Abridgment

Development: Deep Grooving–A Method for Impregnating Concrete Bridge Decks

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ABSTRACT

Polymer impregnation of concrete can be used for the long-term protection of salt-contaminated concrete bridge decks. However, the current impregnation process requires long impregnation times and the development of new equipment. In addition, most monomers are a potential fire hazard. A laboratory investigation was performed to develop a simplified system that will reduce the impregnation time, simplify the equipment needs, and mitigate the potential fire hazards by deep grooving the concrete. The monomer used was an MMA-TMPTMA-AZO system. The laboratory results indicate that the impregnation time can be significantly reduced by optimizing the groove width, depth, and spacing. Optimum drying (by using infrared heaters) and polymerization conditions for the grooving conditions are also presented. The results of the laboratory study demonstrate the feasibility of the method and the need for a full-scale field trial to demonstrate its applicability to field conditions.

In March 1981 the U.S. General Accounting Office estimated the number of deficient bridges to be more than 100,000, with an estimated cost of $33.2 billion needed to replace or rehabilitate bridges in the United States (1). Approximately 50,000 of the deteriorated bridges and $11 to $17 billion of the cost are related to the deterioration of concrete bridge decks. The primary cause of bridge deck deterioration is the corrosion of the reinforcing steel. The corrosion of reinforcing steel in chloride-contaminated concrete is an electrochemical cell. In order for the electrochemical corrosion cell to be active in reinforced concrete, the following conditions must be present:

1. Chloride ion in excess of the threshold level must be present at the anode (corroding site),
2. Oxygen must be present at the cathode (noncorroding site),
3. Moisture must be present to take place in the reaction at both the anode and the cathode, and
4. Moisture must be present in the capillary void system to act as the conductive path between the anode and the cathode.

The corrosion reaction in concrete is an oxygen diffusion limited system. That is, the reaction can occur only as fast as oxygen can be supplied to the cathode.

Current rehabilitation methods, such as removing any deteriorated concrete and overlaying with a latex-modified concrete or applying a preformed membrane and overlaying with an asphaltic concrete, are of limited value because the corrosion cell remains active (2). However, polymer impregnation should stop the corrosion process by encapsulating the in-place chlorides, replacing the electrolyte (capillary moisture) with a dielectric material (polymer), and restricting the ingress of moisture and oxygen by partly filling the capillary void system. No corrosion current could be detected after the deep polymer impregnation of concrete that contained an active chloride-contaminated reinforcing steel corrosion cell (3).

The polymer impregnation method consists of drying the concrete to the desired depth of impregnation, impregnating the concrete with a monomer, and polymerizing the monomer in situ. To improve the present deep polymer impregnation system, several problems must be addressed, especially

1. Reducing the impregnation time,
2. Improving the drying system,
3. Simplifying the current impregnation process,
4. Understanding better the polymerizing rates, and
5. Minimizing the fire hazard.

One approach to improve the impregnation process is to cut grooves in the deck--for example, to a depth of 0.5 in. above the upper reinforcing bars--and to use the grooves as vessels to contain the monomer. After impregnation the grooves can be filled with sand and saturated with the monomer, followed by polymerization of the monomer in the entire mass. The deep grooves would thus eliminate the need for an impregnation vessel. Further, the grooves can be cut on contour lines (lines of equal elevation), thereby eliminating the problems associated with grade, cross slope, and superelevation that are encountered with the ponding method. Also, the method should reduce the impregnation time, simplify the polymerization process by eliminating the need to attach the hot-water polymerization vessel to the deck, possibly provide a more skid-resistant surface, and reduce the bridge-deck maintenance problem by upgrading the strength, freezing and thawing durability, and wear-resistant properties of the concrete. In addition, the deep-grooving method may reduce the fire hazard associated with the impregnation process by decreasing the potential flame surface area.

This study was designed to test the hypothesis that concrete bridge decks can be impregnated with an MMA monomer system by using the deep-grooving method. Thus the study addressed the following tasks:

1. Develop and optimize the deep-grooving impregnation process;
2. Optimize the gas-fired infrared (IR) drying method, considering time and energy expended;
3. Optimize the hot-water polymerization method of the MMA impregnant system, considering time and temperature; and
4. Demonstrate the deep-grooving impregnation system in the laboratory.

EXPERIMENT

Materials and Processes

The concrete mixture design used for preparing laboratory specimens was calculated in accordance with Pennsylvania Department of Transportation (PennDOT) specifications for bridge deck concrete in effect in the late 1960s and early 1970s when most of the Interstate system was being constructed.

