

Electrochemical Removal of Chlorides From Concrete Bridge Decks

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The spalling of concrete bridge decks is largely due to corrosion of the top layer of reinforcing steel. This corrosion is induced by chloride ions, which enter the concrete when deicing salt is applied to the deck surface. The construction of many new bridge decks is based on techniques that either prevent penetration of chloride or ensure resistance to chloride-induced rebar corrosion. However, the many salt-contaminated decks that now exist demand attention. Besides costly patching of spalls, only cathodic protection of the steel is currently available as a remedial measure. This paper presents the results of an investigation of an electromigration method for removing chloride from contaminated concrete decks, which prevents rebar corrosion. In this method, the chloride ion moves through and out of the concrete under an electric field applied between the rebar (cathode) and a surface anode. A preliminary laboratory investigation demonstrated the viability of the technique and identified optimum voltage (100 Vdc), treatment time (12 to 24 h), anode material (platinized titanium), surface electrolyte, and chloride fixant. A field trial on a 3 by 6.1-m (10 by 20-ft) section of chloride-contaminated bridge deck was conducted in which laboratory-optimized parameters were used. Under the best conditions, 90 percent of the chloride was removed from the concrete above the rebar; 88 percent was removed from the concrete immediately adjacent to the rebar. Potential measurements have shown that the previously actively corroding rebar became passive after treatment.

Deterioration of portland cement concrete (PCC) bridge decks is a serious problem in many parts of the United States and has resulted in high maintenance costs to keep the decks in a safe and serviceable condition. Although deck deterioration can take several forms, such as scaling, cracking, or spalling, during the last 10 years or so spalling has become the major contributor to bridge deck deterioration. The increased frequency of spalling of PCC bridge decks appears to be directly related to the increased use of deicing salts (primarily NaCl and CaCl₂) in recent years. Chloride ions accelerate the rate of corrosion of reinforcing steel in the

concrete. The formation of corrosion products on the steel results in a buildup of stresses in the concrete, which is ultimately manifested as spalling of concrete on the deck surface.

If we assume that deicing salts will continue to be used during the foreseeable future, then remedial steps must be taken if the problem is not to worsen. Recognizing this, the Federal Highway Administration and other highway agencies have initiated research and field programs to investigate the feasibility of a number of potential solutions to the problem, including (a) polymer impregnation of bridge decks, (b) cathodic protection of reinforcing steel, (c) protection of the reinforcing steel through the use of various coatings, (d) application of impermeable membranes or coatings to the concrete, and (e) sophisticated rehabilitation procedures involving removal of chloride-contaminated concrete to below-steel levels and subsequent protection of the steel (e.g., with epoxy coatings) before new concrete is placed. One means of providing extended service life to existing chloride-contaminated concrete decks that has not been adequately researched is removal of the chloride from the concrete. This paper describes that process.

A two-phase program was begun at Battelle Columbus Laboratories during July 1973 and was completed in September 1975. The initial laboratory phase was intended to evaluate the feasibility of the removal concept and to identify suitable procedures and equipment. This work was followed by a field phase in which the treatment concept developed in the laboratory was successfully applied to an existing bridge deck in Ohio.

LABORATORY EXPERIMENTS

The electrochemical removal concept involves the migration of chloride ions in concrete under the influence of an electrical potential gradient through the bridge deck concrete and into an electrolyte contained above it. The potential gradient is produced by applying a direct current source between the reinforcing steel and an electrode contained in the electrolyte above the bridge deck. An ion exchange resin contained in the electrolyte captures the chloride ions before they reach the anode. Thus, the evolution of chlorine gas is prevented, and corrosion of

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the anode is minimized.

The laboratory phase of the program involved studies of 76 by 152-mm (3 by 6-in) concrete cylinders and 117 by 152 by 23-mm (46 by 60 by 9 in) concrete slabs. The specimens were prepared with concretes in which pre-selected quantities of chloride had been added to the mix water. The initial work was directed at identifying

1. A suitable anode material,
2. A suitable ion exchange resin, and
3. A suitable electrolyte.

Then the effect of concrete and process variables on the electrochemical removal of chloride ion was investigated. The variables studied included

1. The magnitude of the applied electrical potential gradient,
2. The duration of treatment, and
3. The initial chloride content of the concrete.

Pretreatment and posttreatment measurements of chloride content at various levels in the concrete were made by using the techniques described by Berman (1).

The initial laboratory work showed that calcium hydroxide solution (0.1 normal concentration) was suitable surface electrolyte, platinized titanium was the optimum anode material, and Dowex 2-X8 was a suitable anion-exchange resin to capture chloride as it emerged from the concrete.

The amount of chloride removed for a given treatment time increased as the applied dc voltage increased. At 100 Vdc (the maximum voltage used in the program), treatment times of 16 to 48 h resulted in significant reductions in the chloride content depending on the initial chloride level and distribution. Treatment at 50 V was not sufficient to provide significant levels of chloride removal within a reasonable time period. The treatment time necessary for chloride removal increased as the initial chloride content of the concrete was increased. However, for concrete with a high chloride content (4.15 kg/m³ or 7 lb/yd³), substantial reductions in total chloride were achieved in a 24-h period.

Although the efficiency of the chloride removal technique was quite low, it did significantly reduce the chloride content of the concrete below what is now considered a threshold value for the corrosion of the reinforcing steel. Attempts to improve the efficiency of the treatment by changing the composition of the electrolyte solution were not successful.

The temperature of the concrete (laboratory specimens) during electromigration treatment at 100 V increased from 24 to about 52 C (75 to 125 F). The elevated temperature exposure had no obvious adverse effect on the integrity of the concrete. For the laboratory specimens, there appeared to be a chloride removal threshold. This residual chloride content was 0.02 percent or about 0.47 kg/m³ (0.8 lb/yd³) of concrete. A portion or all of this residual chloride is present in an insoluble form and hence is not amenable to easy removal by the electrochemical technique.

Given the positive results obtained in the initial experiments, the electrochemical removal investigation was continued on the large simulated bridge deck slabs. The experimental arrangement used is shown in Figure 1. The slabs were constructed in several lifts, with concrete containing Cl⁻ (added as NaCl to the mix water) above the top rebar mat. Concrete composition and rebar placement and size were the same as in the actual bridge deck selected for study.

