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REPORT

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USE OF POLYMERS IN HIGHWAY CONCRETE

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT

190

USE OF POLYMERS IN HIGHWAY CONCRETE

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WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

BRIDGE DESIGN
CONSTRUCTION
GENERAL MATERIALS
MAINTENANCE, GENERAL

TRANSPORTATION RESEARCH BOARD
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WASHINGTON, D.C. 1978

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors. Each report is reviewed and processed according to procedures established and monitored by the Report Review Committee of the National Academy of Sciences. Distribution of the report is approved by the President of the Academy upon satisfactory completion of the review process.

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FOREWORD

*By Staff
Transportation
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This report is recommended to materials engineers, maintenance engineers, construction engineers, and bridge design engineers engaged in combating the problem of premature deterioration of concrete bridge decks. In the research described, laboratory studies and field trials were combined to demonstrate the feasibility of polymer impregnation of concrete bridge decks from the upper surface to depths that will encase the top layer of reinforcement to arrest or prevent spall- and pothole-causing corrosive action. Impregnation equipment used in the field trials was smaller than would be needed in a commercial application, but shows potential for scale-up. The report contains a field manual that will be useful to anyone who may want to explore further the practical use of the polymer impregnation process.

The search by highway engineers for positive means of preventing the serious spall and pothole damage in bridge decks that is caused by corrosion of the reinforcing steel has led to examination of a wide and diverse variety of potentially corrective and preventive measures. Among these are waterproofing membranes and mastics, polymer-modified concretes, dense concretes, cathodic systems to protect the steel, and plastic coating of the steel. None to date has achieved universal success, one reason being that the degree of salt contamination that exists in the concrete at the time the control measure is applied has a strong influence on success. This research was directed primarily at finding a means for protecting bridge decks that have become salt-contaminated but do not yet show outward signs of deterioration.

In the study reported herein, the researchers first demonstrated in the laboratory that polymer impregnation of structurally sound, typically salt-contaminated concrete could be achieved to considerable depth provided the concrete is brought to a bone-dry condition. It was shown also that impregnation arrested corrosion of the reinforcing steel, virtually eliminated freeze-thaw damage, and substantially increased resistance of the concrete to chemical attack. Water absorption and loss by abrasion were decreased severalfold. With promising results having been achieved in the laboratory, activity was transferred to the field where demonstration projects were carried out on two bridge decks, both structurally sound and one severely salt-contaminated. Using gas-fired infrared heaters for drying the concrete, moderate pressure to aid monomer impregnation, and hot water to cause polymerization, it was demonstrated that deep (up to 4 in. [10cm]) polymer impregnation could be achieved under field conditions. The equipment and techniques developed for the demonstrations are of a nature to permit scaling up for practical use. This research employed a methyl methacrylate mixture, although other monomer systems probably can be used.

Deep polymer impregnation is costly (estimated by the researchers at about

\$6 or \$7 per sq ft [\$65 or \$70 per m²] on a commercial basis at current prices). However, situations may well exist where it can be the least-cost alternative if experience shows that use of the process will extend appreciably the service lives of treated bridge decks. Before it can receive recognition as a standard means of deck protection, however, more must be known about such matters as the effect of the high temperatures involved in the drying process (600° F [316° C] at the surface) on the concrete materials and structural performance, and the practicability of using the highly volatile and flammable monomer in the field construction situation, especially when traffic is allowed to use the deck during treatment.

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USE OF POLYMERS IN HIGHWAY CONCRETE

SUMMARY

The major research finding described in this report demonstrated the technical feasibility of field impregnation of structurally sound, salt-contaminated concrete bridge decks with polymer to a depth of 4 in. (10 cm). Following preliminary small-scale field trials in two different locations, using two drying methods and two impregnation methods, the most promising combination was selected and demonstrated in three larger scale trials. The techniques and principles used are applicable to commercial-scale application, and, although the equipment used was smaller than that proposed for commercial-scale applications, it can be scaled-up readily. The specific findings for the various research areas are detailed as follows.

MONOMER SELECTION

All field trials used a 90:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture containing a 0.5 percent azobisisobutyronitrile initiator. Despite the flammability and vapor pressure of this monomer mixture, it was handled safely without hazard in the field trials. It is likely that any other monomer system produced by future research can also be handled safely—provided its physical, chemical, fire hazard, and health hazard properties are known.

DRYING METHODS AND CRITERIA

Concrete can be impregnated with monomer to any desired depth provided it is dried to that depth. The time required for drying depends on the heating rate and surface temperature attained.

In order to achieve impregnation to the specified depth, the concrete must be heated until the temperature at the specified depth is 230 F (110 C), assuming the deck can withstand the associated thermal stresses. The application of heat to the surface of the concrete must not permit surface temperatures to exceed 500 F (260 C) during the first hour, and should not be permitted to go above 675 F (375 C) at any time. Gas-fired infrared heaters were found to be the most efficient means of drying the concrete, although torches may also be used.

IMPREGNATION METHODS AND CRITERIA

Field impregnation of dried concrete substrates have been carried out at atmospheric and greater-than-atmospheric (30 psig (207 kPa)) pressure. Since the time required for impregnation varies directly with the square of the desired depth of impregnation and inversely with the square of the applied pressure, pressure impregnations are preferred for field use. A pressure-impregnation chamber covering a 3- x 12-ft (0.91- x 3.66-m) area was developed and used for the field impregnations.

POLYMERIZATION

The 90:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture containing 0.5 percent azobisisobutyronitrile was polymerized *in situ* to high conversions (as indicated by lack of monomer odor) at 158 to 185 F (70 to 85 C). The heating was accomplished by pumping hot water through the pressure impregnation chamber.

EFFECT OF ROADWAY SURFACE CONTAMINANTS

Salt contamination in the concrete substrate was found to decrease the drying rate, impregnation rate, and over-all monomer loading, but not to such an extent that the feasibility of the method was affected. Polymer impregnation immobilizes the salt in the concrete matrix and thus lessens its corrosive effects. Organic surface contaminants are removed by high temperature drying procedures. Polymerization is retarded by surface contaminants at polymerization temperatures of 131 F (55 C) or below, but not at polymerization temperatures above 158 F (70 C).

MECHANICAL PROPERTIES AND DURABILITY

Polymer impregnation of typical bridge deck concrete from the traffic surface, using the foregoing monomer mixture, gave a threefold increase in compressive strength and a twofold increase in split-tensile strength; impregnation of similar concretes and mortars gave a sixfold decrease in the rate of salt penetration and a sevenfold decrease in water absorption and loss by abrasion. Moreover, impregnation of structurally sound, salt-contaminated concrete with the same monomer mixture arrested the corrosion of the reinforcing steel, virtually eliminated freeze-thaw damage, and dramatically increased resistance to chemical attack (etching with hydrochloric acid). The present work also showed that the mechanical properties of polymer-impregnated concrete can be varied systematically by the choice of the monomer; e.g., from a ductile material of strength only slightly greater than that of the control (butyl acrylate) to a very strong, hard, brittle material (methyl methacrylate). Copolymerization of methyl methacrylate-butyl acrylate gives an optimum combination of properties. Preliminary tests of skid resistance after 13 months of service indicated no significant effect of impregnation.

ECONOMICS OF POLYMER-IMPREGNATION OF BRIDGE DECKS

Polymer-impregnated concrete offers an economical solution to the deterioration of concrete highways and bridge decks because of its longer service life and reduced maintenance costs.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

Corrosion of the reinforcing steel and the resulting deterioration of the concrete bridge decks is universally recognized as a critical maintenance problem facing highway agencies today. Highway departments in the United States now spend \$70 million each year on bridge deck repairs, and this amount is expected to "skyrocket" in the future (1). Moreover, the traffic obstruction from reconstruction and repair of deteriorated bridge decks causes inconvenience and expense to highway users. The deterioration is the result of a complex interaction between freezing and thawing, differential expansion and contraction, corrosion of reinforcing steel, chemical attack, high traffic loads, and wear. Concrete, in turn, has deficiencies such as high permeability to water and salt solutions; low strength; high wear rate; and a pronounced tendency to crack, spall, and

hasten deterioration. There is, indeed, a need for concrete with better mechanical properties and corrosion resistance.

Impregnation of concrete with polymers gives promise of improving the mechanical properties and corrosion resistance of the highways and bridge decks already in service. This concept was first demonstrated in the laboratory by the Brookhaven National Laboratory in conjunction with the U.S. Bureau of Reclamation and the Federal Highway Administration (2-7); it was later developed and extended by the University of Texas (8), the present authors (9-12), and others. The original laboratory technique comprised impregnation of previously cured concrete by evacuation to remove air and moisture, infusion with monomer, and polymerization with γ rays from Co^{60} or free-radical initiators. Extension of this technique to field use by substituting surface drying methods for the

evacuation gave only shallow penetrations of monomer (1 in. (2.5 cm) or less). The purpose of the work reported here was to develop the concept of polymer-impregnated concrete for application in the field, where the desired depth of impregnation (4 in. (10 cm)) is sufficient to envelop the top layer of reinforcing steel.

OBJECTIVES

The over-all objective of this research was to develop material systems and application techniques for the practical application of polymer-impregnated concrete to highway bridge decks. Specific technical objectives included:

1. Selection of the monomer system.
2. Development of field techniques and apparatus for surface impregnation of the concrete using the selected monomer system—with the apparatus of appropriate size for field use on bridge decks, but not necessarily as large as would be used in commercial-scale impregnations.
3. Evaluation of the effectiveness of the impregnation techniques in terms of (a) properties and condition of the concrete substrate; (b) preparation of the concrete substrate for impregnation; and (c) properties of the polymer-impregnated concrete (especially durability, skid resistance, abrasion resistance, strength, permeability, etc.).
4. Field demonstration of the impregnation techniques on one or more bridge decks, followed by evaluation tests (see item 3(C)), with the goal of 4-in. (10-cm) impregnation of a structurally sound, salt-contaminated bridge deck.

RESEARCH APPROACH

The research was carried out by an interdisciplinary team comprised of faculty members of Lehigh University and The Pennsylvania State University, with supplemental

support from the Pennsylvania Science and Engineering Foundation (PSEF) and the cooperation and assistance of the Pennsylvania Department of Transportation (PennDOT).

The research approach was based on an interdisciplinary team effort in which the backgrounds and expertise of the team members were brought to bear on the various phases of the problem. These backgrounds included surface chemistry, polymer chemistry, materials science, and civil engineering—all of importance to the solution of the problem. Despite the fact that the work was carried out at two locations 200 mi (322 km) apart, duplication of effort was minimized and the efficient use of the team members' expertise was maximized. Close liaison was maintained not only between the two collaborating groups, but also with government laboratories and agencies, universities, and companies working in the same field.

The research objectives were pursued in four phases:

1. A comprehensive literature search on polymer-modified concrete was carried out to produce a state-of-the-art review, which has been updated and included as an annotated bibliography (Appendix A).
2. Laboratory investigations were carried out on the selection of the monomer system, drying of the concrete, impregnation of the dried concrete, polymerization of the monomer *in situ*, and determination of mechanical properties of the composite, particularly with relation to field application (Appendixes B through G).
3. Field trials based on the laboratory investigations were carried out to demonstrate the feasibility of polymer impregnation of highway bridge decks (Appendix H).
4. A field manual for polymer impregnation of bridge decks was prepared, based on the successful field trials (Appendix I).

CHAPTER TWO

RESEARCH FINDINGS

LITERATURE SEARCH

The search of the literature and consultation with other investigators yielded much information on the preparation and evaluation of polymer-impregnated concrete in the laboratory, but little if any on the impregnation to a depth of 4 in. (10 cm) in the field.

The literature described the laboratory impregnation of concrete with various monomers and the remarkable improvement in such properties as tensile and compressive strengths, Young's modulus, and resistance to sulfate and chloride ions, according to the composition and concentration of the monomer. The only field work described was that done by the Brookhaven National Laboratory on badly deteriorated bridge decks, in which the penetration of monomer into the very porous substrates presents few problems, and the University of Texas on new bridge decks, in which

the goal was a shallow penetration of only about 1 in. (2.5 cm).

Specifically, the literature contained little reference to: (1) the one-sided drying of concrete slabs at temperatures high enough to complete the drying within a reasonable time; (2) the rate of penetration of fluid monomers and prepolymers into the concrete substrate; (3) the laboratory or field impregnation of structurally sound concrete to a depth greater than 1 in. (2.5 cm) without the use of vacuum for moisture removal; and (4) the ability of the polymer to immobilize the salt already in the concrete and thus retard the corrosion of the reinforcing steel.

MONOMER SELECTION

The properties that determine the effectiveness of a monomer in polymer-impregnated concrete are its vis-

cosity, surface tension, and ease of polymerization *in situ* to a high molecular weight conversion. Earlier work used methyl methacrylate and, to a lesser extent, styrene, styrene-polyester, and styrene-acrylonitrile mixtures, either alone or in combination with crosslinking monomers.

The advantages of methyl methacrylate are its very low viscosity and its tendency to undergo rapid autoaccelerating polymerization in bulk. This autoaccelerating polymerization, which is enhanced by the presence of crosslinking monomers, gives high conversions in a short time, once the polymerization is initiated and an adequate heat flux is maintained by heating from one surface.

The disadvantages of methyl methacrylate are its flammability, low flash point, high vapor pressure, relatively high cost, slight toxicity, and slightly irritating character.

In the present work, many laboratory experiments and all field trials used a 90:10 or 100:10 methyl methacrylate-trimetholpropane trimethacrylate mixture containing a 0.5 percent azobisisobutyronitrile initiator. This mixture penetrated into the concrete without complication and polymerized rapidly to high conversions at 167 to 185 F (70 to 85 C). When broken open, the polymer-impregnated concrete specimens exhibited no detectable monomer odor, and showed high tensile and compressive strengths, excellent freeze-thaw resistance, and greatly decreased permeability to water and salt solutions. Safe handling procedures were developed to cope with all the hazards and disadvantages (except high cost).

The present work also showed that the properties of polymer-impregnated concrete can be altered systematically by varying the composition of the monomer mixture. For example, methyl methacrylate, which polymerizes to a hard, brittle polymer, especially when crosslinked, gives polymer-impregnated concrete of much greater strength and higher modulus than the unmodified concrete, but shows no ductility—it fractures without warning (unacceptable to engineers as a material of construction). In comparison, butyl acrylate, which polymerizes to a soft, rubbery, elastic-type polymer, gives polymer-impregnated concrete of strength and modulus only slightly greater than unmodified concrete, but shows great ductility before fracture. Copolymerization of methyl methacrylate (MMA)-butyl acrylate (BA) mixtures gives polymer-modified concrete that combines high strength with adequate ductility.

Although it has been demonstrated that the properties of polymer-impregnated concrete can be varied systematically, it has not been determined what properties are needed for durability and minimum cost in the highway application requiring improvements in durability rather than strength. It is speculated that continual freezing and thawing would eventually damage the adhesive bond between the polymer and cement paste phases, leading to penetration by water and salt and eventual deterioration. This polymer-cement bond would be expected to be more durable if the polymer were rubbery and elastic rather than hard and brittle. However, there are no long-term freeze-thaw or durability studies, to date, to resolve this point; preliminary studies with mortar indicate that the hard polymer PMMA confers greater resistance to salt penetration than the soft polymer PBA.

The cost of the monomer cannot be disregarded; the

material costs of bridge-deck impregnation are estimated to be greater than the labor costs for pressure impregnation, but less for ponding. There are several liquid vinyl monomers—styrene, vinyl acetate, vinyltoluene, acrylonitrile, vinylidene chloride—that are lower in cost than methyl methacrylate, and several acrylate esters that are about the same cost. All of these can be polymerized in bulk at reasonable polymerization rates, especially in combination with crosslinking monomers.

DRYING STUDIES

Drying the concrete is one of the most important and difficult steps in the impregnation process. The monomer cannot penetrate into concrete pores that are filled with water. The concrete in highways and bridge decks must be considered as saturated with water. Earlier work (13) showed that, even after a long period of dry weather, the water content of concrete at a depth greater than 1 in. (2.5 cm) is 60 to 70 percent of the saturation value, and under ordinary conditions it is 90 to 100 percent of the saturation value. This means that the drying must be exhaustive to achieve a 4-in. (10-cm) impregnation, but need be only cursory for an impregnation of 1 in. (2.5 cm) or less.

Various Drying Methods

Several drying methods were studied in the laboratory, and two of these were tested in the field to determine their effectiveness and economy. The methods studied in the laboratory included kerosene-fired and electrically heated blowers, infrared and microwave radiation, direct flame heating, and electro-osmotic and electrical-resistance drying.

The electro-osmotic method, which does not increase the temperature of the concrete significantly, did not remove the water from the pores completely because the conductive current path was lost after only part of the water was removed. Electrical-resistance drying failed for the same reason. The hot-air drying methods did not dry the concrete to a depth sufficient for 4-in. (10-cm) impregnation, because they failed to produce sufficiently high surface temperatures.

Only the propane gas-fired torch, gas-fired infrared, microwave radiation, and hot-air oven drying methods were effective in drying the concrete to the desired depth. Microwave radiation proved to be the fastest method; however, its large power requirement, the unavailability of units large enough for field applications, and inherent safety hazards precluded considering it for this program. Similarly, hot-air oven-drying, although a useful laboratory method, is not practical for field applications. Therefore, the gas-fired torch and gas-fired infrared methods offered the most promise of successful application in the field.

Drying Criteria

Gas-fired torch and gas-fired infrared drying methods were tested in the laboratory to establish the criteria for drying. These studies used 72-in. x 72-in. x 6-in. (1.83-m x 1.83-m x 0.15-m) or 72-in. x 72-in. x 8-in. (1.83-m x 1.83-m x 0.20-m) reinforced concrete slabs with embedded thermocouples and moisture gauges to measure the tem-

perature and humidity at various positions and depths. It was found that surface temperatures of 600 F (316 C) or higher were required to dry the concrete to a depth of 4 to 6 in. (10 to 15 cm) within a reasonable time (4 to 6 hr). These high surface temperatures produced temperature gradients that cracked some of the unrestrained laboratory slabs. However, severe cracking did not occur on bridge decks. This cracking was somewhat avoided in the laboratory by spreading a 1-in. (2.5-cm) layer of sand on the concrete surface and keeping the rate of temperature increase below 100 F (38 C)/hr until the surface temperature reached 600 F (316 C). A temperature of 230 F (110 C) at a 4-in. (10-cm) depth was taken as the criterion for complete drying. This temperature was reached after 4 to 6 hr at surface temperatures of 600 F (316 C) or greater, and was adopted as the drying criterion in the field trials.

Later work with slabs indicates that moisture is lost both during the heating cycle and also after the heating is stopped and the concrete is cooling to ambient temperature. Thus, the moisture may be removed more efficiently by heating the concrete to a surface temperature of 600 to 700 F (316 to 371 C), allowing it to cool, and then reheating before the surface temperature drops below 100 F (38 C). This heating-and-cooling sequence would allow the drying of a larger area at the same time.

Field Drying

The drying tests in the field (PSU test track) gave results consistent with laboratory experience. The concrete bridge deck surfaces were veined with microcracks and macrocracks, which opened up when the surface was heated to high temperatures, but closed when the surface was cooled. The impregnation healed all but the largest of the macrocracks. One deep crack was observed in one field trial. In the large-scale trials (3- x 12-ft areas) using infrared heating, which did not use the sand layer, only shallow surface crazing was observed, with no evidence of delamination of the concrete from the reinforcing steel. The high temperature drying methods were effective in removing oil and grease contamination from the deck surface.

IMPREGNATION STUDIES

Several basic and applied studies were carried out to develop impregnation methods. The basic studies determined the variation of the rate of penetration with time and pressure, as well as the variation of the depth of impregnation with drying conditions. The applied studies comprised the development and testing of procedures and equipment to impregnate concrete slabs in the laboratory and, finally, bridge decks in the field.

Rate of Impregnation

The rate of penetration of monomer into dried concrete substrates followed in part the Rideal-Washburn equation (14), which predicts that the depth of penetration should vary directly with the product $(\gamma t / \eta)^{1/2} \Delta P^{1/2}$, where γ and η are the surface tension and viscosity, respectively, of the monomer; t the time; and ΔP the pressure differential. In this work, however, the rate varied with ΔP , not $\Delta P^{1/2}$ (11).

Therefore, for a given depth of impregnation, doubling the pressure reduces the time fourfold, and, for a given pressure differential, doubling the desired depth of impregnation quadruples the time required. Thus, significant reductions in impregnation time can be achieved by (1) relatively small increases in ΔP and (2) relatively small decreases in the desired depth of impregnation.

Drying Requirements for Impregnation

Concrete mortar specimens with various moisture concentrations were impregnated with the 90:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture containing a 0.5-percent azobisisobutyronitrile initiator. Monomer loadings up to 90 percent of that achievable in completely dried specimens were obtained with moisture contents as high as 20 percent of the saturation value. Therefore, acceptable monomer loadings can be obtained without drying the concrete completely. This is believed due to the fact that some of the water removed is "inter-layer" water in the calcium-aluminum silicates forming the cement paste. Because of the larger molecular sizes and nonpolar nature of the monomer molecules, the monomer does not enter the interlayer regions to an appreciable extent.

Atmospheric-Pressure Impregnation

The simplest impregnation method is atmospheric-pressure impregnation, or "ponding." Although this method requires a much longer time than pressure impregnation to achieve a given depth of impregnation, the size of the area that can be impregnated at one time is virtually unlimited. It is necessary only to provide a suitable container and a vapor-tight cover for the monomer. The time required to impregnate to a given depth is up to four times longer using "ponding" than using pressure impregnation at 15 psig (103 kPa); however, it is possible (in principle) to "bond" an area more than four times greater at one time. The monomer loading is usually slightly less with ponding than with pressure impregnation.

Pressure Impregnation

The impregnation times can be reduced sharply by application of modest pressures; e.g., in the first small-scale field trial, impregnation with the methyl methacrylate monomer mixture to a 4-in. (10-cm) depth can be achieved in about 8 hr using 15 psig (103 kPa) pressure. Such pressure impregnations are easily accomplished in the laboratory; however, this method presents serious problems in field applications, especially in commercial-scale operations. First, it is difficult to seal the edges of the pressure-impregnation device to the bridge deck surface because of its rough surface finish, wear in the wheel paths, and surface deterioration. Second, even modest pressures applied over areas large enough to be considered commercial scale result in the application of very large forces, and it is not possible to hold down even small impregnation units with weights; e.g., an impregnation unit covering a 10-ft x 12-ft (3.0-m x 3.7-m) area at 15 psig (103 kPa) would require a hold-down force greater than 130 tons (1160 kN), which would exceed the load-carrying capacity of the bridge superstructure. Therefore, two bolt-down impregnation

units were developed and built: the first covering a 16-in. (41-cm) diameter circular area and the second covering a 3-ft x 12-ft (0.9-m x 3.7-m) area. Both worked very well—the smaller unit in the laboratory and the first field trial, and the larger in the last two field trials. Moreover, the larger unit is amenable to scaling-up to commercial size. However, because of the strengthening and stiffening requirements, the weight of such an impregnation unit would increase sharply with increasing size (area covered) and pressure. Additionally, it would require holes drilled in the deck for installing tie-down bolts.

From the standpoint of simplicity, low cost, and ease of application, a pressure-mat impregnation unit offers more promise than the bolt-down impregnation units. Pressure-mat impregnation units were designed, built, and used to impregnate 24-in. x 24-in. x 6-in. (61-cm x 61-cm x 15-cm) concrete slabs in the laboratory. This unit comprises a flexible rubber mat with a cellular pattern on the side facing the concrete; pressure is applied to the top of the mat rhythmically, using a roller or hydraulic loading mechanism, so that each cell becomes, in effect, a small pressure impregnation chamber. The unit worked very well in the laboratory, but requires more development before use in field applications.

Choice of Impregnation Method

Both the ponding and pressure-impregnation methods have been demonstrated to be feasible in field applications. The ponding method was used successfully in the first field trial, and the two different pressure-impregnation units were used in all three field trials. The ponding method requires a much longer time for impregnation to a given depth, but can, in principle, be used over a large area. The pressure-impregnation method requires shorter times, but the area that can be impregnated at one time is limited by the weight of the unit and the tie-down mechanism. A detailed cost analysis is needed to decide which of the two methods is better for a given case.

MECHANICAL PROPERTIES AND DURABILITY

Concrete slabs (non-air-entrained type) were impregnated from one side with the 90:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture. The mechanical properties and durability of core specimens from these slabs were compared with those of typical high-quality concrete used in bridge decks. The properties measured were those of significance to the bridge-deck deterioration problem—i.e., tensile and compressive strengths, permeability to water and salt solutions, freeze-thaw resistance, protection of reinforcing steel against corrosion, resistance to chemical attack, abrasion resistance, and skid resistance.

Strength

The core specimens from the slabs showed twofold greater split-tensile and threefold greater compressive strengths than the unmodified control specimens. Young's modulus was not determined for these specimens, but comparable polymer-impregnated concrete cylinders showed a 70 to 100 percent increase in the value of E . Stress-strain

curves of the core specimens showed a higher modulus than the control and brittle fracture without warning. The laboratory cylinders showed that this brittle fracture could be avoided by the addition of butyl acrylate to the monomer mixture, which gave ductile fracture at the expense of only a modest decrease in ultimate strength.

Permeability to Water and Salt Solutions

Mortar specimens showed a 76 to 92 percent reduction in water absorption relative to the unmodified control specimens. After one month's exposure to 8-percent aqueous calcium chloride BA- and MMA-impregnated mortar solution, specimens showed only traces (0.1 percent) of total chloride ion at a depth of 0.25 in. (0.64 cm) and none at all below 0.50 in., in comparison with the 1.6 percent and 0.5 percent found for the unmodified control specimens at 0.25 (0.64 cm) and 1.50 in. (3.81 cm), respectively. After one year's exposure, the MMA-impregnated specimen showed 0.3 percent total chloride ion at the 0.25-in. (0.64-cm) depth, about 0.1 percent at a depth of 0.5 in. (1.27 cm), and undetectable amounts at lower depths, in comparison to 5.5 percent and 0.6 percent at 0.25 in. (0.64 cm) and 1.50 in. (3.81 cm), respectively, for the control specimens and 1.8 percent and 0.1 percent at 0.25 in. (0.64 cm) and 1.50 in. (3.81 cm), respectively, for the BA-impregnated specimens. This reduction in water and salt solution permeability should retard corrosion, which is the major cause of deterioration in concrete bridge decks, of the reinforcing steel.