The impregnant system selected was 100 parts methyl methacrylate (MMA) to 10 parts trimethylopropane trimethacrylate (TMPTMA) to 0.5 parts 2, 2'-azobisisobutyronitrile (AZO), by weight. The MMA system was selected because it is the most commonly used monomer system for impregnating concrete and because it exhibits the material properties needed for the long-term rehabilitation of chloride-contaminated bridge decks (3,4).

Gas-fired IR radiant heating was selected on the basis that it is currently the most efficient and practical method available for the large-scale drying of concrete bridge decks (5).

Hot-water polymerization was selected because of its simplicity and effectiveness (6).

Experimental Design

Figure 1 presents a flow diagram of the experimental design. The horizontal and vertical impregnation rates were determined to aid in the evaluation of the optimum groove spacing, width, and depth. Then the effects of groove width on the rate of impregnation were determined, and the effect of time on the optimized groove width, depth, and spacing were evaluated. The rate of polymerization and drying were investigated, and laboratory demonstrations of the deep-grooving impregnation system were performed.

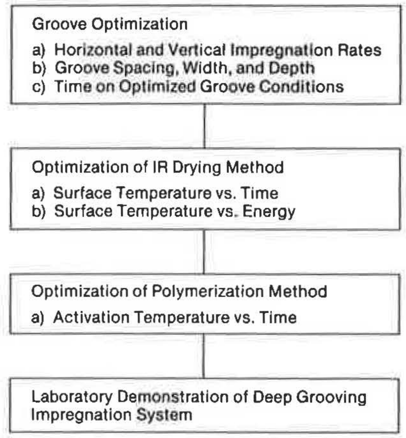


FIGURE 1 Experimental flow diagram.

RESULTS

Horizontal and Vertical Impregnation Rates

A linear-regression analysis was performed on the horizontal and vertical impregnation data. The best-fit line was obtained with the depth of penetration as the dependent variable (expressed in inches) and the square-root of time as the independent variable (expressed in hours). This shows that the data fit the Rideal-Washburn equation for fluid flow in a porous medium, as was found earlier (5). The data in the following table present the results of the linear-regression analyses and indicate that the slopes of the curves are equal:

Impregnation	Slope	Coefficient of Determination
Horizontal	0.731	0.989
Vertical	0.733	0.996

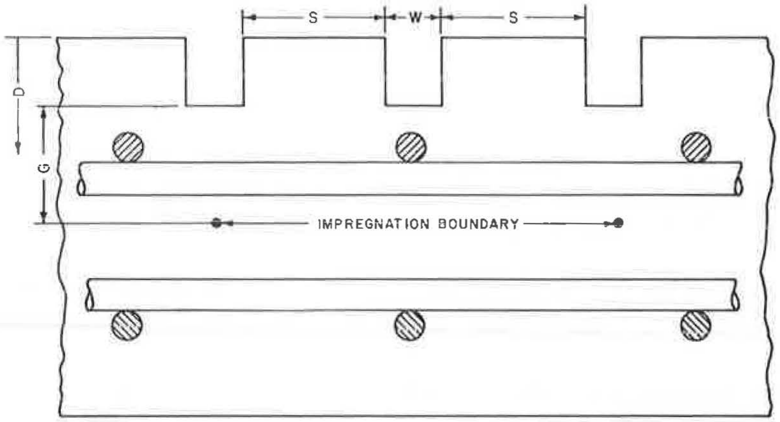
Thus the horizontal rate of impregnation is equal to the vertical

Optimization of Groove Width, Depth, and Spacing

The data presented in Table 1 indicate that as the ratio (S/G) of groove spacing (S) to impregnation depth below the groove bottom (G) (impregnation ratio, see Figure 2) increases from 1.0 at the 3-in. spacing to 1.4 at the 4-in. spacing and to 1.7 at the 5-in. spacing, the depth of impregnation midway

TABLE 1 Depths of Impregnation for Grooved Beams (groove depth 1.5 in.)

