

# PARTIAL POLYMER IMPREGNATION OF HIGHWAY BRIDGE DECKS

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Polymer-impregnated concrete is being considered as a means of increasing the durability of bridge decks. For application to existing bridges, the process includes drying the bridge deck to remove the free moisture in the pores, soaking a low viscosity monomer solution into the concrete, and applying heat to polymerize the monomer. Drying, soaking, and curing requirements are discussed. A limited area of a bridge deck has been successfully polymerized to a depth of approximately 1 in. (2.5 cm). Evaluation studies were conducted to determine the freeze-thaw resistance, skid and wear resistance, and protection against corrosion of the reinforcement in relation to polymer-impregnated concrete. Freeze-thaw resistance was significantly increased, and skid resistance improved significantly for the partially impregnated slabs when the tests were performed when the surfaces were dry. Skid resistance was slightly higher when the surfaces were covered with abrasive grit and kept wet. Wear measurements generally indicated little difference between treated and untreated specimens. Corrosion resistance for slabs with a low-quality polymer impregnation is about 25 times greater than that for unimpregnated slabs.

•POLYMER-impregnated concrete (PIC) development has given rise to many potential applications in the construction industry. The significant increases in strength, stiffness, water permeability, resistance to corrosion, and abrasion resistance (1, 2, 3) suggest many possible applications in highway construction. Although the possibilities of using the material structurally to take advantage of the strength and stiffness are appealing, the most logical uses at first appeared to be in the area of materials improvement for durability. As PIC is proved as a practical, durable material, the structural uses will naturally evolve.

The maintenance of deteriorating bridge decks is a major problem throughout the United States that results in the annual expenditure of many millions of dollars. The primary cause of bridge deck deterioration appears to be the presence of moisture in the concrete, which causes corrosion of the reinforcing and freeze-thaw deterioration. Researchers at the Center for Highway Research at the University of Texas have pursued the idea of developing methods to partially impregnate bridge decks in situ. They theorized that, if such a polymer surface treatment were practical, the increased resistance to water penetration and the strength of the impregnated concrete should result in significant increases in durability.

There were many questions to be answered, but generally they fell into two basic categories:

1. How can the concrete be impregnated with polymer?
2. What are the advantages of the partially impregnated concrete for use on bridge decks?

Research was initiated in 1970 in an attempt to develop and to evaluate polymer surface treatments for bridge decks (3, 4).

## FIELD IMPREGNATION OF BRIDGE DECKS

Prior to this research, practically all of the research had been directed toward full impregnation in which the concrete is fully dried, evacuated, and soaked in a monomer solution until it is fully saturated. The liquid monomer is then converted to a polymer by addition of heat or by irradiation. Under laboratory or plant conditions the full-impregnation process is relatively simple and reproducible.

Surface impregnation in the field is a more complicated process even though only partial impregnation is required. There are three basic interrelated steps in the process: (a) drying the concrete, (b) impregnating the surface zone of concrete with the liquid monomer solution, and (c) polymerizing the monomer. The depth of monomer impregnation is affected by the depth to which the concrete is dried. The type of monomer system affects the requirements for polymerization.

### Drying

Normal weight concrete has 11 to 13 percent voids that are partially filled with moisture under usual environmental conditions. This moisture must be removed to the depth at which monomer penetration is desired. The amount of moisture removed is primarily a function of surface temperature and drying time, although other variables such as air humidity and velocity can also be important.

Initially, concrete was to be dried at less than 200 F (95 C) to avoid any danger of cracking or of excessive thermal expansion. Slabs 40 × 43 in. (102 × 109 cm) were cast and treated under field conditions. Drying was accomplished by air drying in the sun for several months and by using a curing blanket for a minimum of 3 days; these methods developed maximum concrete surface temperatures of 140 to 150 F (60 to 65 C). PIC depths from  $\frac{1}{4}$  to  $\frac{3}{4}$  in. (0.6 to 1.9 cm) were obtained, although there was considerable variation in depth and some of the polymer was faint. However, the durability properties of this material were good as will be discussed subsequently.

Based on later research at the University of Texas, Lehigh University, and the U.S. Bureau of Reclamation, there seems to be little question that higher temperatures are both preferable and safe. The temperature at the depth to which penetration is desired should be at least 212 F (100 C).

