

INTERIM REPORT

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POLYMER IMPREGNATED BRIDGE SLABS

by

Samuel S. Tyson
Highway Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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SUMMARY

The procedure used for producing precast slabs of polymer impregnated concrete (PIC) and described in this report was generally satisfactory from an operational standpoint.

A strength loss of 14%, attributable to the drying step, was observed in PIC cylinders; however, residual strengths for this class of concrete were satisfactory. The freeze-thaw durability of PIC specimens was essentially the same as the excellent performance exhibited by the control concrete.

The average maximum depth of polymer impregnation observed in cores from the slabs was 1.0 in. (25 mm). The impregnated zone was found to contain a series of discontinuous microcracks resulting from the polymer treatment. These cracks allowed Cl^- penetrations at a depth of 0.8 in. (19 mm) that equalled or exceeded those at this depth in the control concrete. Additional research with experimental slabs is recommended with the objective of eliminating the microcracking associated with the impregnated zone.

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INTRODUCTION

The use of polymer materials with concrete has been investigated during the last ten years through the joint efforts of the Federal Highway Administration (FHWA), the Brookhaven National Laboratories, and the Bureau of Reclamation. One material produced by this research effort is known as "polymer impregnated concrete" (PIC). In the production of PIC, a liquid monomer is allowed to infiltrate the surface of a hardened concrete until a desired depth of penetration is achieved, and the monomer subsequently is polymerized by either radiation or thermal-catalytic means.

A monomer system that has been found to be desirable for use in PIC is a combination of the monomers methyl methacrylate (MMA) and trimethylolpropane trimethacrylate (TMPTMA). The MMA-TMPTMA monomer system has a very low viscosity and for PIC surface ponding allows penetration and saturation of the capillary pore structure of the hardened concrete. A sand layer is used on the concrete surface to contain the monomer and minimize evaporation. Test specimens of PIC have shown significant increases in strength and durability and dramatic increases in their resistance to penetration by deicing chemicals when compared to ordinary bridge deck concrete.⁽¹⁾

Concretes with polymers have received attention not only in the United States but also abroad.⁽²⁾ It is clear that this subject will continue to be of interest to highway departments and to the building industry as materials and procedures are developed. For highway applications of polymer materials a summary of FHWA work is available.⁽³⁾

PURPOSE

The purpose of this study is to monitor and report on a field application of polymer materials that has good potential for improving the performance of concrete bridge structures. The particular application being investigated is the use of precast PIC slabs in the widening of a bridge deck.

This study will result in this initial report describing the procedures and materials used and subsequent reports on the performance of the slabs at the ages of 1, 3, and 5 years.

SCOPE

The precast PIC slabs were produced at the Staunton District Office precasting yard for use on a safety improvement project (Project 0042-081-101, M501) at the intersection of Rte. 614 and Rte. 42 in Rockbridge County. This state force project involved the widening of a 10-ft. (3.1-m) span from a 23-ft. (7.0-m) to a 40-ft. (12.2-m) clear roadway width. Three 3 ft. x 10 ft. x 12 in. (0.9 m x 3.1 m x 305 mm) slabs were produced for placement on each side of the existing structure. Four of these slabs, including one curb section, were impregnated to form a protective layer of PIC and the remaining two will serve as controls.

BACKGROUND

Research has been performed in Texas concerning the selection of the most suitable monomer system and the determination of the most effective procedures to use in the production of PIC under field conditions.^(4,5) The results confirmed the findings from previously cited research in which it was shown that the monomer system consisting of MMA and TMPTMA is well suited for surface impregnation and that the physical properties of PIC are superior to those of normal concrete, particularly in terms of strength, freeze-thaw durability, and resistance to intrusion by deicing salts.

The first full-scale field test of the process for producing PIC took place on a bridge deck in the Denver metropolitan area in October 1974. The surface impregnation process consisted of four basic steps:⁽⁶⁾

1. preparation of the concrete surface to remove contaminants such as oil, asphalt, or curing compounds that would prevent or reduce monomer penetration;
2. drying the concrete to a depth sufficient to permit the desired monomer penetration;
3. impregnation of the concrete with liquid monomer to the desired depth; and
4. polymerization of the monomer in the concrete to form the protective barrier.

The time schedule for the activities in this surface impregnation process is shown in Figure 1, along with the optimized time schedule subsequently developed for other treatments.⁽⁷⁾ In the original field treatment process a propane-fired forced hot air heating system was used to dry the concrete and to polymerize the monomer. Later installations have shown that further reductions in the drying and polymerization times can be achieved using either gas-fired radiant heaters or electric infrared heat sources.^(8,9)

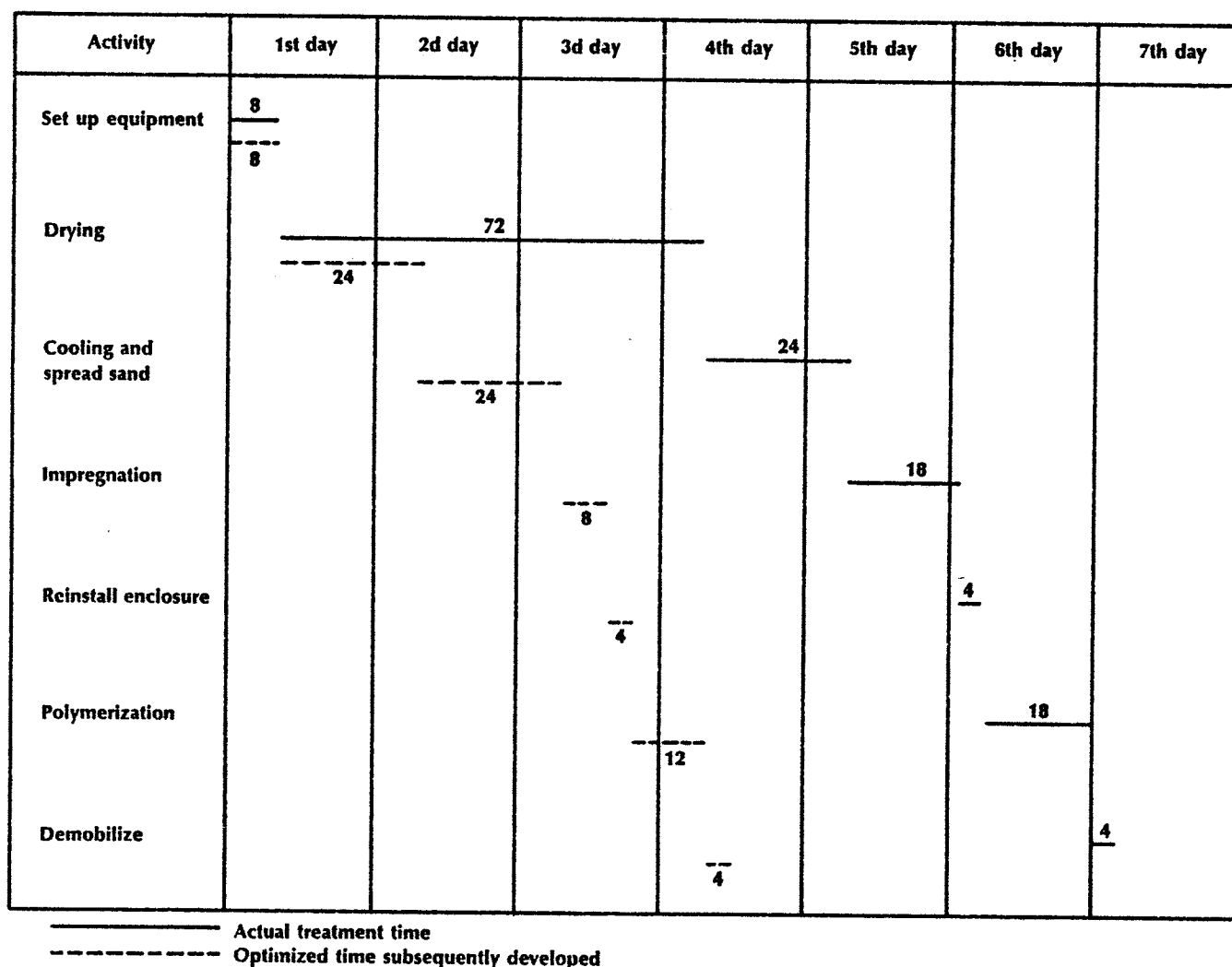


Figure 1. Surface impregnation time schedule (in hours).
(From reference 7)

PROCEDURE

The procedure used for producing PIC in this study generally followed that outlined in a user's manual published by the FHWA.⁽⁸⁾ The equipment and facilities unique to this study are described in the following sections along with a description of each step in the procedure.

Drying

Moisture must be removed from the capillary structure of the concrete so the monomer can fill this space. It is desirable to reduce the moisture content to 1% or less by weight at the desired depth of penetration. No instrumentation was provided in this study to measure moisture contents in the hardened concrete; however, it was assumed that sufficient drying would take place if a temperature of 230°F (110°C) could be attained and maintained for several hours at any desired depth. The trade between drying depth and drying time is important and will be discussed later in this report.

The enclosure used for the drying step is shown in Figure 2. The timber frame enclosure had interior walls and a ceiling made of insulated reflective sheeting and an open bottom. This construction provided a well-insulated enclosure that was light and easily placed over each slab.

Two electric infrared heaters attached to the ceiling of the enclosure were positioned longitudinally along the centerline of each slab during the drying period. A space of approximately 12 in. (305 mm) was provided between these heaters and the top slab surface. Two additional heaters were positioned similarly about 18 in. (457 mm) from the lower slab surface. All of the heaters were rated at 240 volts and 1,800 watts, and were 46 in. (1.2 m) long and weighed 8 lb. (3.6 kg). A top surface heater is pictured in Figure 3.

