

# Extended Corrosion Performance of Impregnation-Treated Concrete Bridge Deck

M. C. Brown, R. E. Weyers, N. S. Berke, R. M. Weyers, and M. M. Sprinkel

A field implementation trial using the grooved deep impregnation technique with calcium nitrite as the impregnate was conducted under SHRP C-103 in July 1990. Presented are the results of the corrosion assessment surveys before treatment and at various intervals over a 9-year period. Corrosion assessment surveys included concrete cover depth, chloride content, corrosion potentials and rates, and calcium nitrite content. The results of the corrosion surveys support the conclusion that the deep impregnation with calcium nitrite has arrested active corrosion cells and has protected the bridge deck section from continued corrosion damage over the 9-year assessment period.

**T**he extent of chloride ion-induced corrosion damage of steel-reinforced concrete bridge decks, superstructures, and substructures in the United States is well known. Present repair methods for concrete bridge elements consist of removing a limited amount of the concrete encompassing spalled and delaminated areas to a depth of 19 mm below the reinforcing steel, cleaning the exposed reinforcing steel, and backfilling the excavated areas with a concrete patch material. Sound but critically chloride contaminated concrete is left in place and subse-

quent spalling of the cover concrete occurs. In addition, the complete removal from exposed steel bars of chloride-bearing corrosion products is difficult, especially on the backside or underside of the reinforcing steel. Corrosion continues in these areas, but at a reduced rate, and limits the service life of the repaired areas.

An example is bridge decks in the United States. Typical repair techniques consist of scarifying the top (6 mm), patching damaged areas (spalls and delaminations), and overlaying with a low-permeable concrete. These decks have a limited service life of 22 to 26 years, regardless of the chloride exposure category—low to severe (1, 2). The cause of the limited service life is the amount of critically chloride contaminated concrete left in place, which is relatively constant because repair is based on the amount of surface damage.

## BACKGROUND

Task 2 of the SHRP research contract C-103 (2) was a feasibility study of new rehabilitation techniques. The study would treat the cause of the damage rather than treat the symptoms, as typical repair techniques do. Task 5 of SHRP C-103 would field validate the construction procedures of the newly developed rehabilitation methods with the intent of monitoring the performance of the field applications for 10 years after construction.

A possible rehabilitation method is to remove all the chloride ion-induced corrosion-damaged concrete and the sound critically chloride contaminated concrete and then replace the concrete with a low-permeable con-

M. C. Brown, R. E. Weyers, and R. M. Weyers, Charles E. Via Department of Civil and Environmental Engineering, 200 Patton Hall, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061-0105. N. S. Berke, W. R. Grace & Company, 62 Whittemore Avenue, Cambridge, MA 02140. M. M. Sprinkel, Virginia Transportation Research Council, 530 Edgemont Road, Charlottesville, VA 22903.

crete that contains a corrosion-inhibiting admixture. The removal of the cover concrete by mechanized mechanical means is relatively inexpensive (3). However, removing the matrix concrete between the reinforcing steel and 19 mm below the reinforcing bars is relatively expensive, even when mechanized hydrodemolition is used (3).

For bridge decks, an alternative is to remove the highly chloride-contaminated cover concrete; patch the damage areas by removing the damaged concrete, cleaning the exposed bar, spraying the exposed bar with a corrosion inhibitor, and backfilling the cavity with a patch concrete containing a corrosion inhibitor; and overlay with a low-permeable concrete containing a corrosion inhibitor. The supposition is that the corrosion inhibitor will diffuse to the depth of the bar and inhibit any active corrosion before the cracking of the remaining concrete and inhibit corrosion from the chlorides diffusing through the low-permeable overlay concrete. For super- and substructure elements, the damaged and critically chloride contaminated concrete adjacent to the damage area would be removed to a depth of 19 mm below the reinforcing steel, the bar would be cleaned and sprayed with a corrosion inhibitor, and the cavity would be backfilled with a concrete containing a corrosion inhibitor.