Electrical power for the large slab work was supplied by a 5-kW portable generator. Voltage was controlled by

a variable transformer, and a full-wave rectifier was used to convert the alternating current to direct current. Electrical connections were made to the reinforcing steel in the concrete and to a 61 by 76-cm (24 by 30-in) platinized titanium electrode (in expanded metal form) on the upper surface of the slab. A wooden dike, sealed with silicone, served to contain the ion exchange resin and the electrolyte solution (0.1 N calcium hydroxide solution).

The work on the large slabs established that significant quantities of chloride ion can be removed from thick concrete slabs by using the electrochemical treatment within a reasonable time period. However, current densities of at least 0.46 A/m² (5 A/ft²) were required for effective electrochemical treatment. Treatment times of 24 h appeared adequate to achieve a significant reduction in chloride ion content. The treatment can be either continuous or intermittent to achieve the same chloride extraction.

The removal of chloride ion was greatest in the concrete overlying the cathode (rebar). Significant but lesser reductions in chloride content were also achieved in concrete adjacent to the cathode areas. It was clear that the problems of scaling the treatment for application to large slabs would be minimal.

BRIDGE DECK EXPERIMENTS

For the electrochemical chloride removal experiments, the bridge deck had to contain substantial quantities of chloride but exhibit no evidence of surface spalling. With the cooperation of the Ohio Department of Transportation, a number of candidate bridges were identified and visited in fall of 1973. The bridges were examined visually for spalling, and electrochemical potential scans were taken to assess corrosion activity of the reinforcing steel.

The bridge selected for study was an 8-year-old, two-lane, steel girder bridge on the southbound lane of US-33 near Marysville, Ohio. The deck was completely free of surface spalls. As a matter of interest, a similar deck less than 100 m (330 ft) away, constructed at the same time by the same contractor, had about 60 percent of the surface repaired due to spalling. A 3 by 6.1-m (10 by 20-ft) area of the bridge deck on the west side lane was chosen for treatment.

Pretreatment Measurements

Pretreatment characterization data were obtained in the form of electrochemical potential scans, chloride analyses, delamination detection, and linear polarization electrode readings.

Potential Scans

Before the selected area was electrochemically treated, a number of potential scans were made of the deck (in November 1973, August 1974, and April 1975). Measurements were made on a 0.3-m (1-ft) grid in general accordance with the technique described by Stratfull (2) by using Cu/CuSO₄ as the reference cell. It has been established that steel showing a potential more negative than about -0.35 V is undergoing active corrosion.

During the 17-month measurement period, the active region of the treatment area increased from 18 to 55 percent. Figure 2 shows the potential profile of the selected section of the deck just prior to the electrochemical treatment (in April 1975).

Chloride Analyses

A number of cores were removed from the 3 by 6.1-m

(10 by 20-ft) area of the deck during the 18-month period preceding the electrochemical treatment. The location of the cores on the deck is shown in Figure 3. The average chloride content as a function of depth in the deck is given in Table 1.

An increase in chloride content at all levels in the deck was noted during the 17-month observation period. Approximate increases were as follows:

Deck Depth (mm)	Content (kg/m ³)
0 to 25	2.4
25 to 51	1.2
51 to 76	0.3

Just before electrochemical treatment, the chloride ion content on the top 25 mm (1 in) of deck was more than 8.9 kg/m³ (15 lb/yd³) while at 25 to 51 mm (1 to 2 in) the content was 2.4 to 5.9 kg/m³ (4 to 10 lb/yd³).

Because of the rather large variation between specimens in measured chloride observed when duplicate cores were taken, we cannot speculate on the differences in chloride content between the high and low corrosion

Figure 1. Experimental setup for the electrochemical removal of chloride ion from simulated bridge deck slabs.

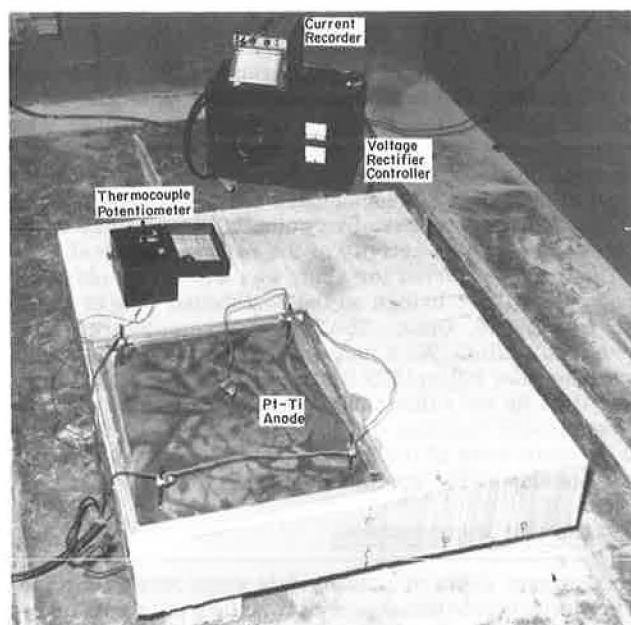
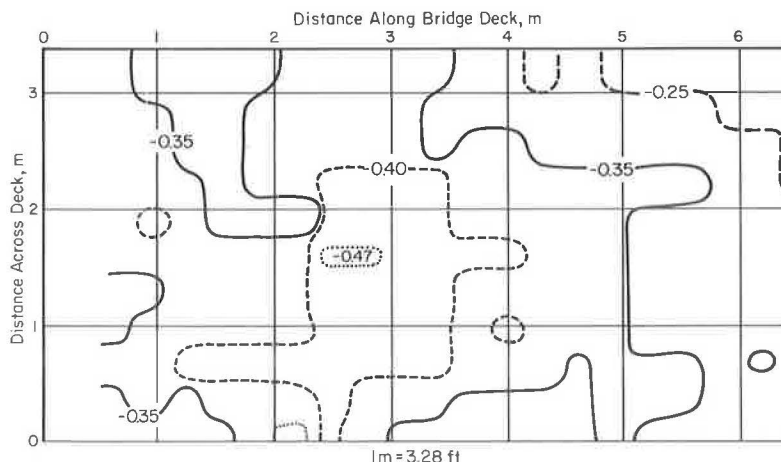


Figure 2. Pretreatment potential scan of bridge deck area (April 1975).



activity areas of the deck.