Freeze-Thaw Resistance

Freeze-thaw tests (ASTM Designation C671) were carried out on core specimens from salt-contaminated and uncontaminated non-air-entrained concrete slabs. All of the core specimens from the polymer-impregnated slabs, salt-contaminated and uncontaminated, showed exceptional resistance to freezing and thawing (they were undamaged after 10 cycles), whereas all of the unmodified control specimens failed quickly—the salt-contaminated ones in the first cycle and the uncontaminated ones in the third cycle.

Protection of Reinforcing Steel Against Corrosion

Scanning electron micrographs of the reinforcing steel rods in core specimens from salt-contaminated, polymer-impregnated concrete slabs showed no signs of corrosion after freeze-thaw cycling, whereas the reinforcing steel rods from salt-contaminated, unmodified control specimens showed significant etching. Polymer impregnation apparently immobilizes the salt in the concrete matrix and thus lessens its corrosive effects.

Resistance to Chemical Attack (Acid Etching)

Core specimens from polymer-impregnated slabs, soaked for 2 hr in 18.5-percent or 37-percent (concentrated) hydrochloric acid, showed no damage to the cementitious matrix, although the limestone aggregate particles were eaten away. Unmodified control specimens disintegrated

so thoroughly and rapidly that this acid-etching test can be used as a measure of the depth of impregnation in core specimens from field trials.

Abrasion and Skid Resistance

The abrasion resistance was measured by the weight loss in an abrasion test instrument constructed specially for this purpose. This loss in weight may be a measure of skid resistance, if wear exposes a surface less resistant than the original. Core specimens from the polymer-impregnated slabs showed 80 to 90 percent smaller weight losses in the abrasion test than the unmodified control specimens.

The skid resistance of these polymer-impregnated specimens was not measured, but others (8) have found it to be the same or slightly greater than that of unmodified concrete.

EFFECTS OF CONTAMINANTS

Concrete bridge decks are contaminated with substances (e.g., deicer salts, grease, oil, asphalt cement, and rubber) that may affect the drying, impregnation, and polymerization processes. The effects of these contaminants were determined by experiment.

Drying

Salt-contaminated concrete requires longer drying times at a given temperature than uncontaminated concrete to remove the moisture. For example, 3-percent sodium chloride in the concrete decreased the moisture removed under the same drying conditions to only 87 percent of that removed from uncontaminated concrete.

High-temperature drying burns off all organic contaminants—grease, oil, asphalt cement, rubber—from the concrete surface.

Rate of Impregnation and Monomer Loading

Salt-contaminated concrete shows slower rates of impregnation and lower monomer loadings than the corresponding uncontaminated concrete. For example, the time required to impregnate concrete infused with 0.3-percent sodium chloride to a 6-in. (15-cm) depth using methyl methacrylate at 60 psig (413-kPa) pressure (after 1.5 hr 28 in. (95 kPa) Hg vacuum to remove the moisture) was 30 percent longer than that required for the uncontaminated concrete, and the polymer loading (after polymerization) was 10 percent less.

Surface-ponding impregnation of core specimens from a 7-year-old bridge deck showed statistically significant correlations (95-percent confidence level) between the chloride ion content 0.25 in. (0.64 cm) below the surface and the rate of monomer impregnation and monomer loading. The higher the salt content, the slower was the rate of impregnation and the lower the monomer loading.

Removal of surface contaminants by various cleaning processes, such as scrubbing with detergent or lye and grit blasting, does not affect the monomer loading.

Polymerization

Laboratory polymerization studies were carried out to determine the effect of various contaminants (e.g., deicer

salts, linseed oil, motor oil and grease, and asphalt cement) on the rate of polymerization of methyl methacrylate. At 131 F (55 C), all of these contaminants except sodium chloride retarded the polymerization rate significantly; at 149 F (65 C), only asphalt cement exerted a retarding effect, and at 167 F (75 C) none of the contaminants retarded the polymerization.

Mechanical Properties

The increase in split-tensile strength and Young's modulus achieved by polymer impregnation was reduced by 15 percent and 40 percent, respectively, by the infusion of 1-percent sodium chloride into the concrete prior to impregnation. However, the impregnated specimens still retained a severalfold advantage over nonimpregnated specimens. The compressive strength was unaffected by the presence of 1-percent sodium chloride.

Freeze-Thaw Resistance

Salt contamination reduced the freeze-thaw resistance of non-air-entrained unmodified concrete (from 3 to 1 cycles), but had no effect on the polymer-impregnated concrete (which was undamaged after 10 cycles).

FIELD TRIALS

Four field trials were carried out: (1) two (1.4 to 1.8 sq ft (0.13 to 0.17 m²)) impregnations on the PSU test track bridge using (a) gas-fired torch drying and pressure-chamber impregnation with steam polymerization, and (b) gas-fired infrared torch drying and ponding impregnation with hot-water polymerization (March 1974); (2) a commercial-scale (72 sq ft (6.7 m²)) impregnation on the PSU test track bridge, using gas-fired infrared drying, pressure-chamber impregnation, and hot-water polymerization (August 1974); and (3) one commercial-scale (36 sq ft (3.3 m²)) impregnation on the northbound traffic lane of the Pennsylvania Route 378 highway bridge over Union Boulevard in Bethlehem, using gas-fired infrared drying, pressure-chamber impregnation, and hot-water polymerization (March 1975).

All field impregnations achieved the goal of a 4-in. (10-cm) impregnation of a structurally sound, salt-contaminated concrete bridge deck. Further details are given as follows.

PSU Test Track—March 1974

In March 1974, two impregnations were carried out on the PSU test track bridge: one using gas-fired torch drying and pressure-chamber impregnation; and the other, gas-fired infrared drying and ponding impregnation.

In one test, the bridge deck was dried for 10 hr using the gas-fired torch drying until the temperature at a depth of 4 to 5 in. (10 to 12 cm) reached 250 F (121 C) and the surface temperature was 700 F (371 C). The deck was allowed to cool for 8 hr, and holes were drilled and inserts installed for bolting down the circular 16-in. (41-cm) diameter impregnation pressure chamber. The deck was impregnated with the 90:10 methyl methacrylate (MMA)-trimethylolpropane trimethacrylate (TMPTMA) mixture containing 0.5-percent azobisisobutyronitrile (AZO) initia-

tor for 8 hr at 15 to 20 psig (103 to 137 kPa) pressure. The monomer was polymerized by feeding 10 to 13 psig (68 to 89 kPa) steam from a pressure cooker through the pressure chamber and over the deck for 10 hr. Core specimens from the polymer-impregnated region, in this test, showed a dense impregnation to a depth of 5 in. (12 cm) with complete impregnation throughout the 7.5-in. (19-cm) depth in some regions.

For the second test, the bridge deck was dried for 10 hr using the gas-fired infrared dryer until the temperature at a depth of 4 in. (10 cm) was 230 F (110 C) and the surface temperature was 675 F (357 C). The deck was allowed to cool for 8 hr, and a 30-in. x 18-in. (76-cm x 46-cm) ponding chamber was sealed to the deck using Silastic rubber. The monomer mixture (100:10 MMA-TMPTMA mixture with 0.5 parts AZO) was allowed to stand in the chamber (which was covered to prevent evaporative losses) for 4 days 10 hr. Then the excess monomer was removed, and 203 F (95 C) bath water was circulated for 10 hr through the chamber to polymerize the monomer. Core specimens from the polymer-impregnated region showed a dense impregnation to a depth of 4.5 in. (11 cm).

These first two field impregnations demonstrated that the goal of this project had been achieved; i.e., the field impregnation of structurally sound, salt-contaminated concrete to a depth of 4 in. (10 cm) is technically feasible.

PSU Test Track Bridge—August 1974

In August 1974, two adjacent 3-ft x 12-ft (0.9-m x 3.7-m) areas on the PSU test track bridge were impregnated using gas-fired infrared drying, pressure-chamber impregnation, and hot-water polymerization. The over-all 6-ft x 12-ft (2-m x 3.7-m) area was dried in three stages using the gas-fired infrared heaters. Each stage required about 4 hr for the temperature at a 4-in. (10-cm) depth to reach 230 F (110 C). The deck was allowed to cool for about 12 hr, and holes were drilled and inserts installed for bolting down the impregnation pressure chamber. The first impregnation was begun at 15 psig (103 kPa) pressure, but leaks around the gasket made it necessary to decrease the pressure; it was impregnated for 7.5 hr at 5 psig (35 kPa) pressure. The second section was impregnated for 3 hr at 15 psig (103 kPa) pressure, followed by 4 hr at atmospheric pressure and 5 hr at 5 psig (35 kPa) pressure. Both sections were polymerized by circulating 170 to 180 F (77 to 82 C) water through the impregnation pressure chamber for 12 hr.

Core specimens showed a dense impregnation to a depth of 3.5 to 4.0 in. (8.9 to 10 cm) and a less dense impregnation extending 1 in. (2.5 cm) or more downwards. The chloride ion concentration in these core specimens ranged from 0.67 to 1.38 lb/cu yd (0.40 to 0.82 kg/m³) at a 0.5-in. (1.27-cm) depth to 0.02 to 0.04 lb/cu yd (0.01 to 0.02 kg/m³) at 2 in. (5 cm).

These field impregnations confirmed the results of the earlier field impregnations and demonstrated that two adjacent areas could be impregnated in sequence. Tests also showed no significant effect of impregnation on skid resistance.

PennDOT Route 378 Bridge in Bethlehem—March 1975

In March 1975, the northbound traffic lane of the Pennsylvania Route 378 (Bethlehem spur route) bridge over Union Boulevard was closed to traffic, and a 3-ft x 12-ft (0.9- x 3.7-m) area was impregnated using gas-fired infrared drying, pressure-chamber impregnation, and hot-water polymerization. The bridge deck was structurally sound, but the slag aggregate was worn and porous at the surface; the deck was contaminated with a high concentration of deicer salts (chloride ion concentrations up to 4.8 lb/ cu yd (285 g/m²)). A 4-ft x 12-ft (1.2-m x 3.7-m) area was dried in two 4-ft x 6-ft (1.2-m x 1.8-m) stages using the gas-fired infrared dryer. The drying time to reach 230 F (110 C) at a 4-in. (10-cm) depth was about 6 hr, for a total time of 13 hr, including time for changing the position of the dryer. During the drying, water oozed out of the top surface of the deck at an expansion joint and on the underside at one location at the end of the permanent steel forms. The precise location of moisture exit on the bottom side could not be determined because of the forms. The deck was allowed to cool for 8 hr, and holes were drilled and inserts installed for bolting down the impregnation pressure chamber (same as used for the August 1974 field trial at PSU test track bridge). New holes had to be drilled in the pressure chamber flange to avoid piercing the reinforcing steel rods while drilling to insert holes. The pressure chamber was evacuated for 30 min at 27 in. (91 kPa) Hg pressure and then pressurized at the 100:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture containing 0.5-percent azobisisobutyronitrile initiator for 75 min at 5 psig (34 kPa), 7.25 hr at 2 psig (14 kPa), 1 hr at 3 psig (21 kPa), and 30 min at 8 psig (55 kPa) pressure. The periodic adjustments in pressure were necessitated by monomer leaking through the deck. Here again, the precise location of exit was obscured by the permanent steel deck forms. The polymerization was carried out by circulating 165 to 170 F (74 to 77 C) water through the impregnation pressure chamber for 12 hr. The chamber was covered with glass-fiber insulation and plastic film so that there was no noticeable monomer odor in the vicinity.

Seven core specimens were taken from the polymer-impregnated and unmodified areas of the deck, and laboratory tests were carried out to determine the depth of impregnation and the properties of the polymer-impregnated regions. The core specimens from the polymer-impregnated regions showed a dense impregnation to a depth of at least 3 in. (8 cm), with a less dense impregnation extending to 4 in. (10 cm) in most regions. The split-tensile strength of one core specimen from a polymer-impregnated region was 606 psi (4.18 MN/m²).

This last field impregnation in the NCHRP 18-2 program on a PennDOT bridge confirmed the feasibility of polymer impregnation of a structurally sound, salt-contaminated bridge deck to a depth of 4 in. (10 cm).

FIELD MANUAL

A field manual for the polymer impregnation of concrete bridge decks has been developed for the guidance of

contractors and highway department engineers, based on the experience gained from laboratory studies and the field impregnations. This field manual includes basic guidelines, data, procedural instructions, acceptance criteria, and safety requirements. The complete field manual is included in this report as Appendix I.

Materials and Methods

The manual prescribes techniques and materials used to achieve 4-in. (10-cm) field impregnations of concrete bridge decks. The monomer system specified is the 90:10 or 100:10 methyl methacrylate (MMA)-trimethylolpropane trimethacrylate (TMPTMA) mixture containing 0.5-percent azobisisobutyronitrile initiator. Recommendations are included for preparing, handling, and storing the monomer mixture, as well as for estimating the quantity required for a given job.

The manual also prescribes the drying requirements to achieve a specified depth of impregnation and the means for monitoring the drying process. The recommended drying system is the gas-fired infrared heaters. Additionally, the manual describes the cooling of the deck prior to im-

pregnation and the protection of the dried areas from the weather.

The equipment, procedures, and monitoring criteria are specified for monomer impregnation at pressures ranging from atmospheric to 15 psig (100 kPa). Procedures and criteria for the hot-water polymerization are also included.

Acceptance Criteria

An attribute sampling plan and acceptance criteria are specified in the manual for quality assurance as to the depth of impregnation and completeness of polymerization. It is not yet possible to estimate the producer's and consumer's risks associated with this sampling plan because of the lack of sufficient data to provide estimates of variance for polymer-impregnation of concrete. Therefore, it may be necessary to modify the sampling plan and acceptance criteria as more experience is gained.

Safety Conditions

The manual also discusses the safety and fire hazards associated with the monomer mixture and the precautions to be taken with the high-temperature drying, in all operations of the impregnation process.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATION

MONOMER SYSTEMS

The field trials used the 90:10 or 100:10 methyl methacrylate-trimethylolpropane trimethacrylate monomer mixture containing 0.5-percent azobisisobutyronitrile initiator. This mixture, which was derived from earlier experiments with methyl methacrylate, functioned well in all of the tests carried out in this program. It had a suitably low viscosity (0.6 cp (6×10^{-4} Pa.s)) and penetrated well into the dried concrete substrate. The addition of the crosslinking monomer increased the viscosity of the mixture somewhat, but the improvement in properties it gave outweighed the increase in viscosity and decrease in penetration rate. Moreover, once inside the concrete, this monomer mixture polymerized readily at temperatures of about 176 F (80 C). The polymerization is autoaccelerating, which helps it reach high conversion in a short time. Usually there is no odor of monomer when the specimens are broken open.

The properties of concrete impregnated with this monomer mixture are generally very good (threefold increases in tensile and compressive strengths, greatly decreased permeability to water and salt solutions, increased resistance to freezing and thawing, increased resistance to abrasion, and no change in skid resistance). Such polymer-impregnated systems are, therefore, well suited to application in highway bridge decks.

The present program, however, did not treat the subject of monomer cost broadly. The cost analysis (see Appen-

dix H) showed that much of the cost of impregnating a concrete bridge deck is for labor. However, for deep impregnation, the estimated monomer cost is about equal to the direct labor costs (not including traffic control) for ponding, and 1.5 times labor costs for pressure impregnation. In any case, the total amount of monomer required for a large expanse of a bridge deck would be very great. Therefore, it is still worthwhile over the long range to consider other less expensive impregnants and monomer systems, and investigation of the long-term durability of various monomer systems would be useful in optimizing selection.

DRYING METHODS AND CRITERIA

Methods

Of the various drying methods investigated, gas-fired infrared radiant heating is the most practical and efficient. Propane-fired flame heating can also be used to achieve effective drying for impregnation to 4 in. (10 cm), but it is less efficient than the gas-fired infrared (IR) and probably more susceptible to variations caused by wind. Furthermore, the gas-fired IR heaters are commercially available and can be obtained in units large enough to be considered practical for bridge deck work. For practical use, units should have a heat output of at least 9,000 Btu/hr/ft² (102 MJ/hr/m²).

Drying Criteria

The concrete should be heated to a temperature of 230 F (110 C) at the depth to which impregnation is to occur. For a specified impregnation depth of 4 in. (10 cm), this results in surface temperatures above 600 F (316 C). To prevent excessively steep thermal gradients (in order to minimize cracking problems), surface temperatures 1 hr after starting the drying process should not exceed 500 F (260 C), and they should never exceed 675 F (357 C). It was found that, when the rate of increase in surface temperature dropped below 10 F (5.5 C/hr) for surface temperatures over 600 F (316 C), a satisfactory degree of drying was effected to a depth of at least 4 in. (10 cm).

IMPREGNATION METHODS

If concrete is sufficiently dried, impregnation with MMA monomer can be achieved to any desired depth using any of a variety of combinations of pressure and time. In general, for a given impregnation depth, the time required varies inversely with the square of the applied pressure.

The most rapid rates and highest polymer loadings may be achieved by impregnation under pressure. With this method, the size, weight, and complexity of equipment needed for economic commercial-scale application must be balanced against the reduction in time requirements through the use of pressure. Further, if the pressure-mat principle demonstrated in this program can be developed to a commercial scale, it certainly would provide a most convenient impregnation procedure in terms of time reduction and ease of handling. Ponding should also be considered as a viable alternative. Although more time is necessary to achieve impregnation to a given depth at a given location, ponding units that are many times larger than those practical for impregnating with pressure chambers can be built.

Obviously, more work is needed to evaluate the relative economics involved for a given case based on the practical size limitations inherent with the methods. The purpose of this research was to establish the technical feasibility of the methods, and this has been shown.

POLYMERIZATION METHODS

The only polymerization method tried in this research—thermal-catalytic using hot-water ponding or steam—was found to work very well in practical field applications.

MECHANICAL PROPERTIES AND DURABILITY

The mechanical properties and durability of concrete impregnated with methyl methacrylate using techniques applicable to field impregnation were found to improve significantly in comparison with nonimpregnated concrete. Compressive strengths were tripled; tensile strengths were doubled; chloride penetration was reduced to less than one-sixth; moisture absorption was reduced by an average of 85 percent; reinforcement corrosion in salt-contaminated concrete was arrested; resistance to chemical attack was dramatically increased; freeze-thaw damage was elimi-

nated; and resistance to abrasion was increased by an average of 85 percent. These results are similar to the findings of other researchers. It was also shown that the stress strain behavior of the concrete can be varied by use of a combination of monomers.

FIELD PROCEDURES

The practicality of transferring the techniques developed in the laboratory for deep polymer impregnation of concrete bridge decks to the field was clearly demonstrated. Although the equipment employed was small in scale, it was designed to permit ready scale-up for commercial field applications. Based on the research carried out in this project, the estimated unit costs for polymer impregnation of concrete bridge decks to depths of 1, 2, 3, or 4 in. (2.5 cm, 5.1 cm, 7.6 cm, 10 cm), using either ponding or pressure impregnation at 15 psig (103 kPa), are given in Table 1. These costs are based on equipment scale-up to commercially feasible size units capable of covering areas 12 ft x 40 ft (37 m x 12 m), but do not include amortization of capital equipment, maintenance, weather delays, or traffic control. The computations for the data contained in Table 1 are given in Appendix H.

The procedures found in this research to provide successful deep (up to 4 in. (10 cm)) impregnation of concrete bridge decks are described in a field manual (Appendix I). The report also presents technical data supporting the feasibility of applying the principles demonstrated to commercial-scale operations. Of course, with additional experience in the field, revision of the detailed procedures may be necessary; similarly, with experience, the procedures for assurance of specification compliance, as presented in the field manual, may require revision. Since there has been no commercial experience to date with the process on bridge decks, the magnitudes of variance of penetration depth and, consequently, the producer's and consumer's risks associated with the proposed compliance standards are not known.

TABLE 1
COST ESTIMATES FOR COMMERCIAL-SCALE
POLYMER IMPREGNATION OF CONCRETE
BRIDGE DECKS

Impregnation Depth, in.	Impregnation Pressure, psig	Total Time hr/sq ft	Material & Fuel Costs, \$/sq ft	Total Cost, \$/sq ft
1	0	0.022	0.86	1.30
2	0	0.055	1.82	2.92
3	0	0.102	2.88	4.92
4	0	0.163	4.06	7.32
1	15	0.016	0.86	1.18
2	15	0.034	1.82	2.51
3	15	0.060	2.88	4.09
4	15	0.096	4.06	5.98

Unit Conversion: $1 \text{ ft}^2 = 0.0929 \text{ m}^2$.

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The deep (up to 4 in. (10 cm)) polymer impregnation of bridge deck concrete in the field has been demonstrated using concrete that is salt contaminated but structurally sound. To achieve this goal, a process consisting of a combination of infrared drying, pressure impregnation, and hot-water polymerization was developed. Commercially available, propane-fired infrared heaters were found to be suitable for use in drying; a special pressure impregnation unit was designed; and a prototype, capable of scale-up, was constructed. While the costs are high, so are the costs of alternative repair methods. With current costs for repair of bridge decks running in the order of \$6 per sq ft (0.09 m²) for repairs that may be expected to last only 3 to 5 years, the estimated costs for polymer impregnation of \$6 per sq ft (0.09 m²) plus the costs of amortizing and traffic control should be economically feasible in view of anticipated greater lifetime.

SUGGESTED RESEARCH

The magnitude of the problem area represented by this research and the myriad possibilities and variables that exist for each of the several phases of the problem required concentration of effort in certain areas, with emphasis on the demonstration of technical feasibility of a combination of process and equipment. Thus, less attention could be devoted to other areas, which were less central to the project goal but which should be worth additional study. Also, as in any research endeavor, unanticipated items that should be studied further were disclosed.

In terms of field applicability of the polymer impregnation of concrete, the pressure-mat concept is particularly attractive, and should merit further research. Parallel research should be done to evaluate the relative economies of the various means of impregnation (pressure chamber, pressure mat, and ponding) and to quantify more precisely the relationships between time, differential pressure, depth, and concrete pore characteristics.

Since the cost of impregnation increases exponentially with the depth of impregnation specified, research should

be carried out to provide a rational basis for specifying the impregnation depths and loadings required for adequate corrosion protection.

With regard to the drying operation, research should be carried out to refine the drying criterion and to develop criteria for concretes containing all types of common aggregates. Most aggregates encountered in this research were carbonates. Conceivably, concretes containing other aggregates, especially siliceous materials, might not be able to tolerate the high temperature differentials used in this research without spalling or otherwise damaging the concrete. The question of potential structural damage due to the high temperatures used requires attention.

It is also proposed to screen various monomer systems in comparison with the 90:10 or 100:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture used in this work. Chapter Three describes the results that can be obtained by copolymerization and points out that there are several monomers that might be used in place of methyl methacrylate at lower cost. Some of these monomers (e.g., styrene) confer about the same mechanical properties as the polymethyl methacrylate, yet their costs are lower. In addition, a rapid screening test should be developed to distinguish between different types of polymer-impregnated concrete, rather than to emphasize the difference between polymer-impregnated concrete and the unmodified controls. Such tests would comprise many different compositions tested for ultimate durability using freeze-thaw as well as abrasion resistance methods. Other nonmonomeric impregnants should also be examined, such as tar and sulfur.

The efficiency of the various impregnants with respect to the resistance to salt penetration and to immobilization of preexistent salt needs to be demonstrated in long-term laboratory and field tests, with emphasis on the ability to prevent or delay corrosion of the steel.

Finally, the acceptance criteria put forth in this research should be evaluated and adjusted, as necessary, first by determining the magnitude of the variance that might be expected in impregnation depth and second by developing a well-defined method of measuring impregnation depth.

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APPENDIX A

LITERATURE REVIEW

Appendix A (which is a state-of-the-art survey covering major aspects of polymer-impregnated concrete as applied to highway bridge decks and including the literature up to March 1975) is not published herewith but is contained

under separate binding, as submitted by the agency to the sponsors, and is available on a loan basis on request to the NCHRP Program Director.

APPENDIX B

MONOMER SYSTEM

MONOMER SELECTION

The monomer selected for the field trials was the 90:10 or 100:10 methyl methacrylate-trimethylolpropane tri-

methacrylate mixture containing 0.5-percent azobisisobutyronitrile initiator. This monomer mixture was selected because: (1) methyl methacrylate was the monomer used in most earlier experiments by other laboratories, so that

there was a considerable background of experience with it (4); (2) methyl methacrylate undergoes a rapid auto-accelerating polymerization, which aids in achieving high conversions in short times *in situ*; (3) methyl methacrylate has a very low viscosity, one of the lowest viscosities of any monomer, which aids in the impregnation; and (4) concrete specimens impregnated with methyl methacrylate and polymerized showed high compressive and tensile strengths as well as other desirable properties.

Since the main thrust of this work was development rather than research, our objectives were to: (1) confirm the earlier results obtained with the methyl methacrylate system; (2) establish an appropriate initiator system, in this case azobisisobutyronitrile; and (3) establish an appropriate crosslinking monomer system, in this case trimethylolpropane trimethacrylate, to enhance the auto-accelerating polymerization and to give a crosslinked polymer of higher mechanical strength.

This monomer system performed well in all of the tests, and its selection was obviously a good choice. However, other monomers should also be considered. For example, styrene-polyester and styrene-acrylonitrile mixtures were found to give even better properties in polymer-impregnated concrete than methyl methacrylate (4). The styrene-polyester mixture is higher in viscosity and, consequently,

can be used only at the expense of penetration time. Styrene-acrylonitrile mixtures are sufficiently low in viscosity but have not been investigated in any detail. The same can be said for other monomer systems.

In March 1973, the prices of all monomers that were available in large volume and high purity (and therefore would be possible candidates for this application) were compiled and are listed in order of increasing cost in Table B-1. The monomers on this list that are gases at room temperature (ethylene, propylene, butadiene, and vinyl chloride) can be eliminated from consideration. This leaves several monomers—styrene, vinyl acetate, acrylonitrile, vinylidene chloride, vinyl toluene—which are lower in cost than methyl methacrylate, and several other monomers—methyl acrylate, ethyl acrylate, butyl acrylate—which are competitive in cost with methyl methacrylate. It should be pointed out that monomers such as vinylidene chloride, whose polymers precipitate on polymerization, may pose problems in field applications. In particular, styrene has about the same mechanical properties as methyl methacrylate when polymerized, but at about one-third the cost. This list points out the work that can be done in this area to optimize the monomer selection with respect to cost.