Temperatures were monitored at a number of locations on the surfaces and at interior points as indicated in Figure 4.

Partial heating records are shown for the four slabs in Figures 5, 6, 7, and 8. These figures are presented in chronological order for the drying step involving slabs numbered 1, 5, 3, and 6, respectively. Several observations may be made. First, a maximum temperature change of 50°F (10°C)/hour was generally maintained at the surface during heating and cooling, and a maximum temperature of approximately 300°F (149°C) was reached at the surface during heating. These criteria were used in an effort to avoid thermal cracking of the slabs.



Figure 2. Enclosure for drying slabs.

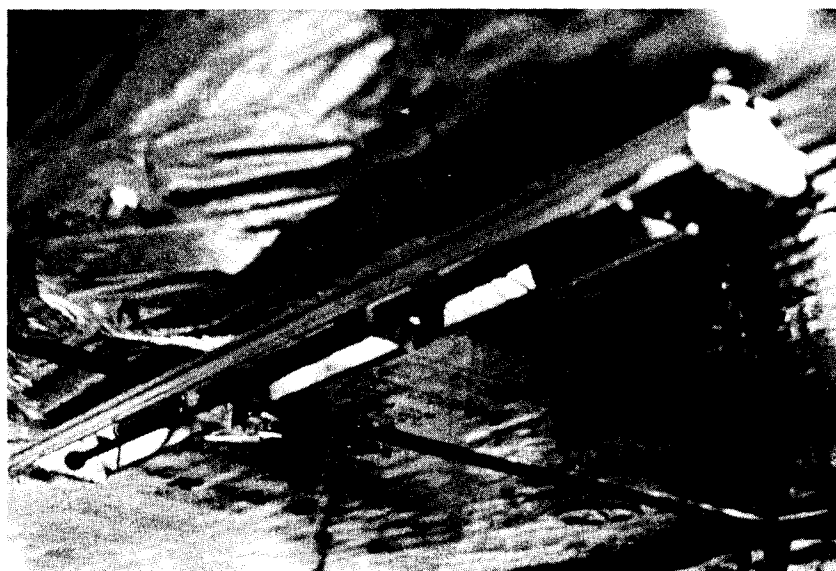
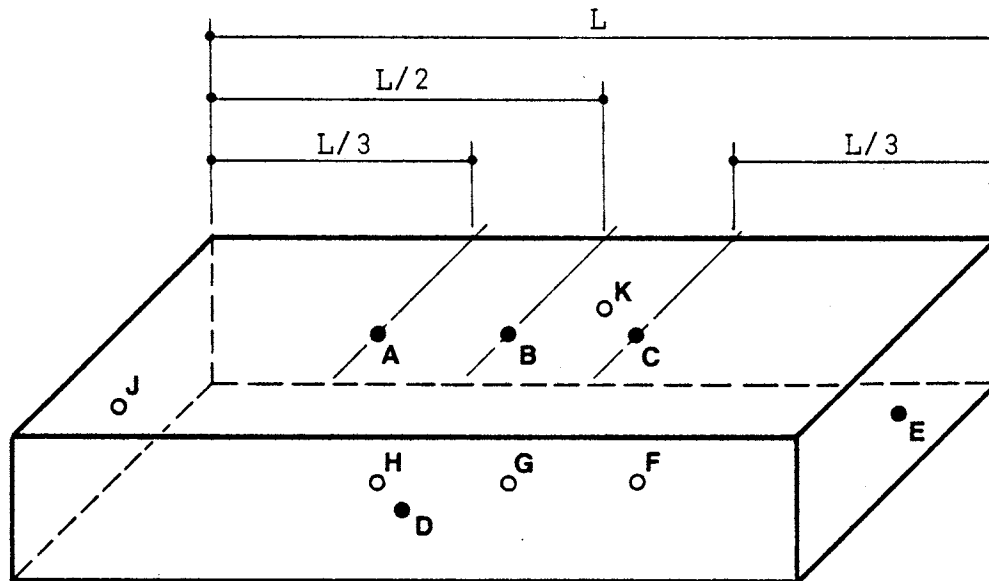


Figure 3. Electric infrared heater in ceiling of drying enclosure.



A - Top left:	Surface	(Slab 1, 5, 3, 6)*
	1 in.-depth	(Slab 5, 6)*
B - Top middle:	2 in.-depth	(Slab 3)*
C - Top right:	4 in.-depth	(Slab 1, 5, 3, 6)*
	Surface	
	1 in.-depth	
	4 in.-depth	
D - Near side:	Surface	
E - Right end:	Surface	
F - Bottom right:	Surface	
	2 in.-depth	
G - Bottom middle:	4 in.-depth	
H - Bottom left:	Surface	
	2 in.-depth	
J - Left end:	Surface	(Slab 1, 5, 3, 6)*
K - Far side:	Surface	

NOTE: Slab dimensions: 3 ft. x 10 ft. x 12 in.
 (0.9 m x 3.1 m x 305 mm)
 1 in. = 25.4 mm

*Slab numbers for which temperature record from given location was used to plot Figures 5,6,7 and 8.

Figure 4. Thermocouple locations in precast slabs.

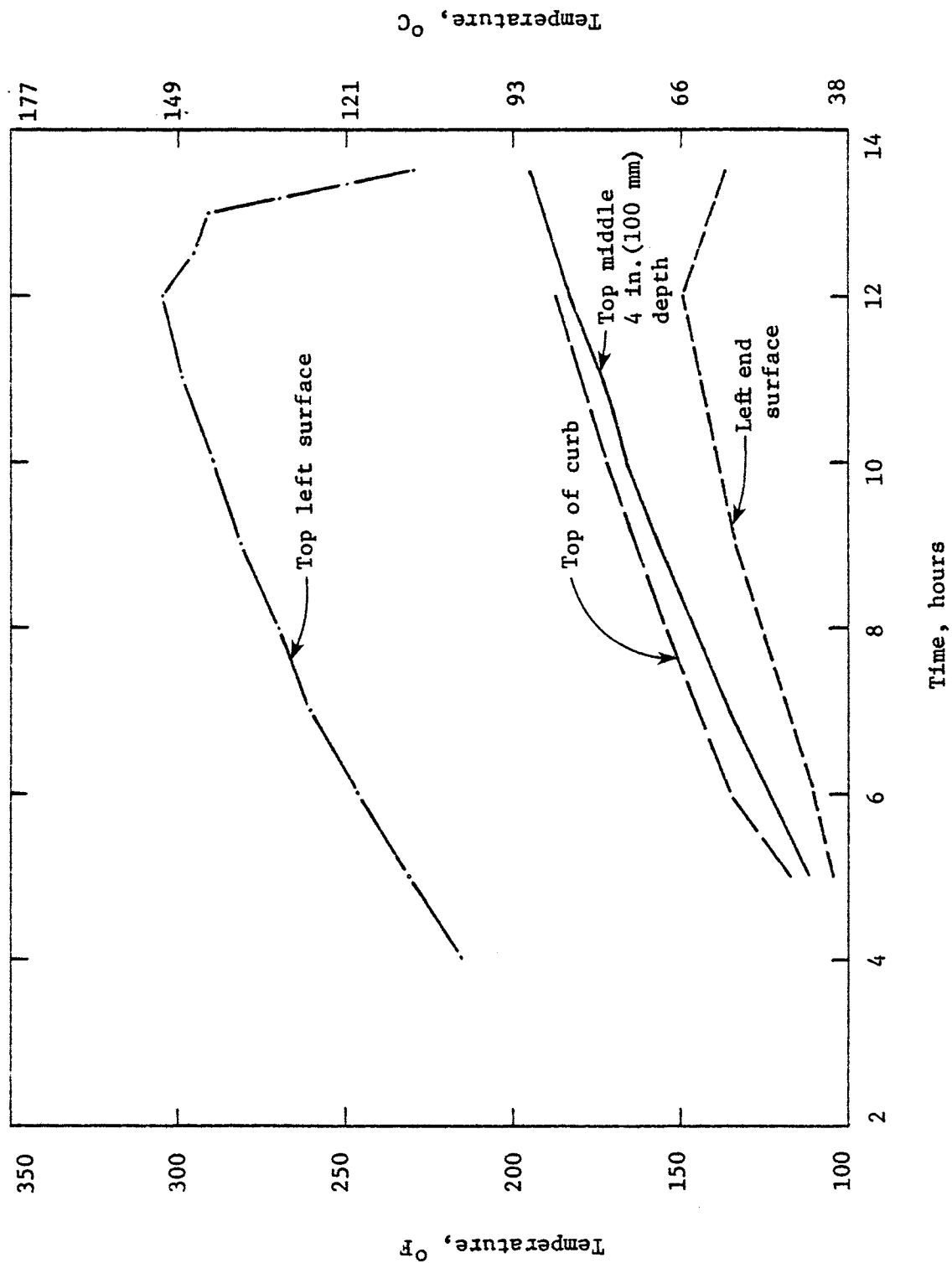


Figure 5. Temperature record during drying phase at selected locations for Slab 1.