For bridge decks with sound concrete and actively corroding reinforcing, a rehabilitation method may be deep impregnation with a corrosion inhibitor using the grooving technique. The deep grooving impregnation technique consists of cutting parallel grooves about 19 mm wide and 38 mm deep and spaced 76 mm on center. The grooves reduce the impregnation time and are used as vessels for the liquid inhibitor. The concrete is dried to a depth of 13 mm below the top reinforcing steel layer by using propane-fired infrared heaters. The concrete is considered dry when the temperature of the concrete reaches 82°C at the impregnation depth. The concrete is allowed to cool slowly to ambient temperature under an insulating mat. The grooves are filled with the liquid corrosion inhibitor and allowed to soak into the concrete. The grooves are then backfilled with a latex modified mortar containing a corrosion inhibitor.

Thirty-one inhibitors were evaluated by using a rapid screening test (4). On the basis of the results, seven inhibitors were selected for phase 2, soak impregnation through a 51-mm-wide groove over two corroding reinforcing bars in concrete laboratory specimens. If applicable, the mortar used to backfill the grooves contained a corrosion inhibitor. Of the seven inhibitor systems, the use of calcium nitrite, by ponding and addition to repair mortar, showed the greatest effectiveness. Zinc borate or sodium tetraborate ranked second (4). Two other inhibitor systems that appeared effective were amine salts in water as the ponding inhibitor and alkanolamine in the mortar, and an oxygenated hydrocarbon as a ponding inhibitor treatment only (4). Subsequent strength testing of the admixture corrosion inhibitors showed that the zinc borate severely

retarded the set and strength gain of portland cement (4). Thus, the borate inhibitor concentration as an admixture had to be limited.

The following four posttreatment inhibitors were further tested on concrete specimens, which were corroding at various rates (5). Treatments consisted of removing the cover concrete to 6 mm of the top of the reinforcing bar, ponding the inhibitor for 1 or 2 days, or drying the concrete to a depth of 51 mm below the top bar and ponding the inhibitor for 1 day. The specimens were then overlaid with the appropriate admixed corrosion inhibitor concrete, where applicable (5). The four posttreatments were as follows:

- Oxygenated hydrocarbon as a ponding posttreatment corrosion inhibitor and overlaid with a low permeable concrete,
- Amine salts in water as the ponding inhibitor and an alkanolamine as the concrete admixture for patch and overlay materials,
- Calcium nitrite in water as both the ponding inhibitor and the admixture corrosion inhibitor, and
- Sodium tetraborate in water as the ponding inhibitor and admixture corrosion inhibitor.

The results showed that the oxygenated hydrocarbon is a very effective posttreatment corrosion inhibitor. The amino salts and alkanolamines and the calcium nitrite and calcium nitrite systems were effective posttreatment corrosion inhibitors (5). However, the sodium tetraborate-sodium tetraborate system was not an effective posttreatment system and thus was excluded from further test regimens. In addition, the amine salts and oxygenated hydrocarbon severely affected the bond between the overlay and substrate concretes. Further testing showed the bond could be improved by grit blasting the treated surface before placing the overlay concrete.

The ponding method for posttreatment applications of corrosion inhibitors is not very practical as a field application method. Further work concentrated on developing multiple inhibitor spray-on applications (5). The systems evaluated on slabs taken from a bridge were the oxygenated hydrocarbon, amine salts-alkanolamines, and the calcium nitrite-calcium nitrite posttreatments. The purpose of this further testing was to develop the field validation construction procedures (5).

The cover concrete of three bridge deck slabs that were removed from a Pennsylvania bridge deck was milled off with a commercial milling machine to within the depth of the top mat of reinforcing steel. Three equal spray-on applications of the posttreatment inhibitor were applied at the following rates: oxygenated hydrocarbon, 1.67 L/m<sup>2</sup>; amine salts, 5.36 L/m<sup>2</sup>; and calcium nitrite, 3.57 L/m<sup>2</sup>. The slabs were then overlaid with an admixed corrosion inhibitor concrete, where applicable. On the basis of these trials, the field validation construction procedures were developed (2).