Figure 1 shows the temperature gradients in a 6-in. (15-cm) slab for a surface temperature that increases to 320 F (160 C). Thermocouples were inserted into holes drilled from the bottom surface and were located at various depths from the heated surface. Temperatures are shown for times varying from 30 to 180 min after the heat source was applied. Although the temperature varied with depth, the change in temperature with time was approximately constant. After 1 hour, only the upper  $\frac{1}{2}$  in. (12.7 mm) of concrete is heated to 212 F (100 C) or higher. The concrete is heated to 212 F (100 C) at a depth of 1.7 in. (4.3 cm) after 2 hours, and at nearly 2.5 in. (6.3 cm) after 3 hours. These temperature gradients and rates depend on the rate of temperature buildup on the surface. Temperature gradients can be predicted analytically with good accuracy.

The drying time required to achieve a particular depth of polymer impregnation has been found to be considerably longer than the time required to achieve a temperature of 212 F (100 C) at the same depth. Figure 2 shows the depth of polymer impregnation achieved for a surface temperature-time relationship similar to the one shown in Figure 1. From Figure 1 it was observed that a temperature of 212 F (100 C) was reached nearly 2.5 in. (6.3 cm) from the surface after 3 hours. However, the depth of polymer impregnation after 4 hours of drying was only about 0.6 in. (1.5 cm). Slightly over 8 hours of drying produced a polymer depth of 1.25 in. (3.1 cm).

At this time, drying is the most difficult step in the process from a practical standpoint. The maximum or optimum temperature for drying is still not well defined. It is reported that other researchers have used temperatures of 500 to 700 F (260 to 370 C) and even higher without serious effects. We think the maximum temperatures should not exceed 300 F (149 C) until more experience is gained in large-scale field treatments.

Figure 1. Temperature gradients in 6-in. (15-cm) concrete slab heated from upper surface.

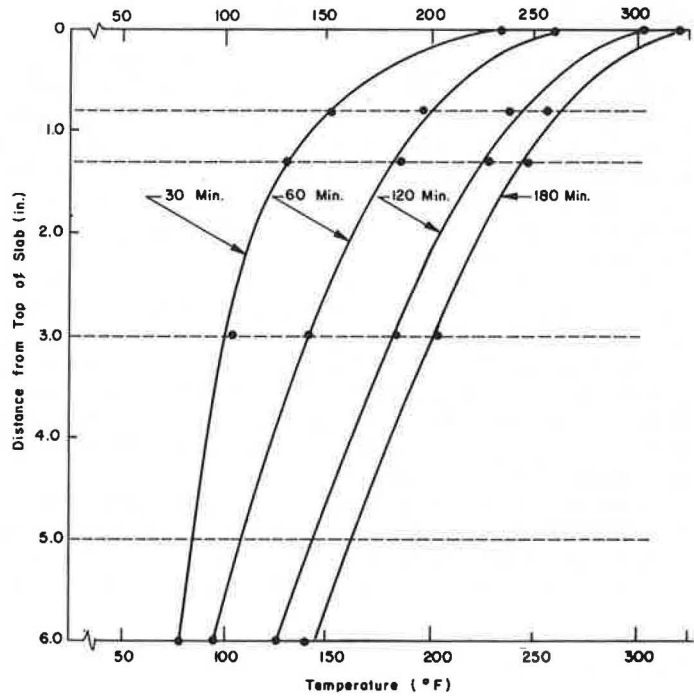
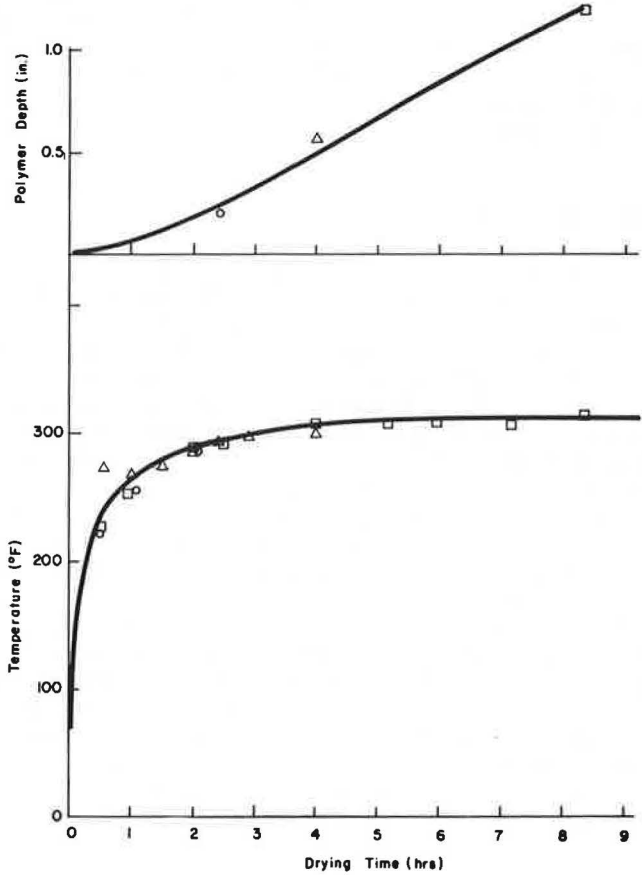


