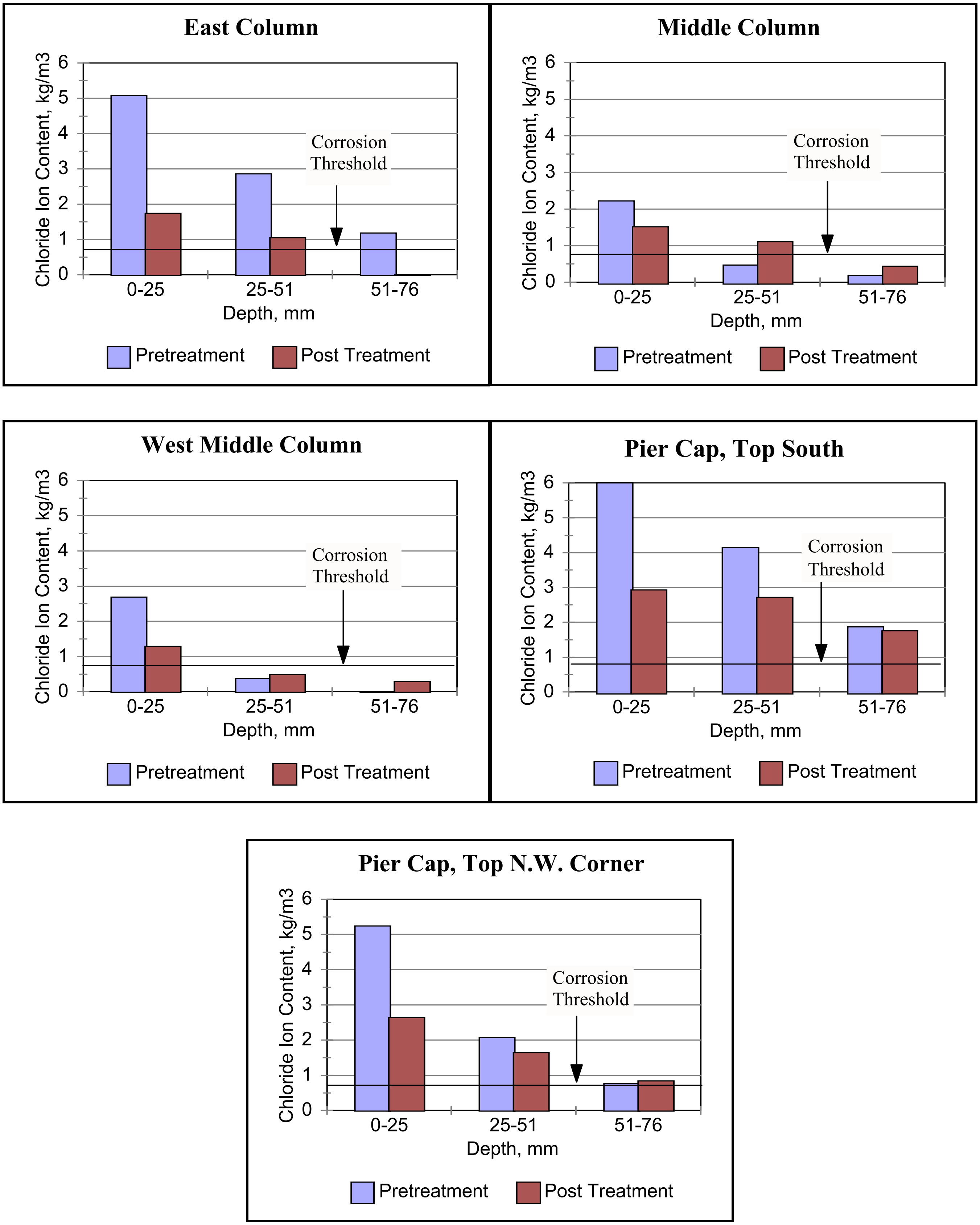

Figure 8. Pre- and Post Treatment Acid-Soluble Chloride Levels. Five Sampling Locations