The following five posttreatment field validations were conducted (6):

- Minnesota—bridge deck posttreatment of SR-TH3 over Southview Boulevard, St. Paul;
- Washington—substructure posttreatment of Route 104 over the Hood Canal, Port Gamble;
- New York—substructure posttreatment of Elmwood Avenue over WA-198, Buffalo;
- Pennsylvania—substructure posttreatment of Route 2042 over I-81, Wilkes-Barre; and
- Virginia—deep impregnation of a bridge deck with a corrosion inhibitor (calcium nitrite), US-460 over VA-723, Christiansburg.

Because questions remained about the adequacy of the bond between the substrate and the overlay or patch concrete for the spray-on posttreatment amine salts and oxygenated hydrocarbon inhibitors, field trials of the complete posttreatment systems were not performed. The oxygenated hydrocarbon system was not field validated, and the spray-on amine salts inhibitor was not used for the amine salts-alkanolamine system. The alkanolamine admixture inhibitor was used in substructure patch concrete and in overlay concrete (6).

A previous paper presented the field validation corrosion testing results for the complete posttreatment calcium

nitrite spray-on inhibitor-calcium nitrite admixture inhibitor system for the Pennsylvania substructure and the Minnesota bridge deck (7). The conclusions were based on data after 2 years for the substructure and 2.5 years for the bridge deck. The effectiveness of the calcium nitrite posttreatment system could not be determined at that time; longer assessment periods are needed to determine the effectiveness of the corrosion inhibition posttreatment system. Also, it was shown that the corrosion current density of reinforcing steel in the substrate concrete decreases under low-permeable low-slump dense concrete overlay concrete as the moisture content of the substrate concrete decreases.

This paper presents the corrosion testing of the Virginia deep impregnated bridge deck section with calcium nitrite. Details on the field validation construction process are presented elsewhere (6). Figure 1 presents a plan view of the treated area and sample locations.

## RESULTS

The bridge deck section, a  $2.43 \times 6.1$  m section of the breakdown lane, was impregnated in the summer of 1990. The bridge, built in 1967, was about 23 years old at the time of treatment. Corrosion condition surveys were conducted before treatment and 2 months and 1, 2, 4, 8, and