Figure 2. Effect of drying on polymer depth.



## Monomer Systems and Application

The monomer system that was used initially consisted of methyl methacrylate (MMA), 10 percent (wt) trimethylpropane trimethacrylate (TMPTMA) and 1 percent (wt) benzoyl peroxide (BP). More recently, other catalysts have been used because of their improved mixing characteristics and their longer storage life when in solution. This monomer system has a low viscosity, which is essential to achieving good penetration without overpressure. In addition, polymerization occurs relatively fast at temperatures of 150 F (66 C) or higher. Other monomers that have been used are isobutyl methacrylate (IBMA) and isodecyl methacrylate (IDMA).

A  $\frac{1}{4}$ -in. (0.6-cm) sand layer is used on the surface to hold the monomer in place during soaking and to prevent monomer evaporation from the concrete surface. The monomer solution is sprinkled or sprayed onto the sand in the usual amount of  $\geq 3,000$  to  $4,000 \text{ ml/m}^2$  ( $0.073$  to  $0.089 \text{ gal/ft}^2$ ). The primary requirements are to initially moisten the sand thoroughly and to keep it moist during the soaking period. A plastic sheet or aluminum foil is applied during the soaking period to retard evaporation. It is also necessary to keep the temperature of the slab to  $<100 \text{ F}$  ( $38 \text{ C}$ ) to prevent polymerization from occurring.

Figure 3 shows the polymer impregnation achieved for soaking times ranging from 5 to 8 hours in 6-in. (15-cm) slabs that had been thoroughly dried. A soaking time of 4 hours produced an impregnated depth of 1 in. (2.54 cm). Longer soaking times of 7 or 8 hours resulted in about 1.5 in. (3.8 cm) of polymer depth.

## Polymerization

The two most common methods for polymerizing a monomer in concrete are radiation and thermal-catalytic processes. Because of the weight of shielding and the potential safety hazards for a mobile irradiator, this research has relied on thermal-catalytic methods. Several sources of heat have been investigated: solar energy, microwave ovens, reactive monomer systems, heating blankets, steam, and ponded hot water. Currently, steam and ponded hot water appear to be the most practical means of achieving polymerization.

### Ponded Hot Water

Hot water can be ponded by erecting a simple framework on the slab and lining it with a waterproof membrane such as polyethylene film. The sand cover is usually left in place because the time required for removal would permit evaporation of the monomer from the slab. Water heated to about 195 F (90 C) is ponded to a depth of approximately 3 in. (7.5 cm). This produces a maximum temperature on the slab surface of about 140 F (60 C). The slab surface was initially at room temperature. The water was removed after 2 hours after which the slab temperature dropped rapidly.

Figure 4 shows the polymer depth for different application times of the water. Both lightweight aggregate fines and regular sand were investigated. For 2 hours of hot water application over regular sand, a 1.25-in. (3.2-cm) polymer depth was achieved. The use of lightweight aggregate fines resulted in only about 60 percent as much impregnated depth, apparently because of the greater insulating effect.

The advantages of hot water are (a) uniform heat, (b) creation of an airtight barrier over the concrete that eliminates monomer evaporation, and (c) progression of polymerization without additional application of heat or energy after the hot water is initially applied. This last advantage minimizes the problems encountered in mechanical or electrical failures during polymerization. The curing time could be accelerated by use of submersible heaters or a hot water circulating system. Insulation for the sides and top would be required for large-scale treatments to reduce the energy requirements. An enclosed water bag may have some merit.

The disadvantages of ponded hot water are that it is difficult to use on superelevated

Figure 3. Effect of soaking time on polymer depth.