One discrepancy in Table 3 is the apparent increase in chloride ion concentrations at the steel reinforcement level (51-76 mm). One possible explanation for the discrepancy may be due to the sampling technique. When drilling into the concrete, there is always the risk of scraping the side of the hole with the drill bit, contaminating the sample with concrete from the surface layer. Sampling errors would be more evident at depths where the chloride concentrations are very low. Another factor may be due to the ECE process itself. Chloride ions are migrating, resulting in redistribution of chloride ions throughout the concrete. One anode sub zone may have redistributed chloride ions, possibly due to uneven current distribution or variable resistance in the concrete from changing moisture levels. Since each sub zone was electrically isolated from another, it is unlikely that chloride transport across sub zones occurred. For most locations, chloride redistribution, rather than removal, has occurred at the level of reinforcement. The east column was the exception, with complete chloride removal at the level of reinforcement. Chloride removal was greatest near the surface, diminishing toward the level of reinforcement. The ECE process should remove about 20 to 50 percent of the chloride present, and removing chlorides around the reinforcement is an important benefit. The lack of chloride removal at the level of reinforcement, however, was minimized by hydroxyl ion (OH^-) generation.

Throughout the operation of the ECE process, hydroxyl ions were generated around the reinforcement. The production of hydroxyl ions creates more alkalinity at the surface of the steel, which tends to repassivate the steel and helps to prevent the onset of corrosion. Hydroxyl ions also serve to lower the Cl^-/OH^- ratio, reducing the ability of the remaining chlorides to initiate corrosion(5). The restoration of the steel reinforcement to the passive state will increase the remaining service life of the substructure.

Three cores, 93 mm diameter and 230 mm long, were taken before and after the ECE process. The cores were tested for compressive strength using ASTM C42. The results are shown below in Table 4. According to ASTM C42, the length to diameter (L/D) ratio of the tested sample must be between 1.90 and 2.10. For the initial cores, this was the case. The post treatment cores, however, were tested with L/D ratios greater than 2.10, invalidating the results. This required recoring and retesting, which took place the third week in September 1999. The test data are included in the contractor's report (Appendix C). All cores were taken at the same elevation to reduce differences in concrete composition. The data in Table 4 show no significant differences in the compressive strength averages, which agrees with prior findings on the effects of ECE on the mechanical properties of concrete(6). The apparent decrease in the compressive strength of 10.2 MPa for the East Column may be attributed to concrete non homogeneity, along with the apparent increase in compressive strength for the other columns. The minimum specified compressive strength is 24.0 MPa for substructure concrete.

Location	Pretreatment (4/9/99) Compressive Strength, MPa	Post treatment (9/21/99) Compressive Strength, MPa
East Column	53.5	42.7
Middle Column	43.2	50.8
West Column	44.9	49.0
Average (over Columns)	47.2	47.5

Table 4: Compressive Strength Results, ASTM C42. Corrected to L/D = 2.0.

The post treatment copper-copper sulfate half-cell potential survey (ASTM C876) was taken on September 21, 1999. Eighty-one percent of the readings were more positive than -200 mV, the region characteristic of very little corrosion. Table 5 summarizes the potential survey. The contractor's report (Appendix C) contains the raw data and sampling locations. Six months should elapse before a potential survey is done, to allow time for the steel to depolarize(7). Because of time constraints, the survey had to be finished earlier to allow for a pre-winter application of a penetrating sealer. Surveying before six months have elapsed may result in electropotentials that are more negative, showing more corrosion activity than what is occurring. These potentials are expected to become more positive with time, resulting in an increase in the percentage of readings in the passive range (> -200 mV). One cathode connection to the steel reinforcement was left intact on the south face of the pier, for future surveys that should verify the positive potential shift.

Location	Number of Measurements					
	> -200 mV (passive)		-200 mV to -350 mV (uncertain)		< -350 mV (active)	
	Before	After	Before	After	Before	After
East Column	1	7	4	2	4	0
Middle Column	5	8	4	1	0	0
West Middle Column	3	6	4	1	0	0
Pier Cap, Top South	0	7	7	2	2	0
Pier Cap, Top Northwest Corner	2	3	2	6	6	1

Table 5: Potential Measurements (-mV versus Cu-$CuSO_4$ electrode, ASTM C876)

Vector Construction, Inc., was required to furnish a final report, as outlined in the work plan. The report (Appendix C) details the ECE process from the contractor's perspective. Except as noted, all test data were furnished by Vector Construction, Inc., and its subcontractors. The author was present during most of the ECE installation process, chloride sampling, compressive strength specimen coring, and during the pre- and post treatment copper-copper sulfate half-cell potential surveys.