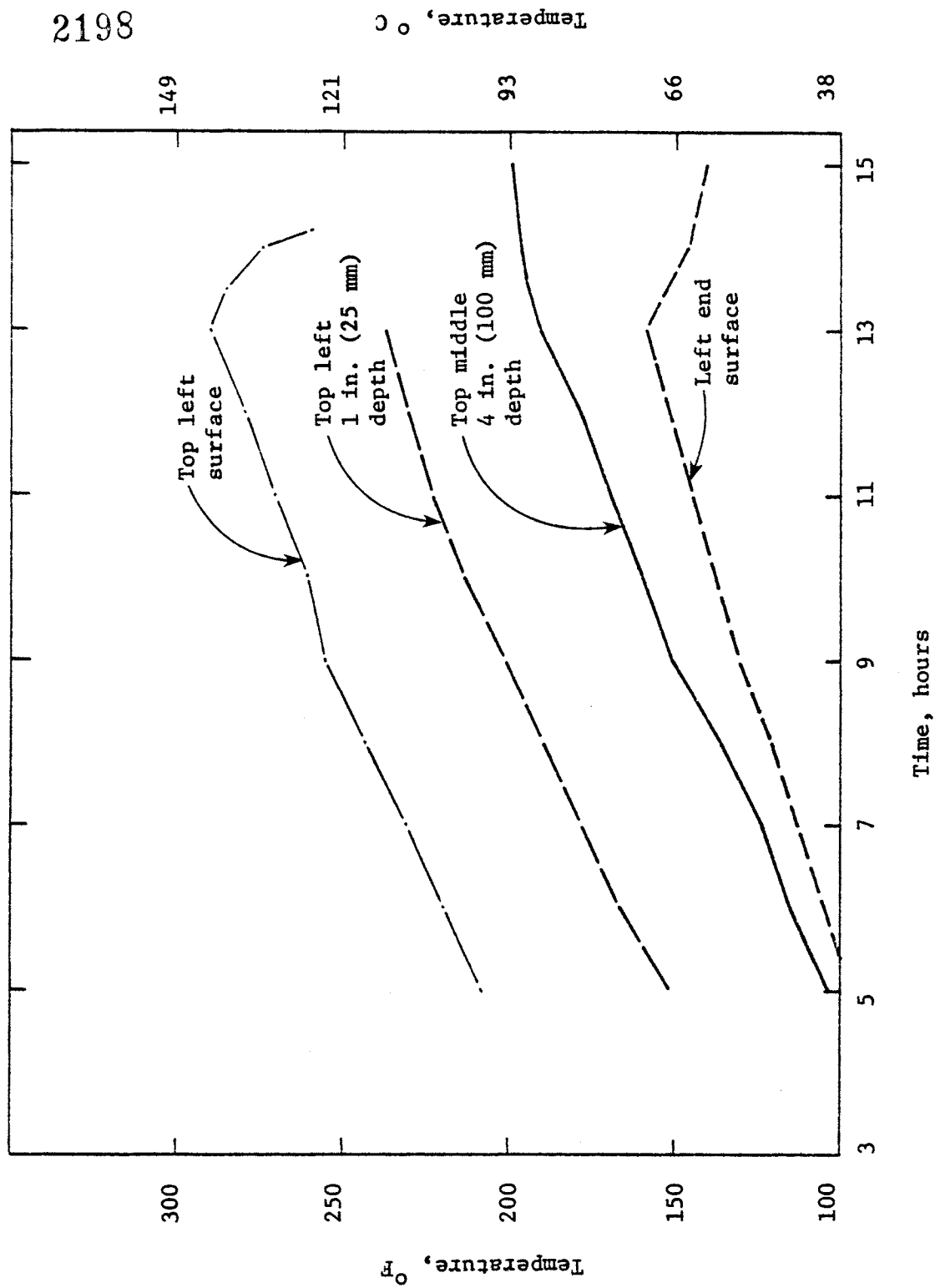


Figure 6. Temperature record during drying phase at selected locations for Slab 5.

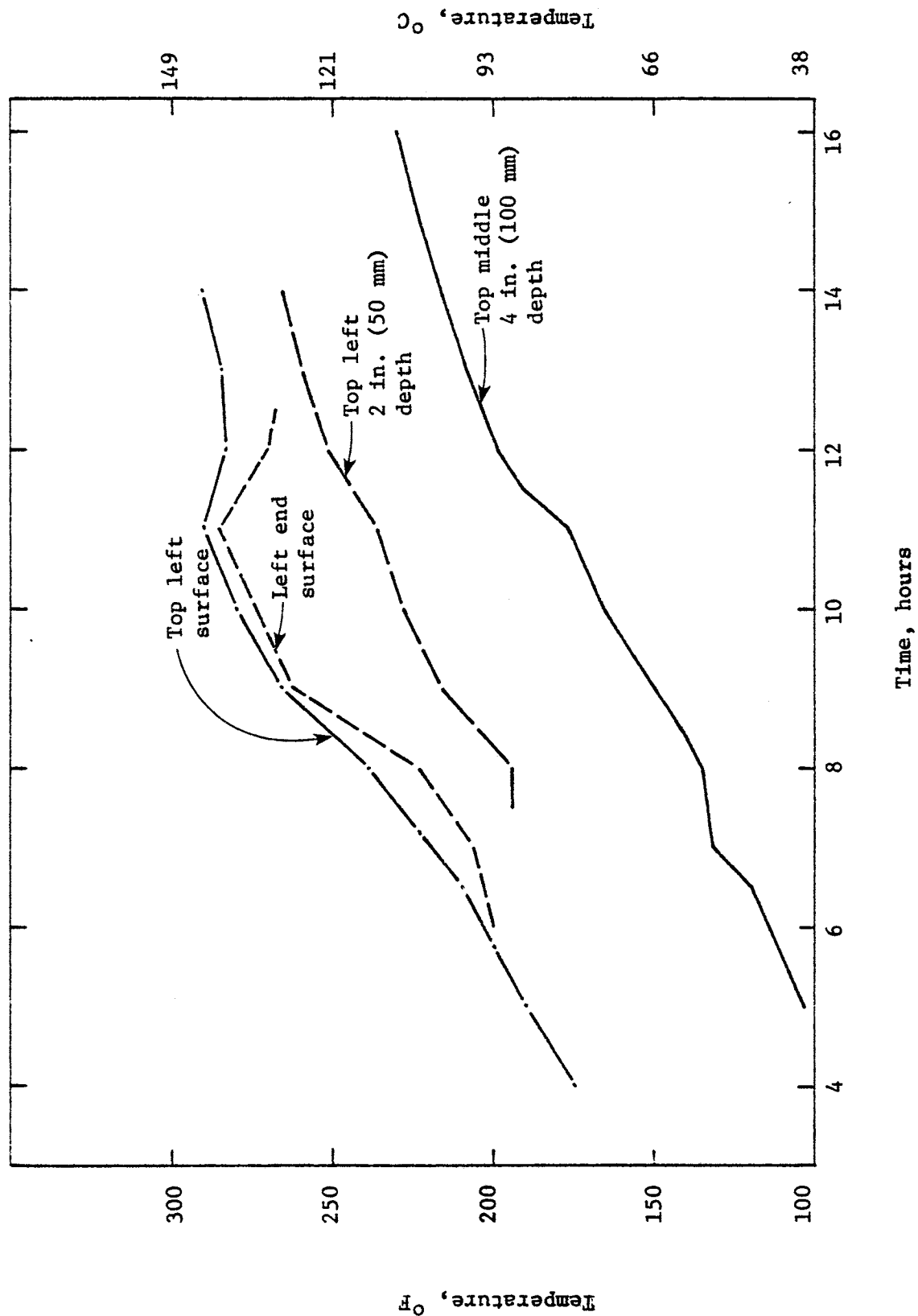


Figure 7. Temperature record during drying phase at selected locations for Slab 3.