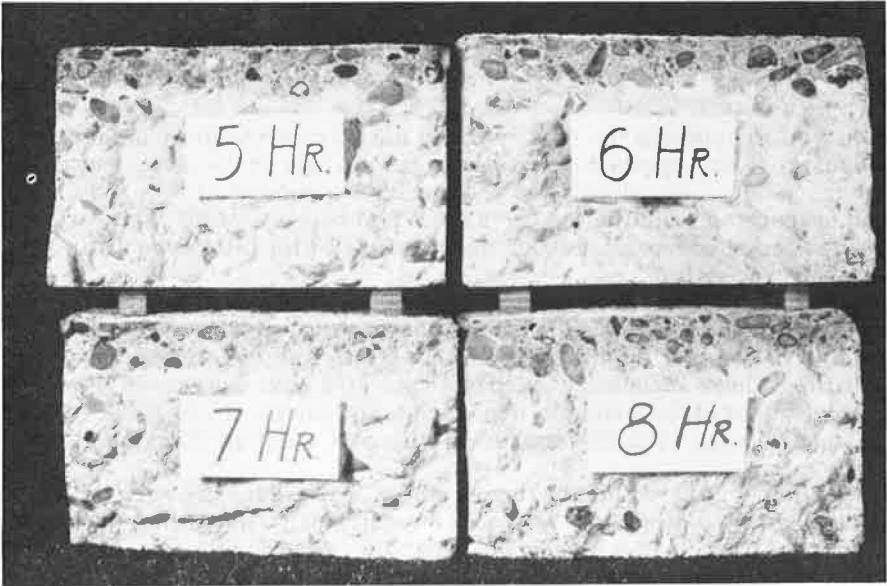
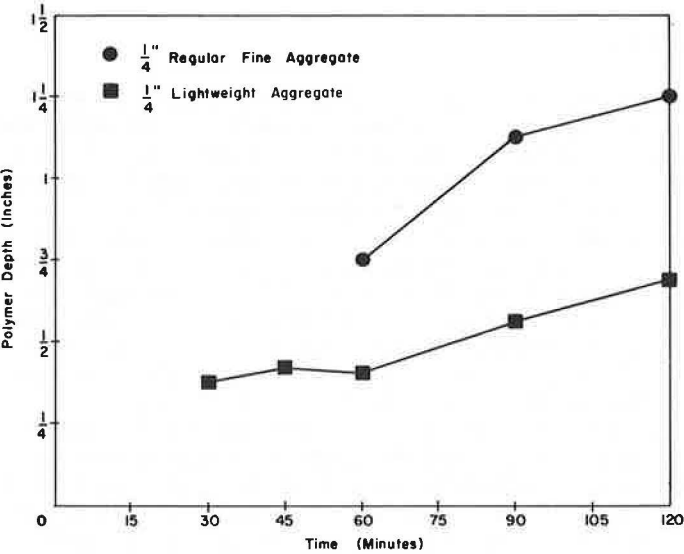


Figure 4. Polymer depth as a function of curing time with hot water.



bridge decks and to move from one location to another and that relatively large amounts of water are required.

### Steam

Steam has worked well to generate the heat required for polymerization. In the first attempts to use steam, it was sprayed directly onto the surface of the slabs that had been soaked with monomer. The slabs were polymerized to a depth of  $\frac{3}{4}$  in. (2 cm), but the monomer had evaporated from the top  $\frac{3}{16}$  in. (0.5 cm) because of the high surface temperature. A number of evaporation barriers were tried with little success in an attempt to reduce the evaporation.

Steam injected into an enclosure over the slab heats the slab more slowly and to a lower maximum temperature. However, slab temperatures can be increased to 203 F (95 C) in a short time. Polymer depths of 1 to 2 in. (2.5 to 5 cm) are regularly obtained in slabs that have been adequately dried and saturated with monomer. Figure 5 shows the polymer depth of slabs heated to a surface temperature of 170 F (77 C) and cured for 30, 60, and 90 min. The 30-min curing time was about as effective as the longer times.

The advantages of steam are (a) higher temperatures that reduce the curing time, (b) usability on superelevated decks, (c) less water requirement, and (d) simpler movement without the ponded water. The disadvantages are the need for steam-generating equipment and for a continuous supply of steam for the curing period. The continuous supply may require a backup capability in case of a malfunction. It will be necessary to have an easily portable, well-insulated enclosure to minimize labor and energy requirements.