Delamination Detection

In April 1975, before the electrochemical treatment, maintenance personnel of the Ohio Department of Transportation examined the selected area of the bridge deck for delamination by using a sounding rod. There was no evidence of any delamination despite the significant areas of high corrosion activity.

Electrochemical Treatment of the Deck

After deck characteristics before treatment were identified, electrochemical experiments were begun on April 7, 1975. The total area treated was 18.6 m² (200 ft²). The treatment area was broken down into five 3.4-m² (40-ft²) sections (Figure 3) that were treated individually.

Wood ponding frames 50 mm (2 in) deep, which contained four 0.76 by 1.2-m (2.5 by 4-ft) compartments, were used to hold the ion exchange resins. After the deck was swept, the frames were sealed to the bridge deck surface with construction caulking compound. Weights were placed on the frames to prevent movement and to aid in maintaining a leakproof seal.

The electrolyte solution of saturated Ca(OH)₂ was placed in the ponding frame to a depth of 12 to 25 mm (1/2 to 1 in). Dowex 2-X8 ion exchange resin in the OH⁻ form was slurried into the electrolyte to a depth of 6 to 9 mm (1/4 to 3/8 in). It was rather difficult to maintain a homogeneous dispersion of the resin in the electrolyte.

A 0.7 by 1.2-m (2.25 by 4-ft) platinized titanium anode was then placed in each of the four compartments within the ponding frame. The anodes were supported about 12 mm (0.5 in) above the bridge deck by small wood blocks. The anodes were kept covered with electrolyte solution at all times. Figure 4 shows the compartmentalized ponding frames and one of the generators used in the experiment. The frame in the background contains the electrolyte, resin, and anodes.

Electrical contact was made with the top layer of the reinforcing steel in the treatment area through 6 by 25 by 100-mm (1/4 by 1 by 8-in) mild steel studs that were arc welded to the rebars. The rebars were exposed by coring along the berm side of the treatment area. Direct current power leads were attached to the rebar contact studs and to vertical studs that were welded to the titanium anodes in each compartment. Electrical power was supplied by two trailer-mounted, gasoline-driven, direct current generators. A schematic of the experimental technique is shown in Figure 5.

Figure 3. Location of cores taken from treatment area.

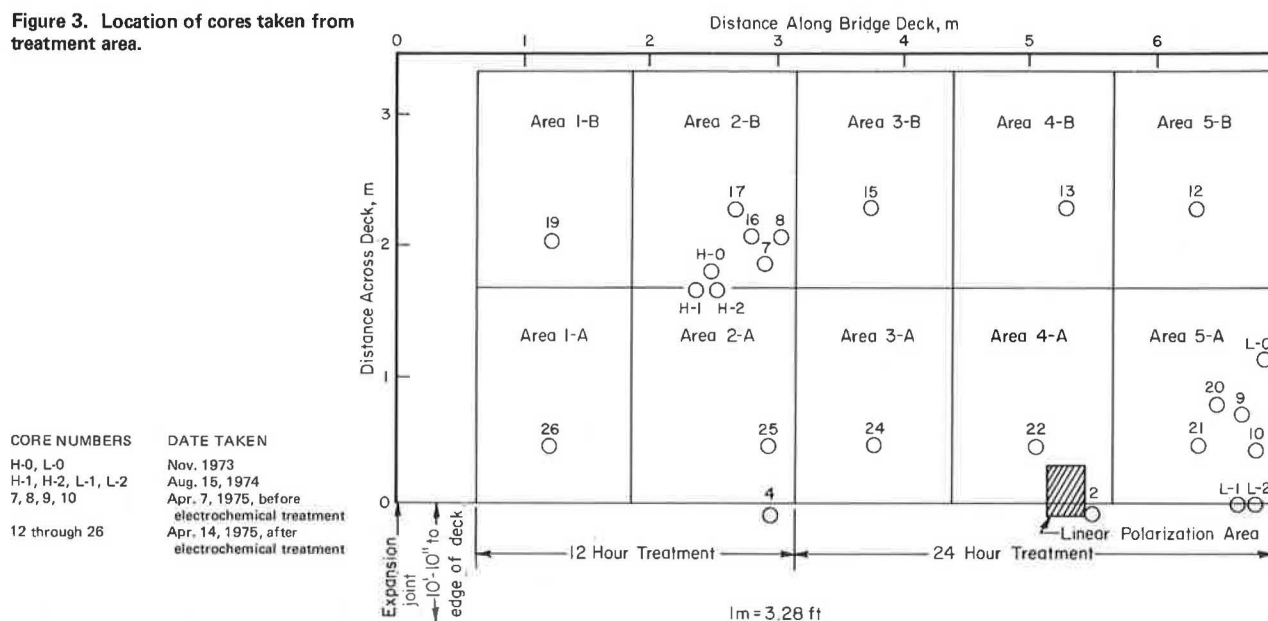


Table 1. Average chloride content of cores taken from bridge deck from November 1973 to April 1975 (before electrochemical treatment).

Deck Depth (mm)	Chloride Ion Content ^a					
	Cores Taken on November 1973		Cores Taken on August 1974		Cores Taken on April 7, 1975	
	Percent	Kilograms per Cubic Meter	Percent	Kilograms per Cubic Meter	Percent	Kilograms per Cubic Meter
0 to 25	0.31	6.9	0.40	8.9	0.41	9.2
25 to 51	0.16	3.6	0.23	5.2	0.20	4.5
51 to 76	0.05	1.1	0.06	1.4	0.06	1.4
76 to 102	0.01	0.2	0.01	0.2	0.01	0.2
102 to 127	0.01	0.2	0.01	0.2	—	—

Note: 1 mm = 0.039 in; 1 kg/m³ = 1.69 lb/yd³.