The rust stains from corrosion of the sacrificial steel anode mesh are clearly visible in Figure 9, which posed an aesthetic problem. The stains were not removed when the substructure was power washed after treatment, but were removed upon subsequent sand blasting before the sealant application. Penetrating sealants will protect the pier from future ingress of chloride ions, and should last at least five years. Masterseal GP from Master Builders, a two component epoxy based penetrating sealer, was used for the pier surfaces, except the top of the pier cap. This product is believed to be an effective barrier to chlorides from deicing salts. AkaCote 700, a two component epoxy-polyamide based light grey colored penetrating sealer from Akemi, was used for the pier cap top. The sealer application was completed on October 26, 1999. Figure 10 shows the final product, with a slight amber tint, as compared with the other substructure components. The sealants, however, highlighted areas where epoxy was injected into cracks during the ECE installation. Patched areas also appear darker than the surrounding concrete.

Figure 9 *Rust Stains from the ECE Process*

Figure 10 *ECE Treated Pier with penetrating sealants applied.*

CONCLUSIONS

The overall performance of ECE was evaluated by chloride analysis and half-cell corrosion potential surveys. Passivity of the reinforcing steel was regenerated; eighty-one percent of the readings after the ECE treatment were more positive than -200 mV, the region characteristic of very little corrosion. Chloride levels were reduced at locations above the steel reinforcement, with no adverse effects to the structural integrity of the concrete. At the reinforcement, chloride levels were redistributed, except one location where chlorides were completely removed. However, it was expected that all chloride contamination at the reinforcement depth would be reduced below the corrosion threshold. Despite the incomplete removal of chloride contamination from around the reinforcement, ECE has reduced the ability of the remaining chlorides to initiate corrosion by repassivating the steel. Electrochemical chloride extraction appears to work well, given the resources available at a remote location.

Improved performance of ECE could be obtained by increasing water usage to saturate the concrete, allowing for a greater applied current. In remote locations, installing a larger water storage tank can allow for an increase in water use, and reduce the expense of refilling. The cost of ECE for a particular application, however, is still difficult to judge. Increasing the surface area to be treated for a given location, by treating all the substructure units, should provide a net decrease in cost per unit area. Different types of concrete members, and different locations, are also expected to have a significant impact on treatment costs. Treating substructures that have at least ten years projected service life, or that require minimal repair is desirable to maximize the benefits of ECE.

Because of the variability in chloride removal at the steel reinforcement, it is recommended that ECE be studied further with additional field trials. More substructure units should be treated with ECE and evaluated before adoption as a standard alternative substructure rehabilitation method in Michigan.

REFERENCES

1. R. Weyers, et. al., *"Concrete Bridge Protection, Repair, and Rehabilitation Relative to Reinforcement Corrosion: A Methods Application Manual,"* Report No. SHRP-S-360, Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

2. J. Bennett, K.F. Fong, and T.J. Schue, "*Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Field Trials.*" Report No. SHRP-S-669, Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

3. J. Bennett, T. Schue, "*Chloride Removal Implementation Guide.*" Report No. SHRP-S-347, Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

4. ASTM C1218/C1218M-97, *"Standard Test Method for Water-Soluble Chloride in Mortar and Concrete,"* Vol. 04.02, American Society for Testing and Materials, West Conshohocken, PA, 1999.

5. Burns, D., "*Norcure Electrochemical Chloride Extraction Project",* Final Report for Contract 98-0573, Vector Construction, Inc., June 1999, Reference No. 4.

6. J. Bennett, T. Schue, et. al., "*Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Laboratory Studies.*" Report No. SHRP-S-657, Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

7. J. Bennett, T. Schue, "*Evaluation of Norcure Process for Electrochemical Chloride Removal from Steel-Reinforced Concrete Bridge Components.*" Report No. SHRP-C-620, Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

Appendix A

FHWA Work Order
MDOT Work Plan
MDOT Special Provision of June 16, 1997
for ECE

Appendix B

Concrete Mix Proportioning Data
October, 1957

Bridge Proportioning Data For Type 35S Concrete, Vibrated, Medium Consistency, 10-1-1957

	Total Computed Mix				Moisture Percent					
Pour, Pier #4	Cement, Sacks	Sand, kg	Coarse Aggregate, kg	Water, kg	Sand	Coarse Aggregate	Actual Water added at mixture, liters	Air Content, Percent	Slump, mm	Sacks of Cement per 0.76 m^3 of Concrete
G,D,E,F (Columns)	5.9	523.6	945.9	80.0	6.7	1.2	79.4	7.3	76	5.9
H,J (Cap)	5.9	517.7	948.6	83.6	5.5	1.5	83.2	5.1	89	5.9

½ Ounce Darex added per Sack.