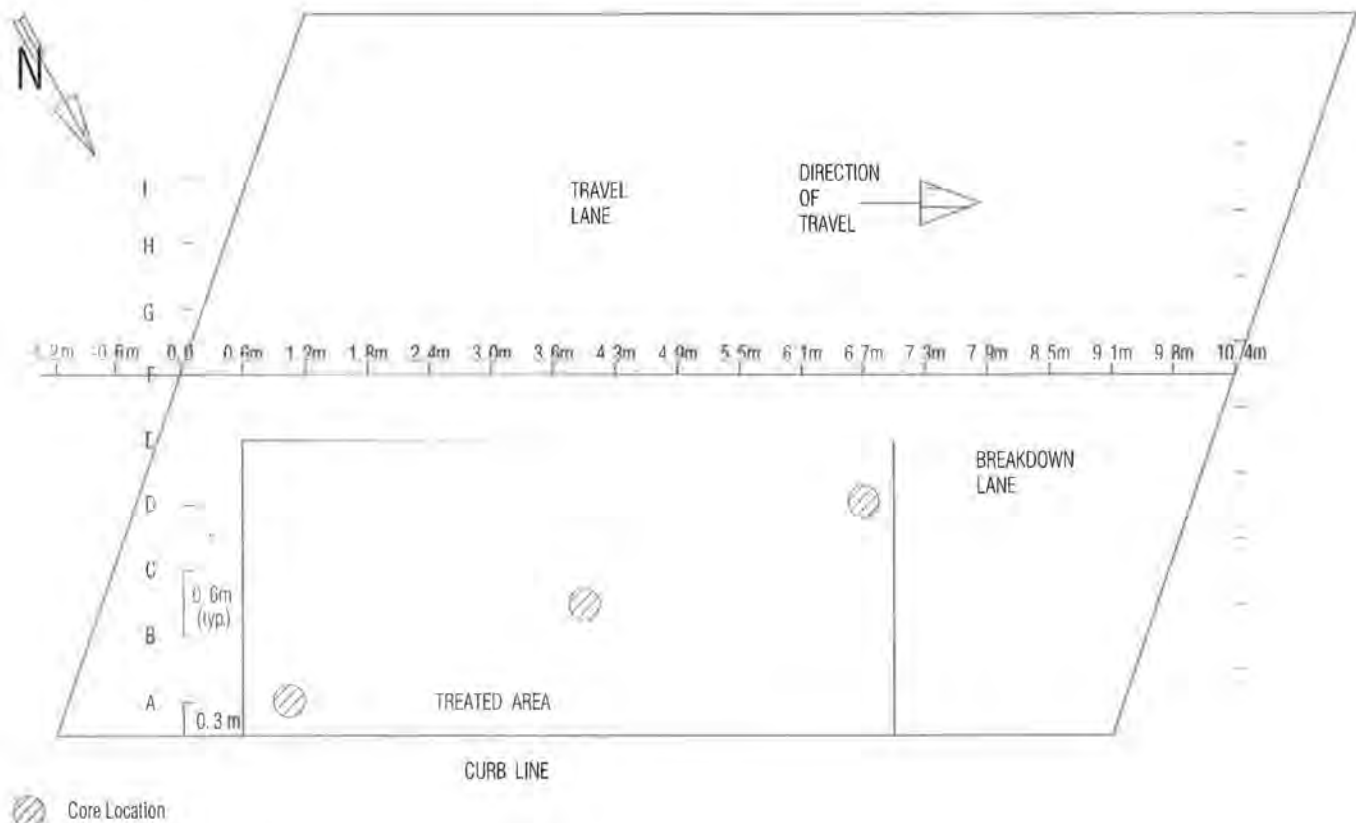


FIGURE 1 Span 1, US-460 over VA-723.

9 years after treatment. The corrosion surveys included chloride content, calcium nitrite content, corrosion potentials and rates, and delamination soundings. Presented here are the pretreatment and the 2-month and 1-, 4-, 8-, and 9-year corrosion survey results.

### Delamination Survey

Table 1 presents the results of the delamination surveys. The surveys were performed by using the chain-drag method and supplemented with a 1.4-kg hammer to delineate the extent of the delaminations.

The three delaminations detected in the treated area were 0.07, 0.15, and 0.35 m<sup>2</sup>. The number and extent of the delaminations have not increased since they were first

detected 1 year after treatment. Thus, the delaminated area has remained stable over an 8-year period.

### Cover Depth and Chloride and Nitrite Content

Forty cover depth readings were taken within the treated area. The readings were taken on a 0.61 × 0.61 m grid by using a pachometer. The average cover depth was 54 mm, the standard deviation was 6.3 mm, and the range was 31 to 62 mm. Of the 40 measurements, only 1 was less than 38 mm and only 3 were greater than 57 mm; 36 measurements were between 38 and 57 mm.

Table 2 presents the acid-soluble chloride contents for the treated area before treatment and at about 2 months and at 8 years after treatment. Two sampling techniques

**TABLE 1 Delamination Survey of Calcium Nitrite-Impregnated Bridge Deck Section**

Survey Date	Age of Treatment, yrs	Number Delaminations	Delaminated Area, m <sup>2</sup>	% Area Delaminated
6/90	Pretreatment	0	0	0
7/91	1	3	0.6	4.0
9/94	4	3	0.6	4.0
6/99	9	3	0.6	4.0

**TABLE 2 Chloride Content of Treated Area Before and After Treatment**

Pretreatment: Sample Date 6/90, drilled powder samples					
Depth, mm	Chloride Content, kg/m <sup>3</sup>				
	A 6.7		B 3.0		
13	2.6		3.1		
25	2.5		2.2		
38	1.6		1.7		
51	1.2		1.1		
64	1.2		0.94		

Posttreatment:

	*Sample Date 9/90 100 mm cores			Sample Date 8/98 100 mm cores					
				A 0.9		B 3.7		D 6.7	
	A 0.9	B 3.7	D 6.7	Mortar	Conc.	Mortar	Conc.	Mortar	Conc.
6	3.6	1.3	2.1	4.9	3.1	5.5	4.6	5.9	4.1
19	2.9	2.2	0.41	5.3	2.8	7.6	4.5	5.5	3.8
32	2.1	0.9	0.23	5.0	1.9	5.6	3.4	4.4	2.5
44	2.5	1.2	0.59		1.9		2.1		1.9
59	1.8	0.88	0.53		1.6		1.5		1.7
70	2.2	0.88	0.47		1.5		0.98		1.5
82	1.5	0.65	0.47		--		1.4		1.3