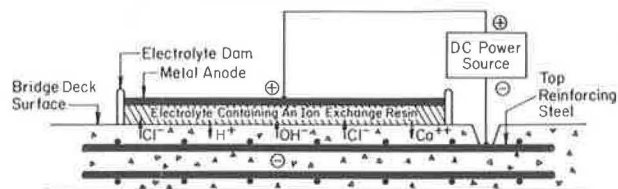
^aBased on dry concrete weight of 2242 kg/m³ (140 lb/ft³).

Figure 4. Chloride extraction hardware in position on bridge deck.



Each of the five treatment areas (Figure 3) was served by 2 dc generators, one generator supplying power to a 1.7-m² (20-ft²) area. In all cases, effort was made to maintain generator output at the maximum rated capacity of 120 V. In practice the voltage generally fluctuated between 100 and 120 V. Areas 1 and 2 were treated for 12 h, and areas 3, 4, and 5 were treated for 24 h.

Figure 5. Experimental technique used for electrochemical removal of chloride ions from a PCC bridge deck.



The ion exchange resin was omitted in the treatment of area 4. This resulted in a noticeable odor of free chlorine above the electrolyte ponds during the treatment period.

The temperature of the electrolyte ponds was measured during treatment periods with a thermometer. In addition, temperature of the concrete deck was measured by use of thermocouples inserted into small holes drilled into the concrete. Pavement temperature was monitored just above a rebar and about 3.8 cm (1½ in) below the concrete surface, midway between rebars. Two-person crews provided full-time monitoring of the experiments throughout the treatment period. Data were obtained on applied current and voltage and on slab and electrolyte temperature, as a function of treatment time.

After the electrochemical treatment, the electrolyte-resin solution was pumped off, and 7.6-cm (3-in) core samples taken from the treated area. The resin was returned to the laboratory for regeneration.

Table 2. Average chloride ion content of bridge deck before and after electrochemical treatment.

Deck Depth (mm)	Before Treatment		After Treatment				Average Cl ⁻ Removed (%)	
			12-H		24-H			
	Percent	Kilograms per Cubic Meter	Percent	Kilograms per Cubic Meter	Percent	Kilograms per Cubic Meter	12 H	24 H
0 to 25	0.409	9.2	0.295	6.6	0.194	4.3	28	53
25 to 51	0.201	4.5	0.093	2.1	0.059	1.3	54	71
51 to 76	0.054	1.2	0.029	0.7	0.019	0.4	46	67
76 to 102	0.013	0.3	0.012	0.2	0.012	0.2	Nil	Nil

Note: 1 mm = 0.039 in; 1 kg/m³ = 1.69 lb/yd³.

Table 3. Amount of chloride removed from bridge deck.

Deck Depth (mm)	Treatment Area	Duration of Treatment (h)	Maximum Current (A)	Charge Passed ^a	Chloride Removed (%)
0 to 25	1A	12	47	54	44
	1B	12	45	56	36
	2A	12	100	100	29
	2B	12	50	54	15
	3A	24	96	70	89
	3B	24	87	70	91
	4A	24	35	—	19
	4B	24	28	26	24
	5A	24	53	45	62
	5B	24	30	13	21
25 to 51	1A	12	47	54	68
	1B	12	45	56	69
	2A	12	100	100	66
	2B	12	50	54	32
	3A	24	96	70	93
	3B	24	87	70	90
	4A	24	35	—	51
	4B	24	28	26	51
	5A	24	53	45	75
	5B	24	30	13	58

Note: 1 mm = 0.039 in.

^aCalculated as the area under the current/time curve divided by treatment time. 2A arbitrarily assigned value of 100.

No major problems were experienced during the experiment. A careful posttreatment visual examination revealed that no cracks in the concrete occurred as a result of the treatment.

Posttreatment Measurements

The results of the electrochemical treatment were monitored through posttreatment measurements of chloride content, electrochemical potential measurements, and linear polarization (LP) electrode measurements.

Chloride Analyses

Posttreatment cores 7.6 cm (3 in) in diameter were taken from the treated areas (Figure 3). These were cores 12, 13, 15, 16, 17, 19, 20, 21, 22, 24, 25, and 26. Cores 16 and 20 were taken 12.7 cm (5 in) deep. All other cores were taken only to the level of the top reinforcing steel (about 50 mm or 2 in). Most of the cores were then sectioned into 25-mm-thick (1-in) slices although cores 15, 16, and 17 were sectioned in 12-mm ($\frac{1}{2}$ -in) slices to permit a better discrimination of the chloride concentration profile.

In several cases, the concrete immediately adjacent to the reinforcing rod (about 6 mm or $\frac{1}{4}$ in in radius) was analyzed separately.

Table 2 gives a summary of chloride analyses before and after treatment. Although there was some variation in measured chloride from specimen to specimen, a reasonable assessment of effect of treatment param-

eters on chloride removal could be made.

Deck Depth of 0 to 25 mm (0 to 1 In)

The average pretreatment chloride ion content in the top 25 mm of the treated area of the deck was 0.409 percent (9.2 kg/m³ or 15.5 lb/yd³) as measured on cores 7, 8, 9, and 10. For an initial chloride content of 0.409 percent, the reduction in chloride as affected by the treatments is given in Table 3 for the various treatment areas. The average chloride removed in the top 25 mm (1 in) was 31 percent in 12 h and 51 percent in 24 h.

A general correlation existed between maximum current and charge passed and the amount of chloride removed. Certain treatment areas did not conform to this generalization (areas 2A and 2B).

Deck Depth of 25 to 51 mm (1 to 2 In)

The average chloride ion content at a deck depth of 25 to 51 mm (1 to 2 in) in the treated area was 0.201 percent (4.5 kg/m³ or 7.6 lb/yd³) as measured in cores 7 and 9. For a pretreatment value of 0.201 percent, the reduction in chloride in the 25 to 51-mm concrete level as affected by the treatment is also given in Table 3.

As for the first 25 mm, there was a general correlation between maximum current and charge passed and the amount of chloride removed. The average chloride removed at a depth of 25 to 51 mm (1 to 2 in) was 59 percent in 12 h and 70 percent in 24 h. A comparison of the data for the two depths shows that a significantly greater percentage of chloride was removed at the 25 to 51-mm level than at the 0 to 25-mm level.