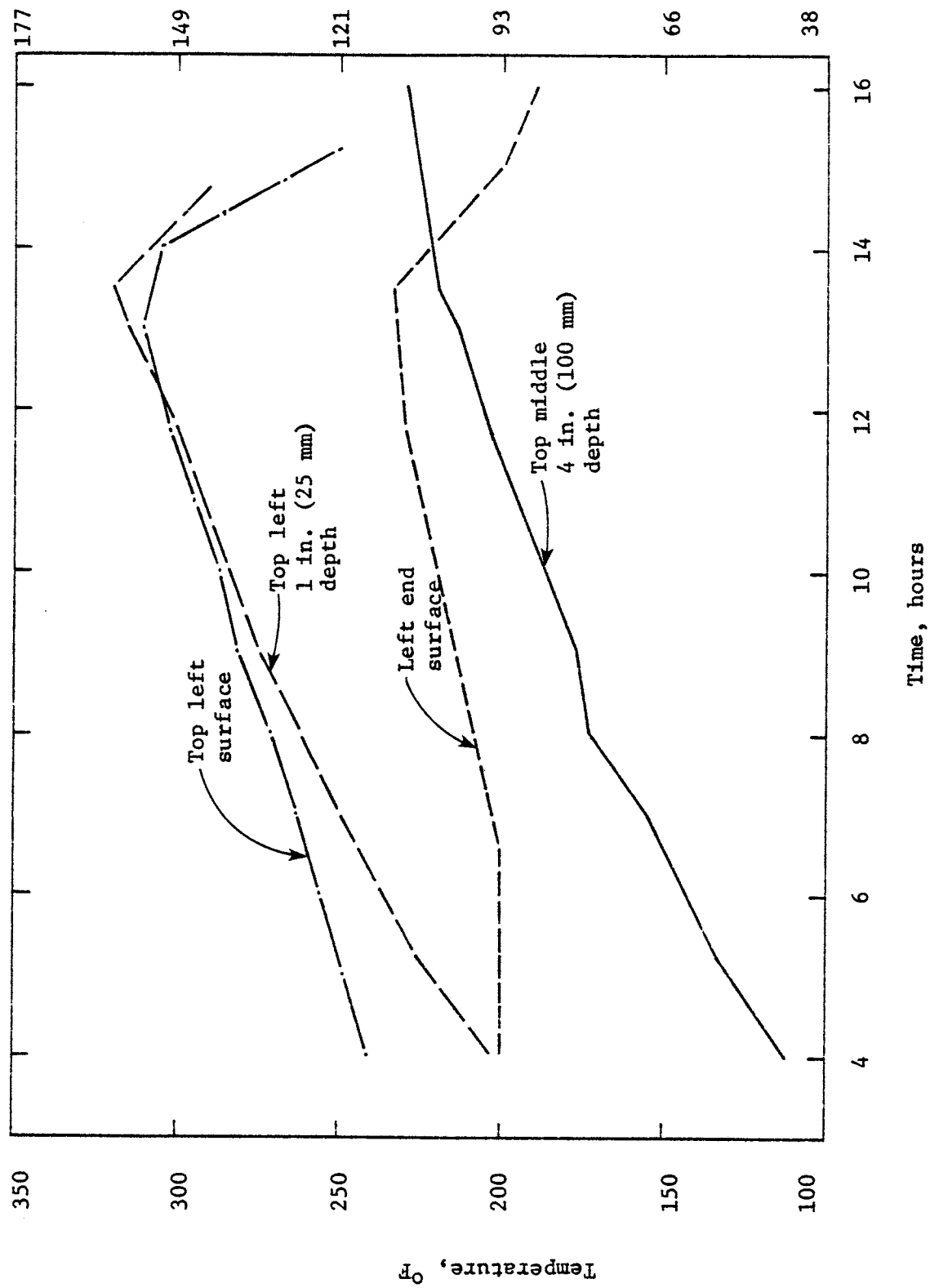


Figure 8. Temperature record during drying phase at selected locations for Slab 6.

Additionally, some observations can be made concerning other maximum temperatures reached at the surfaces and at depths within the slabs. When reviewing these records it should be borne in mind that the criteria selected for drying were, first, that an internal temperature of 230°F (110°C) would be achieved and held at some measured depth for several hours; and second, that the length of the heating period would be limited to allow a new heating cycle to be started on a daily basis. It was recognized that this approach would probably result in monomer penetrations of 1 in. (25 mm) or less, but it was felt that this would be sufficient protection if the desired daily drying treatment cycle could be implemented.

The major portion of the drying-heating phase for slab number 1, a curb section, is shown in Figure 5. Unfortunately, the thermocouples at the 1-in. and 2-in. (25- and 50-mm) depths were not functioning so the temperatures at these depths could not be monitored. The heaters were individually powered so they could be turned off as needed during the heating phase to prevent overheating of individual areas of the slab surface. In this and subsequent drying phases, the top left surface thermocouple is used to indicate the surface temperature of the slab since all thermocouples across the bottom and top surfaces followed these temperatures closely.

The heating of slab number 1 was continued for 13 hours, at which time all heaters were turned off and venting of the enclosure was begun to cool the slab prior to removing it from the drying enclosure. As can be seen in Figure 5, a maximum temperature of approximately 200°F (93°C) was reached at the 4-in. (100-mm) depth, which suggests that adequate temperatures for drying should have been attained at shallower depths.

The other observation from Figure 5 is that the temperature of the end surfaces was not sufficient to promote drying. The left end surface temperatures, representative of temperatures at both ends of the slab, did not exceed 150°F (66°C) during the drying phase.

The insulation around the bottom portion of the drying enclosure was improved and the same heating procedure was followed for slab number 5. In Figure 6 it can be seen that similar temperatures were attained at the points of interest. In this case the thermocouple at the 1-in. (25-mm) depth was functioning and indicated a temperature of 240°F (116°C) before the power was terminated after 13.5 hours of heating. The overall temperatures were not significantly different from those in Figure 5 for slab number 1.

During the third drying phase the system was modified after about 8 hours of heating by adding a portable oil-fired, hot air blower. The temperatures for slab number 3 in Figure 7 can be seen to rise more rapidly after this point. The heating was continued for 16 hours, during which time the temperatures at the 2-in. and 4-in. (50-mm and 100-mm) depths reached 265°F and 230°F (129°C and 110°C), respectively. A significant improvement in the heating was noted in that the temperatures at the end surfaces paralleled the heating curve for the top and bottom surfaces. This suggests that the slab may have been heated sufficiently on all surfaces to allow impregnation of the monomer.

The dual heating system was used for the drying phase for slab number 6. From the heating record for this slab, shown in Figure 8, it is seen that some variations in the maximum temperatures attained are apparent at all locations except the 4-in. (100-mm) depth. The heating was extended in this case from 16 to 18 hours, then all heaters were cut off and venting was begun. The end surfaces reached a maximum temperature of 235°F (113°C). In Figure 9 the drying enclosure containing the electric infrared heaters is shown with the oil-fired, forced air heater installed at one end.



Figure 9. Oil-fired, forced air heater installed at end of drying enclosure to supplement electric infrared heaters.

Monomer Soak

Each of the four slabs was cooled for approximately 12 hours prior to introducing it to a monomer bath. The surface temperature of the slabs was, therefore, 100°F (38°C) or less prior to its contact with the monomer. This precaution was to prevent early polymerization at the surface. The internal slab temperature at the 4-in. (100 mm) depth was 120°F (49°C) or less at the time the monomer soaks began. The monomer liquid was at the ambient temperature of from 45°F to 65°F (7°C to 18°C) at the beginning of the soaking periods.

The monomer used was MMA; however, the cross linking agent TMPTMA was not used because the attainment of increased strength was not an objective of this study. The catalyst, Luazo 79, was added in the amount of 0.5% by weight of the MMA. Since the catalyst made the MMA sensitive to polymerization temperatures of 160°F to 180°F (71°C to 82°C), the MMA could be reused for impregnating the second through fourth slabs without any danger of bulk polymerization at ambient temperatures.

The procedure used for impregnating each slab was to place it, after cooling, in an aluminum tank designed to be used for both the impregnation and polymerization steps. The slab was then submerged in enough catalyzed MMA liquid to cover the top surface with 2 in. (50 mm) of monomer. The slab rested on reinforcing bars placed transversely at the one-third points to allow the monomer ready access to the underside of the slab.

By submerging the entire slabs in the monomer bath it was possible to subject all surfaces of the slabs to infiltration by the MMA. For the small slab sizes involved in the study this was the most practical method to use for impregnating the slabs. If only the top surfaces had been impregnated, it would have been necessary to construct dikes around each slab, which would have been much more time consuming than using the tank bath. Also, since the slabs will likely be subjected to salt rundown at all joints in the finished structures, it is desirable that all surfaces be afforded some degree of polymer protection.

Each slab was soaked in the monomer bath for 6 hours. During the soaking period, the tank was covered with a sheet of polyethylene and plywood covers to retard evaporation of the monomer. After the soaking period, the monomer was pumped out of the tank and returned to shipping drums using hand-operated fuel pumps such as the one shown in Figure 10. A small amount of monomer, perhaps a gallon (3.8 liters), could not be pumped from the bottom of the tank.



Figure 10. Hand-operated fuel pump for transferring monomer.

Polymerization

The polymerization step was begun immediately after the monomer soaking period. After the monomer was pumped from the aluminum holding tank, the slab was shrouded with a polyethylene sheet and the tank was refilled with water to cover the slab. The water was cycled from this water bath with an electric pump and a system of pipes and valves into two 50-gallon (190-liter) water heaters shown in the background in Figure 11. Periodically as the water heaters raised the temperature of the static water to 170°F (77°C), the water was recycled into the tank holding the slab. Concurrently, four submersible, 240-volt coil heaters in the holding tank were powered continuously to help raise the temperature of the bath. While the water heater tanks were recovering, the pump was used to circulate water through the soaking tank to assure a distribution of uniformly heated water.

A period of 4 to 5 hours was required to bring the water in the holding tank up to a temperature of 170°F (77°C). An additional 4 hours were required to raise the temperature at the 2-in. (50 mm) depth within the concrete to this temperature. The temperature of the water bath was maintained at the curing temperature range of 160° to 200°F (71°C to 93°C) for the next 4 hours by operating the submersible heaters and the circulating pump.

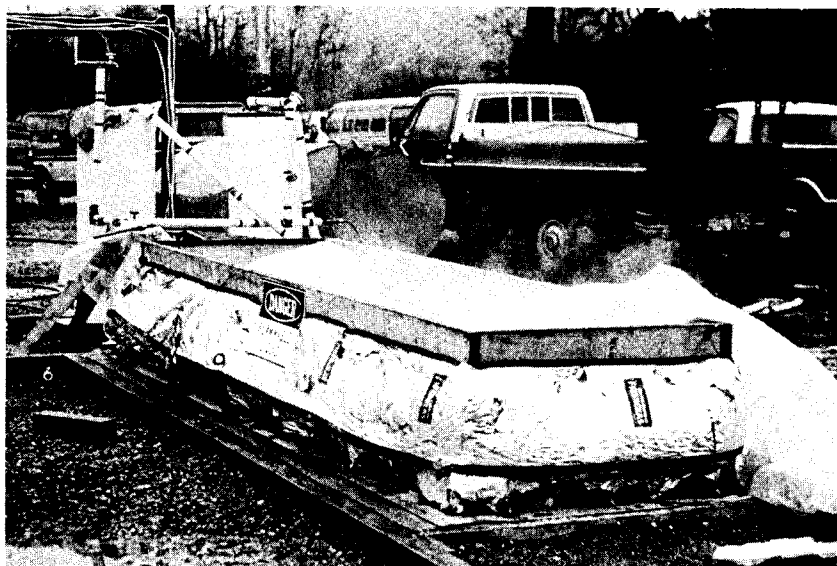


Figure 11. Insulated aluminum tank used for monomer soak and hot water bath.