Specimen	Depth at Centerline of Groove (in.)	Depth at Centerline Between Grooves (in.)	Depth of Centerline of Groove (in.)	Depth at Pond Area (in.)	Depth Gained (in.)	Impregnation Ratio
Groove spacing = 3 in., groove width = 1.125 in., impregnation time = 24 hr						
G-9	4.5	4.5	4.5	3.625	0.875	1.0
G-10	4.625	4.5	4.625	3.5	1.125	1.0
Groove spacing = 5 in., groove width = 1.125 in., impregnation time = 24 hr:						
G-11	4.5	3.5	4.5	3.25	1.25	1.7
Groove spacing = 4 in., groove width = 1.125 in., impregnation time = 24 hr:						
G-12	4.375	3.75	4.375	3.375	1	1.4
Groove spacing = 4 in., groove width = 0.875 in., impregnation time = 24 hr:						
G-13	4.5	4.25	4.5	3.25	1.25	1.4
Groove spacing = 4 in., groove width = 0.625 in., impregnation time = 24 hr:						
G-14	4.25	4	4.25	3.25	1	1.4
Groove spacing = 2.25 in., groove width = 0.75 in., impregnation time = 16 hr:						
G-17	3.75	3.75	3.75	2.25	1.5	1.0
Groove spacing = 3 in., groove width = 0.75 in., impregnation time = 16 hr						
G-18	3.625	3.625	3.625	2.5	1.125	1.4



S = GROOVE SPACING G = IMPREGNATION DEPTH BELOW GROOVE BOTTOM
IMPREGNATION RATIO = S/G
D = POND IMPREGNATION DEPTH
GROOVE RATIO = G/D

FIGURE 2 Impregnation ratio and groove ratio.

between the grooves decreases for the 24-hr impregnation time. Figures 3-5 illustrate the effects of an increasing impregnation ratio. That is, as the impregnation ratio increases to greater than 1.0, the boundary of the impregnation becomes more sinuous. Also, the depth of impregnation, or the shape of the impregnation boundary, appears not to be affected by reducing the groove width from 1.125 to 0.625 in. (see Table 1).

The data in Table 1 also indicate that time has no effect on the impregnation ratio. At an impregnation ratio equal to 1.0, the boundary impregnation is straight; at 1.4 it becomes slightly sinusoidal.

The average depth gained through grooving versus surface ponding for the beams presented in Table 1 is about 1.125 in. This is about 75 percent of the groove depth. Of more interest than the depth gained, per se, is the depth of impregnation below the groove base (G) expressed in terms of the depth of impregnation by ponding (D) (groove ratio = G/D; see Figure 2). For grooved and ponded impregnation data presented in Table 1, the mean groove ratio is 0.90, with a standard deviation of 0.05. Therefore,

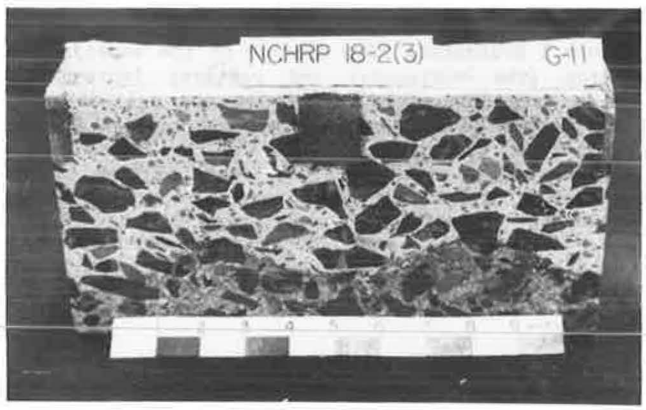


FIGURE 4 Grooved beam after polymer impregnation (impregnation time = 24 hr, groove spacing = 5 in., groove width = 1.5 in., groove depth = 1.5 in., impregnation ratio = 1.7).

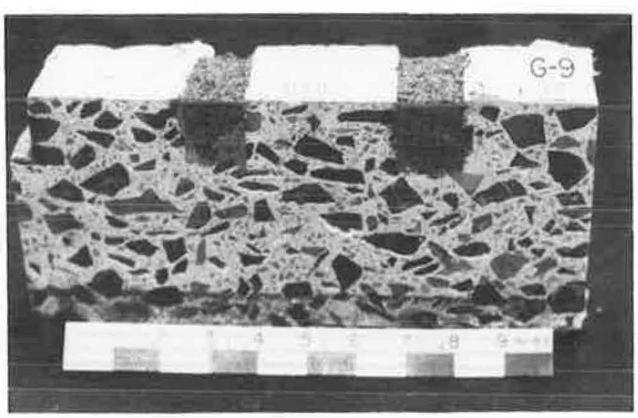


FIGURE 3 Grooved beam after polymer impregnation (impregnation time = 24 hr, groove spacing = 3 in., groove width = 1.5 in., groove depth = 1.5 in., impregnation ratio = 1.0).