Copolymerization is another approach to optimize the properties-cost relationship. From the list of monomers that are lower in cost than methyl methacrylate, it would be desirable to try styrene-acrylonitrile, styrene-methyl methacrylate, vinyl acetate-acrylonitrile, vinyl acetate-acrylate ester, and vinylidene chloride copolymers. It is of interest to note that, in latex-modified concrete, the vinylidene chloride copolymer latexes are superior to all other types.

As yet, however, there is no standard of comparison for monomers other than measurement of mechanical and physical properties of the polymer-impregnated concrete in laboratory tests. No polymer-impregnated concrete specimens have been tested for ultimate durability in any test that is comparable to actual service life. Many accelerated laboratory tests for freezing and thawing, salt solution penetration, abrasion resistance, or other properties have been carried out. However, these tests tend to demonstrate the superiority of polymer-impregnated concrete over unmodified concrete rather than to differentiate between different types of polymer-impregnated concrete. Polymer-impregnated concrete is too new, and there are too few specimens out on exposure in the field to determine its ultimate durability.

Nevertheless, ultimate durability is the objective of all of the research and development work carried out on polymer-impregnated concrete. Therefore, it would be desirable to develop methods of testing to distinguish between different types of polymer-impregnated concrete. Not only are different types of polymers available, but, as mentioned previously, copolymerization can also be used to prepare a wide variety of compositions tailored to the specific application. For example, concrete impregnated with methyl methacrylate has high modulus and high ultimate strength, but undergoes brittle fracture, a property which is somewhat unacceptable to civil engineers; concrete impregnated with butyl acrylate has a modulus and ultimate strength

TABLE B-1

TYPICAL MONOMER COSTS IN BULK¹ AND AS IMPREGNATED²

Monomer	Cost/lb	Cost/sq ft
Ethylene	\$0.0325	\$ ---
Vinyl Chloride	0.050	---
Styrene	0.0675	0.111
Vinyl Acetate	0.0875	0.157
Butadiene	0.095	---
Acrylonitrile	0.130	0.239
Vinylidene Chloride	0.140	0.306 - 0.350
Propylene	0.145	---
Vinyltoluene	0.180	0.289
Methyl Methacrylate	0.185	0.346
Ethyl Acrylate	0.190	0.341
Methyl Acrylate	0.200	0.359
Butyl Acrylate	0.200	0.359
Isobutyl Acrylate	0.200	0.359
Ethylhexyl Acrylate	0.230	0.413
Butyl Methacrylate	0.290	0.543
Isobutyl Methacrylate	0.380	0.712
Ethyl Methacrylate	0.425	0.796

Unit Conversions: 1 lb = 0.454 kg

1 sq ft = 0.092 m².

1. Chemical Marketing Reporter, March 26, 1973.

2. Assuming impregnation of concrete of 15% porosity to a depth of 2 in. (5.08 cm).

only slightly greater than that of unmodified concrete, but shows greater ductility before fracture than unmodified concrete. Butyl acrylate mixtures have strengths almost as great as that of methyl methacrylate alone, but show ductility before fracture (see Appendix E). Similar relationships are expected for other monomer pairs.

Therefore, it is proposed to develop a laboratory test to distinguish between different types of polymer-impregnated concrete and to confirm these differences by tests in the field, with this program to run concurrently with the testing of concrete impregnated with the methyl methacrylate-trimethylolpropane trimethacrylate mixture. One possible approach to such differentiation is the freeze-thaw test. The current test (ASTM designation C671) is too time consuming for the large number of specimens in the proposed study (probably 200 to 500). Such a large number of specimens requires a simplified test procedure. Various procedures have been discussed; for example, circular discs of 2- to 3-in. (5.08- to 7.62-cm) diameter and 0.125- to 0.250-in. (0.32- to 0.64-cm) thickness, with a 0.125-in. (0.32-cm) diameter hole near one edge, could be hung on hooks in a freezer chest, frozen, allowed to thaw, immersed in water, then frozen again, until the mortar became so weak that it would fall off of the hook. Large numbers of these discs could be prepared and impregnated. Daily recycling would allow 365 cycles per year. In this way, many different monomer combinations, developed systematically from a basic understanding of polymerization fundamentals, could be tested to determine which offered the most promise. At the same time, the question could be answered as to which would combine adequate properties in the field with lowest cost.

Some hint of this problem is found in the present work, in which concrete impregnated with various proportions of butyl acrylate and methyl methacrylate were tested by freezing and thawing. Beforehand, it was speculated that the hard, brittle, high-modulus polymethyl methacrylate, under the differential expansion and contraction of the freeze-thaw testing, would eventually separate from the cement paste phase (i.e., the polymer-cement adhesive bond would fail, but the soft, rubbery polybutyl acrylate would form a polymer-cement adhesive bond that would remain intact through many freeze-thaw cycles). However, some preliminary experiments showed that the best resistance to salt penetration was obtained with the polymethyl methacrylate rather than with the polybutyl acrylate specimens; the effect of freezing and thawing remains to be determined. Also, the abrasion resistance tests showed that the harder and more brittle the polymer, the better the abrasion resistance of the corresponding polymer-impregnated concrete (e.g., styrene was the best, followed by methyl methacrylate, isobutyl methacrylate, in that order). These results demonstrate why it is important to carry out this screening program.

MONOMER PENETRATION RATE STUDIES

Since no engineering or scientific data were available on the rate of impregnation of concrete by monomers at various pressures, it was necessary to obtain the data (15). Experiments were conducted on both mortared concrete and slabs (see Appendix D).

Impregnation of Mortar Cylinders

Small 1-in. x 2-in. (2.5-cm x 5.1-cm) portland cement mortar cylinders were prepared and used in the first impregnation experiments. The organic liquids—acetone, styrene, methyl methacrylate, acrylic acid, trimethylolpropane trimethacrylate (TMPTMA)—were commercial grade and were used as received. Laboratory distilled water was used. The portland cement mortar cylinders were prepared using a 12:24:64 water-portland cement (type II), Ottawa silica sand (ASTM C-109) mix and were cured for 28 days in water at room temperature.

The cylinder volume was determined by saturating it with water, measuring its weight in air and then in water, using Archimedes' principle. For the liquid sorption experiments, the cylinders were dried to constant weight under an infrared lamp, weighed in air, then immersed in the liquid. The weight in the liquid was measured periodically after immersion until a constant weight was attained, usually in 60 to 120 min for the less viscous liquids. The weight at zero time was calculated from the cylinder volume and specific gravity of the liquid, using Archimedes' principle.

To obtain reproducible liquid sorption curves, the cylinders must be dried thoroughly, since incompletely dried cylinders sorb less liquid, according to the residual volume of water. This residual water cannot be driven out by penetration of even water-miscible liquids. Since the same cylinder was used in a series of sorption experiments, it was necessary to remove the sorbed liquid before the next experiment. Volatile liquids such as acetone, methyl methacrylate, styrene, or water were removed by heating with the infrared lamp. Less volatile liquids were removed by immersing the cylinder for 24 hr in a series of acetone baths and finally removing the acetone by heating. With these procedures, the same cylinder could be used again and again, each time giving reproducible sorption values.

The sorption-time variation for styrene, as shown in Figure B-1, is linear over most of the time range up to the asymptotic approach to equilibrium. Similar results were found for MMA. However, the corresponding curve for the 90:10 styrene-acrylic acid mixture shows initially a smaller linear slope up to an inflection point at about 55 percent of equilibrium, followed by a second linear region of even smaller slope. Despite these differences in slope, the equilibrium sorption values were the same, suggesting a specific interaction between the acrylic acid and the potential cement substrate to reduce the effective pore radius. The curve for the much slower penetration of styrene into the salt-filled cylinder (not shown) shows a single linear region over most of the time range.

The curve for a 90:10 styrene-TMPTMA mixture was also linear and in good agreement with that for styrene, an important observation because of the common use of trimethylolpropane trimethacrylate as a crosslinking agent in polymer-impregnated concrete and its very slow rate of penetration.

The slower penetration of styrene into the salt-filled cylinder (3-percent NaCl by weight) can be explained by a reduced pore radius and volume. At equilibrium, the sum of the salt and styrene volumes is equal to the porosity (14.5 percent), consistent with a simple volume additivity rule. This observation is also important because of the

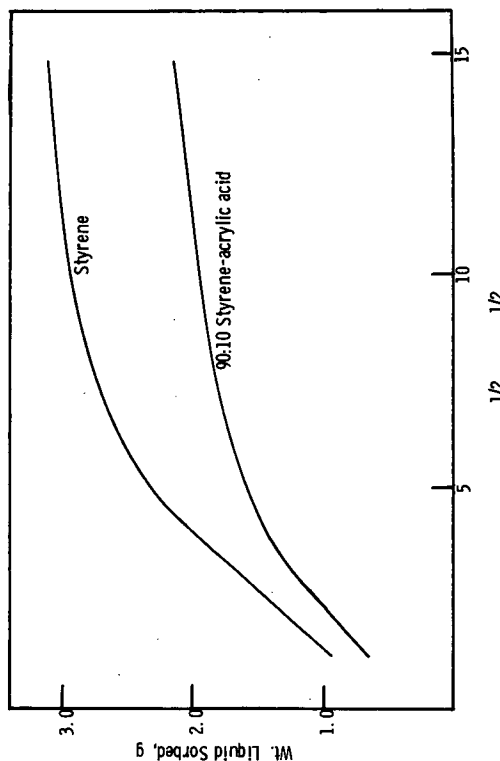


Figure B-1. Variation of sorption of monomer into mortar with square root of time.

practical requirement of impregnating bridge decks that are contaminated with deicing salts (see Appendix F).

The rate of penetration of monomer into large slabs can be predicted from the laboratory experiments using these small cylinders. For example, the application of 2-lb (0.9-kg) styrene/ft² (0.9 m²) of surface should give penetration to a depth of 2.4 in. (6.7 cm) in 9.6 hr, in comparison with the 2-in. (5.1-cm) value reported (16) for penetration of methyl methacrylate under rather similar conditions.

Impregnation of Concrete Slabs

Impregnation tests were carried out on 24-in. x 24-in. x 6-in. (61.0-cm x 61.0-cm x 15.2-cm) concrete slabs prepared and dried to constant weight. These slabs were impregnated by bolting on the pressure impregnation unit on top and pressurizing with the monomer at various pressures. Figure B-2 shows the results of these tests as compared with those from laboratory experience. It can be seen that the results from concrete cylinders and slabs are consistent; in other words, all results follow the predictions of the Rideal-Washburn equation with respect to time, although not with respect to pressure (see Appendix D).

Impregnation of Concrete Cylinders from Top Surface

Series of cylinders were made with PennDOT AA concrete, and after 28 days of moist curing the lateral sides were coated with epoxy. These cylinders were then impregnated from the top surface with MMA-TMPTMA-AZO (100:10:0.5 by weight) at various overpressures in an impregnation chamber described by Weyers (17).

These cylinders were impregnated at 0, 25, 50, and

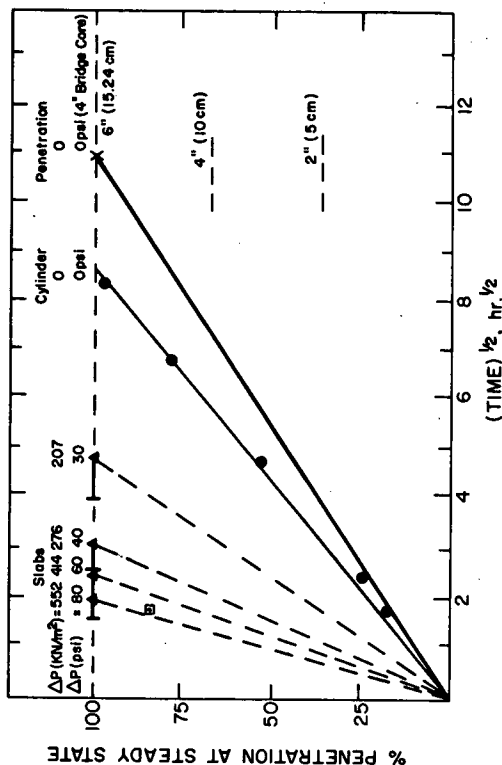


Figure B-2. Variation of monomer penetration into 6-in. concrete slab with time as a function of applied pressure (● = cylinder, ▲ = slab; note, for comparison, bridge deck core impregnated in laboratory (14) at ΔP = 75 psi and X = 0 psi).

TABLE B-2

PRESSURE IMPREGNATION OF CONCRETE CYLINDERS FROM TOP SIDE ONLY

Pressure (psig)	Slope ¹ (g/hr ^{1/2})	Total Monomer Gained (g)	Error of Regression	Intercept
0	9.5	95.1	0.998	-4.84
25	27.7	92.2	0.997	4.68
50	32.7	91.3	0.999	10.99
75	49.6	92.3	0.999	-9.08
Rate vs. Pressure	0.50	---	0.980	11.0

Unit Conversion: 1 psig = 6.89 kPa.

1. Slope corresponds to data plotted in Figures B-4 and B-5.

75 psig (0, 170, 340, and 520 kPa). Table B-2 gives some of the data concerning these impregnations. The cylinders were not impregnated to achieve full penetration except in the case of 0 psig. Figure B-3 shows photographs of the cross section cut from the four cylinders impregnated from the top surface only. The dark areas indicate the presence of polymer, and one can observe from the tone of the dark areas that loading was nonuniform—with the highest loadings occurring at the top. The presence of the light lines in the middle and bottom sections of the cylinders are cracks that are not filled completely with PMMA. Figure B-3 also shows decreasing penetration with increasing pressure for approximately the same weight gain of monomer. Hence it appears that, for a given increase in pressure and same

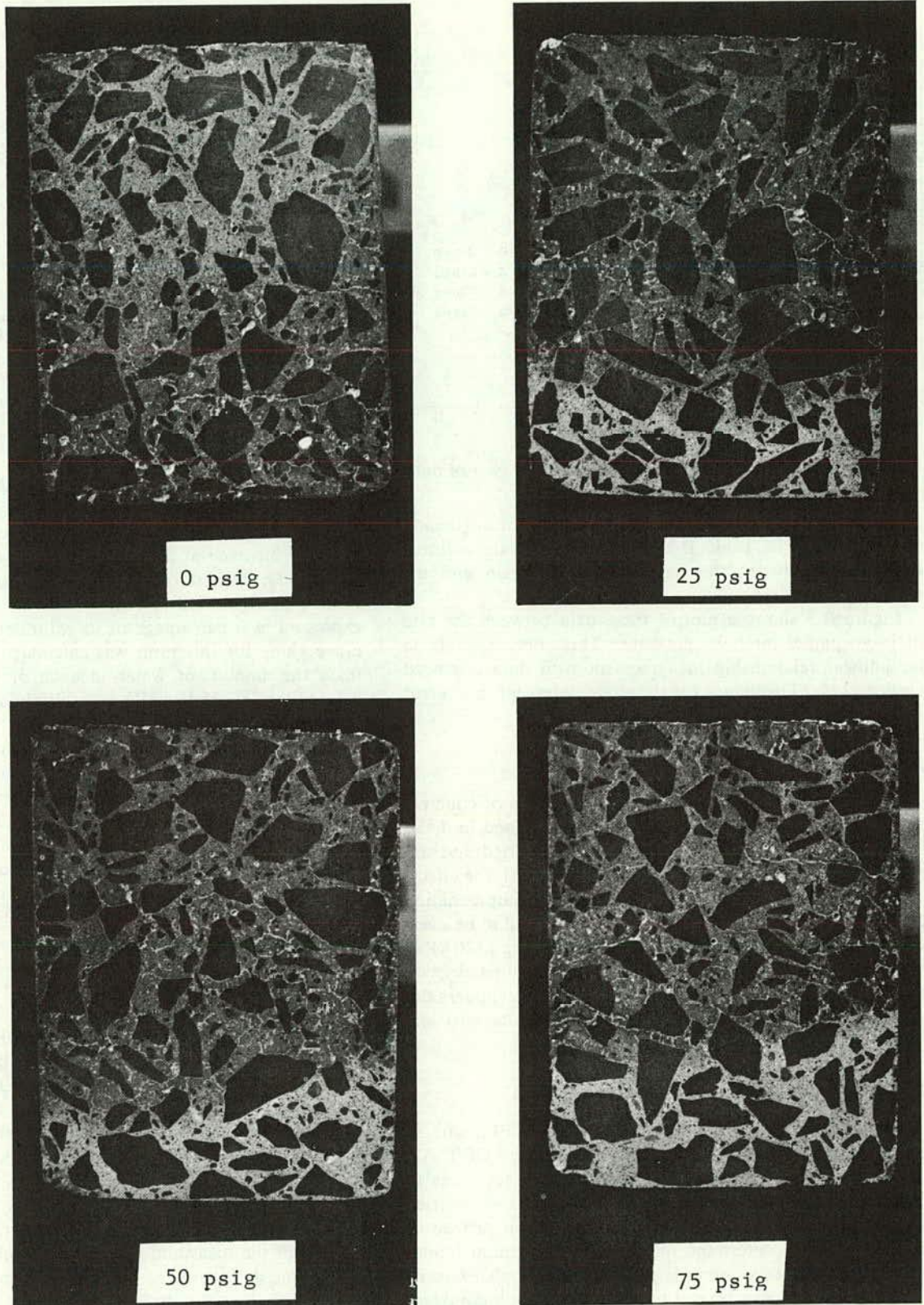


Figure B-3. Cross section of cylinders impregnated at four different pressures.

amount of monomer, the percent void volume filled with monomer will increase and the depth of penetration will decrease.

Figure B-4 presents the weight of monomer gained as a function of the square root of time for pressures of 0, 25, 50, and 75 psig (0, 170, 340, and 520 kPa). Linear re-

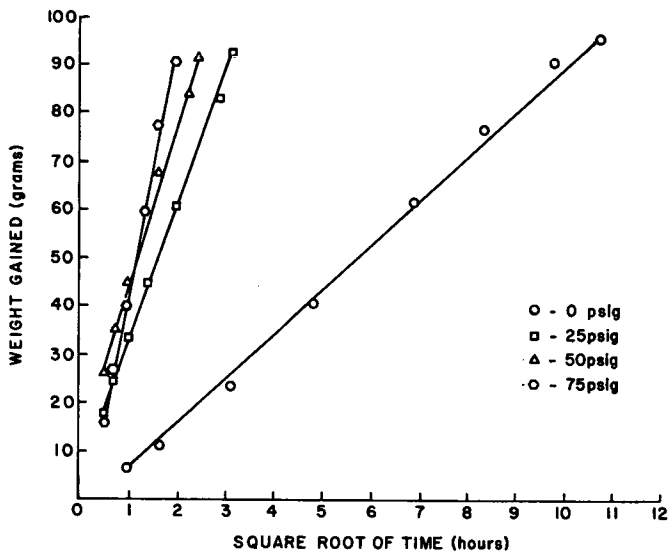


Figure B-4. Weight gained as a function of square root of time.

gression analysis, slope intercept, and error of regression data are given in Table B-2. The data indicate a linear relationship between the monomer weight gain and the square root of time.

Figure B-5 shows a plot of these data between the rate of impregnation and the pressure. This curve appears to be a linear relationship in agreement with data discussed earlier (11). The values for the slope, intercept, and error of regression data are given in Table B-2.

Effect of Contaminants on Penetration Rate

The effects of contaminants on impregnation of concrete bridge deck cores and cast cylinders are discussed in detail in Appendix F. These cylinders were oven dried and impregnated from the top surface only. In general, the effects of deicer salts appear to decrease the rate of impregnation at atmospheric pressure, but this effect appeared to be overcome by the application of overpressure (75 psig (520 kPa) was the only overpressure tested on salt-contaminated specimens). The quantity of MMA uptake by the cylinders did not appear to be influenced by the deicer salts at 0 and 75 psig (520 kPa).

Penetration Rate as Affected by Degree of Drying

A group of 30 cylinders were cast (4 in. (10.2 cm) in diameter by 8 in. (20.3 cm) long) using PennDOT AA concrete (18). The purpose of this series of tests was to determine the moisture contents in the cylinders when dried with an infrared joint heater applied to the top surface of the cylinders, to determine the rate and maximum monomer uptake when monomer is ponded on the top surface of the cylinder after drying, and to observe if different ambient temperatures affect the impregnation.

These cylinders were divided into five groups of six cylinders each. Three cylinders from each group after drying were used for ponding impregnation at an ambient temperature of 68 F (20 C), and the other three cylinders were used for ponding at 40 F (4.4 C). All cylinders prior to

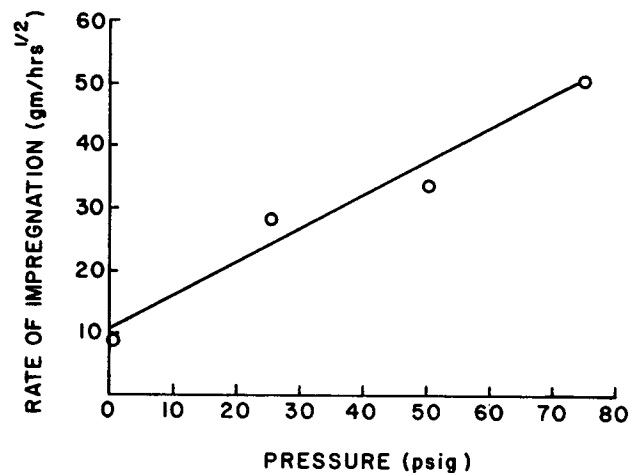


Figure B-5. Rate of impregnation as a function of pressure (1 psi = 6.89 kPa).

drying were cured in a fog room for 28 days at 100-percent relative humidity at 68 F (20 C). After the hydration period was complete, six cylinders (Group I) were placed in a forced air oven at 302 F (150 C) for drying to constant weight. The weight total of moisture removed from each of these cylinders dried at 302 F (150 C) was obtained and expressed as a percentage of its saturated weight. The average value for this ratio was calculated and used to estimate the amount of water in each of the 24 remaining cylinders (Groups II to V) by multiplying this ratio by the saturated weight of each cylinder.

The perimeters of all cylinders were coated with epoxy resin in order to prevent water or monomer from egressing through the sides. The coating was done when the oven-dried specimen (Group I) was cooled to room temperature after drying and before the saturated cylinders of Groups II to V were subjected to infrared drying technique.

For infrared drying, the top surfaces of Groups II to V cylinders were placed about 11 in. (27.9 cm) below a 120,000 Btu (130 MJ) infrared heater. The cylinders were supported by a steel grid (5 in. (12.7 cm) above the ground), which allowed the moisture to move out freely from the bottom of the laterally coated cylinders. Aluminum foil was placed around and flush with the top surface of the cylinders. By using this method, the radiant infrared heat was only absorbed by the specimens from their top surfaces and the moisture could only be removed from the specimens from their bottom surfaces, which approximates drying of a concrete slab or bridge deck from one surface only. Certain cylinders during casting had copper-constantan thermocouples embedded at 4 in. (10.2 cm) from the surface so that the temperature could be correlated with the measured temperature from large-scale slab and bridge deck trials, as reported in Appendixes G and H. Table B-3 gives the drying data, estimated moisture content, and temperature at the centers of the cylinders for the series of tests (18).

After the cylinders were dried, they received an extra epoxy resin coating on the lateral surfaces prior to impregnation. In order to contain the monomer on the top surfaces of the cylinders, a section of tin can was placed

around the cylinder top. Silastic rubber was applied to seal the gap between the top of the cylinder and the can. When the Silastic rubber was cured, the MMA-TMPTMA-AZO system (100:10:0.5 by weight) was ponded on the surface and pools were covered with aluminum foil to reduce evaporation. Weight gain of the specimens was recorded at the 3rd, 12th, and 24th hr after ponding and every 24 hr thereafter until the monomer uptake was less than 0.035 oz (1 g) per day. As previously mentioned, three cylinders from each group of specimens were impregnated at an ambient temperature of 68 F (20 C) and three at 40 F (4.4 C). Polymerization was achieved after the specimens had achieved an equilibrium state of impregnation, by placing the cylinders in a hot water bath that was maintained at 167 F (75 C) for 24 hr.

Table B-4 lists the monomer loading and depths of penetration for the oven-dried specimens. One result of these data shows that it may be possible to impregnate completely through 8 in. (20.2 cm) of concrete if the specimen or deck is dry enough, but the length of time may be prohibitive. Another result indicates that ambient temperature may affect the depth of penetration achieved (6.5 in. (16.5 cm) for 40 F (4.4 C) versus 8 in. (20.3 cm) for 68 F (20 C)), but the percent of total monomer uptake versus time is nearly the same for the different ambient temperatures.

Table B-5 gives the data for monomer loading and estimated depth of penetration for the infrared-dried specimens. Thermal expansion cracks appeared in the top surfaces of all infrared-dried cylinder specimens. These cracks were uniformly and radially distributed on the top surfaces. They were shallow and not serious enough to cause any concrete separation. However, as evident from the data in Table B-5, these cracks appeared to influence the rate of monomer impregnation as compared to the oven-dried specimens. In 24 hr after impregnation began, all infrared-dried specimens had taken up about 87 percent of the total monomer uptake as compared to about 37 percent for the oven-dried specimens, and in 48 hr all the infrared-dried specimens had taken up about 95 percent as compared to about 47 percent for the oven-dried specimens. Although the final depth of penetration is different, this percentage of the total monomer uptake for the infrared-dried specimens is about the same regardless of the final temperature at 4 in. (10.2 cm) below the surface. It must be pointed out that it took about 4 days to achieve this maximum monomer loading in the infrared-dried specimens. This is one of the reasons why 4 days was chosen for the ponding time in the large slab and bridge deck trial experiments discussed in Appendix G. This study also shows that even though an estimated 20 percent of the total moisture may remain in the top 4 in. (10 cm) of concrete after drying to 250 F (121 C) at 4 in. (10.2 cm) with an infrared heater, heavy penetrations of monomer to a depth of about 3.5 in. (8.9 cm) can be achieved.