The water was pumped from the bath after an elapsed time of 12 hours. Figure 12 shows a slab being lifted from the tank. The white sheet of material on top of the slab is a layer of polymerized monomer. As mentioned earlier, this monomer remained in the tank after the monomer soaking and, being less dense than water, floated at the surface of the water bath, where it polymerized.

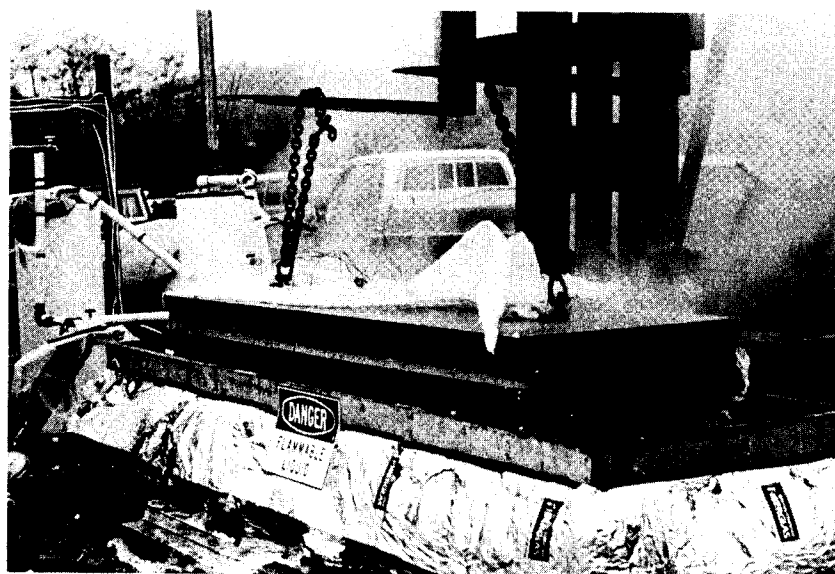


Figure 12. PIC slab being removed from tank.

CONCRETE CHARACTERISTICS

The characteristics of the concrete involved in this study were determined during the fresh stage and after hardening. These characteristics are presented and discussed in the following sections.

Fresh Concrete

The concrete mixture used for fabricating the precast slabs was a Virginia Department of Highways and Transportation Class A-4 concrete with a design minimum compressive strength at 28 days of 4,000 psi (27.6 MPa). The mixture included a crushed limestone coarse aggregate and a siliceous fine aggregate. The mixture proportions for 1 yd.³ (1 m³) of concrete are listed in Table 1.

The characteristics of the fresh concrete and ambient conditions were measured during placement and are shown in Table 2.

The characteristics of the fresh concrete and the ambient conditions indicate good control of the concrete as placed in the precast units. The slabs were cured with polyethylene covers after a broom finish was applied. Curing compound was not used as it might have restricted the penetration of the monomer liquid.

Table 1

Mixture Proportions for 1 yd.³ (1 m³) of A-4 Concrete

<u>Ingredient</u>	<u>Weight</u>	
	<u>lb./yd.³</u>	<u>kg/m³</u>
Cement (Type II)	635	377
Coarse aggregate	1,771	1,051
Sand	1,119	664
Water	295	175

Table 2

Characteristics of Fresh Concrete and Ambient Conditions

<u>Unit</u>	<u>Measure</u>
Slump	3.5 in. (89 mm)
Air content	4.9%
Unit weight	139.9 lb./ft. ³ (2,241 kg/m ³)
Concrete temperature	80°F (27°C)
Air temperature	63°F (17°C)
Wind velocity	0 mi./hr. (0 km/hr.)
Relative humidity	50%

Hardened Concrete

Other characteristics of the concrete were determined from samples cast at the time of placement and from cores drilled from the hardened slabs after the polymer treatment. These characteristics included polymer depth, compressive strength, freeze-thaw durability, and chloride ion penetration. The samples tested in this program are listed in Table 3.

The cast specimens were cured for 28 days in a moist room at 72°F (22°C). Subsequently they were stored under laboratory conditions of 70°F (21°C) and 50% relative humidity for a period of 6 weeks until the polymer treatment process for the slabs was begun.

In addition to the concrete specimens listed in Table 3, a number of lightweight aggregate concrete cylinders were available when the polymer treatment process was performed. Some of these cylinders were selected as controls and others were treated to form lightweight PIC. The results of this additional work are presented in the Appendix.

Table 3
Test Samples

<u>Sample Size*</u>	<u>No.</u>	<u>Test</u>
Cast Specimens:		
6 in. x 12 in. cylinder	6	Compressive strength
	2	Microscopic examination
3 in. x 6 in. cylinder	12	Background and penetrated Cl ⁻
3 in. x 4 in. x 16 in. prisms	5	Freeze-thaw durability
	1	Microscopic examination
Cores:		
4 in. diameter	6	Penetrated Cl ⁻
	4	Microscopic examination

*in. x 25.4 = mm

Polymer Depth

During the drying of the fourth slab (no. 6) the specimens designated for the polymer treatment in Table 3 were placed in the enclosure and dried. Then the specimens were soaked in monomer and polymerized along with the slab. Replicate specimens were maintained in the laboratory to serve as controls.

Several specimens of each type were cut and polished to determine the depth of polymer in them. It was found that the polymer impregnated zone appeared darker than the unimpregnated concrete, and that the difference in coloration was more easily distinguished after the polished specimens were heated in an oven for about 10 hours at 150°F (66°C) to drive away moisture from the unimpregnated concrete. The specimens were marked with dark ink just inside the polymer impregnated zone. Photographs of two specimens are shown in Figures 13 and 14, where it may be observed that the depth of polymer impregnation varied from 0.25 to 0.40 in. (6 to 10 mm).

Since the specimens were placed alongside the fourth slab for the drying phase of the treatment, it can reasonably be assumed that the degree of drying and the subsequent depth of polymer impregnation achieved in the sides of the slabs were similar to those observed in the specimens. No attempt was made to core the sides of the slabs.



Figure 13. PIC zone around 3.0 x 4.0 in. (76 x 102 mm) prism section.

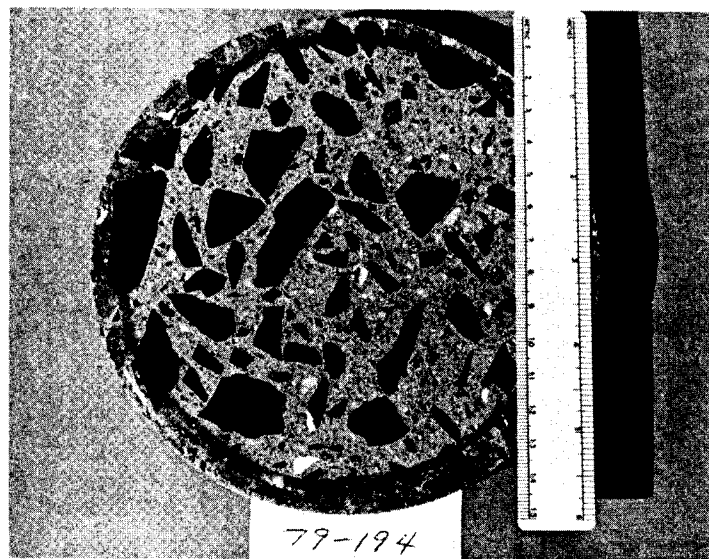


Figure 14. PIC zone around 6.0-in. (152-mm) diameter cylinder section.

Cores were taken from the top surface of each of the polymer impregnated slabs. These cores, measuring 4 in. (102 mm) in diameter, were cut vertically, polished and dried in the same way that the polished specimen sections were handled. Photographs of the core sections are shown in Figures 15, 16, 17 and 18. This arrangement of the cores corresponds to the chronological arrangement of the heating records shown in Figures 5, 6, 7 and 8. It may be observed in Figures 15 through 18 that the average depth of polymer impregnation is 0.25, 0.50, 0.75 and 1.00 in. (6, 12, 18 and 25 mm), for slabs 1, 5, 3 and 6 respectively. These results indicate a gradual improvement in the drying phase, which can be observed in the heating records in Figures 5 through 8, as the operation progressed. The best drying was achieved for the fourth slab, as reflected in the depth of polymer impregnation, and the heating record for this slab should be used as a guide for any further treatments using similar equipment.

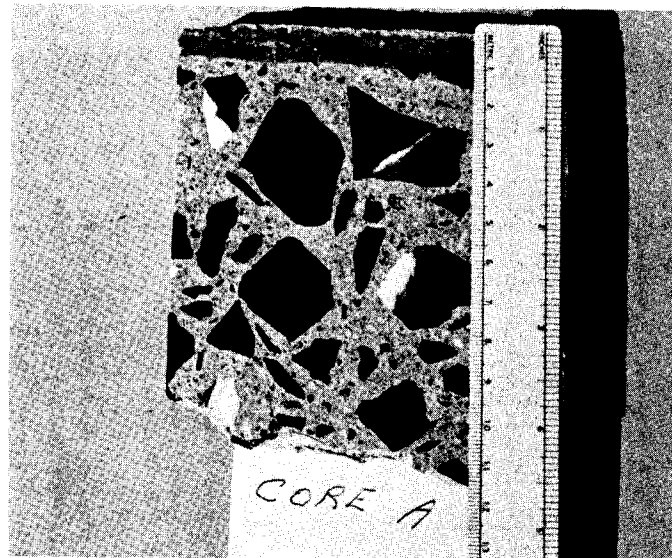


Figure 15. PIC zone in upper portion of core section from slab no. 1.