### SMALL-SCALE FIELD TREATMENT

In addition to laboratory treatments and simulated field treatments, a limited small area on a new bridge deck in Austin, Texas, was successfully treated. The bridge had already been sprayed with linseed oil but had not been opened to traffic. An area 12 × 12 ft (3.7 × 3.7 m) was selected to be treated, and one-half of the area was lightly sandblasted to remove the linseed oil. One-half of each sandblasted strip and each non-sandblasted area was dried for 72 hours, with a kerosene construction heater with a blower, and undried. A maximum surface temperature of 270 F (132 C) was measured. The monomer system (MMA, 1 percent BP, and 10 percent TMPTMA) was applied to a  $\frac{1}{4}$ -in. (6.35-mm) sand cover and soaked overnight for approximately 13 hours. Just before the monomer was applied, a cloudburst passed over the bridge and rainwater broke the dike that had been erected around the test area and wet most of the sand on the undried area. Only the nonwet area was treated with the monomer that was polymerized with steam heat. Cores taken from the sandblasted area indicated a polymer depth of about 1 in. (2.54 cm). The nonsandblasted, dried area was not successfully impregnated. This indicates the need to remove the linseed oil film. For this test, a light steel frame 24 in. (61 cm) high was used to support a tarpaulin enclosure for drying. Figure 6 shows the uncovered frame while sand is being spread over the slab. The same enclosure was used to contain the steam heat during curing.

A 4-in. (10-cm) core taken from the sandblasted, dried area has undergone 155 cycles of freeze-thaw testing. A steel ring was attached to the treated surface, and a  $\frac{1}{4}$ -in. (0.6-cm) depth of water is maintained on the specimen. No deterioration has been observed except minor surface scaling typical for all treated slabs during freeze-thaw tests.

One other field treatment has been attempted on an older bridge deck. The drying and monomer application steps apparently were quite successful, but polymerization was not achieved when continued malfunctions of the steam generator occurred and prevented the necessary slab temperatures from being attained.



## EVALUATION OF SURFACE-TREATED SLABS

The performance of surface-impregnated concretes has been evaluated for freeze-thaw durability, resistance to water penetration, surface wear and abrasion, and skid resistance (3, 4). Long-term tests have been under way to evaluate the protection afforded reinforcement in polymer-impregnated slabs subjected to frequent applications of saltwater spray. Following is a summary of some of these evaluations.

### Freeze-Thaw Behavior

A large number of specimens have been subjected to freeze-thaw tests to determine their durability. These specimens were tested with a  $\frac{1}{4}$ -in. (0.6-cm) depth of water ponded within a 7.8-in.-diameter (20-cm) steel ring bonded to the surface.

One series of specimens, treated under simulated field conditions, provided a good indication of the durability of surface-impregnated slabs that would be representative of less-than-ideal quality. These 1.0- × 1.0-ft (30- × 30-cm) specimens were sawed from 40- × 43- × 5.5-in.-thick (102- × 109- × 14-cm) slabs that had been cast, dried, and cured outdoors. The slabs were air dried for several months and then further dried with a heating blanket for a minimum of 3 days. The usual monomer system was applied to the slabs, which were covered with lightweight fine aggregate. Some were cured with heating blankets, and others were cured with ponded hot water. The low temperatures used for drying, which were typical for the earlier treatment processes in the study, produced polymer depths of  $\frac{1}{4}$  to  $\frac{3}{4}$  in. (0.6 to 1.9 cm). The color of the polymer was relatively light indicating a low polymer loading. This was due to the low drying and the high quality of the unimpregnated concrete that developed 6,400 psi (44 126 kPa).

The treatments are given in Table 1. Slabs 8 and 9 were treated with a second reactive monomer system consisting of MMA, 4 percent (wt) lauryl peroxide (LP), and 4 percent (wt) n, n-dimethyl-p-toluidine (DMPT), which polymerized in a short time and bonded the aggregate cover to the slabs. It was theorized that the lightweight aggregate topping would provide a skid-resistant topping that would also provide additional protection to the impregnated concrete. Figure 7 shows the control specimen after 40 cycles and a treated specimen after 120 cycles, which was the arbitrary limit of freeze-thaw cycles.