	Sample Date 8/98 drilled powder samples		
	A 0.9	B 3.7	D 6.7
19	5.2	3.7	3.7
32	4.3	3.5	--
44	2.1	2.0	1.6
59	1.9	1.7	1.5
70	1.9	1.4	1.3

\*9/90 chloride content is a composite value for the concrete and mortar for depths 6 to 32 mm.



were used: powder samples extracted with a 28-mm-diameter drill bit and 100-mm-diameter cores drilled with a water-cooled diamond core bit. Chloride contents presented for the 2-month, 100-mm cores are composed values for the concrete and mortar used to backfill the impregnation grooves. The 8-year values for the 100-mm cores are for the mortar and concrete portions of the cores. The drilled powder samples were taken in the concrete between the impregnation grooves. The impregnation grooves were 19 mm wide, 38 mm deep, and 76 mm on center.

As shown in Table 2, the chloride content within the reinforcing steel depth range was greater than the corrosion threshold concentration of 0.71 kg/m<sup>3</sup> before and at 2 months after treatment, except for sample location D6.7. Eight years after treatment, the chloride contents for both the powder and the core samples exceeded the corrosion threshold concentration for the reinforcing steel depth range of 38 to 57 mm at all locations. It is interesting to note that the chloride contents for the drilled powder and core samples are in general agreement with each other.

Table 3 presents the nitrite contents at about 2 months and at 8 years after treatment and in the same manner as the chloride contents. As shown, there has been a significant decrease in concrete nitrite content for the depth range of 44 to 82 mm. Other depths cannot be compared because the 2-month measurements at depths less than 38 mm are composite mortar-concrete concentrations.

The nitrite-to-chloride ratios for the reinforcing steel depth range 38 to 57 mm ranged from 20 to 1.3 at 2 months after treatment and 3.8 to 0.95 at 8 years after treatment. Thus the nitrite-to-chloride ratios were near or greater than the generally accepted inhibition ratio of 1.0 at 8 years after treatment.

### Corrosion Potential and Rates

Table 4 presents the average corrosion potentials, standard deviation, and coefficient of variation for the four grid lines, A through D, within the treated area. Eleven potential measures, 0.6 m apart, were taken along each grid line. Grid line A is 0.3 m from the curb line and grid lines A, B, C, and D are 0.6 m apart. See Figure 1. Measurements were taken before treatment and about 1, 4, 8, and 9 years after treatment.

Before treatment, grid A potentials, adjacent to the curb line, had a high potential for active corrosion. The probability of active corrosion was very low along grid lines B, C, and D, with the lowest probability of active corrosion along grid line D, the farthest from the curb line. Over the 9-year measurement period, grid line A corrosion potentials became more positive and thus have a lower probability of active corrosion. Grid lines B, C, and D became more negative. Of interest is the observation that the corrosion potentials throughout the treated area became more uniform, as illustrated by the decreasing coefficients of variation.

TABLE 3 Nitrite Contents and Nitrite-Chloride Ratios

Posttreatment: Nitrite contents,  $\ell/m^3$  (30% solution of calcium nitrite)

Depth mm	*Sample Date: 9/90, 100 mm cores			Sample Date: 8/98, 100 mm cores					
				A 0.9		B 3.7		D 6.7	
	A 0.9	B 3.7	D 6.7	Mortar	Conc.	Mortar	Conc.	Mortar	Conc.
6	30	47	36	32	14	57	26	48	16
19	27	44	52	22	10	68	31	51	34
32	31	52	63	17	6.5	57	27	48	23
44	12	26	40		6.5		18		17
59	10	33	40		6.0		22		17
70	9.5	34	46		6.0		17		17
82	4.5	19	48				23		13

\*9/90 nitrite content is a composite value for the concrete and mortar for depths 6 to 32 mm.