Concrete Adjacent to Reinforcing Steel

Chloride analyses were run on the concrete enclosing the reinforcing steel (about 6 mm or $\frac{1}{4}$ in in radius) both before and after treatment. The pretreatment data were obtained from cores 2 and 4 taken from the berm section. The posttreatment data were obtained on the remnants of cores 26 (area 1A), 25 (area 2A), 22 (area 4A), and 21 (area 5A). These results are given in Table 4. For the cores analyzed, the average reduction in chloride content in the concrete immediately adjacent to the reinforcing steel was 79 percent. Significantly, the posttreatment cores were from some areas that did not show exceptionally high chloride extraction at the 0 to 25 and 25 to 51-mm (0 to 1 and 1 to 2-in) levels (Table 3).

Potential Scans

Potential scans were taken on the deck 24 h after the final section was treated and then 1 week, 1 month, and 3 months after treatment. The potential scan after 24 h (Figure 6) shows the effects of treatment on the potential. The Roman numerals show chronological order of treatment. The first section treated (5 days before the

scan) exhibits passive potentials. This is in direct contrast to the active values shown by this section before treatment. The second section treated shows a range of potentials from extremely active to moderately passive. This indicates that the extreme cathodic polarization applied to the steel during treatments can take days to decay. Sections III and IV show similar effects. The last section treated, section V, shows potentials well within the cathodic protection range (more active than -0.85 V) for steel.

The scan obtained 1 week after treatment is shown

in Figure 7. The obvious difference is the decay of the cathodic polarization in sections II, IV, and V and the maintenance of passive potentials in these areas. The exception to this is the band of polarization along the midsection of treatment sections II and IV.

The results from the 1-month scan are shown in Figure 8. At this time, the vast majority of the deck exhibited a potential well within the passive range: No readings on the treated surface were more active than -0.30 V. The most passive potentials were exhibited by steel in treatment sections II and V.

Table 4. Chloride content of bridge deck concrete at rebar interface before and after electrochemical treatment.

Treatment Area	Before Treatment		12-H Treatment		24-H Treatment	
	Percent	Kilograms per Cubic Meter	Percent	Kilograms per Cubic Meter	Percent	Kilograms per Cubic Meter
Berm	0.091	2.0	—	—	—	—
Berm	0.058	1.3	—	—	—	—
1A	—	—	0.013	0.3	—	—
2A	—	—	0.012	0.2	—	—
4A	—	—	—	—	0.018	0.4
5A	—	—	—	—	0.021	0.5
Average	0.075	1.7	0.013	0.3	0.020	0.5

Note: Sample about 6-mm-thick (¼-in) concrete surrounding upper half of rebar. $1 \text{ kg/m}^3 = 1.69 \text{ lb/yd}^3$.

Figure 6. Potential scan of treatment area 24 h after final treatment.

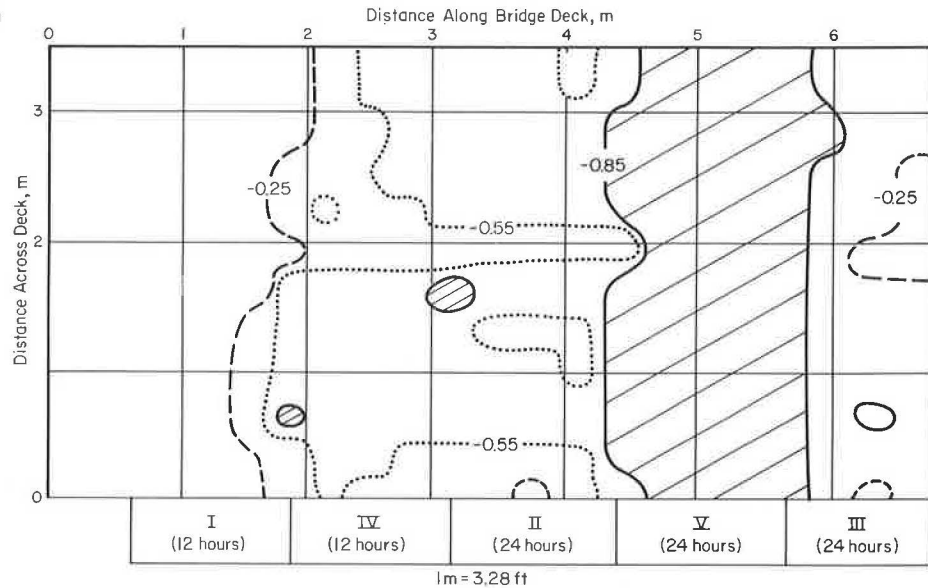


Figure 7. Potential scan of bridge deck 1 week after final treatment.

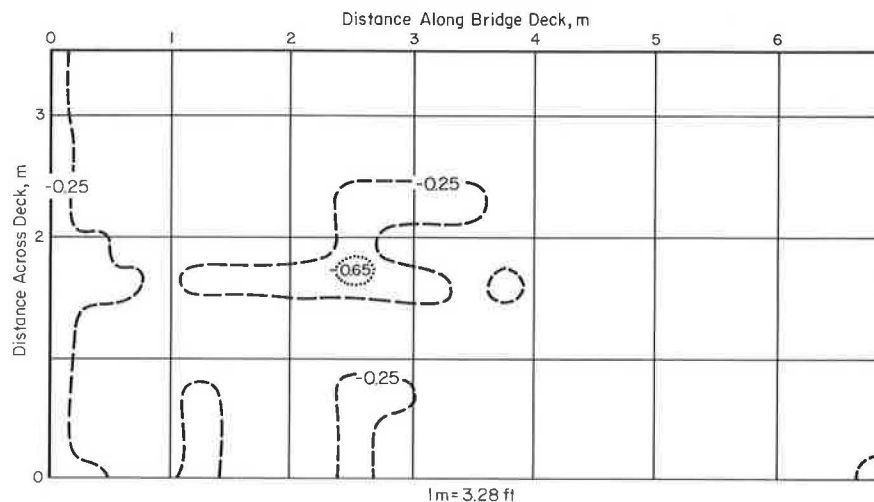


Figure 8. Potential scan of bridge deck 1 month after treatment.