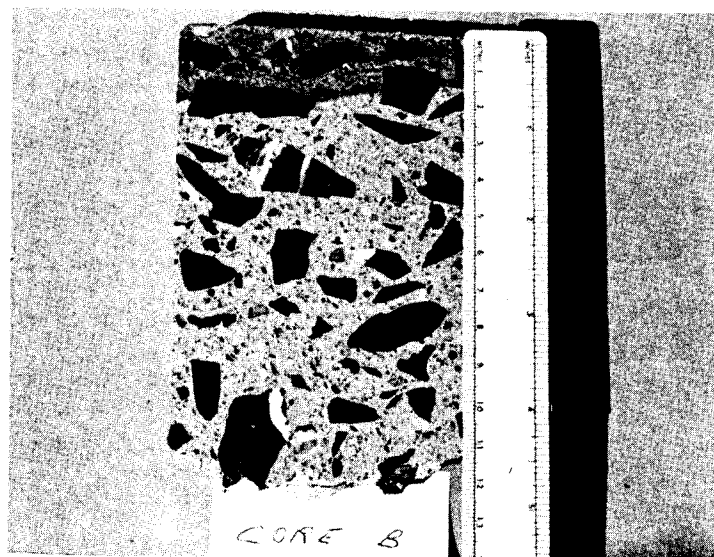


Figure 16. PIC zone in upper portion of core section from slab no. 5.

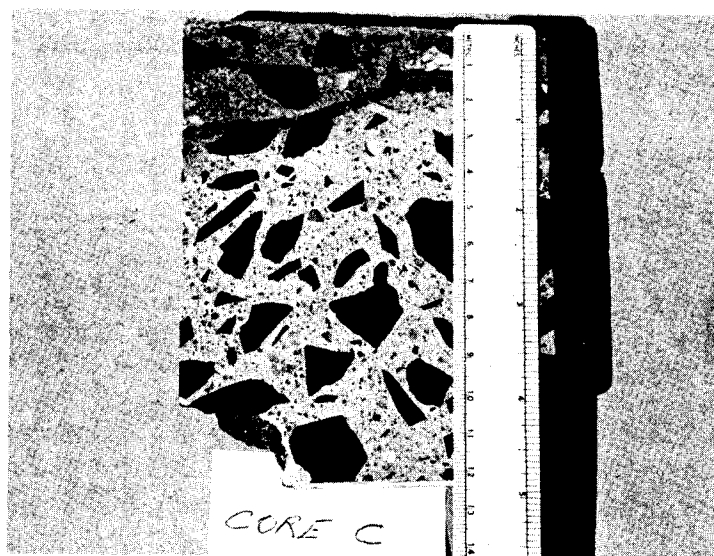


Figure 17. PIC zone in upper portion of core section from slab no. 3

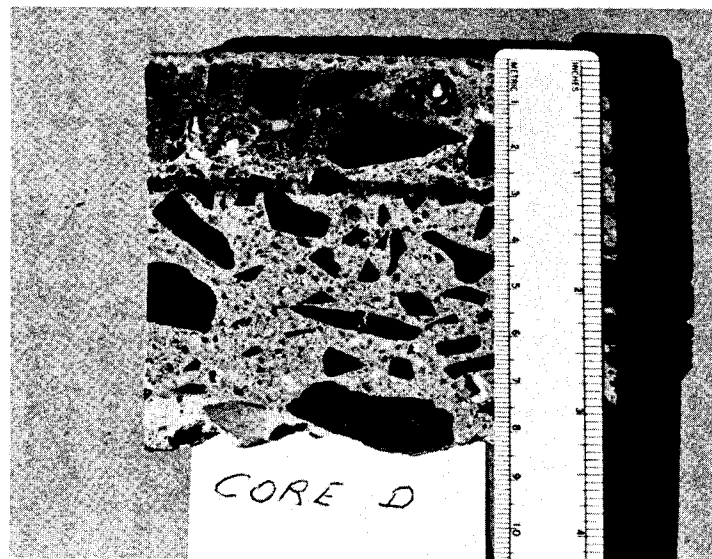


Figure 18. PIC zone in upper portion of core section from slab no. 6.

Compressive Strength

The results of compressive strength tests for 6 in. x 12 in. (152 mm x 305 mm) control cylinders and the cylinders given the polymer treatment are shown in Table 4. The average strength loss of 14%, from 5,550 to 4,730 psi (38.3 to 32.6 MPa), is attributed to the drying process in which temperatures in excess of 200°F (93°C) were attained. This conclusion is reasonable when one considers data from other research in which it was shown that concrete made with a carbonate aggregate lost 10% of its compressive strength when heated to 200°F (93°C).⁽¹⁰⁾

Table 4
Compressive Strength Results

<u>Type Cylinder</u>	<u>Compressive Strength</u>	
	<u>psi</u>	<u>MPa</u>
Control	5,520	38.1
Control	5,550	38.3
Control	5,590	38.5
Avg.	5,550	38.3
PIC	4,510	31.1
PIC	4,860	33.5
PIC	4,810	33.2
Avg.	4,730	32.6

Freeze-Thaw Durability

The resistance of polymer impregnated and control concretes to freezing and thawing cycles was determined in accordance with ASTM C666 Procedure A, modified by the treatment and storage conditions noted earlier. Additionally, the PIC and control specimens were stored in the laboratory at 72°F (22°C) and 50% relative humidity for an additional 2 weeks prior to the beginning of the freezing and thawing tests.

After 79 cycles of freezing and thawing mechanical difficulties were experienced with the testing apparatus and testing had to be suspended for 5 months, during which time the storage conditions were not recorded. These significant variations in the test procedure prevent comparisons of data with those from other laboratories; however, an interpretation of the performance of the PIC specimens is still possible by comparison to the performance of the control specimens. The freeze and thaw test results, after 300 cycles, are summarized in Table 5, where it may be observed that the values for weight loss and relative dynamic modulus are significantly better for both concretes than the failure criteria of 7% (upper limit) and 60% (lower limit), respectively.

Table 5

Average of Freeze-Thaw Test Results

<u>Concrete</u>	<u>Weight Loss, %</u>	<u>Relative Dynamic Modulus, %</u>
Control	2.1	96
PIC	1.4	89

Chloride Penetration

The resistance of PIC and control cylinders measuring 3 in. x 6 in. (76 mm x 152 mm) to the penetration of chloride ions (Cl^-) was determined by soaking the specimens continuously for 120 days in a 2% by weight of water NaCl solution. Additional specimens of each concrete were retained in the laboratory to determine the original or background Cl^- contents of the concretes.

The background Cl^- contents and the amounts of Cl^- penetrating to the 0.5-in. (13-mm) and 1.3-in. (32-mm) depths in the soaked cylinders were determined by titration analysis. Samples for the titration analysis were prepared by first cutting a 0.5 in. (13 mm) thick slab perpendicular to the long axis of the cylinders from the central portion of the specimens. Then 0.5-in. (13-mm) cubes were cut at average depths of 0.5 in. (13 mm) and 1.25 in. (32 mm) from the circular outer boundary of the slabs. This method of sampling had been shown to be effective and reproducible in a previous study.(11)

Core samples were taken from each of the four PIC slabs and two control slabs to determine the amounts of Cl^- that would penetrate these concretes. Since the polymer treatment was applied to the top surface of the cores it was necessary to devise a method of exposing this single surface to Cl^- ponding. A method was devised, as shown in Figure 19, for attaching rubber dikes to the upper portions of the cores so that approximately a 1-in. (25-mm) depth of 2% NaCl solution could be ponded on the top surfaces of the 4-in. (102-mm) diameter cores. The cores were ponded continuously for 90 days. The samples from the cores for chloride analyses were cut from average depths of 0.3 and 0.8 in. (7 and 19 mm) below the central top surface of the cores.

The average Cl^- contents for the cylinders and cores are presented in Table 6. These values, expressed as $\text{lb. Cl}^-/\text{yd.}^3$ ($\text{kg Cl}^-/\text{m}^3$) of concrete, are penetrated quantities, the total Cl^- contents having been adjusted by subtracting the background Cl^- content, which was $0.15 \text{ lb. Cl}^-/\text{yd.}^3$ ($0.09 \text{ kg Cl}^-/\text{m}^3$) of concrete.

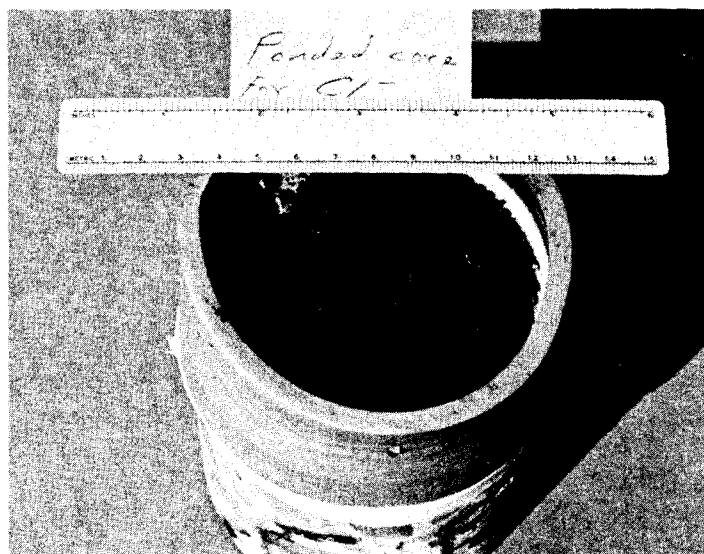


Figure 19. Method for ponding 2% NaCl solution on top surface of cores from PIC slabs.