WETTING PROPERTIES OF MMA ON CONCRETE

Surface Energy Measurement

For a given solid surface, the surface energy of the liquid is useful in predicting the wettability of the liquid, which is

TABLE B-3

DRYING DATA ON 4-IN. DIAMETER BY 8-IN. CONCRETE CYLINDERS

Specimen ¹	Drying Method	Estimated Average ²	Estimated	Final Temp. Center of Cylinder
		Moisture Content in Top 4 in. of Cylinder	Average ³ Moisture Content in 8 in. Cylinder (°F)	
Group I - A & B	Oven	0	0	302
Group II - A & B	Infrared	53	77	195
Group III - A & B	Infrared	44	72	220
Group IV - A & B	Infrared	30	65	245
Group V - A & B	Infrared	19	60	250

- Each group has 6 cylinders, 3 to be impregnated at ambient temperature of 68°F (A) and 3 to be impregnated at ambient temperature of 40°F (B).
- Based on the assumption that all the water removed during infrared drying from the top surface of the cylinder was from the upper 1/2 of the cylinder. Its mathematical form is:

$$\text{Average M.C. (upper 1/2)} = 100 - \frac{\text{cylinder weight loss}}{0.5 \text{ ave TW}} \times 100$$
 where average T.W. is the average total water removed from 6 cylinders in Group I during oven drying.
- Same mathematical equation as average MC (upper 1/2) except the 0.5 factor is removed.

an important parameter in capillary flow of the liquid. If the surface energy of the liquid is low, one would expect it to spread easily on the solid, particularly if the solid has a high surface energy. The surface energy of MMA was obtained on a Fisher Scientific Co. Model 21 Surface Tensiometer (Du Nuoy ring method). A series of measurements were taken with the tensiometer on MMA monomer at 73 F (22.8 C). Five readings were taken and the average value of these readings is 0.16 lb/in. (28 mN/m). The MMA value is about one-half the value of water (0.39 lb/in. (69 mN/m)), and, since water readily wets concrete, one would expect that the MMA would also wet the concrete surface. More detailed information concerning these measurements is given by Pu (18).

Contact Angle Measurement

The solid liquid contact angle is another important measurement in establishing the wetting properties of a monomer. If all other conditions are held constant, the maximum monomer penetration, according to capillary flow theory, would be when the monomer concrete contact angle is zero degrees. A contact angle of zero degrees implies spontaneous spreading of a liquid on a solid surface.

The contact angle measurements were obtained on a goniometer which has, on an optical track, two rotatable cross hairs; a specimen stage with a tilt device; and an illuminator. The contact angle is measured directly from the monomer sessile drop formed on the prepared concrete surfaces.

TABLE B-4

MONOMER LOADING AND DEPTH OF PENETRATION FOR
OVEN-DRIED SPECIMENS (4 IN. DIAMETER x 8 IN.)

Specimen ¹	Final temp.		Percent Total Monomer ³ Uptake and Est. Depth of Penetration ⁴ at Various Impregnation Times							
	at center °F		Impregnation ² temp. °F		3 hr/depth(in.)		12 hr/depth(in.)		24 hr/depth(in.)	
Group I-A	302		68		12.5	0.99	25.5	2.04	34.7	2.78
Group I-B	302		40		12.3	0.80	28.5	1.85	38.4	2.49

Specimen	Percent Total Monomer Uptake and Est. Depth of Penetration at Various Impregnation Times									
	2 days/depth(in.)		4 days/depth(in.)		6 days/depth(in.)		8 days/depth(in.)		10 days/depth(in.)	
Group I-A	45.2	3.62	72.0	5.76	82.6	6.61	88.1	7.05	93.6	7.49
Group I-B	47.9	3.11	67.2	4.37	77.7	5.05	84.3	5.48	90.8	5.90

Specimen	Percent Total Monomer Uptake and Est. Depth of Penetration at Various Impregnation Times						Total Wt(g) of Monomer Gained
	12 days/depth(in.)		14 days/depth(in.)		15 days/depth(in.) ⁵		
Group I-A	97.5	7.80	100.0	8.0	100.0	8.0	170.1
Group I-B	96.2	6.25	99.4	6.46	100.0	6.5	152.0

Unit Conversions: 1 in. = 2.54 cm

$$^{\circ}\text{F} = \left(\frac{9}{5}\right) ^{\circ}\text{C} + 32$$

$$1 \text{ oz} = 28.35 \text{ g.}$$

1. Groups I-A and I-B were comprised of 3 cylinders each. Data are averages of 3 cylinders.
2. The lateral sides of the cylinders were coated with epoxy and monomer was ponded on the top surface only.
3. Monomer system was MMA-TMPTMA-AZO (100:10:0.5 by weight).
4. The estimated depth of penetration is the percent of total monomer uptake at various times multiplied by the total depth of penetration (heaviest loading--visible to the eye).
5. The cylinder that was cut to measure the final depth of penetration (heaviest loading--visible to the eye) had a total monomer uptake that was about the mean of the 3 cylinders in its group.

Concrete specimens for this experiment were made of Class AA cement concrete according to PennDOT specifications except that no air-entraining agent was used in order to obtain a less porous specimen. All test surfaces were ground to obtain a smooth surface.

The polished specimens were placed in the goniometer, and a drop of MMA was placed on the surface. Readings were obtained quickly because of the volatility of MMA. The MMA monomer quickly wetted the concrete surface, and no readable contact angle could be obtained. The MMA drops were placed on other spots on the specimen for consideration of the heterogeneity of the concrete. No readable contact angle could be obtained. The same results were obtained when a crosslinking agent (TMPTMA) and catalyst (AZO) were added to the monomer.

This spontaneous wetting of the clean polished concrete surface by MMA or the MMA monomer system could possibly be caused by the high porosity of the concrete system. To investigate this area, highly compressed cement paste specimens containing less than 1-percent porosity were substituted for the concrete. The instantaneous spreading behavior was again observed, and no readable contact angle

could be obtained.

Another series of tests were conducted in which the concrete surface was slightly wetted with a clean wet facial tissue. The thin water film on the concrete did not change the spreading characteristics of the MMA monomer system.

The effects on the contact angle of the contaminated concrete and MMA monomer system were also investigated. The polished concrete specimens were contaminated with salt, linseed oil, motor oil, and grease. The contact angle on the contaminated concrete was too small to be measured. It must be pointed out that linseed oil, motor oil, and grease readily dissolve in the MMA monomer solution and probably would be carried into the concrete during an impregnation. Another series of tests were conducted on contaminated concrete with t-butyl styrene and epoxy. Measurable contact angles were obtained with the epoxy; details concerning this work are given by Weyers (17).

Detailed descriptions of all contact angle tests are given by Weyers (17) and Pu (18). On the basis of the MMA contact angle tests, one would expect to obtain deep penetration of the concrete with an MMA monomer system.

TABLE B-5
MONOMER LOADING AND DEPTH OF PENETRATION FOR
INFRARED-DRIED SPECIMENS

Specimen ¹	Final	Est. M.C.	Impregnation ²	Percent Total Monomer Uptake ³ and Est. Depth					
	temp. at center	at top 4 in.	temp.	of Penetration ⁴ at Various Impregnation Times					
	°F		°F	3 hr/depth (in.)	12 hr/depth (in.)	24 hr/depth (in.)			
Group II - A	195	53.0	68	41.2	0.72	71.2	1.25	90.5	1.58
Group II - B	195	53.0	40	39.9	0.80	66.7	1.33	85.6	1.71
Group III - A	220	44.0	68	44.8	1.01	74.0	1.67	90.5	2.04
Group III - B	220	44.0	40	37.8	0.94	63.1	1.58	86.5	2.16
Group IV - A	245	30.0	68	38.3	1.15	67.5	2.03	85.4	2.56
Group IV - B	245	30.0	40	37.6	1.22	66.2	2.15	83.5	2.71
Group V - A	250	19.0	68	37.0	1.29	72.8	2.55	88.4	3.09
Group V - B	250	19.0	40	40.5	1.42	69.2	2.42	87.2	3.05

Specimen ¹	48 hr/depth (in.)		72 hr/depth (in.)		96 hr/depth (in.)		120 hr/depth (in.) ⁵		Total Wt (g) Monomer Gained
Group II - A	95.3	1.67	98.8	1.73	100	1.75			58.1
Group II - B	96.7	1.93	99.4	1.99	100	2.0			58.5
Group III - A	96.1	2.16	98.8	2.22	100	2.25			61.3
Group III - B	96.5	2.41	99.3	2.48	100	2.50			64.1
Group IV - A	93.2	2.80	96.7	2.90	99.7	2.99	100	3.0	83.2
Group IV - B	95.8	3.11	97.3	3.16	99.5	3.23	100	3.25	79.8
Group V - A	95.0	3.32	99.2	3.47	99.5	3.48	100	3.5	88.7
Group V - B	94.0	3.29	97.3	3.41	99.9	3.49	100	3.5	93.5

1. Each group (Group II-A, etc.) was comprised of 3 cylinders. Data are average of 3 cylinders.
2. The lateral sides of the cylinders were coated with epoxy and monomer was ponded on the top surface only.
3. Monomer system was MMA-TMPTMA-AZO (100:10:0.5 by weight).
4. The estimated depth of penetration is the percentage of total monomer uptake at various times multiplied by the total depth of penetration (heaviest loading--visible to the eye).
5. The cylinder that was cut to measure the final depth of penetration (heaviest loading--visible to the eye) had a total monomer uptake that was about the mean of the 3 cylinders in its group.

APPENDIX C

DRYING STUDIES

BACKGROUND

It was realized early in the research effort that adequate drying of the concrete would be a major concern in preparing the material for polymer impregnation. Various methods of drying had been reported by others—such as BNL (2), BuRec (2), University of Texas (8), and the Kansas Highway Commission (19) (e.g., methods based on gas-fired infrared heating, microwave heating, hot-air heating, flame heating, and electro-osmosis devices (19)). However, since the goal of this project, in general, posed differ-

ent drying requirements (namely, deep drying from one side using available techniques capable of easy scale-up), extensive drying tests were carried out to determine the best method. Tests were conducted both in the laboratory and in the field; some were begun prior to this study and funded by other sources.

Studies were conducted to determine which techniques might be best utilized, and some were conducted to establish a practical criterion for drying in the field. Experiments were made with mortar cubes, concrete cylinders, and slabs

at the bridge deck of the Pennsylvania Transportation Research Facility.

GENERAL REQUIREMENTS

For preliminary studies, standard portland cement mortar cubes (ASTM C 109-70T) and slabs were prepared and cured. These were then dried under different schedules by a variety of methods, such as ambient air, hot air, infrared, radio frequency, and oven drying. A smooth inverse relationship was generally found to exist between surface temperature reached (regardless of the heat source) and the amount of moisture remaining.

INVESTIGATIONS OF VARIOUS METHODS

Hot Air (Kerosene-Fired Blower and Electrically Heated Blower)

In typical experiments using high-velocity hot air (heated electrically or by a kerosene burner), concrete pieces up to 24 in. x 24 in. x 6 in. (61.0 cm x 61.0 cm x 15.2 cm) were subjected to rapid moving air above 200 F (93 C). Although considerable drying occurred in the concrete, drying the slab at up to 240 F (116 C) for a total of 4 days yielded a net moisture loss of only 76 percent. Since slowness in drying and low degrees of moisture removal were shown to be detrimental to the deep impregnation of concrete, these methods were not favored.

Infrared (IR) Heating

Following earlier work by others, additional studies were made using small cubes and 8-in. x 8-in. x 4½-in. (20.3-cm x 20.3-cm x 11.4-cm) concrete blocks. Large-scale use of IR drying on slabs and on bridge decks themselves was also demonstrated (reported later in this appendix).

In investigations of drying methods, two points regarding IR methods are of special importance:

1. The drying of concrete by such equipment as electrically powered IR heaters requires amounts of power that may be very difficult to obtain in the field because concrete typically has a high total heat capacity per unit area. Relatively high concrete surface temperatures are also required (somewhat > 200 F (93 C)) for sufficient drying for deep impregnations. Thus, electrical power requirements are large.

2. In spite of these power requirements, IR heating tends to be relatively efficient compared to other methods such as hot-air drying. Depending on the exact conditions, propane-fired IR drying may be three times as efficient (relative to propane required) as propane-fired hot air, for instance. Shielding from wind in the field is conveniently accomplished, so that the high surface temperatures required may be easily reached.

Microwave or Radio Frequency (RF)

Microwave or radio frequency heating of concrete can result in rather rapid drying. Since the RF energy is coupled directly with the water, the time required to heat the system depends only on the materials present and the power density available. In fact, the rate of RF drying probably can be as high, or higher, as with any method

thus far reported. Tests on mortar cubes gave complete drying within minutes.

Several points were considered. First was the cost of RF power. The generation of electric power utilizes only about one-third of the heat of combustion in a power plant; the generation of RF power from 60-Hz power requires another significant loss. It is only once the RF power is attained that the efficiency of transforming RF to heat in the concrete is high.

Second, radiation hazards and electrical interference must be reckoned with in using RF power to dry concrete on a large scale. Portable RF drying units are under development elsewhere for patch repair of roads and structures; care is being taken to minimize such problems.

Third, a too rapid release of energy in wet concrete can cause internal damage due to the sudden vaporization of the water. Thus, an upper limit may be set on the drying rate by this factor rather than by the deliverable power per se.

In any case, at least during the period of this contract, the use of RF did not appear to be feasible for large-scale use in drying bridge decks for subsequent impregnation.

Oven Drying

Over drying is often advantageous for laboratory studies. In tests on concrete slabs 24 in. x 24 in. x 6 in. (61.0 cm x 61.0 cm x 15.2 cm), it was also shown to be an effective way to carry out evaluation of parameters such as the change in moisture content with time. Thus, drying 45 hr at 250 F (121 C) resulted in complete drying; the rate depended on the square root of time (11), as expected for a diffusional process.

In larger scale tests, it is possible in principle to field-dry concrete by building ovens to encompass some or all of a structure or slab. Fuel efficiency may be expected to be high, but construction may be expected to be complex and expensive, especially if deep drying is required, as is the case here.

Electro-Osmosis

The motion of liquid through membrane-like media under the influence of an electric field (electro-osmosis) has been previously investigated for possible use in drying concrete (19). Although success has been reported informally by others, at this time the feasibility of using the method does not appear to be sufficiently established for use in this work. Preliminary experiments made in these laboratories did not yield the relative dryness that is required for rapid penetration of monomers. However, further basic studies in the future would be important in establishing the degree of usefulness for concrete structures. In the case of some potentially useful monomer systems, the applicability of electro-osmosis definitely would need to be reevaluated.

Propane-Fired Torch

Application of the technique using a propane-fired torch to dry concrete in the current research was developed and reported (11). The method is quite capable of producing relatively high surface temperatures leading to rapid, deep drying. Typically, the torch is programmed to travel a

given route repetitively. The use of a sand covering to protect the surface from flame-induced degradation was found to be desirable.

In comparison with IR drying, the torch method requires more propane per unit dried, and is probably more readily susceptible to decreases in efficiency due to wind, etc. However, the use of propane to obtain heat may be efficient compared to using electricity generated from oil or other fuel. Only small amounts of electricity are required to move and control the torch. In addition, this method has several other practical advantages: low cost, simplicity, and ease of scale-up.

Electric Resistance Heating

For laboratory work on small scale applications, such as for controlled drying studies, electric resistance heating can be advantageous. This is either through the concrete system or by utilizing the reinforcing steel. However, although it is possible that resistance drying will be developed for large-scale field applications at some later date, for the purposes of the current contract, it was decided that other methods are more applicable, at least at present.

Several disadvantages hinder such large-scale use. The heat capacity of wet concrete is such that very large electrical power requirements result. Very large electrical generators would be required to dry large slabs of concrete in the field. Further, it is difficult to even approximately match impedances between the electrical source and the concrete load in order to obtain efficient power transfer. In general, the impedance and heat capacity can be expected to change with time as drying progresses.

LABORATORY DRYING TESTS ON LARGE SLABS

Funding from the Pennsylvania Science and Engineering Foundation and The Pennsylvania State University were used to conduct laboratory experiments designed to obtain research data for use in field applications, with emphasis on drying rates as a function of parameters such as surface temperature, moisture content, and size. The basic research was also directed toward seeking relationships between specimen temperature, temperature distribution rate of temperature change, and moisture content.

After consideration of the results of investigations of various drying methods, as reported in the previous section, it was decided that IR drying and propane torch drying were the most feasible for studies that would be useful within the period of this contract and would provide relatively efficient use of fuel, time, and cost.

A 6-ft x 6-ft x 6-in. (18.29-m x 18.29-m x 0.15 m) slab was constructed on a raised steel framework with one layer of typical bridge deck reinforcing steel. Thermocouples were placed at depths of ½ in. (1.3 cm), 1 in. (2.5 cm), 2½ in. (6.4 cm), and 4 in. (10.2 cm) from the top for five different locations in the slab. The reinforcing used was composed of No. 4 bars placed on 6-in. (15.2-cm) centers in one direction and No. 5 bars placed on 8-in. (20.3-cm) centers in the other direction. A second slab 6 ft x 6 ft x 8 in. (18.29 m x 18.29 m x 0.20 m) was cast with two layers of reinforcing steel, similar to construction of bridge decks in Pennsylvania. Thermocouples, in this case, were

placed at depths of 2½ in. (6.4 cm) and 4 in. (10.2 cm) from the top surface for monitoring temperature as drying progressed. Design details for these slabs and the concrete mixtures used for them are given in Appendix G.

The two methods—gas-fired infrared (IR) and propane torch—were used in various experiments to determine suitable drying criteria. The moisture content associated with different drying methods and temperatures was established by using moisture gages placed in concrete specimens. In some cases, moisture gages were placed in slab positions. Gas-fired IR heaters have a high relative efficiency compared to some other methods, resulting in a propane consumption of about 2.9 lb/hr (1.3 kg/hr) for 60,000-Btu/hr (63 = MJ/hr) output. This heater (size 2 ft x 1 ft (6.10 m x 3.05 m)) could dry about 2 ft² (0.2 m²). It was secured from Pavement Reclaiming Corp., Buffalo, New York (Model TPRC JH2—Joint Heater).

Figures C-1 and C-2 show the temperature profile data of the 6-ft x 6-ft x 6-in. (18.29-m x 18.29-m x 0.15-m) slab and the 6-ft x 6-ft x 8-in. (18.29-m x 18.29-m x 0.20-m) slab, respectively, during drying tests using the gas-fired infrared heater. Many drying tests were conducted using different sources and the temperature profiles presented are considered to be typical (9). Some of the slab drying tests produced severe cracking (however, on drying a bridge deck, severe cracking was not observed).

For drying of concrete using gas-fired heaters, one can maintain either a constant surface temperature (as in oven drying) or the heater at a constant distance above the concrete. To maintain a constant surface temperature, the surface temperature must be observed and the heater distance above the concrete controlled, as is evident in Figures C-1

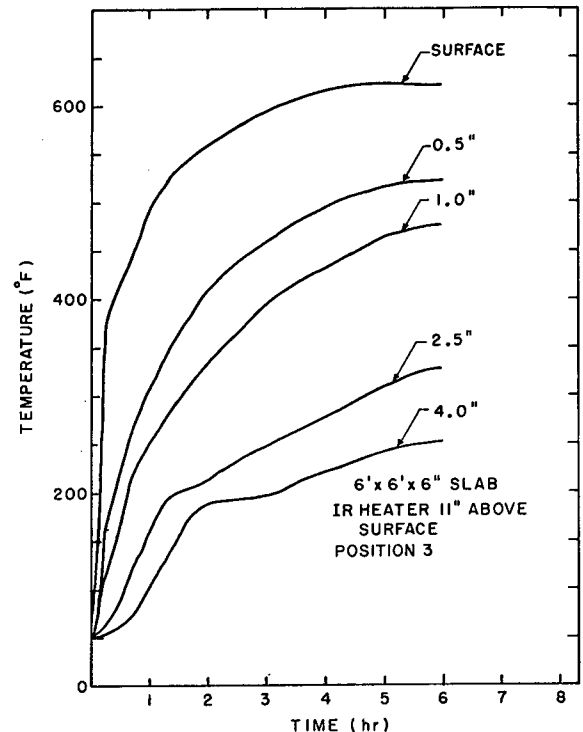


Figure C-1. Temperature profile vs. time for 6-ft x 6-ft x 6-in. slab trial (9) (ambient temperature=70 F).

and C-2. To avoid the continuous monitoring required to maintain a constant surface temperature, one can also choose to maintain a constant difference between the heater and the slab. This was done in this case.

There are two distinct drying periods evident in the curves. In the first period, the average moisture content decreases fairly fast and the temperature rises, after which it remains about constant. This is sometimes called the constant rate period, and capillary flow is believed to be (20) the principal mechanism of moisture migration. This period terminates when the slab temperature begins to increase. A second period is called the falling rate period. Here moisture movement is believed to be mainly by an evaporation and condensation mechanism. In this period, the rate of temperature rise throughout the concrete steadily decreases until equilibrium with the surroundings is reached.

Establishing Criteria for Drying

To predict if the concrete is dry to a prescribed level at 4 in. (10 cm), using IR, a thermocouple can be placed at a depth of 4 in. (10 cm) or one can use the surface temperature as an indication of the temperature at 4 in. (10 cm). The best indication using surface temperature seems to be to observe the rate of surface temperature change once per hour, and, when the rate of increase per hour is 10 F (5.5 C) or less, the temperature at 4 in. (10 cm) approaches equilibrium. This rate occurred about 2 hr after the temperature at 4 in. (10.2 cm) reached about 212 F (100 C). Table C-1 gives the rate of surface temperature change along with the temperature at a 4-in. (10-cm) depth. In summary, there appear to be two ways

TABLE C-1

SURFACE TEMPERATURE RATE COMPARED TO TEMPERATURE AT 4 IN.¹

Test	Surface ΔT ($^{\circ}F$) ² for each	Temperature ($^{\circ}F$) at
	hr after 212 $^{\circ}F$ is reached at 4 in.	4 in. at end of each hr
6' x 6' x 8"	36	212
	1 hr 18	243
	2 hr 5.4	264
6' x 6' x 6" Position 1	27	212
	1 hr 18	236
6' x 6' x 6" Position 3	27.6	218
	1 hr 7.2	238
6' x 6' x 6" Position 4	25.2	213
	1 hr 16.2	235
(crack)	2 hr 12.6	254

1. Ambient temperature was about 70 $^{\circ}F$.

2. ΔT = temperature at end of hour - temperature at beginning of hour.

of expressing the criteria. First, when the rate of temperature change at the surface is 10 F/hr (5.5 C/hr) or less, drying equilibrium in the concrete is nearly attained at 4 in. (10 cm). Alternately, when the temperature at 4 in. (10 cm) is above 230 F (110 C), drying equilibrium is practically attained. The temperature at 4 in. (10 cm) during the test appeared to level out at about 260 F (127 C) when the ambient temperature was 70 F (21 C).

Effect of Drying on Monomer Loading and Moisture Absorption

In order to establish a criterion for drying in terms of impregnation characteristics, a typical MMA monomer system was employed in evaluating monomer penetration: 100:10:0.5 mixtures of MMA, trimethylolpropane trimethacrylate (TMPTMA) and azobisisobutyronitrile (AZO). This system has been very useful in laboratory experiments with bridge deck cores, cast cylinders, and slab and field work.

Drying to 230 F (110 C) or higher at a depth of 4 in. (10 cm) results in ease of penetration under pressure above atmospheric values. It has also been shown by Weyers (17) that the MMA system will soak through 5 in. (12.7 cm) of bridge deck cores in 4 to 11 days if these are properly dried (specimens were oven dried and then vacuum oven dried). In the Weyers' experiments, soaking occurred from the top only and sides were sealed. Additional data are given in Appendixes B, D, and F.

Effects of Heating Rate

After the drying criterion (230 F at 4 in. (110 C at 10 cm)) was adopted, preliminary experiments were also made with 24-in. x 24-in. x 6-in. (61.0-cm x 61.0-cm x

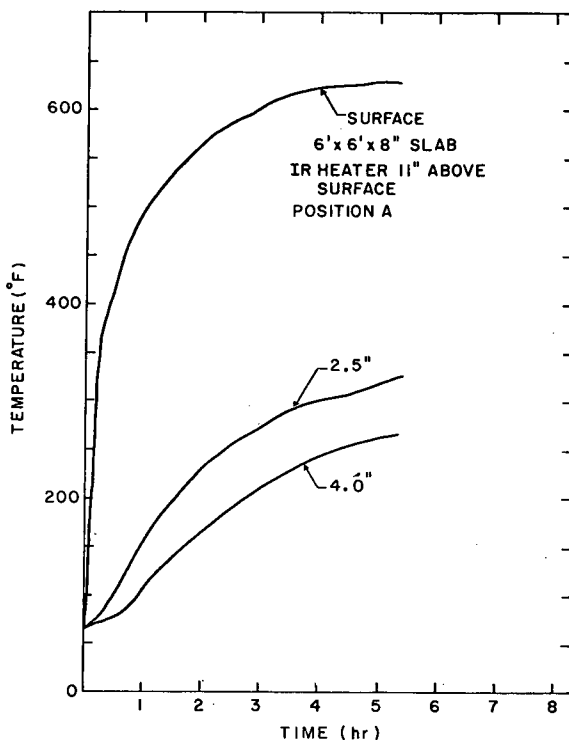


Figure C-2. Temperature profile vs. time for 6-ft x 6-ft x 8-in. slab trial (9) (ambient temperature = 70 F).

15.2-cm) slabs to correlate moisture loss directly with temperature and rate of drying. For this study, 24-in. x 24-in. x 6-in. (61-cm x 61-cm x 15-cm) concrete slab specimens were prepared from a conventional non-air-entrained 1.00:1.92:6.10:6.75 water portland cement (type I), coarse sand-limestone aggregate (1 in. (2.5 cm) maximum) mix with a cement factor of 485 lb/cu yd (287 kg/m³) and a 28-day average compressive strength of 4,750 psi (32,800 kN/m²). The measured air content was 3 percent with a slump of 2.5 to 3.0 in. (6.4-7.6 cm). The slabs were given a normal trowel finish and were cured in the fog room (90 to 100 percent RH) for at least 28 days before the drying and impregnation tests. All slabs contained a nominal steel reinforcement at a 4-in. (10-cm) depth to simulate the structure of the bridge deck. The slabs were tested between 9 to 12 months after casting and were stored in a moist room at 90 to 100 percent RH prior to testing. Six thermocouples were embedded in each of slabs 1, 2, and 3 at various depths and positions. The gas propane torch was used for drying, and the slabs were weighed to monitor moisture content.

Results showed that, as expected, the higher the heating rate, the shorter the time required to reach 230 F (110 C) at any depth (Fig. C-3). However, the shorter the time, the lower the amount of water lost. Although those results cannot be correlated directly with the IR experiments (large slabs or bridge decks), the results might suggest that more work is needed in terms of moisture loss/monomer pickup for a greater variety of concretes and conditions.

It was also found in preliminary experiments that alternate drying could be more efficient than continuous drying (Fig. C-4). During cooling, water continues to evaporate as long as a positive thermal gradient exists with respect to the surroundings. It may be possible, therefore, to reduce the costs of drying by making use of this effect.