Horizontal strain measurements were made on the side of each of the freeze-thaw specimens by means of four stainless steel tabs bounded 8 in. (20 cm) apart, 1.25 cm (4.9 in.) above the bottom surface and 1.25 cm (4.9 in.) below the top surface. Measurements were made with an 8-in. (20-cm) Berri gauge when the slabs were frozen. The strain measurements indicated that eight of the field-treated specimens developed a contraction, 45  $\mu$ in./in. (45  $\mu$ m/m) greater in the top than in the bottom, and the control specimens averaged zero strain differential. The other two treated slabs (8 and 9) exhibited a contraction 120  $\mu$ in./in. (120  $\mu$ m/m) greater in the top. The greater contraction in the top is apparently due to the 30 percent higher coefficient of thermal expansion for polymer-impregnated concrete compared to that for unimpregnated concrete (1). For slabs 8 and 9, the even greater differential was probably caused by the high concentration of polymer in the 0.6-cm layer of intentionally bonded lightweight fine aggregate.

The strains in the top of the slab for the specimens impregnated with MMA are shown in Figure 8 as a function of the number of freeze-thaw cycles. Figure 8 shows that the strain measurements provide a good indication of the impending failure of a slab. The control specimens had an average strain of about 1,500  $\mu$ in./in. (1500  $\mu$ m/m) after only 20 cycles, although failure occurred at an average of 35 cycles. Although slabs 8 and 9 continued for 120 cycles, the volume instability as evidenced by the increasing strains and by cracking observed visually indicated that failure was imminent. Slab 10 developed a strain of about 1,000  $\mu$ in./in. (1000  $\mu$ m/m) at 55 cycles but then stabilized for the remainder of the testing. Moderate cracking and moderate water loss were noted during this period. A relatively large amount of monomer and a long soak time were used in the treatment of this specimen, and this indicates that durability is

**Figure 5. Effect of steam curing time on polymer depth.**



**Figure 6. Application of sand cover to bridge deck.**



**Table 1. Freeze-thaw test treatments.**

Slab Number	Monomer System	Quantity of Monomer (ml/m <sup>2</sup> )	Soak Time (hours)	Soak Time Temperature (C)	Cure Method	Average Polymer Depth (in.)	Polymer Color	Maximum Freeze-Thaw Cycles
1	Control	—	—	—	—	—	—	30
2	MMA <sup>a</sup>	4280	10	23 to 34	HW <sup>b</sup>	0.25 to 0.75	Faint, uniform	120
3	IBMA <sup>a</sup>	3600	10	25 to 34	HW	0.75	Faint, uniform	91
4	IBMA <sup>a</sup>	4500	24	24 to 32	HW	0.5 to 1.5	Faint, uniform	117
5	IDMA <sup>a</sup>	2700	10	25 to 34	HW	0.25 to 0.5	Very faint, uniform	120
6	Control	—	—	—	—	—	—	40
7	IDMA <sup>a</sup>	3600	24	24 to 32	HW	0.25 to 0.5	Dark to faint	117
8	MMA <sup>a</sup>	6750	24	24 to 34	HW	0.5 to 0.75	Faint, uniform	120
	MMA <sup>c</sup>	900						
9	MMA <sup>a</sup>	4500						
	MMA <sup>c</sup>	1350	18	21 to 27	HB <sup>d</sup>	0.25 to 0.5	Faint, nonuniform	120
10	MMA	6750	24	24 to 32	HW	0.5 to 0.75	Faint, uniform	120
11	MMA	9900	18	21 to 27	HB	0.25 to 0.50	Faint, uniform	120
12	MMA	9900	24	20 to 28	HB	0.5	Very faint, uniform	120

Note: 1 in. = 2.54 cm.

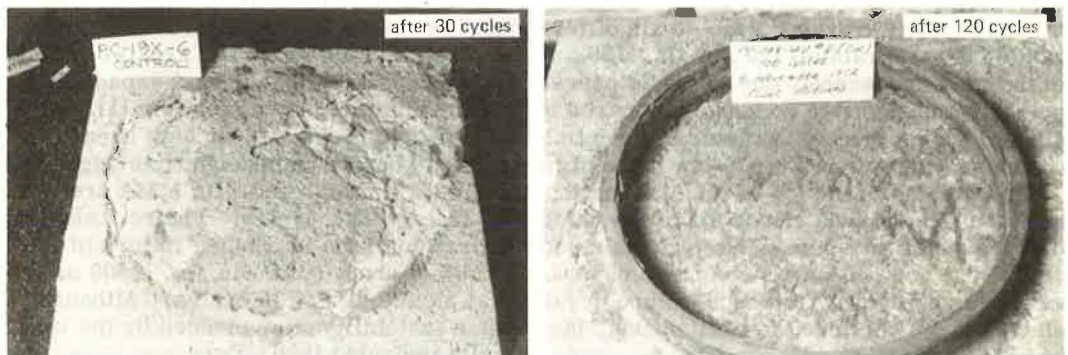
<sup>a</sup>Included MMA, 1 percent (wt) BP, and 10 percent (wt) TMPTMA.