Table 6

Average Penetrated Chloride Contents of Submerged Cylinders and Ponded Cores, lb. Cl^-/yd^3 (kg Cl^-/m^3) of Concrete

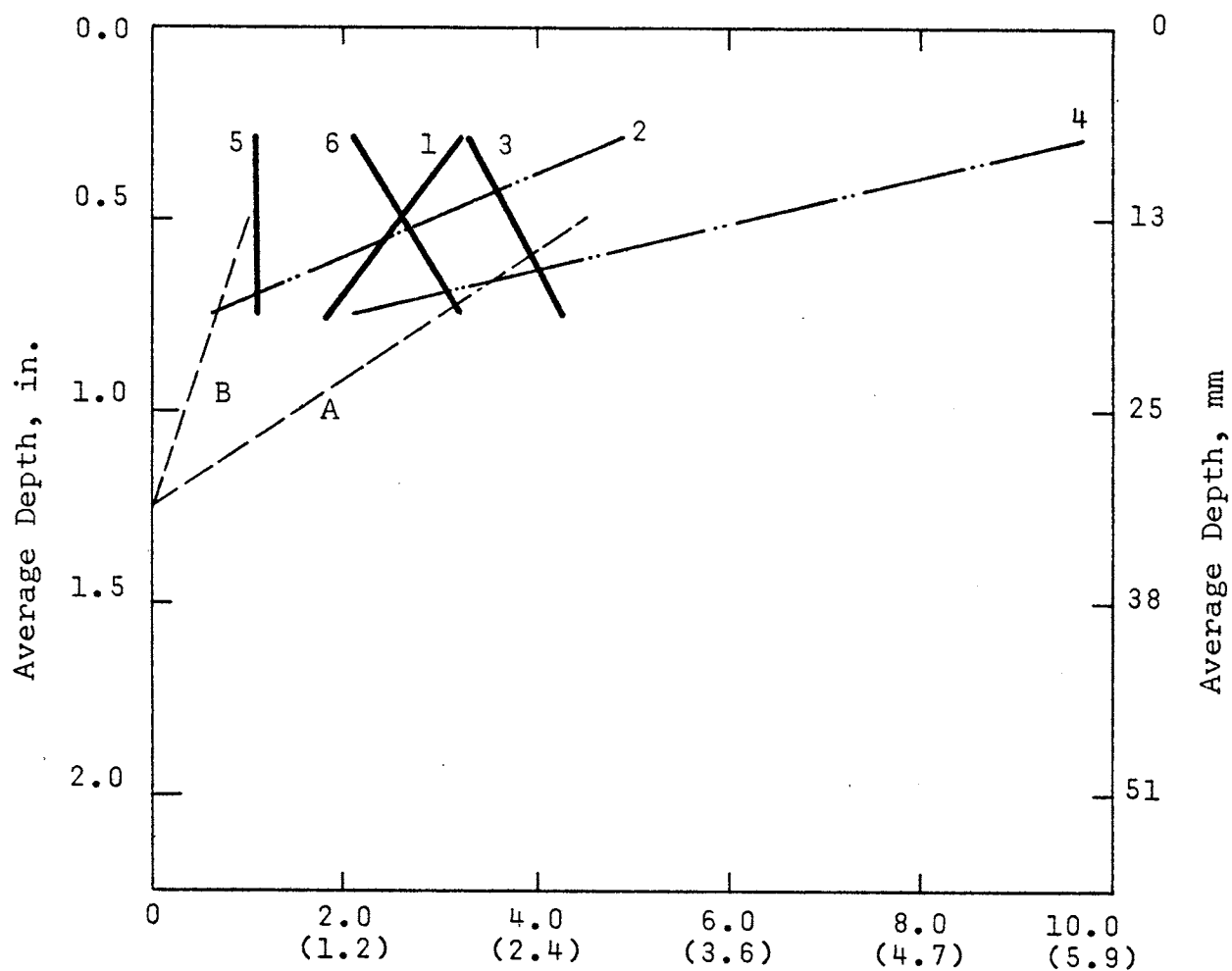
<u>Specimen</u>	<u>Average Sample Depth</u>		<u>Chloride Content</u>	
	<u>in.</u>	<u>mm.</u>	<u>lb. Cl^-/yd^3</u>	<u>kg Cl^-/m^3</u>
Control Cylinders	0.5	13	4.5	2.7
	1.3	32	0.0	0.0
PIC Cylinders	0.5	13	1.0	0.6
	1.3	32	0.0	0.0
Control Cores	0.3	7	7.3	4.3
	0.8	19	1.4	0.8
PIC Cores	0.3	7	2.5	1.5
	0.8	19	2.7	1.6

The information in Table 6 indicates an impressive reduction (fourfold) in the average Cl^- penetration at the shallower sampling depths in the PIC, for both the submerged cylinders and ponded cores, relative to the Cl^- penetration into the control specimens. At the deeper sampling depths, there was no Cl^- penetration into the cylinders; however, there were significant average penetrations into both the control and PIC cores. The average Cl^- penetration at the deeper sampling depth in the PIC cores exceeded that in the control cores by a factor of two, a phenomenon not erstwhile reported.

Because the penetrated Cl^- contents, represented by averages in Table 6, were quite variable among the cores, the same data are represented in graphic form in Figure 20 for individual cores. The plots for cylinders, however, are based on averages of three values since there was relatively little variation among values for replicate specimens of this type.

In Figure 20 the effect of the polymer treatment is still seen to be a reduction of the Cl^- penetration at depths nearest the exposed surfaces of both cylinders (compare upper point of A to B) and cores (compare upper points of 2 and 4 to 1, 5, 3 and 6). However, while the penetrated Cl^- contents for lines 2 and 4 and A and B approach or reach a zero concentration at a depth of approximately 1.0 in. (25 mm), this does not appear to be the general tendency for lines 1, 5, 3 and 6 representing cores from the PIC slabs. The PIC cores, while allowing significantly reduced quantities of Cl^- to occupy the sampling zone near their surface, did not reduce the rate at which the Cl^- reached the lower depth. The chloride penetrations exhibited in Figure 20 for PIC cores from slabs 1, 5, 3 and 6 indicate that despite the beneficial effect of the polymer loading in the upper zone of the concrete, the polymer treatment procedure has introduced a mechanism which counteracts this effect and possibly accelerates the rate of Cl^- penetration at lower depths.

Samples were not obtained in this study for determining the boiling water absorption values for the impregnated and unimpregnated concretes; however, such values from a previous study are given in Table 7.(12) Unimpregnated concretes with normal water-cement ratios are seen to have absorptions of approximately 7.0%. A surface impregnated (PIC) specimen had an absorption of 3.5%, while a totally impregnated specimen had absorption values of 1.0% or less. Future work in the present study should include determinations of absorption values for comparison to those from the previous study to allow a rapid assessment of the relative quality of the polymer treatment.



Penetrated Chloride Content, lb. Cl⁻/yd.³ (kg Cl⁻/m³) of Concrete

- Cores, Control (Slabs 2, 4)
- Cores, PIC (Slabs 1, 5, 3, 6)
- - - Cylinders: A, Control (average of three)
- B, PIC (average of three)

Figure 20. Penetration of Cl⁻ into concretes ponded (cores) with or submerged (cylinders) in 2% NaCl solution.

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Table 7

Boiling Water Absorption Values (From reference 12)

<u>Concrete</u>	<u>Absorption, % weight</u>
Unimpregnated:	
w/c = 0.4	6.4
w/c = 0.5	7.5
Surface impregnated (PIC)	3.5 (1 in. [25 mm] impregnated portion)
Totally impregnated	1.0 (top 1 in. [25 mm]) 0.4 (interior) 1.0 (bottom 1 in. [25 mm])

Microscopic Examination

An examination of polished vertical sections cut through cores from each of the PIC slabs revealed patterns of segmented, and some continuous, microcracks extending from the upper surfaces, plus additional inclined microcracks along the transition zone between the impregnated and unimpregnated depths. In severity of cracking, the ranking from least to most by slab identification numbers was 5, 6, 1, and 3, the same order generally observed in Figure 20 for increasing severity of chloride ion penetration. This agreement strongly suggests that the anomalous Cl^- penetration values for the PIC cores are a function of the observed microcracking.

A summary of the cracks observed in the PIC cores is given in Table 8. Although polished sections of cores from the control slabs were not made for comparison, it seems reasonable, for two reasons, to state that the cracks resulted from the polymer treatment. First, the number of cracks in the core from slab 5, in which the Cl^- penetration was low, totals only 3, whereas each of the others contain significantly greater numbers of cracks. Second, the cracks occur almost entirely in the PIC zones as indicated in Table 8 by the fact that a maximum of 2 cracks was found below the polymer depth in any core.