Coarse Aggregate (C.A.) consisted of natural gravel, Grade 6B. Weight per m^3, 61.2 kgs. (Bone Dry). No other information available.

Specified Minimum Compressive Strength for substructure grade concrete, Type S2 (Type 35S): 24 MPa.

No test data available.

One Sack of Cement weighs 42.7 kg.

Mix Design No. 57 MY-328

Weight per m^3 of (bone-dry) loose C.A. : 61.2 kgs.	
Items	Quantities Per Sack of Cement
Cement (Sacks)	1
F.A. (Kg)	83.2
C.A. -6B (Kg)	158.4
C.A. -4A (Kg)	
C.A. -10A (Kg)	
Water (Kg)	21.1

Appendix C

Vector Construction, Inc.

Final Report
June, 1999

Appendix D

Test Results and Summary
for
Water-soluble Chloride Analysis
ASTM C1218

Summary of Water-soluble Chloride Ion Tests on Selected Sampling Locations.

Sampling Location	East Column				Pier Cap, Top N.W. Corner			
Depth	0-25 mm		51-76 mm		0-25 mm		51-76 mm	
Pretreatment Water-soluble Chloride Test Results	kg/m^3	Percent	kg/m^3	Percent	kg/m^3	Percent	kg/m^3	Percent
Vector Construction	3.59	0.155	0.68	0.029	3.61	0.155	0.41	0.018
MDOT	4.11	0.177	0.71	0.031	3.93	0.169	0.35	0.015
Difference	-0.52	-0.022	-0.03	-0.002	-0.32	-0.014	+0.06	+0.003
Post Treatment Water-soluble Chloride Test Results	kg/m^3	Percent	kg/m^3	Percent	kg/m^3	Percent	kg/m^3	Percent
Vector Construction	1.46	0.063	0.33	0.014	1.66	0.071	0.43	0.019
MDOT	1.67	0.072	0.26	0.011	2.04	0.088	0.49	0.021
Difference	-0.21	-0.009	+0.07	+0.003	-0.38	-0.017	-0.06	-0.002

Percent Chloride Removed (%)

Sampling Location	East Column		Pier Cap, Top N.W. Corner	
Depth	0-25 mm	51-76 mm	0-25 mm	51-76 mm
Vector Construction	59.3	51.5	54.0	-4.88
MDOT	59.4	63.4	48.1	-40.0
Difference (%)	-0.1	-11.9	+5.9	+35.1

Testing & Research Section
Secondary Governmental Complex
P.O. Box 30049
Lansing, Michigan 48909

Job Number
Tested for Information
Control Section Identity
Laboratory No. 99-0001
Date: May 5, 1999

REPORT OF TEST

Report on sample of	CONCRETE CHLORIDES		
Date sampled	April 8, 1999	Date received	April 12, 1999
Source of material	Jackson ECE Site		
Sampled from	Bridge Pier #4, S02 of 38061 Substructure, M-60 and I-94, Jackson, Michigan		
Submitted by	S. Kahl		

	TEST RESULTS	
	Water Soluble Chloride Ion Content	
Field Identification Number	**lb/yd^3**	**kg/m^3**
East Column, 0-1"	6.91	4.11
East Column, 2-3"	1.20	0.71
Top N.W. Corner, 0-1"	6.61	3.93
Top N.W. Corner, 2-3"	0.59	0.35

REMARKS: Tested for Information, ASTM C1218. Precision Check = 0.0012 %, Limits = 0.0037%.

cc S. Kahl
R. Till

Signed ______________________________
Corrosion Specialist

For questions concerning analytical results, please contact Steve Kahl at (517) 322-5655

MICHIGAN DEPARTMENT OF TRANSPORTATION

Testing & Research Section
Secondary Governmental Complex
P.O. Box 30049
Lansing, Michigan 48909

Job Number
Tested for Information
Control Section Identity
Laboratory No. 99-0010
Date: June 24, 1999

REPORT OF TEST

Report on sample of	CONCRETE CHLORIDES		
Date sampled	June 17, 1999	Date received	June 18, 1999
Source of material	Jackson ECE Site		
Sampled from	Bridge Pier #4, S02 of 38061 Substructure, M-60 and I-94, Jackson, Michigan		
Submitted by	S. Kahl		