<sup>b</sup>HW = hot water.

<sup>c</sup>Included MMA, 4 percent (wt) LP, 1 percent (wt) DMPT.

<sup>d</sup>HB = heating blanket.

**Figure 7. Surface of freeze-thaw specimens.**





not a simple function of monomer quantity or soaking time used. The other treated specimens indicated good volume stability.

The strain measurements have provided a more reliable measure of strain stability and freeze-thaw durability than visual observation alone, especially since surface scaling is not the primary mode of deterioration for treated specimens. Visual cracks were usually observed whenever the top strain exceeded about 1,000  $\mu\text{in./in.}$  (1000  $\mu\text{m/m}$ ). It may be reasonable to define the durability range of the concrete as the number of cycles below which the top strain does not exceed a certain value, say 750  $\mu\text{in./in.}$  (750  $\mu\text{m/m}$ ).

Other freeze-thaw tests on specimens in which good polymer impregnation was achieved also indicate good durability. Reinforced specimens with reinforcement in the bottom and in the top and bottom are still in progress after 150 cycles. But the tests on the marginal-quality field-treated specimens are significant because good improvements were obtained over the unimpregnated controls.

### Corrosion Protection

Reinforced companion slabs were treated at the same time and with the same treatments as given in Table 1. These slabs [also 40-  $\times$  43-in.-thick (102-  $\times$  109-cm) slabs] were sprayed with salt water twice daily, 5 days a week, for 20 months to determine the protection against corrosion provided by the surface polymer impregnation. The No. 8 bars had a nominal 1-in. (2.54-cm) cover. After the tests were terminated, the bars were removed and measured to determine the corroded area.

The treated slabs had the same quality of polymer impregnation as given in Table 1. The reinforcing near the edges of the slab, which were not sealed against water intrusion, indicated some corrosion. But considering only interior bars and not the outer 3 in. (7.62 cm) of each interior bar, the bars from the treated slabs had an average of only 1.1 percent of corroded surface area compared to 27.0 percent for the corresponding bars from the unimpregnated controls. The fact that the treated slabs do not represent the quality of polymer impregnation that can now be achieved makes the results even more significant. Studies are in progress to determine the chloride content in the concrete.

### Skid Resistance

The skid resistance of PIC was of considerable interest since it was not initially known if the polymer impregnation would result in a surface with a lower frictional resistance. A series of 2-in.-thick (5.08-cm) trapezoid-shaped slabs, including controls, was placed in the Texas Highway Department wear track facility. The facility has a 10-ft-diameter (3-m) test track over which a nongrooved tire mounted at each end of a weighted beam was driven at 10 mph (16 km/h). Periodically the tire loading was stopped while surface friction measurements were made with the British portable tester (BPT) in accordance with ASTM E 303-69.

Typical skid numbers as a function of wear track loading revolutions are shown in Figure 9. Skid resistance increases with the skid number. For the first 70,000 revolutions (140,000 wheel passes), the slabs were kept dry. An additional 140,000 revolutions were made under wet conditions, and No. 46 silicone carbide grit was used as a wearing agent. Immediately after the grit was applied, the surface was abraded and resulted in a higher short-term skid resistance for all slabs.

Throughout the testing, all treated slabs developed skid numbers, as high as or higher than the controls, that indicate no loss in skid resistance due to polymer impregnation. In fact, before the grit was applied, the skid numbers were significantly higher for the treated slabs. The highest skid resistance was achieved by treating the specimen with the lightweight aggregate topping intentionally bonded to the surface as was previously described for specimens 8 and 9 in the freeze-thaw tests.

During the wear track tests, depth-of-wear measurements were made across the

Figure 8. Top strains of freeze-thaw specimens in frozen state for MMA-treated specimens.