FIELD DRYING TESTS

Infrared Dryer

A slab portion of the deck of the Pennsylvania Transportation Research Facility was first used for field drying studies (termed Field #1). This was followed by a second field test on a larger section of the facility using IR drying only (termed Field #2). Subsequently, a portion of a bridge deck in Bethlehem, Pa., was also IR dried (termed Field #3), adding more experience to drying in the field. In all cases, the dried sections were impregnated with MMA, followed by polymerization to ascertain the drying procedure.

In the first case, drying was accomplished by both propane torch and flame infrared, followed by both ponding and by pressure types of impregnation. Polymerization was accomplished by both hot water and steam. This illustrates the various combinations that can be used in the field to get more than a 4-in. (10-cm) penetration of polymer.

In field test #1, thermocouples were placed in the bridge deck by drilling holes in the concrete. As shown in Figure C-5, the form of the temperature profile with time is similar to that shown in Figures C-1 and C-2 for research slabs. Time to reach a given temperature seems to be longer, compared to the slab tests, because of the low ambient temperature and cooling effect of winds. The equipment failure

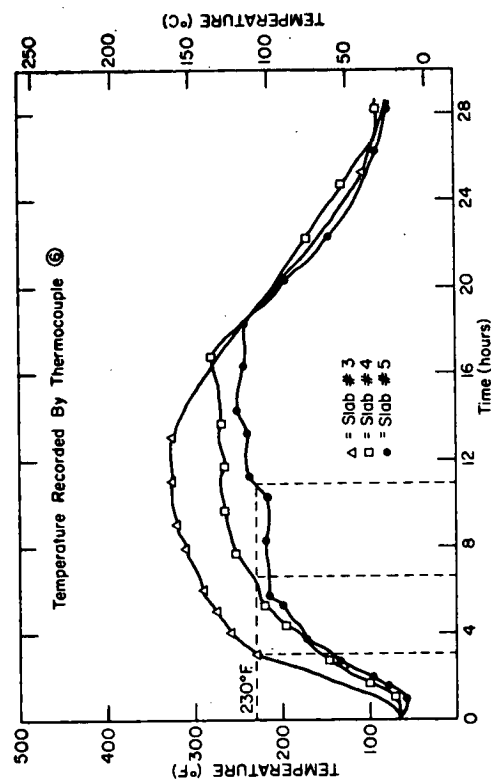


Figure C-3. Temperature vs. time for underside of 24-in. x 24-in. x 6-in. slabs.

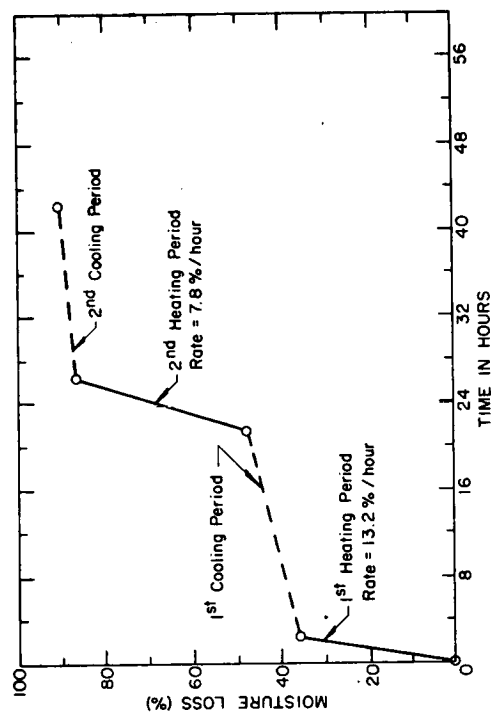


Figure C-4. Moisture loss curve for 24-in. x 24-in. x 6-in. slab dried by alternate heating and cooling.

occurred when the heater was extinguished by high winds. This problem was solved by using a shield around the IR heater. The areas dried were relatively small (3.75 ft² (0.35 m²)), but impregnation to 4 in. (10 cm) with subsequent polymerization was obtained, indicating adequate drying. Table C-2 summarizes the temperature rate data.

Field test #1 for drying indicates that both IR and propane torch drying could achieve adequate results in the

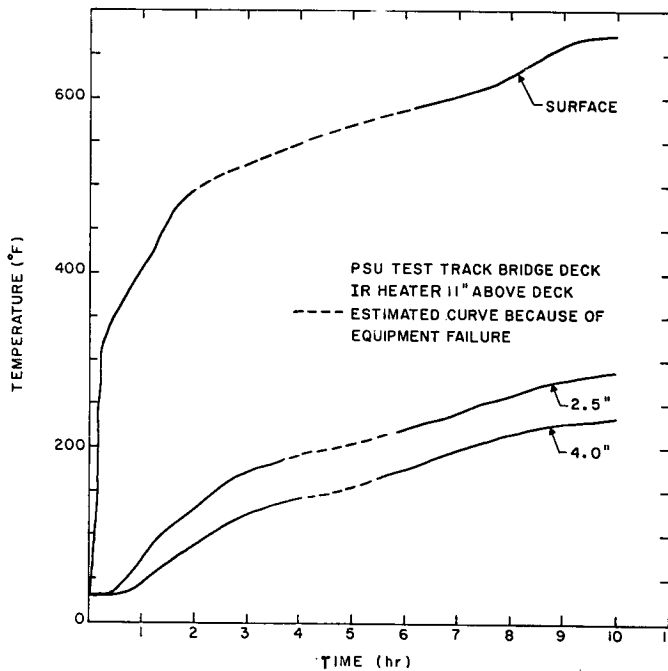


Figure C-5. Temperature profile vs. time for bridge deck drying trial (9).

field. The IR system, as mentioned earlier, tends to use less propane and may be less affected by wind. Propane torch systems could conceivably be cheaper to construct, however.

Field tests #2 and #3 were limited to gas-fired IR drying using a 4-ft x 5-ft (1.22-m x 1.52-m) IR system of 180,000 Btu/hr (130 MJ/hr) capacity. Table C-3 summarizes these findings.

Flame Dryer

As described in Appendix H, the torch unit was used successfully to dry several sections of the Pennsylvania Transportation Research Facility bridge deck. The subsequent

TABLE C-2

SURFACE TEMPERATURE RATE COMPARED TO TEMPERATURE AT 4 IN.¹

Test	Surface ΔT ($^{\circ}\text{F}$) ² for each hr after 212 $^{\circ}\text{F}$ is reached at 4 in.	Temperature ($^{\circ}\text{F}$) at 4 in. at end of each hr
Bridge Deck	22	212
(Field Test #1)	1 hr 36	223
PSU Test Track:	2 hr 9	231

1. Ambient temperature was about 31 $^{\circ}\text{F}$ (-0.56 $^{\circ}\text{C}$).

2. ΔT = temperature at end of hour minus temperature at beginning of hour.

TABLE C-3

SUMMARY OF DRYING TIMES

Test ¹	Drying Times	Max. Surface Temp. $^{\circ}\text{F}$
Field Test 2, PSU Test Track	4 hr	630
Field Test 3, Bethlehem, Pa.	7 hr	680

1. Ambient temperatures were about 77 $^{\circ}\text{F}$ and 50 $^{\circ}\text{F}$, respectively. Drying time is time to reach 230 $^{\circ}\text{F}$ at 4 in.

impregnation was successful to 4-in. (10-cm) depths.

Drying Criterion

Since the laboratory tests showed that a temperature of 230 F (110 C) resulted in drying to 80 percent or more of oven dry weight, this criterion was tested in the first small-scale field trials (see Appendix G). Since the trials were successful, the criterion was adopted. Additional trials may be necessary if the mix design is changed or a high absorption type aggregate is used. Slight alterations of the drying criteria may be necessary to accommodate these variables.

APPENDIX D

IMPREGNATION STUDIES

THEORETICAL ASPECTS

Although the morphology of concretes and mortars is complex, the solid phase may be considered to be a single component, rigid, isotropic material containing a network of interconnected pores (21). Since these pores have a broad distribution of sizes and contain both air and water, the rate of penetration and equilibrium sorption of a given fluid depend on the thermal curing and atmospheric history of the substrate. As will be shown later, however, a mortar specimen with a given porosity and history can give reproducible rates of penetration with a given monomer, so that the different rates observed with various monomers reflect real differences attributable to such properties as interfacial energy and viscosity.

Several approaches have been taken to characterize fluid flow through porous media. Assuming a constant porosity and pressure gradient in the x direction, the application of Darcy's law (22) leads to the following expression for the permeability constant P (the volume of fluid of unit viscosity passing through a unit cross sectional area in unit time):

$$P = \eta q L / A \Delta P \quad (\text{D-1})$$

where η is the viscosity, q the rate of flow through area A (dependent on the porosity), and ΔP the pressure drop through the medium of thickness L . Poiseuille's equation has also been modified by several investigators to give equations involving such measurable parameters of the substrates as the surface area per unit volume S_w :

$$q = [kA v_w^3 / \eta S_w^2] (\Delta P / L) \quad (\text{D-2})$$

where S_w is the specific surface area of the substrate with v voids per unit length, and k is a constant.

Eqs. D-1 and D-2 account for the viscosity of the fluid and the porosity of the substrate; however, they do not account for the capillary-rise phenomenon. The height of rise h of a fluid ascending a capillary pore of radius r is given by the Rideal-Washburn equation (14):

$$r \cos \theta = 2\eta h^2 / \gamma t \quad (\text{D-3})$$

where θ is the contact angle, γ the surface tension of the fluid, and t the time. Thus, for a given contact angle and pore size, the value of h should vary directly with the product $(\gamma t / \eta)^{1/2}$.

The penetration of a fluid into a porous substrate should proceed according to Eqs. D-1 to D-3 (until it is counterbalanced by evaporation from the surface or stopped by entrapped air or water vapor); however, at the time this work was begun these equations neither had been tested with concrete substrates nor was the moisture known. Studies of penetration rate per se are discussed in Appendix B; the studies discussed here were concerned primarily with effects of moisture content and techniques.

CONCRETE AND MORTAR LAB SPECIMENS—EFFECTS OF MOISTURE CONTENT ON MONOMER LOADING

Mortar cubes 2 in. x 2 in. x 2 in. (5.1 cm x 5.1 cm x 5.1 cm) were molded and dried for different periods of time in an oven (221 F (105 C)). When 30, 40, 50, 60, 80, and 100 percent of the water that could be removed from the mortar cubes under the drying conditions stated had been removed, two cubes for each condition were taken from the oven. These cubes were allowed to cool and then were soaked in the MMA-TMPTMA-AZO system for 3 days. The cubes were then polymerized by a thermo-catalytic procedure. The important result of this test was that if 20 percent of the water that could be removed from the mortar under the drying condition stated remained, impregnations of approximately 90 percent of the monomer that could be impregnated at 0-percent moisture content could be achieved. This implies that good monomer loadings could be achieved at 20 percent or less moisture contents. A detailed discussion and the results of this test are given by Pu (18).

PRESSURE METHOD

Slabs

Concrete slab specimens, 24 in. x 24 in. x 6 in. (61 cm x 61 cm x 15 cm), were prepared from a conventional non-air-entrained 1.00:1.92:6.10:6.75 water-portland cement (type I), coarse sand-limestone aggregate (1 in. (2.5 cm) maximum) mix with a cement factor of 485 lb/cu yd (287 kg/m³) and a 28-day average compressive strength of 4,750 psi (32,800 kPa). The measured air content was 3 percent with a slump of 2.5 in. to 3.0 in. (6.4 cm to 7.6 cm). The slabs were given a normal trowel finish and were cured in the fog room (90- to 100-percent relative humidity) for at least 28 days before use in drying and

impregnation tests. All slabs contained a nominal steel reinforcement at a 4-in. (10-cm) depth to simulate the structure of the bridge deck, and one 72-in. x 72-in. x 8-in. (180-cm x 180-cm x 20-cm) slab was prepared to the PennDOT AA specification.

In these tests, the 24-in. x 24-in. x 6-in. (61-cm x 61-cm x 15-cm) slabs were oven dried at 257 F (125 C), whereas the 72-in. x 72-in. x 5-in. (183-cm x 183-cm x 20.32-cm) slabs were dried using the propane-torch assembly (Appendix C).

Impregnation and Polymerization

The completely dried 24-in. x 24-in. x 6-in. (61-cm x 61-cm x 15-cm) concrete slabs were positioned on supports with their lower surfaces exposed and subjected to impregnation from their upper surfaces. Details of the equipment used are presented in Appendix G.

The first slab was dried and impregnated at a pressure of 30 psi (210 kPa). After 17 hr, a dark spreading patch of monomer appeared on the underside of the slab; by 24 hr, this patch had grown to a diameter of 18 in. (46 cm)—larger than the diameter of the area impregnated from the upper surface. At this point, the impregnation device was removed, and a 0.5-in. (1.3-cm) layer of sand was spread over the area enclosed by the gasket and wetted with additional monomer to minimize evaporative losses during polymerization (8, 23). The slab was then wrapped in polyethylene film, and live steam was played on its surface for 5 hr to polymerize the monomer mixture. After polymerization, the polymer loading of this slab was determined to be approximately 5.5 percent.

When the slab was broken, only a slight odor of monomer was detected, indicating that the polymerization had proceeded to high conversion. Moreover, the appearance of the fracture cross section was similar to that of other polymer-impregnated specimens. The dark polymer-impregnated region can be distinguished readily from the light unimpregnated region. The diameter of the impregnated region was 21 in. (53 cm) on the upper surface and 18 in. (46 cm) on the lower surface of the slab, indicating that the impregnating monomer had spread laterally beyond the 16-in. (41-cm) diameter enclosed by the gasket. Also, the lighter 0.25-in. (0.6-cm) surface layer on the bottom indicated that some monomer was lost from the lower surface by evaporation. Examination of the fracture cross section with a magnifying glass showed that, in the polymer-impregnated region, fracture usually occurred through the aggregate particles, but in the unimpregnated region it typically occurred around the particles.

This first slab impregnation was successful in that it achieved the deepest impregnation in sound concrete reported to date. To confirm and extend this result, other slabs were dried and impregnated. The parameters investigated included the pressure applied during impregnation, the substitution of isobutyl methacrylate for methyl methacrylate in the monomer mixture, the use of hot-water ponding instead of steam to polymerize the monomer, and the presence of salt as a contaminant in the concrete substrate (see Appendix F).

In these experiments, the pressure was varied from 30 psi to 80 psi (210 kPa to 550 kPa). The impregnation pro-

ceeded smoothly in all cases, but there was some leakage of monomer around the gasket at pressures greater than 60 psi (410 kPa). An increase in the pressure decreased the time required for penetration to the full 6-in. (15-cm) depth; e.g., from 17 to 24 hr for 30 psi (210 kPa) to 2.0 to 3.5 hr for 80 psi (550 kPa). These times are expressed as ranges—the first value denotes the first appearance of monomer on the underside of the slab; and the second value, the time required for complete impregnation. Apparently, the monomer mixture penetrates first through the channels and microcracks from which the water has been removed and only later fills the micropores and large voids as it spreads both downward and laterally through the slab.

Isobutyl methacrylate was substituted for methyl methacrylate in two slabs in this study, because it is less volatile and therefore less subject to loss by evaporation. Moreover, polyisobutyl methacrylate is more flexible and less brittle than polymethyl methacrylate and thus may be better able to withstand repetitive freezing-and-thawing cycles.

All of the slabs were polymerized by heating for 5 to 8 hr using steam, except for one slab which was polymerized overnight using hot-water ponding on its surface. During the course of the polymerization, the temperature of the water decreased from 140 F (60 C) to 100 F (43 C), and some monomer was lost by evaporation from the underside of the slab.

Cylinders

A series of concrete cylinders were cast with a concrete mixture used by the Pennsylvania Department of Transportation. After 28 days of moist curing (100-percent relative humidity at 68 F (20 C)), these cylinders were dried to constant weight and impregnated with salt solutions. A mixture of one part CaCl_2 to three parts NaCl was used in preparing the salt solutions. The cylinders were impregnated with a 1.0-, 2.5-, 4.0-, and 6.0-percent salt solution (by weight). The acquired salt contents were analyzed by a titration procedure developed by Berman (24). The concrete specimens acquired chloride levels of 0.125, 0.318, 0.500, and 0.750 percent by weight of mortar for 1.0-, 2.5-, 4.0-, and 6.0-percent salt solutions, respectively.

After the specimens were salt contaminated, they were again dried in a forced air oven to constant weight. The lateral sides were coated with epoxy, and the cylinders were impregnated from the top surface with MMA-TMPTMA-AZO (100:10:05 by weight) at 75 psig (517.1 kPa) overpressure in an impregnation chamber described by Weyers (17).

The impregnation data for the salt-contaminated cylinders are given in Table D-1. The error of regression showed that the impregnation level tends toward a linear function of the monomer weight gain in grams as a function of the square root of time. However, the slope of the curve (rate of impregnation) varied by about 25 percent among the cylinders prepared from a single batch mix.

In order to analyze the variability in the impregnation rates for the cylinders, the percent MMA gained at 2 hr and the total percent volume filled with MMA was compared with the percent salt used. The correlation coefficients were compared for significance at the 95-percent confidence

level. Since correlation was not established for the percent salt solutions and the total percent volume filled with MMA or the percent MMA gained in 2 hr, the presence of 0.750-percent chloride appeared to have no effect on penetration.

Additional impregnation studies for salt-contaminated specimens are discussed as follows and in Appendix F.

PONDING METHOD

Cores

The impregnation of cast cylinders by ponding MMA-TMPTMA-AZO (100:10:0.5) is discussed in detail in Appendix B. It appears from these data that, if the cylinder is sufficiently dry, deep impregnations (up to 8 in. (20.3 cm)) can be achieved. Also, when the cylinders are dried from the top surface using infrared heat, heavy impregnations of up to 3.5 in. (8.9-cm) from the surface can easily be achieved.

Cores obtained from three salt-contaminated bridge decks were impregnated with MMA-TMPTMA-AZO (100:10:0.5 by weight) by ponding on the top surface only. Prior to impregnation, the lateral sides of these cores were coated with epoxy, and the cylinders were dried in a forced air oven (240 F (110 C)) for 3 days; they were then placed under vacuum in an oven at 250 F (121.1 C) for 24 hr. The MMA system was ponded on the top surface, and the impregnation was continued until the monomer system soaked through about 5 in. (13 cm) of the core. The deicer salts appeared to decrease the rate of impregnation (17). The study is discussed in detail in Appendix F.

Slabs

Large-scale slab studies (6 ft x 6 ft x 6 in. (18.29 m x 18.29 m x 15.2 cm) and 6 ft x 6 ft x 8 in. (18.29 m x 18.29 m x 20.3 cm)) showed that, after drying with infrared heat to a prescribed drying schedule, ponding over the dried area with a MMA-TMPTMA-AZO (100:10:0.5 by weight) system produced impregnation to about a 4-in. (10-cm) depth in 4 days. These results are discussed in more detail in Appendix G.

PRESSURE MAT

The foregoing results show that the bolt-down impregnation unit was suitable for carrying out impregnation at greater-than-atmospheric pressure. However, this type of apparatus is limited in terms of weight and mobility; therefore, a better method of pressure impregnation was sought: a pressure mat impregnation unit.

The first pressure mat experiment used a molded rubber door mat comprised of diamond shape cells about 0.5 in. (1.3 cm) deep except for an elliptical area in the center that was marked "Welcome." This mat was inverted with the cell-side down on a dried 24-in. x 24-in. x 6-in. (60.96-cm x 60.96-cm x 15.24-cm) concrete slab and held in place by a bolted-down metal sealing strip around the edge of the slab and the mat. Monomer was introduced into the cells of the mat through the same pressurizing apparatus used before, but this time arranged so that the monomer was injected

TABLE D-1
LABORATORY CYLINDERS—IMPREGNATION DATA AT 75 PSIG

Cylinder Number	Slope (g/hr ^{1/2})	Error of Regression	Monomer	Total	Percent at 2 hr	Percent Volume Filled	Percent Salt Solution	Total Pressure Time (hr)
			Gained in 2 hr (g)	Monomer Gained (g)				
PS 1-1	61.5	0.998	78.7	108.0	78.7	11.2	1.0	3.5
PS 1-2	68.1	1.000	80.8	114.0	80.8	11.8	1.0	3.0
PS 1-3	55.3	0.998	78.7	102.2	78.7	10.6	1.0	3.5
PS 2-1	64.7	1.000	76.0	113.4	76.0	11.7	2.5	3.5
PS 2-2	63.2	0.997	85.3	109.0	85.3	11.3	2.5	3.0
PS 2-3	64.0	0.999	73.1	115.0	73.1	11.9	2.5	3.5
PS 3-1	55.2	0.996	75.8	108.9	75.8	11.3	4.0	4.0
PS 3-2	56.1	0.993	83.9	106.0	83.9	11.0	4.0	3.5
PS 3-3	66.0	0.978	93.9	111.5	93.9	11.5	4.0	3.0
PS 4-1	60.5	0.990	85.7	112.8	85.7	11.7	6.0	3.5
PS 4-2	43.2	0.987	81.3	107.2	81.3	11.1	6.0	4.0
PS 4-3	67.6	0.999	91.7	108.0	91.7	11.2	6.0	3.0
PS 5-1	54.8	0.994	84.2	102.0	82.5	10.5	0.0	3.5
PS 5-2	64.6	0.993	94.3	101.6	92.8	10.5	0.0	2.5
PS 5-3	70.0	0.997	100.0	100.0	100.0	10.3	0.0	2.0

Unit Conversions: 1 psi = 6.9 kPa

1 oz = 28.4 g.

into the cells between the back of the mat and the concrete substrate. This whole assembly was mounted in a hydraulic press that was subjected to an unloading and loading cycle to simulate the effect of a roller going over and over such a pressure mat in actual practice (Fig. D-1).

It was found after 5 hr of impregnation that the monomer struck through the bottom of the slab and, about the same time, the center of the mat around the "Welcome" sign deteriorated and so disintegrated. The monomer infused into the slab was polymerized in the conventional way, and the slab was broken to determine the depth of penetration. It was found that the monomer had penetrated to a depth of at least 5 in. (12.7 cm) throughout the slab under the area covered by the mat and a black layer of dissolved rubber showed the forefront of the monomer impregnation. These results indicated that the pressure mat technique is feasible.

Therefore, a mat was designed and prepared from Neoprene rubber, specially for this purpose. This rubber mat was clamped into position and subjected to the loading and unloading cycle in the same manner as before. Again, the impregnation was virtually complete.

These experiments demonstrate that the pressure mat technique, although not yet developed to commercial scale, has considerable promise and should be developed further (25).

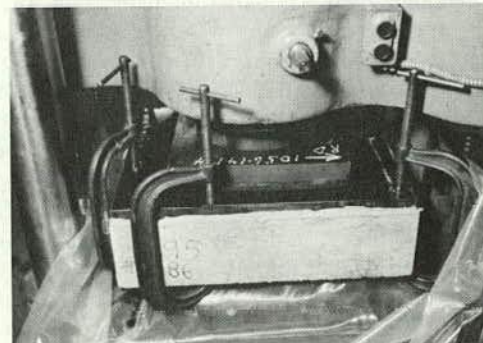
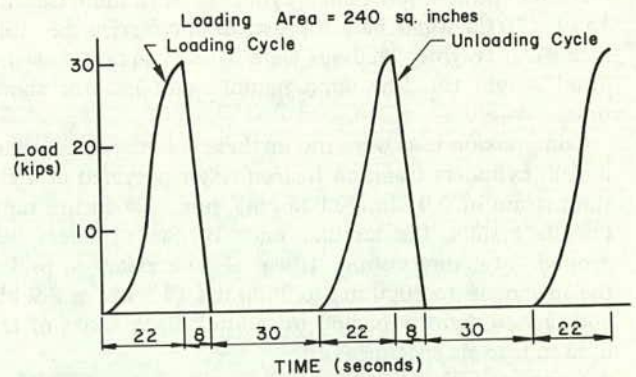


Figure D-1. Pressure mat impregnation method showing typical load cycle (top) and apparatus (bottom).

APPENDIX E

PROPERTIES OF POLYMER-IMPREGNATED CONCRETE

Several monomers (for example, MMA and BA) are of potential interest in bridge deck impregnation; from a longer range point of view, other impregnants are also worth consideration. Since properties such as strength and durability presumably depend on the nature of the impregnant, several studies of these and related properties were made using cement mortars and concrete cylinders, slabs, and cores (10, 11, 12, 25, 26). The effects of salt on mechanical properties are discussed in Appendix F.

MECHANICAL PROPERTIES

Stress-Strain Behavior: Concrete and Mortar Cylinder Specimens—Monomer Systems

Experimental Details (10, 11)

Portland cement mortar cylinders (1-in. (2.5-cm) diameter; 2-in. (5.1-cm) height) were prepared using a 12:24:64 water-portland cement (type II), Ottawa silica sand (ASTM C-109) mix and cured under water for 28 days at room temperature. The cylinders were dried in an air oven for 3 hr at 302 F (150 C), placed in a vacuum chamber, and subjected to vacuum for 15 min; they were then immersed in monomer (various mixtures of MMA and BA) containing 0.5-percent azobisisobutyronitrile for up to 3 hr at atmospheric pressure. Unless specified otherwise, these monomer-impregnated cylinders were immersed in a 158 F (70 C) water bath for 4 hr to polymerize the monomer. The polymer loadings were 5 to 7 percent, based on dried weight for 3-hr impregnations and less for shorter times.

Compression tests were run on these polymer-impregnated mortar cylinders using an Instron tester operated at a constant strain of 0.01 in. (0.025 cm)/min. To ensure reproducible results, the circular ends of the cylinders were ground flat before testing. It was also necessary to preload the specimens to 1000 lb f to 2000 lb f (4.5 kN to 8.9 kN) and unload, before loading to failure. Each series of tests used four to six specimens.

Concrete cylinders (3-in. (7.6-cm) diameter; 6-in. (15.2-cm) height) were prepared using water, portland cement (type I), sand, and gravel ($\frac{3}{8}$ in. (1.0 cm)) according to ASTM C33-67. After one day at room conditions, the cylinders were cured for 28 days in a moist room (90 to 100 percent RH), and were then stored for 14 days at room conditions. They were subsequently dried, impregnated with monomer (MMA, BA, MMA/BA mixtures, and MMA/BA/TMPTMA mixtures), and polymerized in a manner similar to that of the smaller mortar cylinders. The polymer loadings were between 4 and 6 percent, based on dried weight. Typical compositions and loadings are given in Table E-1.