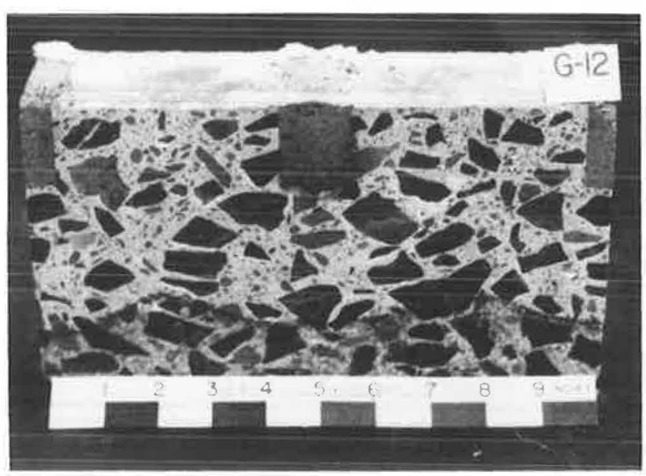


FIGURE 5 Grooved beam after polymer impregnation (impregnation time = 24 hr, grooved spacing = 4 in., groove width = 1.5 in., groove depth = 1.5 in., impregnation ratio = 1.4).

for a specified depth of 2.25 in. below the groove base, a mean depth of impregnation of 2.50 in. by ponding would be required.

For 99 percent of the time, the range of the depth of the impregnation below the groove base would be 1.93 to 2.63 in. for a mean depth of impregnation by ponding equal to 2.5 in. If the groove were cut to 0.5 in. above the reinforcing steel bars, an impregnation depth of 1.75 in. below the groove base would be required to encapsulate the upper reinforcing steel mat, assuming No. 5 bars.

Optimization of Polymerization Time

Strength data presented in Table 2 were used to determine the time for in situ polymerization of the MMA system in concrete. The data indicate that, as expected, the time for polymerization increases with decreasing activation temperatures. The time for polymerization was about 8 hr at 114°F and decreased to 1 hr at 148°F.

By using the hot-water polymerization method on the surface of a typical 8-in. concrete bridge deck slab, an equilibrium temperature of 124°F is reached in 16 hr at a 4-in. depth with the surface temperature at 208°F. Therefore, based on the strength gain data, a suggested polymerization criterion is to maintain the hot-water equilibrium temperature at about 124°F for a period of 5 hr. A total polymerization time of 21 hr is then required.

TABLE 2 Compressive Strength Gain of MMA-Impregnated Mortar Cubes as Related to Time and Activation Temperature

	Compressive Strength (psi) at Bath Temperature (°F)			
Time (min)	114°	122°	130°	148°
0	1,800	1,800	1,800	1,800
15	-	-	-	3,250
30	-	-	1,680	6,000
40	-	-	-	7,200
60	2,430	2,330	2,500	9,100
120	2,320	2,650	8,220	-
180	2,750	4,380	8,170	-
240	3,150	6,310	-	-
300	5,450	8,540	-	-
360	-	9,450	-	-
420	6,830	-	-	-
480	7,650	-	-	-
510	7,350	-	-	-

Optimization of IR Drying Method

The flow of heat during the heating cycle extends 12 in. beyond the heated area. To better estimate the drying energy used, the energy required to heat the area outside of the heated area was calculated and subtracted from the total energy (in pounds of propane used). Figure 6 shows the heating and drying time and energy used as a function of surface temperature.

As illustrated, the heating time (time to raise the temperature at a depth of 4 in. from ambient to 220°F) decreased and the rate of energy use increased as the surface temperature increased. However, for the drying time (heating time plus the time required for the slab to cool to 100°F) and energy used, there appears to be an optimum condition at approximately 600°F, as both functions initially decrease and then increase as the surface temperature increases.