Field Identification Number	**TEST RESULTS**	
	Water Soluble Chloride Ion Content	
	lb/yd^3	**kg/m^3**
East Column, 0-1"	2.81	1.67
East Column, 2-3"	0.44	0.26
Top N.W. Corner, 0-1"	3.43	2.04
Top N.W. Corner, 2-3"	0.82	0.49

REMARKS: Tested for Information, ASTM C1218. Precision Check = 0.0027 %, Limits = 0.0037 %.

cc R. Till
S. Kahl

Signed ______________________________
Corrosion Specialist

For questions concerning analytical results, please contact Steve Kahl at (517) 322-5655

Testing & Research Section
Secondary Governmental Complex
P.O. Box 30049
Lansing, Michigan 48909

Job Number
Tested for Information
Control Section Identity
Laboratory No. 99-0029
Date: November 18, 1999

REPORT OF TEST

Report on sample of	CONCRETE CHLORIDES		
Date sampled	April 8, 1999	Date received	November 4, 1999
Source of material	Jackson ECE Site		
Sampled from	Bridge Pier #4, S02 of 38061 Substructure, M-60 and I-94, Jackson, Michigan		
Submitted by	S. Kahl		

Field Identification	TEST RESULTS	
	Acid Soluble Chloride Ion Content	
	kg/m^3	Percent (%)
East Column, 0-25 mm	5.09	0.219
East Column, 25-51 mm	2.86	0.123
East Column, 51-76 mm	1.18	0.051
Middle Column, 0-25 mm	2.22	0.096
Middle Column, 25-51 mm	0.47	0.020
Middle Column, 51-76 mm	0.19	0.008
West Middle Column, 0-25 mm	2.69	0.116
West Middle Column, 25-51 mm	0.38	0.016
West Middle Column, 51-76 mm	< 0.10	< 0.004
Pier Cap, Top South, 0-25 mm	9.14	0.393
Pier Cap, Top South, 25-51 mm	4.15	0.179
Pier Cap, Top South, 51-76 mm	1.87	0.081
Pier Cap, Top N.W. Corner, 0-25 mm	5.24	0.226
Pier Cap, Top N.W. Corner, 25-51 mm	2.07	0.089
Pier Cap, Top N.W. Corner, 51-76 mm	0.76	0.033

REMARKS: Pretreatment samples. Tested for Information, AASHTO T260-94. Precision Check = 0.0037 %, Limit = 0.0067%.

cc S. Kahl
R. Till

Signed ______________________________
Corrosion Specialist

For questions concerning analytical results, please contact Steve Kahl at (517) 322-5655

Testing & Research Section
Secondary Governmental Complex
P.O. Box 30049
Lansing, Michigan 48909

Job Number
Tested for Information
Control Section Identity
Laboratory No. 99-0030
Date: November 19, 1999

REPORT OF TEST

Report on sample of	CONCRETE CHLORIDES		
Date sampled	June 19, 1999	Date received	November 4, 1999
Source of material	Jackson ECE Site		
Sampled from	Bridge Pier #4, S02 of 38061 Substructure, M-60 and I-94, Jackson, Michigan		
Submitted by	S. Kahl		

Field Identification	TEST RESULTS	
	Acid Soluble Chloride Ion Content	
	kg/m^3	Percent (%)
East Column, 0-25 mm	1.74	0.075
East Column, 25-51 mm	1.05	0.045
East Column, 51-76 mm	< 0.10	< 0.004
Middle Column, 0-25 mm	1.52	0.065
Middle Column, 25-51 mm	1.11	0.048
Middle Column, 51-76 mm	0.44	0.019
West Middle Column, 0-25 mm	1.29	0.056
West Middle Column, 25-51 mm	0.49	0.021
West Middle Column, 51-76 mm	0.29	0.012
Pier Cap, Top South, 0-25 mm	2.93	0.126
Pier Cap, Top South, 25-51 mm	2.71	0.117
Pier Cap, Top South, 51-76 mm	1.75	0.075
Pier Cap, Top N.W. Corner, 0-25 mm	2.64	0.114
Pier Cap, Top N.W. Corner, 25-51 mm	1.64	0.071
Pier Cap, Top N.W. Corner, 51-76 mm	0.84	0.036

REMARKS: Post treatment samples. Tested for Information, AASHTO T260-94. Precision Check = 0.0024 %, Limit = 0.0067%.

cc S. Kahl
R. Till

Signed ______________________________
Corrosion Specialist

For questions concerning analytical results, please contact Steve Kahl at (517) 322-5655 KahlS@michigan.gov