Compression (ASTM C39-66) and split tensile (ASTM

TABLE E-1

TYPICAL POLYMER LOADINGS IN 3-IN. x 6-IN. CONCRETE CYLINDERS

Specimens	Number of Specimens	Polymer, as a Percentage	Average Polymer Loading, as a Percentage by Weight
(1)	(2)	(3)	(4)
AI	4	100 MMA	4.8
AII	8	60 MMA + 40 BA	4.3
BI	4	90 MMA + 10 TMPTMA	5.2
BII	8	70 MMA + 20 BA + 10 TMPTMA	4.6
BIII	8	60 MMA + 30 BA + 10 TMPTMA	4.9
BIV	8	50 MMA + 40 BA + 10 TMPTMA	5.1

Unit Conversion: 1 in. = 2.54 cm.

C496-66) tests were run on these polymer-impregnated concrete cylinders using a Baldwin hydraulic tester (300,000-lbf (1.33-MN) capacity). The tester was operated at constant hydraulic flow rate, and hence at an approximately constant load rate (40 to 50 lb f (180 to 220 N)/sec.), during the loading phase. Thus, the crosshead speed was not constant throughout the test, but increased after rupture of the specimen began. The strain was plotted as a function of stress, using the output from strain gages attached to various parts of the specimen.

Effect of Monomer Loading

As shown in other studies (5, 27, 28, 29), the compressive strength of polymer-impregnated mortar or concrete is a direct function of the polymer loading. Typical results are shown in Figure E-1 for a 90:10 MMA:BA mixture. It may also be seen that polymerization by intermittent heating to 140 F (60 C) rather than at a steady 158 F (70 C) yields higher strengths at a given loading—perhaps due to the formation of a higher molecular weight polymer.

Effect of Polymer Composition

Figures E-2 through E-10 and Table E-2 show typical results of the stress-strain measurements. It is obvious that the modulus, strength, ultimate strain, and energy-to-break of the portland cement mortar are increased dramatically by impregnation with polymethyl methacrylate (PMMA). This is in agreement with data reported by other investigators (5, 27, 30, 31). Although the absolute values and relative improvement of these properties are smaller than those

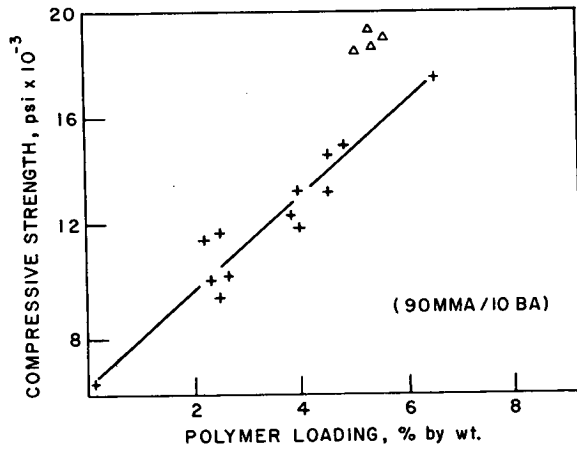


Figure E-1. Effect of polymer loading on compressive strength (by Instron tester: crosshead speed 0.01 in./min for mortar specimens (1 in. x 2 in.) impregnated with MMA/BA copolymers (90/10); polymerization continuous at 70 C (+), intermittent at 60 C (Δ); 1 in. = 2.54 cm, °F = 5/9 C + 32, 1 psi = 6.89 kN/m²).

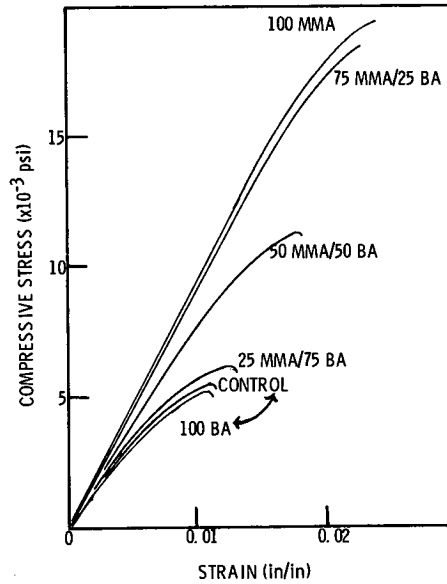


Figure E-2. Polymer-impregnated mortar: typical compressive stress-strain curves.

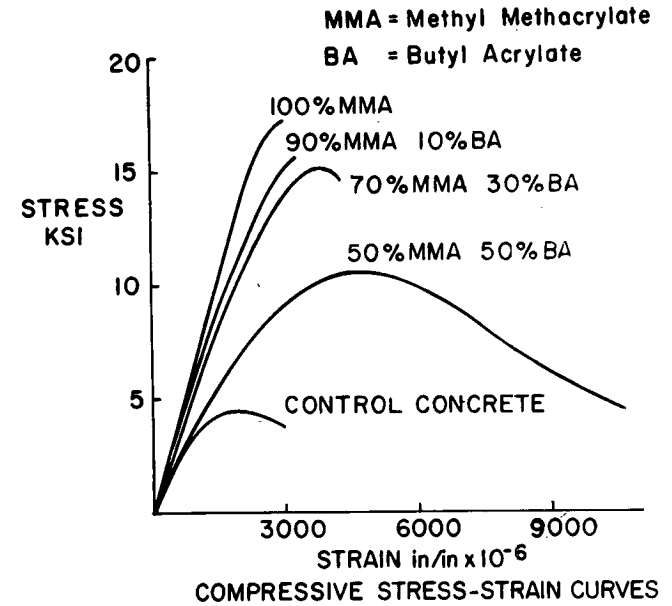


Figure E-3. Polymer-impregnated concrete: compressive stress-strain curves as a function of polymer composition.

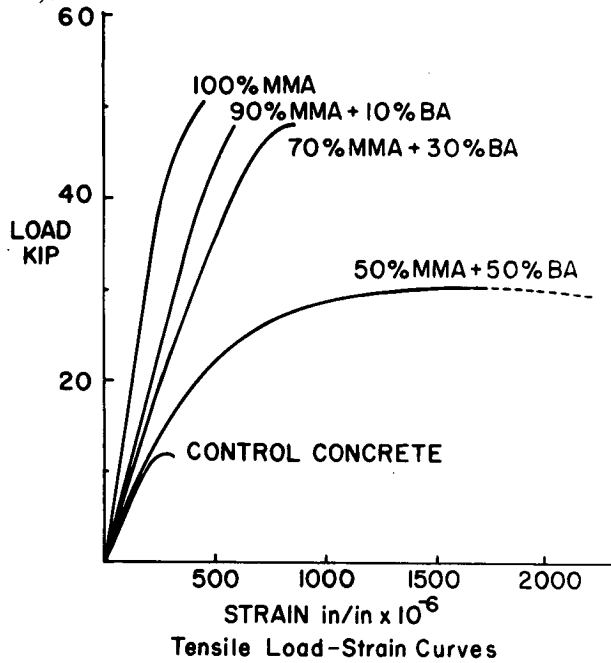


Figure E-4. Polymer-impregnated concrete: tensile load-strain curves as a function of polymer composition.

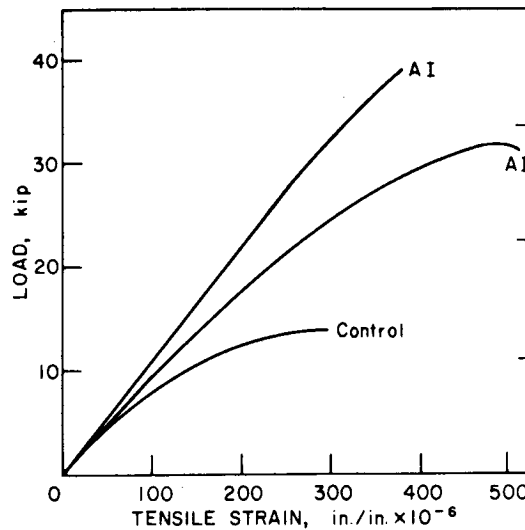


Figure E-5. Tensile load-strain curves (hydraulic tester) for 3-in. x 6-in. concrete cylinders impregnated with MMA/BA 60/40 mixture.

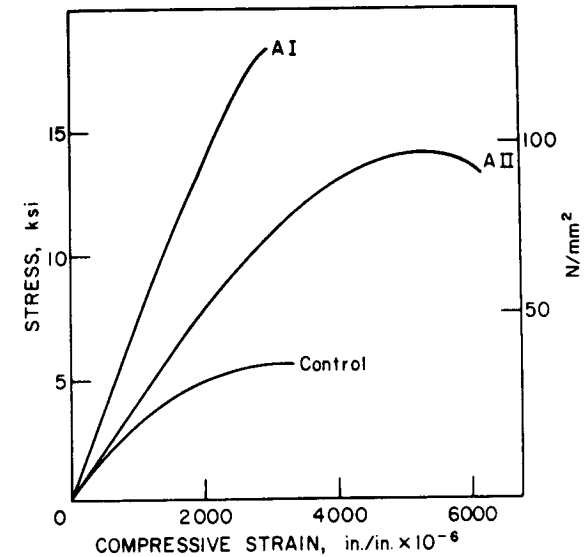


Figure E-6. Compressive stress-strain curves (hydraulic tester) for 3-in. x 6-in. concrete cylinders impregnated with MMA/BA 60/40 mixture.

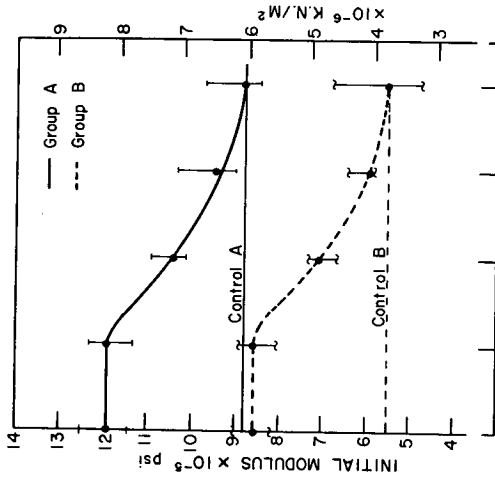


Figure E-7. Polymer-impregnated mortar: variation of compressive modulus with strain rate as a function of polymer composition (Instron tester).

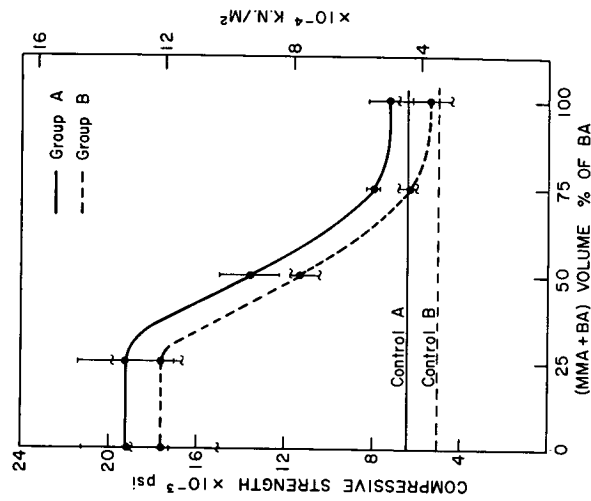


Figure E-8. Polymer-impregnated mortar: variation of compressive strength with strain rate as a function of polymer composition.

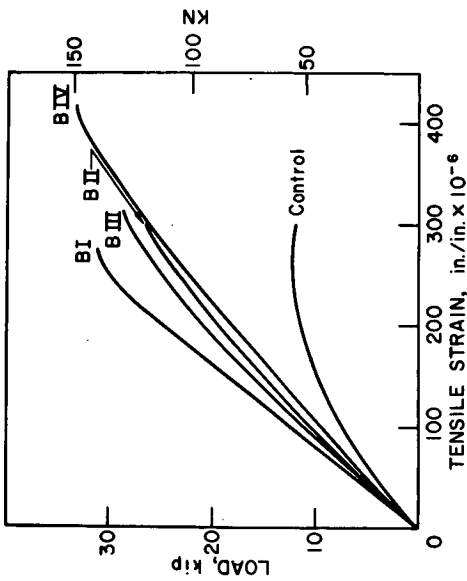


Figure E-9. Tensile load-strain (hydraulic tester) for 3-in. x 6-in. concrete cylinders impregnated with various MMA/BA/TMPTMA mixtures.

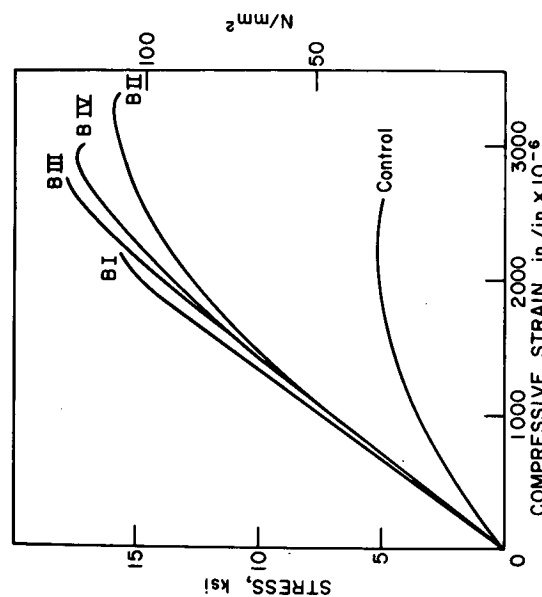


Figure E-10. Compressive stress-strain curves for concrete impregnated with various composition of MMA, BA, and TMPTMA.

reported by Auskern and Horn (32, 33), the polymer loading is also proportionately lower. Also, as reported in Ref. (32), the stress-strain curves show a high degree of linearity, with only a slight tendency to yield at very high strains. Thus, the impregnation of portland cement mortar with PMMA gives a dramatic increase in strength, stiffness, and over-all toughness that is accompanied by a corresponding decrease in ductility due to progressive yielding (this ductility is not obvious in the control specimen of Fig. E-2, probably because of the small specimen size). It is interesting to note that a high level of elastic and brittle behavior is achieved by impregnation of the mortar with PMMA, which by itself is normally ductile in compression.

However, as the proportion of BA in the monomer impregnation mixture is increased past 25 percent, the tensile and compressive strengths show a corresponding decrease, confirming results of a separate study (34). By controlling the percent BA in the mixture, a wide range of stress-strain behavior from brittle to ductile may be obtained. (It is important to note that, because of the small specimen size, which results in catastrophic failure once cracking begins,

caution must be exercised in interpreting the variation of stress as a function of strain. Thus, the decrease in ultimate strain at high proportions of BA may reflect the test method as much as the properties of the specimen, at least at the strain rate used. The stress concentration in the cementitious matrix will be higher, the lower the modulus of the polymer, so that failure will occur first in the BA-rich samples as long as the specimen must follow the crosshead motion without relaxation. Even so, the incorporation of BA in the monomer mixture confers a significant degree of yielding prior to failure, and a peak stress is observed for compositions containing 50 percent or more BA. Thus, ductility is conferred by the BA—although under these testing conditions, it is not reflected in the breaking strain. This is consistent with the observation that not only those specimens containing 75 percent or more MMA broke with sharp audible cracks.)

Effects of adding the crosslinking agent, TMPTMA, are shown in Table E-2 and Figures E-9 and E-10 for specimens BI to BIV, inclusive; compositions are given in Table E-1. It is noted that the addition of 10 percent TMPTMA as

a crosslinking agent of various combinations of MMA and BA increases the Young's modulus of PIC, but has a complex effect on strength. Although 10 percent TMPTMA causes a decrease in both tensile and compressive strengths for the case of 100-percent MMA, the compressive strengths for the MMA-BA combinations with TMPTMA pass through a maximum for a 60:30:10 mixture, with the maximum value being similar to the value for 100-percent MMA. However, in all cases the use of TMPTMA tends to reduce ultimate strain and ductility (in the sense of yielding).

Results and Discussion

In summary, the brittle behavior of PIC impregnated with MMA can be modified by incorporating a monomer, BA, which confers a degree of rubberiness to the resultant copolymer. For example, a 60/40 MMA/BA combination shows a pronounced increase in ductility (or the ability to yield and deform at stresses close to the maximum observed before failure) compared to a 100-percent MMA-impregnated specimen, at the expense of only a 20-percent reduction in the ultimate strength and some 20-percent reduction in Young's modulus. Incorporation of a crosslinking agent (TMPTMA) in the monomer mixture has several effects: (1) a slight decrease in tensile and compressive strengths in the case of MMA alone; (2) a slight decrease in tensile strength for all MMA/BA compositions studied (up to 40 percent BA); (3) a slight decrease to a negligible change in compressive strength, depending on the concentration of BA; and (4) a general reduction in Young's modulus and ductility, along with an increase in Young's modulus. Thus, a wide variety of stress-strain and ductility characteristics can be obtained by suitable variation in monomer composition. In any event, in contrast to the predictions of a simple pore-filling model (32), the modulus (and probably other properties) of the polymer must play a significant role in whatever relationship is used to predict behavior of the polymer-impregnated composite. This observation is consistent with the findings of Gebauer et al. (35); namely, that the strength of polymer-impregnated ceramic depends on whether the measurements are made at a temperature above or below the second-order transition temperature of the polymer.

The fact that significant reinforcement requires a polymer to be in the glassy and not the rubbery state is further supported by tests with mortar specimens containing mixtures of BA and MMA polymers. As shown in Figure E-11, about the same degree of reinforcement (in terms of compressive strength) is obtained with any compositions as long as it is at a temperature below its glass temperature, T_g . As temperature is raised above T_g , the degree of reinforcement is reduced, eventually becoming negligible. Interestingly, it may be noted that the inflection point of the transition for the MMA systems (this point usually corresponding closely to the T_g) is higher than for the homopolymer ($T_g \cong 302$ F (150 C)). In contrast, the BA systems display the inflection point close to that reported for the homopolymer ($T_g \cong 126$ F (52 C)). It thus seems likely that the rigid polymer within the pores is in a highly strained configuration.

With respect to the role of the polymer, the foregoing

TABLE E-2

TYPICAL MECHANICAL PROPERTIES OF POLYMER-IMPREGNATED 3-IN. x 6-IN. CONCRETE CYLINDERS^a

Specimen	Tensile	Compressive	Young's Modulus ^b
	Strength, in kips Per square inch	Strength, in kips per square inch	kips per square inch x 10 ³
(1)	(2)	(3)	(4)
AI	1.38	18.6	7.5
AII	1.13	14.4	4.0 ^a
A Control	0.50	5.5	3.4 ^a
BI	1.10	16.1	7.8
BII	0.94	16.4	7.1
BIII	1.01	18.4	7.1
BIV	1.18	17.8	7.1
B Control	0.44	5.4	4.1 ^a

Unit Conversions: 1 psi = 6.89 kN/m² = 6.89 kPa.

1 in. = 2.54 cm.

a. For compositions, see Table E-1.

b. Young's modulus for AII and all controls is the "secant modulus" measured at a stress one half the ultimate value. The "tangent modulus" is given for the other specimens. Values based on compressive tests.

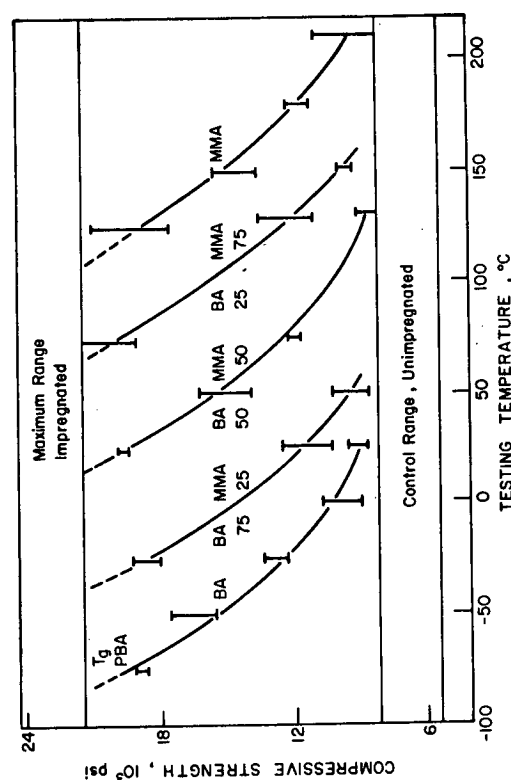


Figure E-11. Effect of temperature on compressive strength of polymer-impregnated mortars containing polymers and copolymers of *n*-butyl acrylate (BA) and methyl methacrylate (MMA).

results show that the polymer in PIC plays an active role in the reinforcement of the cementitious matrix and not merely a passive pore-filling role. Unfortunately, several expressions proposed for the quantitative prediction of composite properties in terms of constituent properties do not

work well with PIC. Although the present study has not progressed far enough to permit rigorous evaluation of these expressions, the preliminary results indicate that neither the porosity model of Auskern and Horn (32) nor the model of Hobbs (36) can account for the observed effect of polymer modulus. The variations in PIC modulus as a function of polymer modulus predicted by these models are less than 10 percent, compared with the observed variation of 36 percent. The flat-shaped pore model proposed by Hasselman et al. (37) predicts a more significant variation (about 27 percent) for a probably-not-unrealistic length-to-width ratio of 5.

Nevertheless, it is interesting to consider the effects of polymer modulus on stress concentrations both in the cementitious matrix and in the polymer phase (38). For inclusions of PMMA, the stress concentration in the matrix is reduced almost threefold for a flat-shaped pore with a length-to-width ratio of 5; on the other hand, the stress concentration in the polymer is increased significantly. These effects are almost (but not quite) negligible for inclusions of the lower modulus PBA. Thus, even if the modulus of PIC cannot yet be predicted accurately, and the fact that the polymer does not fill the pores completely, the higher modulus polymer not only must reduce the stress concentration in the matrix, but it also must aid in the stress transfer to the polymer-filled pore. This conclusion complements the findings of Isenburg and Vanderhoff (39), in that a latex polymer incorporated in the mix plays an active role in minimizing stresses when microcracks form during curing; and the conclusion of Tazawa and Kobayashi (40) and Auskern and Horn (41), in that the inclusion of polymer in PIC increases the fracture energy significantly.

Stress-Strain Behavior: Slabs and Cores— Monomer Systems

In order to characterize the effectiveness of impregnation in slabs used to model bridge deck concrete, stress-strain behavior, which is closely related to the percent loading with polymer, was determined for several kinds of specimens: slabs and cores impregnated with different monomer systems, both before and after freeze-thaw testing. The effects of salt contamination are discussed in Appendix F.

Experimental Details

The concrete slab specimens (24 in. x 24 in. x 6 in. (61.0 cm x 61.0 cm x 15.2 cm)) were prepared from a conventional non-air-entrained 1.00:1.92:6.10:6.75 water-portland cement (type I), coarse sand-limestone aggregate (1 in. (2.5 cm) maximum) mix with a cement factor of 485 lb/yd³ (287 kg/m³) and 28-days-average compressive strength of 4750 psi (32800 Pa). The measured air content was 3 percent with slump of 2.5 to 3.0 in. (6.4 to 7.6 cm). The slabs were given a normal trowel finish and were cured in the fog room (90- to 100-percent relative humidity) for at least 28 days before use in drying and impregnation tests. All slabs contained a nominal steel reinforcement at a 4-in. (10-cm) depth to simulate the structure of the bridge deck. All slabs were dried for 45 hr in an oven at 257 F (125 C). Impregnation of the slabs and cores taken from them was effected as described in Appendix D (in the case of slabs impregnated from one side) and

by vacuum-pressure impregnation in a closed chamber (in the case of cores). With the exception of two slabs, which were impregnated with isobutyl methacrylate (IBMA), the monomer system was 90:10 MMA:TMPTMA, with 0.5-percent AZO. One of the slabs impregnated with IBMA was impregnated only partially.

Results and Discussion

Table E-3 compares strength measurements made both in direct compression and split tension of cores subjected to freeze-thaw testing (see also Appendix H) and control cores not subjected to this test. The core identification is the same as that used in Table E-2. The variations include cores from both unimpregnated and polymer-impregnated slabs, cores from unimpregnated control slabs that were impregnated and polymerized in the laboratory, and the substitution of isobutyl methacrylate for methyl methacrylate in the monomer mixture. In general, the strengths of these cores were not as great as those of 3- x 6-in. (7.5- x 15.0-cm) cylindrical specimens cast in the laboratory, presumably because of possible distortion and cracking during the core-drilling operation and incomplete impregnation (for the polymer-impregnated cores).

Although the number of specimens tested is small and the results show the usual experimental scatter, some generalizations can be made. Before freeze-thaw testing, the strengths of the polymer-impregnated cores were 2.5 to 3.0 times greater than those of the unimpregnated cores. After freeze-thaw testing, the strengths of the polymer-impregnated cores were the same or even slightly greater because of the annealing during heating for 60 hr at 212 F (100 C) (after freeze-thaw testing, the cores were subjected to the water absorption test, redried, and then used in the strength tests). The strengths of the unimpregnated cores from salt-contaminated slabs decreased after freeze-thaw testing because the cores were dried at high temperatures (>>212 F (100 C)) before they were contaminated with salt and redried for the water absorption test (this is observed even for specimens not subjected to freeze-thaw testing; e.g., compare the strengths of cores 4-6 and 5-6 in compression and cores 4-8 and 5-6 in tension). The strengths of the uncontaminated, unimpregnated cores were slightly greater after freeze-thaw testing, however, because the control cores not subjected to freeze-thaw testing were not dried before the strength test and the corresponding cores subjected to freeze-thaw testing were dried only once at low temperatures (220 F (104 C)) for the water absorption test. The polymer impregnation seems to heal the microcracks formed during high-temperature drying as no such strength reduction was observed for salt-contaminated cores after impregnation from this work and other tests on laboratory specimens. The presence or absence of salt contamination, or the substitution of isobutyl methacrylate for methyl methacrylate in the monomer mixture, had little or no effect on the strengths of the polymer-impregnated cores before or after freeze-thaw testing.