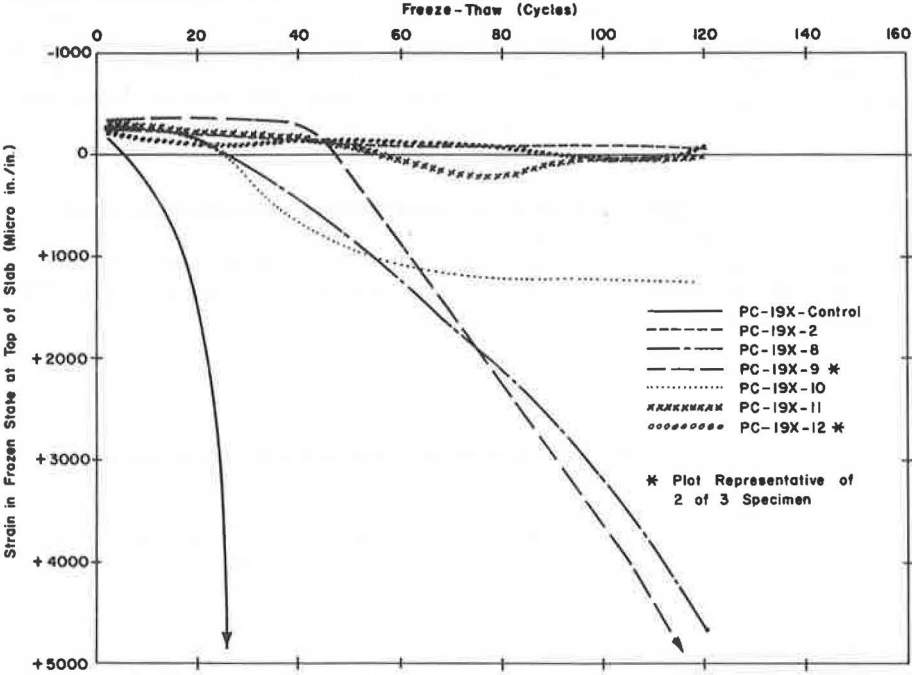
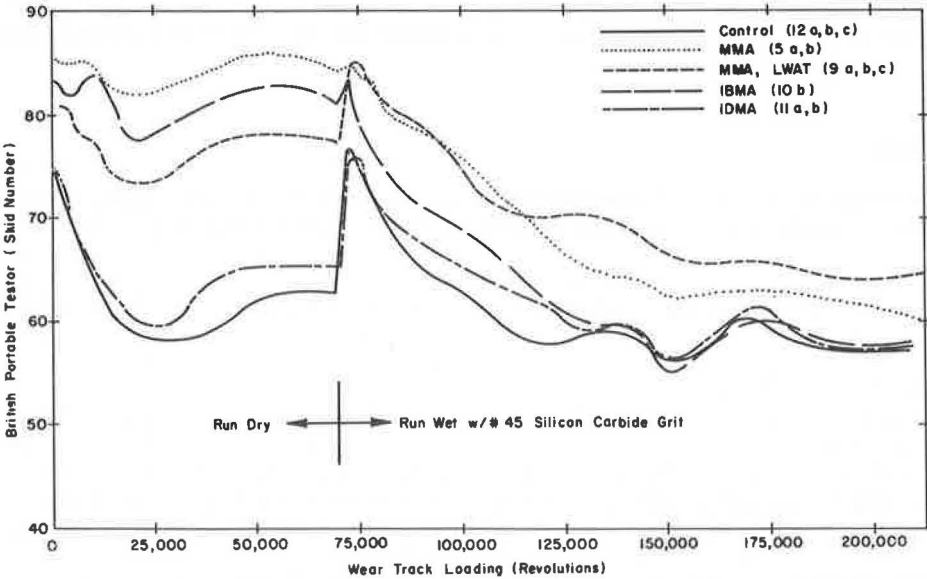


Figure 9. Skid numbers from wear track tests.



wheel path on each test slab. These measurements provided a measure of the cross section worn away during the tire loading. There was no appreciable difference in wear between the controls and treated slabs except for the specimens with the lightweight aggregate topping. After the grit was applied, the wear in these slabs was more than twice as great as that in the other specimens.

## CONCLUSIONS

Partial polymer impregnation of concrete can be accomplished by properly drying the concrete, impregnating it with an appropriate low-viscosity monomer solution, and curing it with external heat. A limited test treatment on a bridge deck has confirmed the validity of the process.

Extensive evaluations of partially impregnated slabs have shown that

1. The freeze-thaw resistance is significantly increased,
2. Corrosion of reinforcing in PIC slabs is about 5 percent of that found in unimpregnated slabs,
3. Skid resistance is lower and in some cases higher than for control slabs, and
4. Wear is generally about the same for both control and impregnated concrete.

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The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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