Posttreatment Concrete Nitrite-Chloride Mass Ratio

Depth mm	Sample Date 9/90, 100 mm cores			Sample Date 8/98, 100 mm cores		
	A 0.9	B 3.7	D 6.7	A 0.9	B 3.7	D 6.7
32	—	—	—	0.88	2.10	2.4
44	1.3	6.0	18	0.95	2.3	2.4
59	1.6	9.9	20	0.99	3.8	2.6
70	1.6	1.0	26	1.1	4.6	3.0
80	0.78	8.0	27	—	4.1	2.6

**TABLE 4** Corrosion Potential Surveys of Calcium Nitrite-Impregnated Area, Average, Standard Deviation, and Coefficient of Variation (CSE, mV)

Statistical Parameter	Date									
	*6/90	7/91	9/94	8/98	6/99	*6/90	7/91	9/94	8/98	6/99
	Grid Line A					Grid Line B				
$\bar{X}$	412	323	312	314	284	184	287	273	288	293
$\sigma_{n-1}$	119	45	35	24	28	50	21	46	33	49
CV, %	29	14	11	8	10	27	7	17	11	17
	Grid Line C					Grid Line D				
$\bar{X}$	142	244	246	262	311	91	284	248	246	283
$\sigma_{n-1}$	33	23	26	24	22	32	48	46	29	23
CV, %	23	9	11	9	7	35	17	19	12	8

\*Pretreatment measurements

Table 5 presents the linear polarization (3LP) corrosion rates at 10 locations within the treated area. As shown, grid line A corrosion rates are considerably higher than those for grid lines B and D before treatment. Over the 9-year measurement period, the corrosion rates along grid lines A and B have decreased considerably, and grid line D has remained at a relatively low rate of corrosion. At 8 and 9 years after treatment, all corrosion rates are relatively low, although the chloride content at the reinforcing steel depth is considerably above the corrosion threshold concentration at the same measurement locations. See Table 2.

## DISCUSSION OF RESULTS

Over the 9-year corrosion assessment period, the chloride contents have increased to above the corrosion threshold concentration within the treated area, the calcium nitrite concentrations have decreased at the measurement depths, the corrosion potentials have become almost uniform, and the nitrite-to-chloride ratio has remained near or above 1.0. During this period, the corrosion rates have decreased to a near uniform low rate. Although delamina-

tions were detected within the treated area 1 year after treatment, it may be that the delaminated areas were small at the time of treatment and thus were not detected until the 1-year posttreatment condition assessment, or the chloride content and corrosion rate may have been too high for the treatment to be effective in these areas. However, of interest is the observation that the delaminated areas have not increased in the 8-year period since they were detected.

## CONCLUSIONS

The following were found for deep impregnation of the treated area with calcium nitrite, over the 9-year assessment period:

- Growth of delaminations beyond 1 year after treatment was stopped.
- Corrosion potentials have become more uniform, with a lower probability of active corrosion.
- Corrosion rates have decreased.
- Chloride contents have increased to above the corrosion threshold concentration of 0.71 kg/m<sup>3</sup> at the reinforcing steel depth.

**TABLE 5** 3LP Corrosion Rate Measurements of Calcium Nitrite-Impregnated Area ( $\mu\text{A}/\text{cm}^2$ )

Grid Location	Measurement Date				
	*6/90	7/92	9/94	8/98	6/99
A 1.8	6.4	1.3	4.6	1.0	0.9
A 4.2	7.3	2.8	2.3	—	—
A 6.7	1.5	1.5	1.0	—	—
B 0.6	1.1	2.5	0.5	—	—
B 3.0	1.2	1.7	0.5	—	—
B 4.2	0.8	2.6	1.5	0.8	0.6
D 0.6	0.8	1.6	0.4	—	—
D 1.2	0.7	2.0	0.6	0.9	0.8
D 3.7	—	—	0.5	—	—
D 6.7	—	—	—	0.6	0.7

\*Pretreatment measurements

- Calcium nitrite concentrations have decreased at the measurement depths.
- Calcium nitrite-chloride ratio has decreased from a range of 20 to 1.3 down to a range of 3.8 to 0.95 at the measured reinforcing steel depths.
- For the reported assessment period of 9 years, depth impregnation with calcium nitrite has been an effective corrosion posttreatment technique.

## ACKNOWLEDGMENTS

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