Visual observations of the slab during the drying

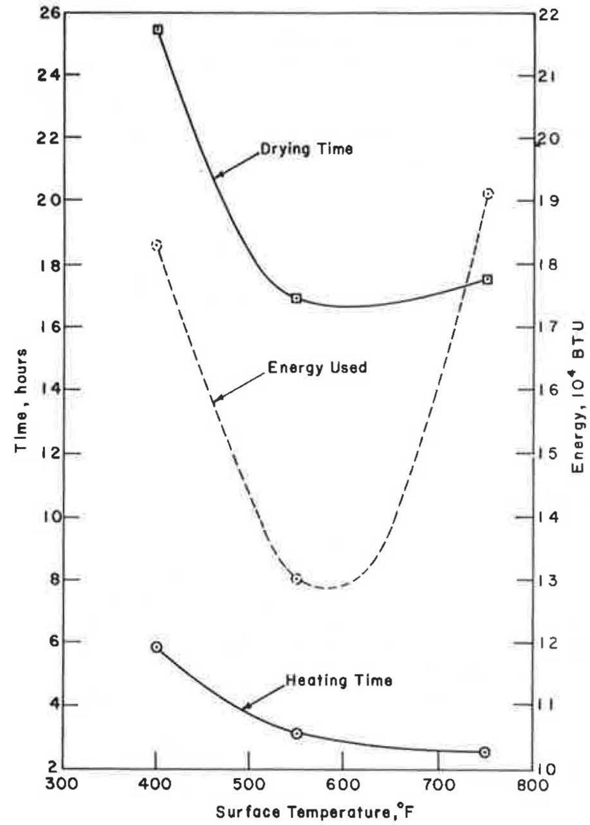


FIGURE 6 Drying and heating time and energy.

cycle indicated that the slab cracked only once during each test cycle. For all three drying tests, the crack was at the centerline of the heater at the edge of the slab, extended through the depth of the slab and 6 in. inward along a line parallel to the centerline of the heater, and ended at the outside face of the heater shield.

A microscopic survey of a polished section sawn from a core from each of the test areas showed no evidence of cracking. That is, at a magnification of 100X, no cracking was visible between the paste and aggregate, within the paste, between the paste and reinforcing, or anywhere within all three of the examined areas.

Laboratory Demonstration of Deep-Grooving Impregnation Method

A 6-ft by 6-ft by 8-in.-thick slab, designed to simulate a section of bridge deck, was constructed in the laboratory. Cores taken from the slab were impregnated for 9, 16, and 40 hr. The rate of impregnation was equal to 0.579 in. per $\sqrt{\text{hours}}$ with a correlation coefficient of determination equal to 0.997. The depth of impregnation was 2.5 in. at 16 hr and was determined to be sufficient for a required depth of impregnation of 2.25 in. with a groove ratio equal to 0.90 (0.90 x 2.5 in. = 2.25 in. = required depth of impregnation below the groove base). The groove spacing was set at 2.25 in. by using the optimum impregnation ratio of 1.00 [groove spacing = (impregnation ratio)(required depth of impregnation below the groove base)]. The optimum groove width was calculated to be 0.75 in. by using a 10 percent by volume MMA loading rate. However, the grooves were cut 0.5 in. wide because of the limitations of the saw.

The three areas dried for the optimization of the IR heating method were impregnated and polymerized by using the ponded hot-water method and the depth of impregnation was determined (see Table 3). The boundary of the impregnation was straight and the depth of impregnation was below the upper rebar mat for all three cores.

TABLE 3 Depths of Impregnations for Grooved Slab

Specimen	Depth at Centerline of Groove (in.)	Depth at Centerline Between Grooves (in.)	Depth of Centerline at Groove (in.)
S-400	3.625	3.625	3.625
S-550	3.75	3.625	3.625
S-750	4.125	4.125	4.125

CONCLUSIONS

1. It is concluded that the grooving of concrete to a depth of 1.5 in. before impregnation with an MMA system can reduce the time required for impregnation--16 hr for grooving versus 45 hr for surface ponding to obtain an impregnation depth of 3.75 in. Also, the method obviates the need for the impregnation chamber required for ponding and pressurized methods.
2. The optimum groove spacing is equal to the required depth of impregnation below the groove base.
3. The impregnation time required for the groove method can be determined from the surface pond impregnation rate by using a groove ratio of 0.90.
4. Minimum energy costs for drying before impregnation can be attained by heating for ~3 hr at a surface temperature of ~600°F. Under such conditions, cracking was not observed in the interior of the test specimens, although cracks from the nearest free edges of the slab to the edge of the heated area did occur.
5. Optimum polymerization conditions were found to be 5 hr at a steady-state temperature of 122°F, which corresponds to a conservative 21 hr of heating with a hot-water pond at a surface temperature of 208°F.

ACKNOWLEDGMENT

The authors wish to acknowledge the support of the National Cooperative Highway Research Program of the Transportation Research Board in funding the research described here as part of a larger project.

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The authors are responsible for the accuracy of the data and the conclusions and opinions.

Publication of this paper sponsored by Committee on Structures Maintenance.