Table 8
Summary of Cracks in PIC Cores

Order of Treatment	Slab No.	Polymer Depth, in. (mm)	Number of Cracks		
			Total	Below Polymer	Continuous from Surface
2nd	5	0.50(12)	3	0	0
4th	6	1.00(25)	8	1	2
1st	1	0.25(6)	10	2	2
3rd	3	0.75(18)	18	2	1

The importance of the total number of individual microcracks in the matrix versus the number that are continuous from the surface is also apparent in Table 8, recalling that the listing order, 5, 6, 1 and 3, is the order of increasing severity of Cl^- penetration. While the 1 or 2 continuous cracks in three of the cores certainly played a role in allowing Cl^- to penetrate the concrete, the increasing severity of Cl^- penetration clearly appears to be related to the total number of microcracks, which increases from a minimum of 3 to a maximum of 18, in the matrix.

The cracking which occurred during the polymer treatment probably resulted from thermal gradients created during the drying (heating and cooling) phase; however, this cannot be verified from the temperature records. Also, even though the concrete was not subjected to thermal shock, the slow heating rate could have produced significant pore pressures with attendant microcracking.⁽¹³⁾ The polymerization phase must also be considered as a possible time during which at least some of the microcracks originated or were extended, since such cracks existing at the time of the monomer soak might reasonably have been expected to be filled with monomer and subsequently sealed during polymerization.

Regardless of the mechanism for the cracking, the evidence available at this time shows that the cracks are restricted primarily to the polymer impregnated zone, and that after the polymer treatment adequate sealing had not been achieved to prevent unacceptable concentrations of Cl^- from penetrating the concrete.

Additional research directed towards developing field procedures for polymer impregnation should address the problem of cracking. To help identify and eliminate the mechanism or mechanisms for cracking, cores should be taken both before and after the drying phase, as well as after the polymerization phase.

COST INFORMATION

The total cost of fabricating and treating the PIC slabs was \$8,837.32 for materials, equipment, and labor. These costs were funded by the FHWA Implementation Division.

If the cost of reusable materials was distributed over ten such projects, the cost per unit area of PIC bridge deck would be \$283/yd.² (\$338/m²). This cost could be compared with well-documented cost figures for similar bridge widening work performed by state forces in 1976.⁽¹⁴⁾ Using an annual inflation rate of 10% for those costs, and adding the cost of a latex modified concrete protective system, the comparative figure would be \$145/yd² (\$173/m²), which would make the PIC system 1.95 times more expensive than the type construction used in the state force work.

The PIC system could be made significantly less expensive by using thermostatic controls rather than workmen to monitor the heating and polymerization steps. Also, as in any repetitive process, the treatment should be expected to become more efficient with experience. The present major difficulty with the system, however, is in determining how to eliminate the microcracking problem in order to make the system effective.

CONCLUSIONS

The procedure used in this study for producing PIC slabs in a field situation was generally satisfactory from an operational standpoint. The special equipment and facilities required for treatment of the slabs were adapted from items available through established supply sources. Safety requirements for handling the monomer were similar to those associated with ordinary liquid fuels and presented no problems. Training for operators needed to perform the steps of the polymer treatment was minimal and no difficulties would be expected in implementing such procedures in any Virginia Department of Highways and Transportation field office.

The physical characteristics of the PIC were examined and compared to those of the control concrete. A strength loss of 14% attributable to the drying step was observed for the PIC cylinders; however, the residual strength was well above the level required for this class of concrete. The freeze-thaw durability of the PIC was essentially equal to the excellent durability of the control concrete. The average maximum depth of polymer impregnation achieved for a slab was 1.0 in. (25 mm); however, the impregnated zone was found to contain a series of discontinuous microcracks resulting from the polymer treatment. These cracks allowed Cl⁻ penetrations at a depth of 0.8 in. (19 mm) equalling or exceeding those at this depth in the control concrete.

The cost of this operation per unit of surface area for the slabs treated was quite high. However, if the treatment could be modified to eliminate the microcracking problem and produce the intended protective system, the cost per unit of surface area to protect several small bridges each year would be competitive with that of other protective systems.

PIC cannot be recommended as a protective system for bridge slabs at this time. Additional research using experimental slabs should seek to eliminate the microcracking problem associated with the impregnated zone. In addition to the testing performed in the present study, cores for microscopic examination should be removed from treated slabs before and after each step of the procedure. Companion cores should be used to determine such characteristics of the concrete as Cl^- penetration and boiling water absorption.

RECOMMENDATIONS

On the basis of information presented in this report the following recommendations are made.

1. PIC should not be implemented as a protective system for bridge slabs at this time.
2. Additional research should be conducted with experimental slabs in an effort to eliminate the microcracking associated with the impregnated zone.
3. The cost per unit of treated surface area to protect several small bridges each year would be competitive with that of other protective systems, and the use of PIC should be considered contingent upon the findings from research as suggested in recommendation 2 above.

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APPENDIX

LIGHTWEIGHT AGGREGATE PIC CYLINDERS

A total of 18 lightweight concrete cylinders measuring 6 x 12 in. (152 x 305 mm) were available at the time of the polymer treatment for the slabs included in this study. The lightweight concrete cylinders were provided by George C. Koss of the Solite Corporation. Mixture proportions for the lightweight concrete are listed in Table A-1.

Table A-1

Mixture Proportions for 1 yd.³ (1 m³) of Lightweight Concrete

<u>Ingredient</u>	<u>Weight</u>	
	<u>lb/yd.³</u>	<u>kg/m³</u>
Cement (Type II)	611	363
Lightweight Coarse Aggregate	850	505
Sand	1,415	839
Water	325	193

The cylinders were cast approximately 60 days prior to the polymer treatment. Even though their curing history was not documented, they were stored in a moist environment for the final 14 days prior to the polymer treatment. The testing program for control and PIC lightweight cylinders is given in Table A-2.

Table A-2

Testing Program for Lightweight Concrete Cylinders

<u>Test</u>	<u>Lightweight Samples</u>	<u>Number of Cylinders</u>
Compressive Strength	Control	3
	PIC	3
Background Cl ⁻ and Microscopic Examination	Control	3
	PIC	3
Penetrated Cl ⁻	Control	2
	PIC	3

The examination of polished sections cut from the cylinders revealed an impregnation depth for the polymer of approximately 0.10 in. (3 mm). This is significantly less than the polymer depths of 0.25 to 0.40 in. (6 to 10 mm) which were observed in the specimens of normal weight concrete. The difference between depths of impregnation in the lightweight and normal weight concrete specimens would most logically be the result of differences in the amount of moisture removed from each during the drying phase. The lightweight cylinders were heated in the drying enclosure with slab 3 and the normal weight specimens with slab 6, for which the temperature records are shown in this report in Figures 7 and 8, respectively. While an improvement in the drying phase was noted for slab 6 as compared to slab 3, this would not appear to account fully for the shallower polymer penetration in the lightweight cylinders. The lightweight cylinders may have had a higher initial moisture content and this would have adversely affected the drying depth for the heating period that was provided. Absorption tests were not performed for this concrete; however, it is known that lightweight concretes may show markedly higher levels of water absorption than normal weight concretes.*

The compressive strength test results for lightweight concrete cylinders with and without the polymer treatment are given in Table A-3, where it can be seen that no significant change in strength occurred.

Table A-3

Compressive Strength Results for Lightweight Cylinders

<u>Type Cylinder</u>	<u>Compressive Strength</u>	
	<u>psi</u>	<u>MPa</u>
Control	3,500	24.2
Control	3,750	25.9
Control	3,570	24.6
Average	3,610	24.9
PIC	3,470	24.0
PIC	3,590	24.8
PIC	3,570	24.6
Average	3,540	24.6

*Guide for Structural Lightweight Concrete, ACI Report 213R-79, American Concrete Institute, 1979, p. 18.

The control and PIC lightweight cylinders used for measuring amounts of penetrated Cl^- were continuously submerged, sampled, and analyzed as described in this report for normal weight concrete specimens, with the exception that an additional average sampling depth of 2 in. (51 mm) was used. The average penetrated Cl^- contents of the submerged lightweight cylinders are listed in Table A-4. The background Cl^- content of this concrete was $0.06 \text{ lb. Cl}^-/\text{yd.}^3$ ($0.04 \text{ kg Cl}^-/\text{m}^3$) of concrete.

Table A-4

Average Penetrated Chloride Content of Submerged
Lightweight Concrete Cylinders, $\text{lb. Cl}^-/\text{yd.}^3$ ($\text{kg Cl}^-/\text{m}^3$)
of Concrete

Specimen	Average Sample Depth		Chloride Content	
	in.	mm	$\text{lb. Cl}^-/\text{yd.}^3$	$\text{kg Cl}^-/\text{m}^3$
Control	0.5	13	5.3	3.1
	1.3	32	0.3	0.2
	2.0	51	0.1	0.1
PIC	0.5	13	1.0	0.6
	1.3	32	0.1	0.1
	2.0	51	0.0	0.0

The average penetrated Cl^- contents in Table A-4 show a substantial reduction at the 0.5 in. (13 mm) sampling depth from 5.3 to 1.0 $\text{lb. Cl}^-/\text{yd.}^3$ (3.1 to 0.6 $\text{kg Cl}^-/\text{m}^3$) of concrete for the lightweight control concrete and PIC, respectively. A comparison of data in Table A-4 to lines A and B for normal weight concrete cylinders in Figure 20 of this report shows that the results for the lightweight and normal weight concretes are nearly identical, with and without the polymer treatment, respectively. Therefore, as regards the submersion test for Cl^- penetration, the 0.10 in. (3 mm) polymer depth in the lightweight concrete cylinders afforded protection comparable to the 0.25 to 0.40 in. (6 to 10 mm) polymer depth in the normal weight concrete cylinders.