Several slabs were broken open to observe fracture patterns. Typically, the appearance of the fracture cross section (Figs. E-12 through E-14) was similar to that of other polymer-impregnated specimens. The dark polymer-impregnated region can readily be distinguished from the light

TABLE E-3

COMPRESSIVE AND TENSILE STRENGTHS OF POLYMER-IMPREGNATED CONCRETE
BEFORE AND AFTER FREEZE-THAW TESTING (ASTM C671)

Impregnation ¹	Salt Content	Before Freeze-Thaw Testing					
		Compressive Strength			Tensile Strength		
		Core	in psi	(kN/m ²)	Core	in psi	(kN/m ²)
Surface Impregnation of Slab ²	None	1-6 ³	8850	(61000)	1-1 ³	910	(6280)
Surface Impregnation of Slab ⁴	0.3% ⁵	2-3	10260	(70800)	2-5	850	(5870)
None (Unimpregnated Control Slab)	None	4-6	3790	(26100)	4-8	530	(3620)
None (Unimpregnated Control Slab)	0.3% ⁵	5-6	3540	(24400)	5-6	420	(2860)
Surface Impregnation of Slab ⁶	None	6-6 ³	8850	(61000)	6-4 ³	830	(5710)
Lab Impregnation of Core from Unimpregnated Slab ⁷	None	----	-----	-----	----	---	-----
Lab Impregnation of Core from Unimpregnated Slab ⁷	0.3% ⁵	----	-----	-----	----	---	-----
Surface Impregnation of Slab ²	None	1-3 ³	8520	(58800)	1-5 ³	900	(6240)
Surface Impregnation of Slab ⁴	0.3% ⁵	2-2	12030	(83000)	2-1	1050	(7240)
None (Unimpregnated Control Slab)	None	4-3	4080	(28100)	4-2	560	(3850)
None (Unimpregnated Control Slab)	0.3% ⁵	5-1	2970	(20500)	5-2	310	(2160)
Surface Impregnation of Slab ⁶	None	---	----	-----	---	---	-----
Lab Impregnation of Core from Unimpregnated Slab ⁷	None	4-5 I	11610	(80080)	4-4 I	1020	(7010)
Lab Impregnation of Core from Unimpregnated Slab ⁷	0.3% ⁵	5-9 I	11130	(76760)	5-5 I	980	(6750)

- 90:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture containing 0.5% azobisisobutyronitrile initiator.
- 2.0 hr vacuum (25 in. or 63.5 cm Hg); 40 psi (280 kPa) pressurization.
- Partially impregnated.
- 1.5 hr vacuum (28 in. or 71 cm Hg); 60 psi (410 kPa) pressurization.
- 0.3% salt = 12 lb/yd³ or 7.1 kg/m³.
- 1.5 hr vacuum (28 in. or 71 cm Hg); 60 psi (410 kPa) pressurization; isobutyl methacrylate substituted for methyl methacrylate.
- Laboratory vacuum (1.5 hr)-pressure (60 psi [410 kPa]) chamber.

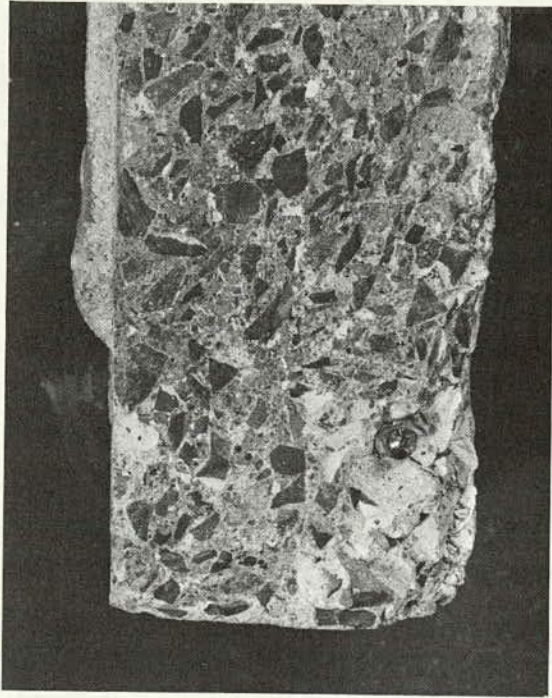


Figure E-12. Fracture cross section of first impregnated slab showing polymer-impregnated and unimpregnated regions (note that fracture occurred through aggregate particles in polymer-impregnated region and around particles in unimpregnated region).

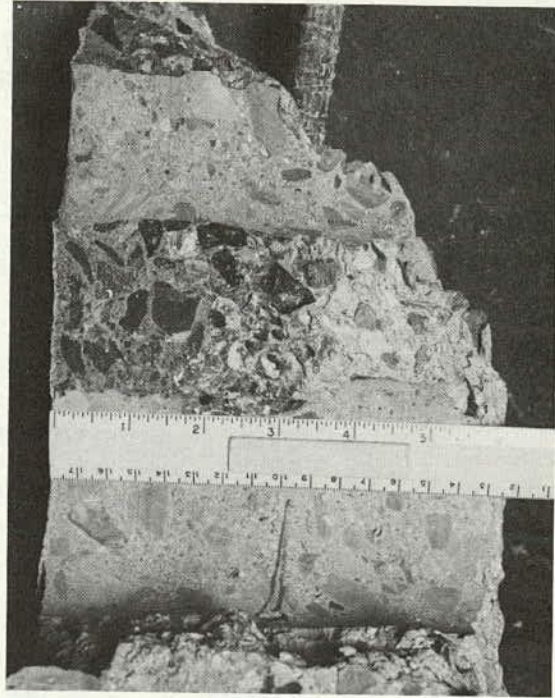


Figure E-13. Close-up of IBMA impregnated slab section (note uniformity of coloration in impregnated portions).

unimpregnated regions. The lighter 0.25-in. (0.6-cm) surface layer on the bottom indicated that some monomer was lost from the lower surface by evaporation. Examination of the fracture cross section with a magnifying glass showed that, in the polymer-impregnated region, fracture occurred through the aggregate particles; however, in the unimpregnated region, it occurred around the particles.

No evidence was found for a plane of weakness at the interface between the monomer front and the unimpregnated portion of a partially impregnated specimen (Figs. E-13 and E-14). As expected, however, strengths are somewhat lower than for fully impregnated specimens (Table E-3).

It may be concluded that the benefits noted for the impregnation of cylinders are maintained in slabs and, at least with cores, are maintained after rigorous freezing and thawing.

Stress-Strain Behavior: Cylinders—Other Impregnants

From a long-range point of view, the use of impregnants that are cheaper than typical vinyl monomers would be desirable. Although such impregnants will tend to be more viscous than vinyl monomers, the combination of deep drying and pressurization may offer considerable potential for process development. For this reason, exploratory studies (25) were conducted using sulfur, whose use as a concrete impregnant had been described previously (42, 43); a low-viscosity tar; tar-sulfur mixtures; and barium hydroxide (44). Impregnation details are given in Ref. (44).

Experimental Details

Experiments with sulfur impregnation were conducted using 3-in. x 6-in. (8-cm x 15-cm) cylindrical specimens prepared from a conventional non-air-entrained 1:2.0:3.42:4.16 water-portland cement (type I), coarse sand-limestone

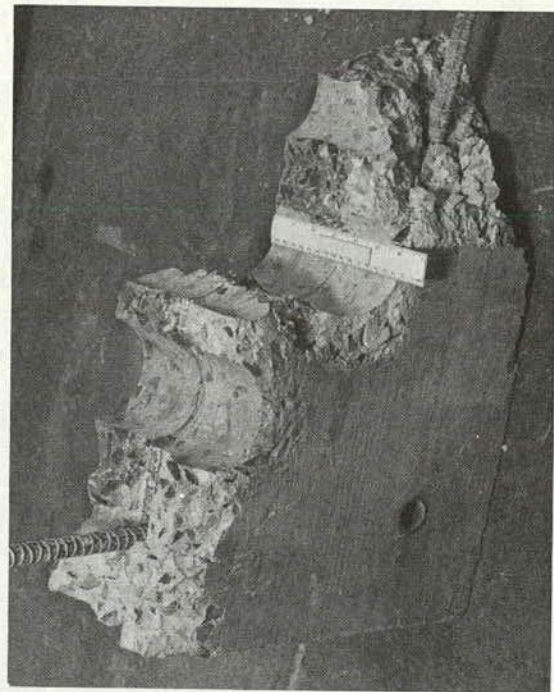


Figure E-14. Over-all view of partially impregnated slab after curing (note evenness of impregnation and fracture of all aggregates in impregnated area).

aggregate (1 in. (3 cm) maximum) mix with a 28-day average compressive strength of 4000 psi (28 MPa). The measured air content was 3 percent with a slump of 4.5 in. (11 cm). All cylinders were cured in a fog room (90- to 100-percent relative humidity).

For experiments with the other systems, mortar specimens (1.0 in. x 2.0 in. (2.5 cm x 5.0 cm)) were prepared using a water-portland cement (type I), Ottawa sand mix in the proportions 0.5:1.0:0:2.7, and were cured for 28 days.

Results and Discussion

Typical results for the systems are given in Table E-4 and Figure E-15. It may be seen that sulfur impregnation yields a twofold improvement in compressive strength and Young's modulus; a similar improvement (not shown) is observed for the split-tensile strength. The sulfur-tar mixture gives a lesser improvement in compressive strength, whereas tar alone has no significant effect. These results are quite consistent with the earlier discussion concerning the need for high modulus in a reinforcing impregnant. No results could be obtained with the barium hydroxide, which appeared to attack the specimens.

CHLORIDE PENETRATION IN PIC

In view of the generally improved resistance of PIC to corrosion (e.g., by acids and sulfates), it may be expected that penetration by the chloride ion may also be reduced, in comparison with the unimpregnated matrix. Indeed such an effect has already been noted (44). However, several questions arise: (1) in practice, polymer impregnation does not fill all the available capillary pores; (2) the matrix-polymer bond may conceivably undergo degradation during service, especially under freeze-thaw cycling; and (3) in principle, both the inherent permeability to salts and the stability of the matrix-polymer bond depend on the state of the polymer (i.e., whether it is glassy and brittle, or rubbery and tough).

To determine the relative effectiveness of various polymers in PIC on reducing chloride penetration, static tests using standard portland cement mortar specimens were conducted for a period of 12 months. Two monomers were used: MMA, which yields a glassy, brittle polymer at room temperature; and BA, which yields a rubbery, tough polymer. For the chloride determination, a new technique was developed using electron microprobe analysis to follow salt migration into the concrete.

Experiments

Standard portland cement mortar cylinders, 1 in. x 2 in. (2.5 cm x 5.0 cm), were used for the salt penetration experiments; MMA and BA monomer systems were used to represent a glassy and rubbery polymer, respectively. The cylinders were prepared using a 12:24:64 water portland cement (type II), Ottawa silica sand (ASTM C-109) mix and cured under water for 28 days at room temperature. After drying in an air oven for 3 hr at 302 F (150 C), specimens were placed in the vacuum for 15 min, then immersed in monomer (MMA or BA) for 3 hr at atmospheric pressure. The monomer-impregnated cylinders were then immersed in a 158 F (70 C) water bath for 4 hr to polymerize the monomer. These conditions of drying, impregnating, and polymerization were sufficient to ensure reasonably complete filling of the specimen void space; the polymer loadings were based on dried weight. Since BA is 20 percent less dense than MMA, the volumetric loadings were close in each case.

After impregnation by the procedures previously described, the mortar cylinders were exposed to 8-percent aqueous $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ solutions. Following the convenient

TABLE E-4

STRENGTH OF IMPREGNATED MORTAR SPECIMENS

Impregnant	Specimen	% Loading	Compressive
			Strength ($\text{psi} \times 10^3$)
Sulfur ¹	29	10.2	1.50
	30	10.1	1.48
	31	11.5	1.53
	39	11.6	1.14
Sulfur-Tar (80-20)	40	11.9	1.05
	41	10.7	1.18
	43	7.3	0.64
	44	6.7	0.64
Tar	45	6.9	0.64
	48	--	0.65
Control Specimens	49	--	0.77
	50	--	0.70

Unit Conversion: 1 psi = 6.9 kN/m^2 = 6.9 kPa.

1. Impregnation time, 60 hr; not predried.

procedure of Ost and Montfort (45), solutions were contained in covered polyethylene sheaths tightly fitted on the cylinders and adjusted to extend above the top surface for about 1 in. (2.5 cm). The curved surfaces of the cylinders were closely wrapped with waterproof tape to insure the axial flow; a screen support was used to provide free circulation of air underneath. After different exposure periods, cylinders were broken and the chloride concentration in the past phase was determined at different depths by electron microprobe analysis (46). At a given depth, small speci-

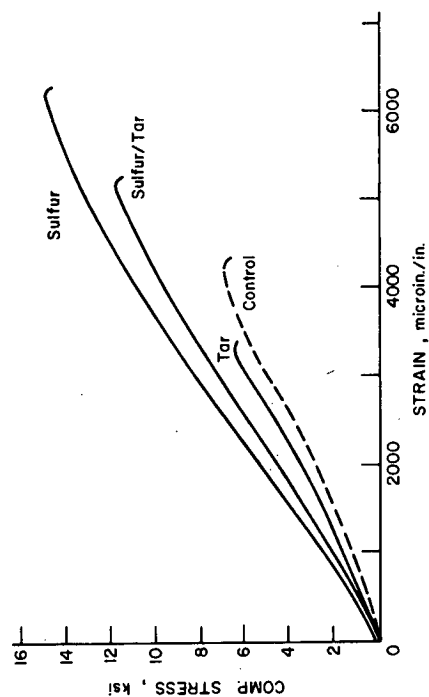


Figure E-15. Stress-strain data for impregnated concretes (1 psi = 6.89 kN/m^2 ; in. = 2.54 cm).

mens were removed and coated with a thin carbon layer; three areas in the cement phase— 3.1 to 3.9×10^{-3} in. (8 to $10 \mu\text{m}$)—were scanned and 10-sec. counts (for chloride ion) were taken in duplicate.

Although the absolute numerical values include all chloride content, and thus exceed those corresponding to “free” chloride determinations by other techniques, the values provide a sensitive measure of total chloride penetrated and also a relative measure of chloride ions available for corrosive reactions. Thus, comparison with results obtained by the potentiometric analysis of cores (Appendix F) reveals that the microprobe technique “sees” chloride concentrations that are about 3 times those measured for the “available” chloride.

Results

After only one month of exposure, the plain mortar showed a significant amount of chloride (1.6 percent Cl or 6 percent $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ at a depth of 0.25 in. (0.6 cm)) at different depths in the mortar (Fig. E-16). However, for both BA- and MMA-impregnated mortars, only traces of chloride (<0.1 percent Cl (= 0.4 percent $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$) by weight of cement paste) were found at a depth of 0.25 in. (0.6 cm). At lower depths, the chloride values from electron microprobe fall into the range of background scatter, so that detection of deeper penetration in the impregnated mortars will require much larger exposure times. At least for a one-month exposure, both BA- and MMA-impregnated mortars gave similar results. As time progressed, chloride continued to penetrate; after one year, the concen-

tration reached 5.5 percent at a 0.25-in. (0.6-cm) depth and 0.6 percent at a 1.5-in. (3.81-cm) depth, as shown in Figure E-17. In contrast, the concentration in the BA-impregnated specimens was much less—0.4 percent at a 0.25-in. (0.6-cm) depth and ~ 0.1 percent (background of detection) at a 0.5-in. (1.3-cm) depth. However, the BA specimens were not as effective after one year; chloride concentrations reached 2 percent at a 0.25-in. (0.6-cm) depth and 0.6 percent at a 0.5-in. (1.3-cm) depth.

Conclusions

Impregnation of portland cement mortar with polymers of MMA or BA (glassy and rubbery, respectively) reduces calcium chloride penetration after one month's exposure to an 8-percent solution, by an order of magnitude, regardless of the state (rubbery or glassy) of the polymer used. Preliminary tests show, however, that BA is not as effective after a 12-month exposure. Freeze-thaw cycling tests will, of course, be necessary to complete the picture of the role of the polymer.

CORROSION TESTS

Some slabs (Table E-3) were cored in such a way that a section of the steel reinforcing rods placed at the 4-in. (10-cm) depth was removed as an integral part of the core. This was done deliberately to determine whether the monomer had permeated the porous concrete matrix around the rods and whether the filling of the pores in this matrix by polymer would inhibit corrosion of the rods. If the channels left around the rods by evaporation of water were not filled with polymer, water could permeate these channels during the freeze-thaw tests and corrode the rods, causing severe dilation and eventual failure of the concrete.

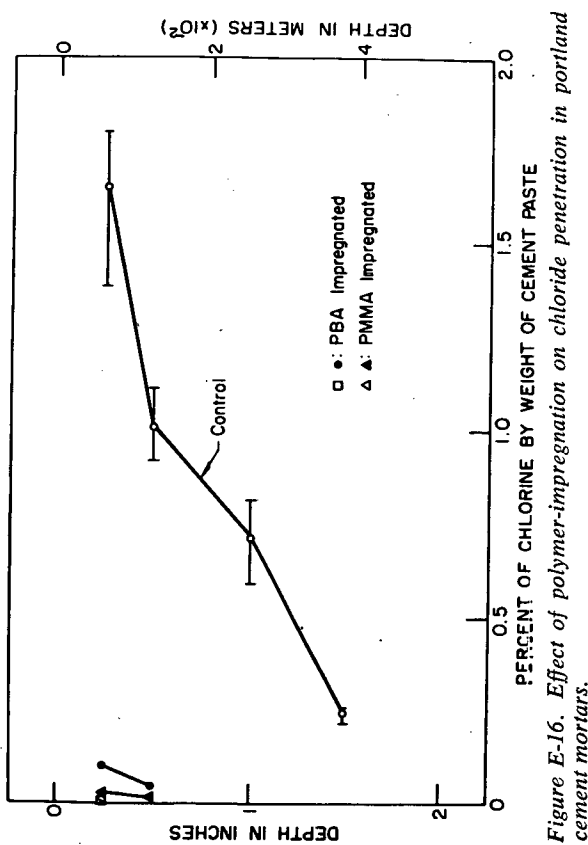


Figure E-16. Effect of polymer-impregnation on chloride penetration in portland cement mortars.

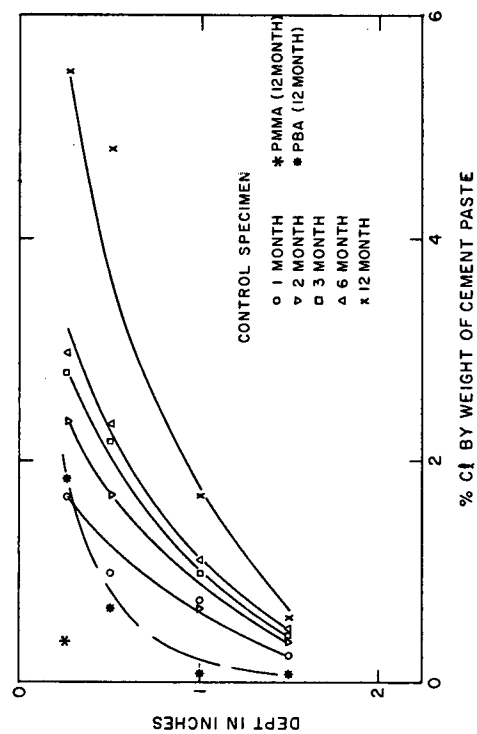


Figure E-17. Effect of polymer impregnation on absorption of chlorides.

The reinforcing rods in cores from uncontaminated slabs, both polymer-impregnated (slab 1) and unimpregnated (slab 4), showed no sign of corrosion after freeze-thaw testing (see Appendix F), indicating that the presence of salt is necessary for corrosion. However, the reinforcing rods in cores from the unimpregnated salt-contaminated slab 5 showed considerable corrosion after freeze-thaw testing, whereas those in cores from the polymer-impregnated, salt-contaminated slab 2 showed no visible signs of corrosion. Figure E-18 shows scanning electron micrographs of the near-end sections of the reinforcing rods, depicting corrosion in core 5-3 and none in core 2-1. Thus, although no quantitative measurements have been made, the impregna-

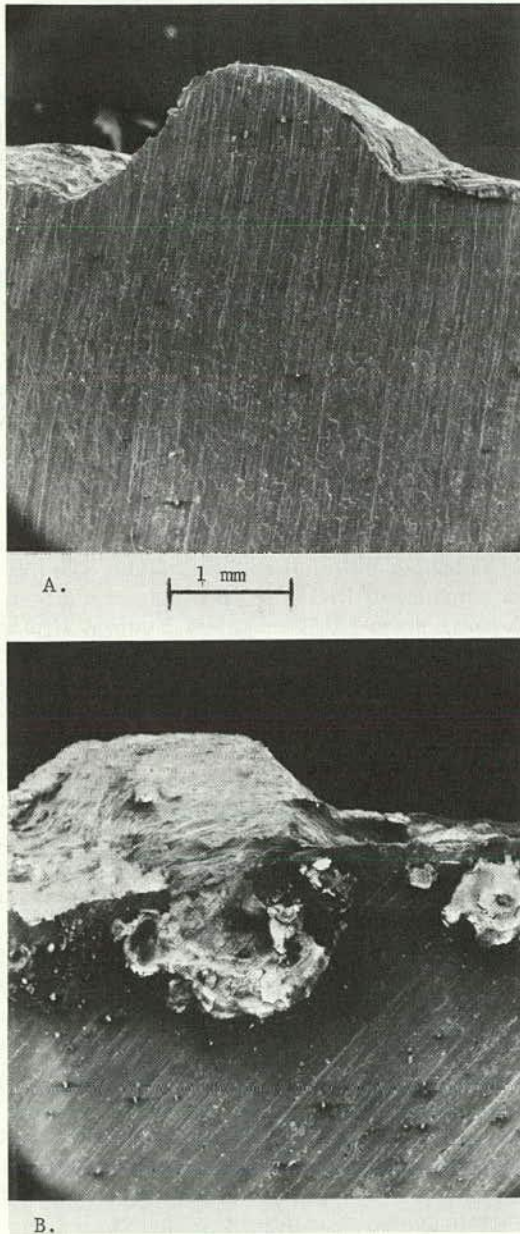


Figure E-18. Scanning electron photomicrographs of near end sections of steel reinforcing rods in salt-contaminated concrete slabs after freeze-thaw testing: (A) polymer-impregnated core 2-1; (B) unimpregnated core 5-3, polymer loading 5 wt %.

tion of porous concrete with monomer and its subsequent polymerization prevent corrosion of the reinforcing rods, perhaps by immobilizing the contaminating salt by eliminating the water flux that carries it through the concrete to the rods. Evidently a loading of 5 wt percent of polymer is sufficient. Further tests will be needed to determine the limiting loading possible.

ACID ETCHING

One core from each concrete slab (Table E-3) was sawed lengthwise; one-half was etched by soaking in 18.5-percent aqueous hydrochloric acid for 2 hr, and the other was polished to show the morphology and coloration. Figure E-19 compares the appearance of the acid-etched half with that of the polished half after freeze-thaw testing (control cores 2-7 and 4-1 were not subjected to freeze thaw). Acid etching caused disintegration of the unimpregnated cores; the cementitious matrix was broken down and the aggregate particles were attacked and dissolved. The polymer-impregnated cores showed remarkable resistance to the acid-etching; the cementitious matrix was unaffected by the acid, whereas the aggregate particles were eaten away. The polished sections show clearly the uniform coloration of the polymer-impregnated cores.

Figure E-20 shows cores from the highway bridge deck treated in the same manner. These polymer-impregnated cores show the same remarkable resistance to acid etching as did the polymer-impregnated cores from the slabs; the cementitious matrix was unaffected by the acid etching, but the aggregate particles were eaten away. This resistance to

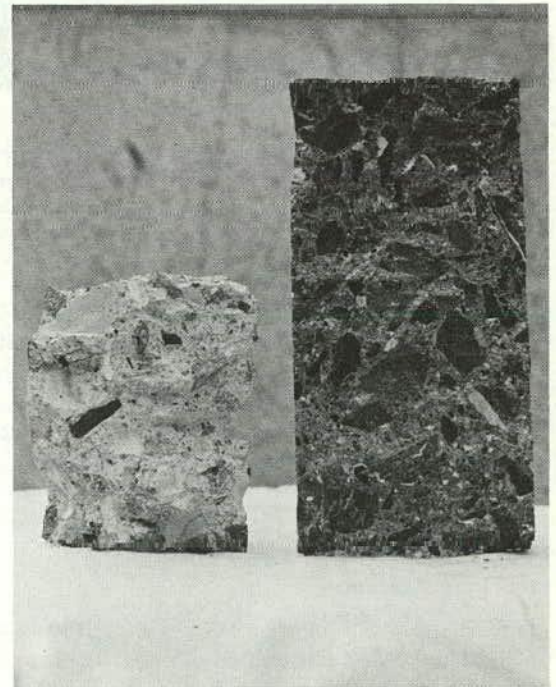
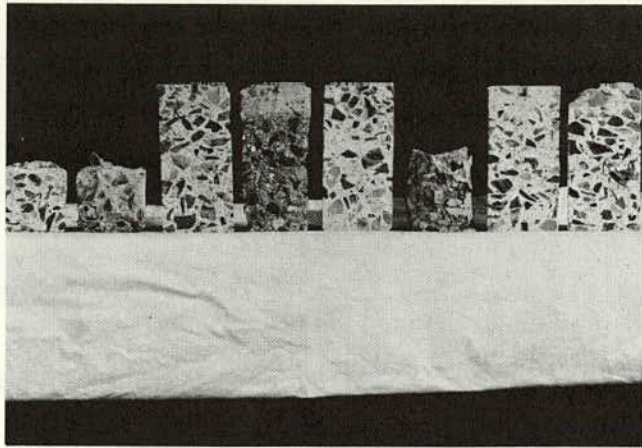
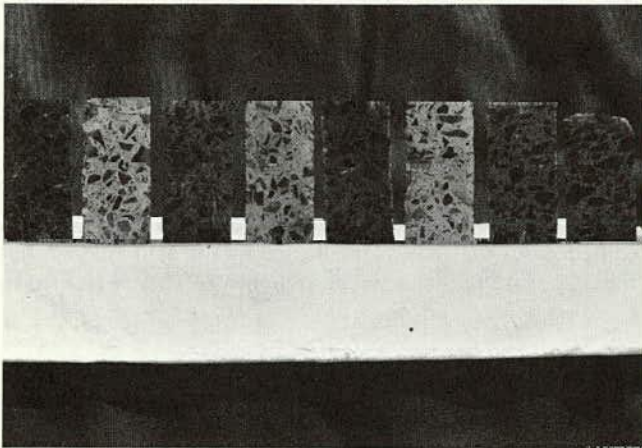


Figure E-19. Fracture cross sections of cores from (A) salt-contaminated unimpregnated concrete slab 5; (B) polymer-impregnated concrete slab 2 (note uniform dark coloration and difference of fracture mode of polymer-impregnated core).