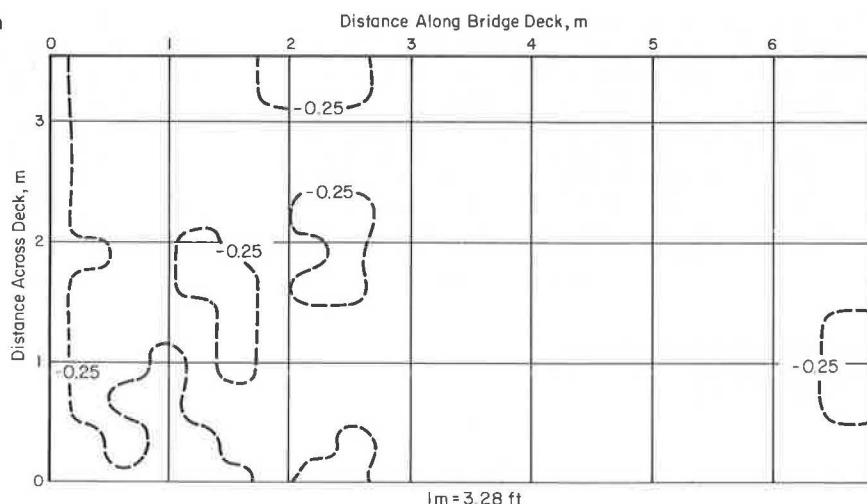
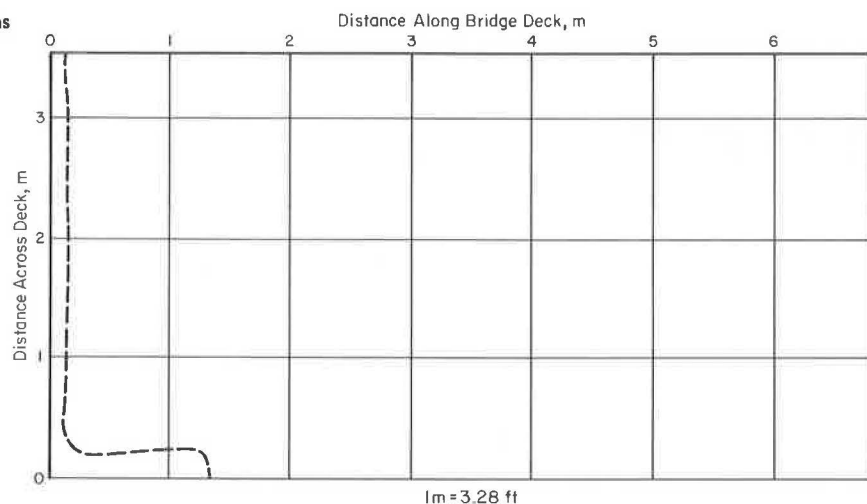


Figure 9. Potential scan of bridge deck 3 months after treatment.



The 3-month scan (Figure 9) shows that potentials of the treated area were within the passive range. A check of potentials outside the area, however, revealed that active corrosion of the steel was continuing in such areas, possibly enhanced by the large adjacent passive area generated by the electrochemical treatment.

Linear Polarization Readings

Corrosion rates of the reinforcing steel as deduced from LP electrodes were measured prior to treatment and 1 week, 1 month, and 3 months after treatment. The results were as follows:

Date	Corrosion Rate (m/year)	Date	Corrosion Rate (m/year)
April 7	0.5	May 23	0.6
	0.5		0.5
April 21	1.1	July 15	0.4
	0.8		0.3

Thus, 1 week after treatment, the linear polarization electrodes were showing a corrosion rate almost twice as high as before treatment. However, 1 month after treatment, the corrosion rate had dropped to that observed before treatment.

The reasons for this unexpected behavior may be the

destruction of the passive oxide film on the rebar by the cathodic treatment and its subsequent growth after treatment.

DISCUSSION OF RESULTS

The principle of using electromigration methods to extract chloride ion from salt-containing reinforced concrete has been shown effective in laboratory experiments and on a bridge deck in the field. For the concrete situated vertically above the reinforcing steel, an average of 31 percent of the chloride was removed after 12 h and 51 percent after 24 h of treatment. For concrete at the 25 to 51-mm (1 to 2-in) level, these values were 59 percent and 71 percent. Peak extraction values of more than 90 percent were obtained.

Because the chloride content of the concrete immediately adjacent to the reinforcing steel is the determining factor in initiation and continuation of corrosion, the reduction in chloride level at this location to below 0.02 percent is extremely significant. The literature suggests that this is close to or below the lower limit for initiation of corrosion (3, 4). The potential scan before the treatment showed that more than 55 percent of the treatment area rebar was actively corroding. Posttreatment scans (up to 3 months after treatment) showed that all active corrosion had ceased, and the rebar exhibited passive

potentials. Linear polarization results also support this conclusion. The combination of cathodic polarization of the rebar and chloride removal probably led to this effect. Cathodic polarization effectively stopped corrosion during treatment, and the level of chloride after treatment was insufficient to reinitiate the corrosion.

The long-term effect of the extraction procedure on rebar corrosion is not yet known. After treatment of a full-size bridge deck, the concrete surface would be waterproofed to ensure that further application of de-icing salt would not cause chloride penetration. (This was not practicable in the field experiment described here.) However, because not all the chloride is removed, there may be a tendency for chloride redistribution by diffusion under concentration gradients. The effect of this process on long-term initiation of rebar corrosion is unclear at this time.

The hardware used in the field experiment is probably not wholly suited for scale-up to treatment of a full-size deck, particularly if that deck shows sharp transverse or longitudinal gradients. Further development of surface electrolyte containment procedures is necessary to optimize the technique.

CONCLUSIONS

1. The extraction of chloride ions from salt-contaminated concrete by electromigration techniques has been shown to be feasible.
2. Optimum applied voltages, treatment times, surface electrolyte, and anode material were determined from laboratory investigations.
3. Treatment of a 3 by 12.2-m (10 by 40-ft) section of a bridge deck removed up to 90 percent of the chloride present in the concrete above the top reinforcing steel.
4. Pretreatment and posttreatment potential scans showed that all active corrosion of the reinforcing steel in the treatment area was halted after chloride extraction.

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Discussion

T. R. Cantor, Port Authority of New York and New Jersey

Conceding that the corrosion of rebars could be arrested by the method described, the paper states that the porosity of the deck will be increased. This porosity will cause the deterioration of the deck-rebar system, and therefore the whole procedure would appear not to be useful. In addition, some of the data and methodology are open to question and could result in misleading conclusions.

DECK DETERIORATION

A reinforced concrete bridge deck functions because the concrete on top carries the load in compression (its strongest mode) and the reinforcing bars carry the tension load (weakest mode). If the function of the upper concrete is lost, there could be no great incentive to preserving the lower tensile steel, which, as I understand it, is the thrust of the paper under consideration.

When the concrete above the rebars is originally properly placed and cured, it is relatively impermeable. In the natural course of events, the concrete becomes more porous for a variety of reasons, among which are loading, temperature stresses, vibration, and freezing and thawing. With time, the pores, fissures, capillaries, crevices, and cracks open and enlarge. These openings collect debris such as dirt and chemicals. Chlorides can certainly be detected among the accumulations. In any case, a damp porous pavement that contains chemicals has all the elements required for the classic electrolytic cell so it is quite reasonable to expect that chloride ions could be encouraged to migrate under the urging of a 100-V potential and so be expelled from the deck.

REBAR CORROSION

For steel to corrode, moisture and oxygen are essential. All other chemicals can only influence the reaction (conversion of iron to iron oxide) by acting as a catalyst in one way or another. Even with all essential materials present, steel will not corrode under specific inhibiting conditions. Because chloride is not a corrosion product, it must in some manner act as a catalyst or improve the conductivity or encourage the formation of local anodes, which means that only traces are required to promote the reaction.

Given the relatively slow corrosion rate of steel in concrete, just small quantities of chloride should be more than adequate to encourage corrosion. The paper states that, at best, only 90 percent of the chloride is removed, which still theoretically leaves ample chloride to promote corrosion.

The authors claim that the steel was apparently reduced to a passive state at least for a limited time on the basis of half-cell potentials. Questions can be raised on the subject of passivity. For example, where did the calcium, sodium, and hydrogen released at the rebar go? Another consideration is that, inasmuch as nothing has been done to perpetuate the passive condition, it seems safe to assume that, in a few months to half a year, the

corrosion would become active again.

POTENTIAL MEASUREMENTS

From theoretical considerations and experience, half-cell potential measurements can only be made where the concrete has some degree of porosity, which then suggests that some degree of deterioration is present or that the concrete is not of the very best impervious quality. Therefore, if half-cell potentials can be measured at all, whether or not corrosion is taking place, the concrete must be porous and susceptible to further increasing porosity and damage.

The paper indicates that the concrete was more porous after the electrical treatment. This is significant since the molecular volume of chloride is larger than the molecular volume of either oxygen or water. Obviously, if chloride can come out, there are sufficiently large channels for oxygen and water to enter the concrete. The presence of water and oxygen should start or continue the corrosion of the rebar after a relatively short time, which suggests that we would be right back where we started.

SEALING

The paper recognizes the increasing porosity problem and suggests that a procedure for overcoming it could be the application of a deck sealant. Sealing of decks is always a good procedure, but, because corrosion can only proceed in the presence of oxygen and water, if the deck is to be sealed why bother to remove the chlorides?

SALT DATA

The methodology used and the data reported seem inadequate to the situation. Unless the data in Tables 1 and 2 are being misinterpreted or the samples are not comparable because of their distance from each other (we have found appreciable differences in chloride content a few inches apart), it is difficult to understand the higher chloride content in August 1974 than November 1973 and no appreciable increase over August in April 1975. Additionally, if the cores were not sliced dry, considerable chloride could be washed from the sample if water was used during slicing.

My own work indicates that, from the end of one salting season in April to the next salting season in October, up to 75 percent of the salt was washed out of the deck at all depths by normal spring and summer rains. A washing procedure might have been used to reduce the chloride before potential application.

SAMPLE PREPARATION

It seems that the sample preparation was inadequate even though the undesirable laboratory procedure of introducing salt did not affect the field results. Nevertheless, it is difficult to understand the deliberate use of saltwater in the preparation of concrete specimens since the samples cast certainly are not normal concrete.

If the object were to load hardened concrete with salt, that could have been easily accomplished by infusing salt solution under vacuum into the specimen, drying, and repeating as often as desired. By this technique, we have achieved salt loadings of more than 120 kg/m³ (200 lb/yd³).

SUMMARY

The need to salvage the many deteriorating bridge decks is generally accepted, but there is small chance

of success if the problem of deterioration is not well understood. The method suggested could do more harm than good because the deck becomes more porous and hence more vulnerable to deterioration. If sealing is then required, why bother with the whole procedure, since sealing itself cuts off the source of oxygen and moisture, without which corrosion cannot occur? The duration of any passivity achieved may be relatively short, so again the question of the benefit of the procedure has to be raised. Further doubts are raised by the salt data and the questionable practice of preparing specimens with saltwater. Finally, for repairs to be effective the bridge deck should be returned to its original design concept with good concrete working in compression over rebars working in tension.

Authors' Closure

The research described in our paper was undertaken on the basis of the widely held premise that the primary cause of concrete bridge deck spalling is the chloride-induced corrosion of the top level of reinforcing steel in the deck. It was therefore assumed that the removal or immobilization of the chloride ions in the concrete could halt or reduce corrosion of the reinforcing steel. Inasmuch as Cantor does not concur with the original premise, his criticism of the chloride removal concept is understandable.

DECK DETERIORATION

Cantor has interpreted the thrust of the paper to be one of "preserving the lower tensile steel" in a concrete bridge deck. From the viewpoint of preservation, our interest lies in preserving the concrete above the top level of reinforcing steel; this concrete is destroyed as a result of chloride-induced corrosion of the top level of reinforcing steel.

Cantor states that, in the natural course of events, concrete becomes more porous because of loading, temperature stresses, vibrations, and freezing and thawing. It is generally understood that properly cured concrete becomes less porous with age as cement hydration progresses. The factors he mentions have no effect on concrete porosity per se; they can cause gross cracking of the concrete deck, but these cracks are not essential for the migration of chloride ion into the concrete.

REBAR CORROSION

We do not believe that the mechanism of aqueous corrosion of steel outlined by Cantor is correct. The pH of the solution in which the steel is exposed has a dominant role in defining the nature and extent of corrosion. For example, in dilute sulfuric acid, steel corrodes rapidly, whereas even in the presence of air steel is resistant to corrosion in alkaline solution with pH > 12. This latter situation in fact obtains in chloride-free concrete; in such an environment, the steel forms a thin oxide film on its surface that protects it from further corrosion. The steel is said to be in the passive condition. The action of chloride apparently is to destroy the protective qualities of this film, and rapid corrosion can then ensue. The manner in which the chloride breaks down the film is as yet uncertain; the breakdown occurs initially at discrete points on the steel surface, which spread laterally; these are the anodes to which Cantor refers. The concentration of chloride necessary to cause film

breakdown is known to increase as the pH increases; more than trace quantities of chloride are necessary to cause the film breakdown process at the pH of moist concrete (12.5).

In the reported work on the bridge deck, the best removal achieved was a 90 percent reduction in the total chloride contained in the top 52 mm (2 in) of concrete. Cantor is concerned that this situation "theoretically leaves ample chloride present to promote corrosion." What is important here is the distribution of this residual chloride, inasmuch as any chloride at the rebar surface can induce (or reinduce) corrosion. We showed that chloride ion removal was always greatest from the concrete immediately adjacent to the reinforcing steel. Chloride concentrations at this level were obviously reduced by treatment to values below which corrosion would continue or reinitiate within a 3-month time interval (from the potential measurements). The crucial factor here is possible time-dependent redistribution of residual chloride after treatment, which may lead to renewed corrosion. This possibility is the focus of current research.

Cantor acknowledges that the removal treatment apparently reduced the steel to a passive state but is concerned that "inasmuch as nothing has been done to perpetuate the passive condition . . . , in a few months to half a year, the corrosion would become active again." As we discussed in the paper, we recognized from the outset that, once the chloride ion was removed by the electrochemical treatment, it would be necessary to seal the concrete (e.g., membranes or polymer impregnation) to prevent subsequent ingress of new chloride as a result of further applications of deicing salt. The possibility of residual chloride redistribution has already been discussed.

POTENTIAL MEASUREMENTS

With regard to measurement of half-cell potential, we agree strongly that such measurements can only be made when the concrete is an electrolytic conductor. However, concrete in normal service is a conductor. It only ceases to be a conductor when all free moisture has been removed. Cantor believes that half-cell measurements can only be made where the concrete has some degree of porosity. He further says that the presence of this porosity suggests that some degree of concrete deterioration is present. We must assume that the deterioration to which Cantor refers is gross cracking of the concrete, because all concrete has a measurable porosity. The ability to measure half-cell potentials in our opinion in no way confirms that the concrete is of poor quality or is deteriorating, as Cantor suggests. Cantor states that the paper "indicates that the concrete was more porous after the electrical treatment." This conclusion is not stated in the paper, for we made no measurements of concrete porosity either before or after treatment. Some oral discussion on possible porosity problems occurred after presentation, when unpublished Kansas data were discussed that indicated an increase in the porosity of concrete after electrochemical treatment.

SEALING

Cantor states that "sealing of decks is always a good procedure, but, because corrosion can only proceed in the presence of oxygen and water, if the deck is to be sealed why bother to remove the chlorides?" The bulk of opinion at this time indicates that the sealing of existing salt-contaminated decks is not always good practice. This is related to the presence of moisture in the

deck and the diffusion of oxygen from the lower surface of the deck. Thus, oxygen and moisture are not excluded by the sealing process and corrosion will continue in the presence of chloride.

The Federal Highway Administration in fact has recommended that membranes not be placed on a deck if the chloride content is higher than 0.89 kg/m^3 (1.5 lb/yd^3) at the rebar level.

SALT DATA

Cantor's remarks concerning our methodology of measurement of chloride in the concrete are (a) the nonuniform distribution of chloride in field concrete and (b) the wet coring method which, it is claimed, could wash considerable chloride from the sample. First, we stated that we took into account the large specimen-to-specimen variation in measured chloride content. Second, the amount of chloride washed from a concrete core during the 5-min coring process is negligible.

Cantor's statement that 75 percent of salt is washed out from bridge decks by normal spring and summer rains is surprising. So far as we know, this phenomenon has never been reported in the literature by other workers. In fact, work on flushing techniques on chloride-contaminated concrete at Battelle, not reported in this paper, led to the conclusion that the technique was ineffective in removing the chloride.

SAMPLE PREPARATION

The practice of adding chloride ions to the laboratory concrete samples was an expedient to provide chloride ions in the free water phase of concrete. Drying and vacuum impregnation of the large slab specimens used in the program were not a possibility.

The similarities in results from the electrochemical removal treatments in the laboratory and field lead us to conclude that this expedient did not compromise our experimental approach.

SUMMARY

The concluding statements made by Cantor reaffirm that his interpretation of the causes of concrete bridge deck spalling is quite different from the more usually held view. Thus, he questions the need for and the possible problems attendant on prevention of the deck spalling problem based on electrochemical removal of chloride ion.

Our work was undertaken on the assumption that chloride in concrete decks is undesirable and leads to corrosion of the reinforcing steel and that the condition of the deck can be stabilized or improved by removing the chloride and by then taking steps to prevent subsequent ingress of further chloride. The objective of the research, to develop a technique for removing chloride ions from concrete bridge decks, was met. This is the necessary first step in evaluating the utility of this unique approach for preventing bridge deck spalling. As we state in the paper, however, the overall technical and economic viability of this approach remains to be demonstrated.