A.



B.

Figure E-20. Sawed cross sections of cores subjected to freeze-thaw testing: (A) acid-etched; (B) polished (note virtually complete disintegration of cementitious matrix and aggregate particles in unimpregnated cores).

acid etching was uniform over the entire 5-in. (12.7-cm) depth of the core, indicating that the impregnation and polymerization were complete to that depth. This is supported by the uniform coloration of the polished sections. The polymerized monomer-sand topping was also unaffected by the acid etching. Sulfur impregnation was also shown to inhibit etching (25).

FREEZE-THAW TEST

Laboratory Specimens

Freeze-thaw tests, in accordance with ASTM Designation C671, were carried out on non-salt-contaminated and salt-contaminated specimens of polymer-impregnated concrete. Control specimens of nonimpregnated concretes of each type were also tested for purposes of comparison. The specimens consisted of 3-in. (7.6-cm) diameter cores drilled from 6-in. (15.2-cm) thick test slabs. Two types of im-

pregnation were employed: surface impregnation of the slabs and impregnation of cores in a vacuum-pressure chamber. The monomer system used throughout was MMA + 10-percent TMPTMA. Three specimens were tested for each treatment level. The freeze-thaw tests were carried out until specimen failure occurred, as defined in ASTM C671, or until 10 cycles had been run.

The results of the freeze-thaw tests are given in Table E-5. It should be mentioned that, although ASTM C671 defines the end of the period of frost immunity as the point at which the dilation is more than twice the dilation of the previous cycle, the concrete may also be considered as having failed when the dilation exceeds approximately 400 to 500 microin. (1.0 to 1.3×10^{-3} cm). This is the elastic limit for a 6-in. (15.2-cm) specimen (approximately 70 to 80 microstrain).

As indicated in Table E-5, the nonimpregnated specimens all failed early—the salt-contaminated ones in the first cycle and the non-salt-contaminated ones in the third cycle. It should be noted that, in order to sensitize the test, none of the concretes in this study were air entrained; the poor frost resistance of the control specimens is thus to be expected. Also, it is interesting to observe that the salt-contaminated control specimens failed sooner than non-salt-contaminated ones, in agreement with field observations. With one exception, all of the polymer-impregnated specimens displayed exceptional resistance to freezing and thawing. Moreover, no evidence for corrosion of the rebar was noted even in the presence of salt. The single anomalous result (specimen 2-6) was subjected to an additional 25 freeze-thaw cycles (noninstrumented) in order to visually expose the susceptible portion of the specimen. Confirming suspicions, the lower portion of the specimen deteriorated badly, indicating incomplete impregnation. The exceptional performance of PIC in the presence of salt loadings as high as 12 lb/cu yd (7.1 kg/m^3) confirms related observations by different tests (8), and shows the potential of polymer-impregnated concrete as a means to alleviate deterioration of highways and bridge decks.

Specimens from Field Impregnation Study

One core specimen from each of the 3-ft x 12-ft (0.91-m x 3.66-m) areas impregnated on the research facility bridge (see Appendix H) was subjected to 11 freeze-thaw cycles in accordance with ASTM C671. Control specimens from nonimpregnated concrete adjacent to each of the impregnated areas were tested also. In all cases (impregnated and control) the dilations (expansions during freezing) were very small (averaging about 10 percent of the elastic limit of the concrete), were transitory, and failed to show any tendencies to increase with time. The high quality, air-entrained concrete in this deck is obviously very frost resistant. Therefore, although polymer impregnation will most certainly improve its frost resistance, it would take either a much larger number of freeze-thaw cycles or a more severe freeze-thaw test to demonstrate the improvements.

ABRASION TESTS

To determine whether polymer impregnation can improve surface wearability, an accelerated test method was

TABLE E-5
FREEZE-THAW RESISTANCE (ASTM C671)

Specimen Number	Impregnation Procedure	Type of Concrete	Dilation, micro in. (cycle)									
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
4-2	None (Control)	No salt contamination	60	30	660	930	1000	1560	1250	1500	1480	1460
4-3			70	180	1130	1230	1520	1900	1830	+	+	+
4-4			70	30	1100	1220	1700	2080	+	+	+	+
5-1	None (Control)	Salt-contaminated slab (salt content 0.3 wt %)	+	+	----	----	----	----	----	----	----	----
5-2			+	+	----	----	----	----	----	----	----	----
5-3			+	+	----	----	----	----	----	----	----	----
5-5	1-1/2 hr vac & 60 psi pres-sure vac.-press. chamber.	Salt-contaminated slab	30	20	20	20	20	30	20	30	30	30
5-8			30	30	20	20	30	30	0	40	30	30
5-9			20	20	0	30	40	30	0	50	40	30
4-4	1-1/2 hr vac & 60 psi pres-sure vac.-press. chamber.	Non-salt-contaminated slab	100	30	40	40	20	50	30	20	20	10
4-5			60	30	30	30	20	40	20	20	10	30
4-9			50	30	30	20	20	20	30	20	20	30
2-1	1-1/2 hr vac & 60 psi pres-sure - slab surface impreg.	Salt-contaminated slab	40	10	10	30	20	30	30	*	30	40
2-2			30	20	10	20	20	20	20	*	40	30
2-6			840	1690	2500	----	----	----	----	----	----	----
1-2	2 hr vac & 40 psi pressure - slab surface impreg.	Non-salt-contaminated slab	40	20	0	30	0	30	0	30	20	*
1-3			20	20	10	20	10	20	0	20	20	20
1-5			40	40	20	20	20	20	0	20	10	30

+ - Off scale
 ---- - No test run
 * - Equipment malfunction

NOTE:

(1) Monomer used: MMA + 10% TMPMA

(2) After 3rd cycle, specimen 2-6 was cycled an additional 25 times. Bottom portion of specimen (apparently not impregnated) visibly deteriorated.

Unit Conversions: 1 micro in. = 2.54×10^{-6} cm

1 psi = 6.89 kPa.

sought that would be representative of the field conditions of rolling and sliding friction accompanied by high impact. Of the many test methods proposed, no one method can predict the actual abrasion resistance of concrete in service because of the sensitivity of abrasion resistance of concrete to the details of testing, proportioning, placing, finishing, curing, and protection.

Test Apparatus

For this work, the ball bearing abrasion test method was selected in preference to sand blasting, grinding wheels, and other abrasive devices because it comes the closest to the actual abrasive action in the field. This method depends on the abrasive action of rapidly rotating steel balls under load

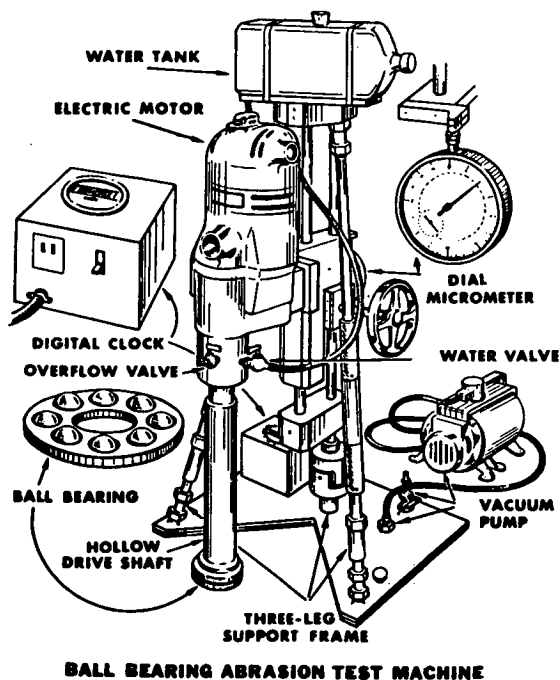


Figure E-21. Abrasion test apparatus.

on a wet concrete surface. Water is used to flush loose particles from the test path, bringing the ball into contact with sand and stone particles still bonded to the concrete surface, thus providing impact as well as sliding friction.

Figure E-21 shows the test apparatus; it consists of a motor-driven hollow vertical shaft resting on and turning ball bearings that rest on the concrete surface. As the ball bearings cut into the concrete surface, depth-of-wear readings can be taken continuously as a function of time without stopping the test. The abrasion tool is comprised of eight $2\frac{3}{32}$ or 0.71875-in. (1.83-cm) diameter steel balls equally spaced in a retaining ring to form a ball circle of 2.50-in. (6.35-cm) diameter. The wear tool is given a breaking-in period of 300 sec, during which the balls become slightly textured and distorted, so that their apparent diameter is slightly larger. During the remainder of the tests, the balls were reduced in diameter to a value slightly less than the original diameter due to the sliding friction. The wear tool was discarded when the diameter of the steel balls was reduced to 0.7175 in. (1.82 cm).

The hollow vertical drive shaft is provided with a flanged bearing plate at its lower end grooved to match the ball circle of the abrasion tool and a centered $\frac{1}{8}$ -in. (0.32-cm) diameter orifice to permit a constant flow of water. The drive shaft is provided with an adjustment of plumbness to the test surface. The total load on the ball bearing is 27 lb (12.3 kg)—including the weight of the drive motor, hollow drive shaft, and contained water. The motor is capable of turning the drive shaft at 1000 rpm under load. The dial indicator has a 0.5-in. (1.28-cm) travel and reads to the nearest 0.0001 in. (0.00025 cm).

A 1-gal ($3.8 \times 10^{-3} \text{m}^3$) plastic tank mounted on the motor base supplies water, which flows by gravity through the hollow drive shaft and orifice in the flange plate onto the concrete surface. The machine base is provided with a vacuum hold-down device with three support points.

Test Specimens

Eight 24-in. x 24-in. x 6-in. (61-cm x 61-cm x 15-cm) slabs were prepared and impregnated with various monomer mixtures (see Table E-6). The slabs were aged for 30 days, dried thoroughly, impregnated with monomer, and polymerized. Slab 13 was impregnated with partially polymerized styrene; after 2 hr, this viscous solution had penetrated less than 0.033 in. (0.8 cm) into the substrate, so the impregnation was discontinued. The excess monomer solution was removed from the surface and mixed with dry sand in 1:1 ratio. This mixture was spread over the surface of the slab, and the slab was wrapped with polyethylene film and was steam polymerized. Slab 14 was prepared similarly by mixing dry sand with the excess 90:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture on the surface and polymerizing.

For the abrasion test, the slabs were clamped securely on rigid stands and leveled to approximate the rigidity of a slab in place. This procedure was considered satisfactory, even though the rate of wear measured by this method is affected by sample sizes smaller than a slab in place, because the purpose of this work was to compare the abrasion resistance of polymer-impregnated concrete with that of unimpregnated concrete rather than to determine the abrasion resistance of a polymer-impregnated concrete slab in place per se.

Abrasion Test Results

Three or more tests were made on representative surfaces of each slab and averaged to give the depth of wear-time curves, as shown in Figures E-22 and E-23, and the values for average depth of wear, as given in Table E-6. The average depth of wear of the polymer-impregnated slabs was significantly smaller than that of the unimpregnated control slabs. For example, the improvement in abrasion resistance measured at 1200 sec was 80 to 90 percent for the methyl methacrylate monomer mixture, 50 to 60 percent for the isobutyl methacrylate monomer mixture, and 600 to 700 percent for the styrene-sand topping.

The polymer-impregnated slabs also showed more uniform abrasion resistance than the unimpregnated control slabs; the curves in Figures E-22 and E-23 for the polymer-impregnated slabs resemble more a half-parabola inclined toward the time axis than the unimpregnated control slabs, which show more abrasion on the surface than at greater depth.

The styrene-sand topping on slab 13 proved remarkably resistant to abrasion (curve 8 in Fig. E-23); the abrasion test gave only a slight polishing action to the surface. When the styrene-sand topping was removed before testing, the initial rate of wear was much greater, about 50 percent of that for the unimpregnated control slab; as the surface was worn away, the rate of wear decreased but eventually exceeded that of the control slab, indicating that the viscous, partially polymerized styrene used for the impregnation had penetrated only slightly below the surface.

The rate of wear for the methyl methacrylate-sand topping (slab 14, curve 9 in Fig. E-23) was considerably greater than for the styrene-sand topping of slab 13, per-

TABLE E-6
ABRASION RESISTANCE OF POLYMER-IMPREGNATED CONCRETE

Slab	Figure	Curve	Monomer ¹	Impregnation ²	Average depth of wear at 1200 seconds in inches (cm)	Percent improvement in abrasion resistance
9	11	2	90:10 MMA-TMPTMA	Partially Impregnated	0.06725 (0.1708)	80
10	11	3	90:10 MMA-TMPTMA	Partially Impregnated		
11	11	4	90:10 IBMA-TMPTMA	Partially Impregnated	0.0778 (0.1976)	55
12	11	5	90:10 IBMA-TMPTMA	Partially Impregnated		
13	12	8	Partially Poly- merized Styrene	0.25-in. Styrene- sand Topping	0.0170 (0.0432)	608
19	12	9	90:10 MMA-TMPTMA	0.25-in. 90:10 MMA-TMPTMA- sand Topping	0.0640 (0.1626)	88
15	11	1	None (Unimpregnat- ed Control Slab)		0.1205 (0.3061)	---
16	12	6	None (Unimpregnat- ed Control Slab)			

1. MMA = methyl methacrylate; IBMA = isobutyl methacrylate; TMPTMA = trimethylolpropane trimethacrylate; monomer mixture contained 0.5% azobisisobutyronitrile initiator.

2. 1.5 hr vacuum (28 in. or 71 cm Hg); 60 psi (410 kPa) pressurization.

haps because polystyrene is harder and more brittle than polymethyl methacrylate. However, the rate of wear for the methyl methacrylate-sand topping of slab 14 was the same as that for the slabs impregnated with the methyl methacrylate monomer mixture, perhaps because in this case the impregnation proceeded to some distance below the surface. The rate of wear for the slab impregnated with the isobutyl methacrylate monomer mixture was slightly greater than that for the slab impregnated with the methyl methacrylate monomer mixture.

It is interesting that the steel balls used for abrasion testing of the polymer-impregnated slabs were worn away very little or not at all during the test compared with the substantial reduction in diameter of the steel balls used for the unimpregnated control slabs.

WATER ABSORPTION

Experimental Details

In the case of water absorption tests (11) run on various freeze-thaw-tested cores and control cores, the cores were saturated by soaking in water for 24 hr at room tempera-

ture and then weighed to the nearest gram (1 oz = 28.4 g). The water-saturated cores were heated in an oven for 60 hr at 220 F (104 C) to drive off the evaporable water and were then reweighed; the difference between the two weights was taken as the total water absorption of the core.

Results and Discussion

Results for the various polymer-impregnated cores (core identifications the same as in Tables E-3 and E-5) are summarized in Table E-7.

Several generalizations can be made from these results. First, the water absorption of the polymer-impregnated cores was less than 0.5 to 1.5 percent of the total weight of the core and was only 10 to 20 percent of that of the unimpregnated cores, in good agreement with the 83- to 95-percent reduction in water absorption reported for polymer-impregnated cylindrical specimens cast and impregnated in the laboratory under controlled conditions (2). Also, there was no significant difference in water absorption between freeze-thaw-tested polymer-impregnated cores and polymer-impregnated cores not subjected to this test,

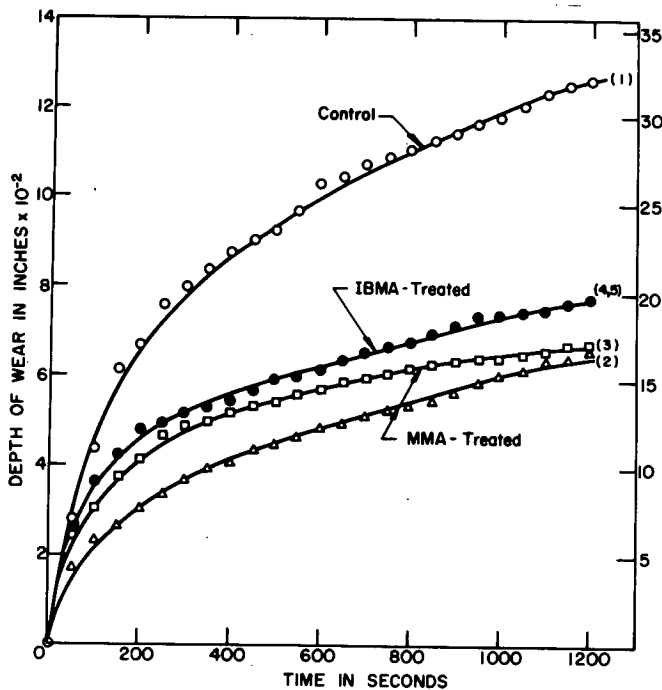


Figure E-22. Variation of depth of wear with time for polymer-impregnated and unimpregnated concrete slabs.

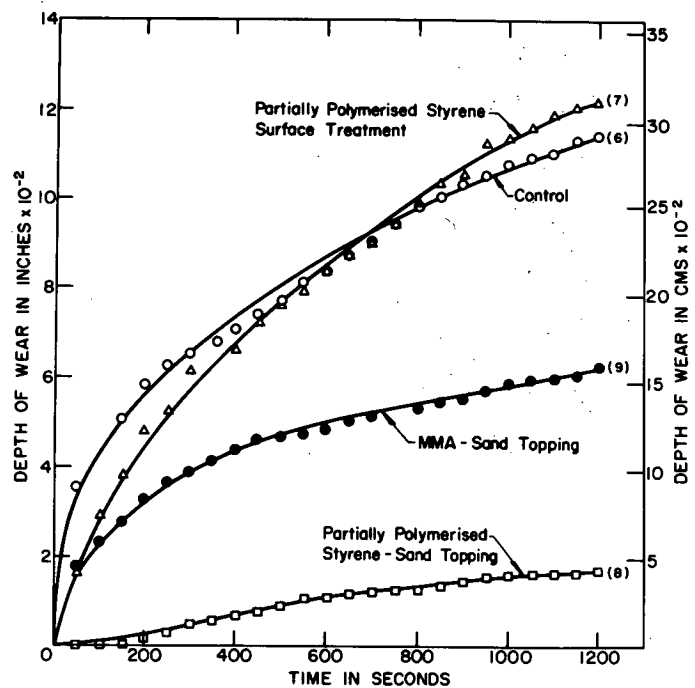


Figure E-23. Variation of depth of wear with time for polymer-impregnated, polymer-sand topped, and unimpregnated concrete slabs.

demonstrating again that polymer-impregnated concrete is remarkably resistant to freezing and thawing. Second, the water absorption was greater for cores taken from control slabs and impregnated in the laboratory vacuum-pressure chamber than for cores taken from polymer-impregnated slabs (e.g., compare the average of 19.3 percent for cores 5-51, 5-81, and 5-91 with 12.9 percent for cores 2-1, 2-2, and 2-6), even though the polymer loading was greater for the former. (Perhaps the polymer fills the pores of the latter type in a different manner.)

Finally, a single polymer-impregnated core taken from a bridge deck impregnated in the field (see Appendix H) showed lower water absorption than cores taken from polymer-impregnated slabs, indicating that equally good or better results may be expected from the field trials than from the laboratory impregnations.

Additional results on bridge deck cores (47) confirm the efficacy of impregnation in reducing water absorption.

Results for the other impregnants (sulfur, tar, tar-sulfur mixtures, and barium hydroxide) are given in Table E-8. Again, significant reductions up to 99 percent were noted for the sulfur, tar, and sulfur-tar combinations.

SKID RESISTANCE

Extensive studies by Fowler et al. (8) showed that the impregnation of highway-type concrete with PMMA resulted in a significant improvement in the skid resistance

(as measured by the British portable skid tester) of dry unworn specimens and in a slight (5 to 10 percent) improvement (wet) relative to unimpregnated controls after wear and polishing had occurred. Researchers at BNL (48) also reported only small effects in the case of impregnation with a polyester-styrene mixture: a slight decrease in the direction of the broom grain and essentially no change in the transverse direction.

In view of these results, measurements were confined in this study to the area of the large-scale field trial (Appendix H) on the PSU test track deck and were made only after 13 months of service. Tests were run in triplicate, with the help of B. Bright of the Transportation Research Institute, using a newly calibrated British portable skid tester. The general test procedure outlined in ASTM E303 was followed. Air and water temperatures were 62 F (17 C) and 60 F (16 C), respectively.

Two areas within the impregnated area, and one control area outside, were selected; each area was scrubbed, washed, and conditioned by preliminary tests. The following scale readings were obtained: control area, 84 (± 0); area 1, 84 (± 1); and area 2 (a slightly rougher area), 88 (± 3). Clearly, these results support the observation by others (Refs. 8, 48)—namely that impregnation with PMMA does not induce a degradation of skid resistance in concrete. (Tests on the Rt. 378 deck will probably be made by PennDOT after at least one year has elapsed since impregnation.)

TABLE E-7
 WATER ABSORPTION OF POLYMER-IMPREGNATED CONCRETE
 BEFORE AND AFTER FREEZE-THAW TESTING

Impregnation ^a	Salt Content, as a Percentage	Core	Water Absorption, in grams	Water Absorption as a Percentage, Based on Concrete	Reduction in Water Absorption, as a Percentage	
					Compared to Controls Subjected to Freeze-Thaw	Compared to Controls Not Subjected to Freeze-Thaw
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Surface Impregnation of Slab ^b	None	1-2 ^c	27	1.6	78	76
		1-3 ^c	24	1.4		
		1-5 ^c	22	1.3		
Surface Impregnation of Slab ^d	0.3 ^e	2-1	12	0.67	87	87
		2-2	13	0.74		
		2-6 ^f	14	0.88		
Lab Impregnation of Core from Unimpregnated Slab ^g	None	4-41	18	1.1	83	82
		4-51	19	1.1		
		4-91	17	1.0		
Lab Impregnation of Core from Unimpregnated Slab ^g	0.3 ^e	5-51	21	1.2	81	80
		5-91	19	1.1		
		5-81	20	1.2		
Impregnated Bridge Deck Core	----	----	12	0.54	92	89
None (Unimpregnated Control Slab)	None	4-2	104	6.07	--	--
		4-3	113	6.55		
		4-7	110	6.36		
None (Unimpregnated Control Slab)	0.3 ^e	5-1	105	5.82	--	--
		5-2	107	5.96		
		5-3	107	5.94		
Surface Impregnation of Slab ^{d,h,i}	None	6-6	10	0.59	91	91
		6-4	9	0.5		
Surface Impregnation of Slab ^{d,i}	0.3 ^e	2-7	9	0.5	91	91
None (Unimpregnated Control Slab) ⁱ	None	4-1	108	6.17	--	--
None (Unimpregnated Control Slab) ⁱ	0.3 ^e	5-4	102	5.9	--	--

Unit Conversion: 1 oz = 28.35 g.

a. 90:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture containing 0.5% azobisisobutyronitrile initiator.

b. 2.0 hr vacuum (25 in. [640 mm] Hg); 40 psi (280-kPa) pressurization.

c. Partially impregnated.

TABLE E-7
(Continued)

- d. 1.5 hr vacuum (28 in. [710 mm] Hg); 60 psi (410-kPa) pressurization.
 e. 0.3% salt = 12 lb/cu yd (7.1 kg/m³).
 f. Unimpregnated region of core failed in freeze-thaw test.
 g. Laboratory vacuum (1.5 hr)-pressure (60 psi [410 kPa]) chamber.
 h. Isobutyl methacrylate substituted for methyl methacrylate.
 i. Cores not subjected to freeze-thaw test.

TABLE E-8
WATER ABSORPTION OF IMPREGNATED MORTAR SPECIMENS

Impregnant	Specimen No.	Average ¹ Percent Loading	Average Water Absorption (g)	Average ² Percent Reduction in Water Absorption
B _a (OH) ₂ Solution ³	1-7	2.3	2.02	47
Molten Sulfur ⁴	8-14	12.5	0.03	99
	29-33	10.5	0.06	98
Tar ⁵	15-21	6.8	0.10	97
Sulfur-Tar (80-20)	22-28	11.2	0.05	99
Water (Control)	34-38	7.8	3.84	--
Unit Conversion: 1 oz = 28.35 g.				

1. Percent Loading = $\frac{\text{impregnated weight-dry weight}}{\text{dry weight}} \times 100$; immersion time = 24 hr.

2. Percent reduction in water absorption = $\left[\frac{\text{water required for saturation-water absorbed}}{\text{water required for saturation}} \times 100 \right]$.

3. Ba(OH)₂ dissolved in its own water of crystallization; surface of concrete specimens severely attacked by the solution.

4. Specimens 8-21 and 34-38 immersed in water for 24 hr; the remaining specimens immersed in water for 72 hr.

5. Tar used was AASHTO Specification M-214-65; specific gravity, 1.08.

APPENDIX F

EFFECTS OF CONTAMINANTS

Experiments were carried out to examine the effects of contamination of concrete with deicer salts and roadway deposits (grease, oil, rubber) on the drying, impregnation, and polymerization processes. The effects of the contaminants on the mechanical and durability properties of polymer-impregnated concrete were also studied.

EFFECT ON DRYING

Laboratory studies on the effects of deicer salt contamination on drying were carried out on concrete cylinders (10). The characteristics of the concrete mixture are given in Table F-1.

Twenty-four 3-in. (7.6-cm) diameter by 6-in. (15.2-cm) high concrete cylinders were made from the batch and were fog cured for 28 days. All specimens were dried at 260 F (125 C) for 24 hr. The specimens were then divided into three groups of eight specimens each. The first group, designated D, was submerged in water; the other two groups,

TABLE F-1

CONCRETE MIXTURE PROPORTIONS AND PROPERTIES

Water/Cement Ratio (by weight)	0.5
Water, lb (kg)	24.4 (11.1)
Cement, lb (kg)	48.8 (22.1)
Sand, lb (kg)	104.5 (47.4)
Coarse Aggregate, lb (kg)	113.5 (51.5)
Air Entraining Agent, cm ³	10
Air Content, %	7
Slump, in. (cm)	2.75 (7)

DI and DII, were submerged in 3-percent (by weight) sodium chloride solution for a period of 48 hr. All specimens were then dried to constant weight in a circulating oven at 260 F (125 C). The salt-contaminated specimens experienced weight losses that averaged only about 87 percent of weight loss experienced by the non-salt-contaminated specimens at the time the latter had achieved constant weight (17 hr). After an additional 49 hr of drying, the salt-contaminated specimens showed an average weight loss that closely approached that of the noncontaminated specimens at 17 hr (98 percent). Specimen set DII was subsequently re-soaked in the salt solution for another 48-hr period and dried to constant weight to produce a higher level of salt-contaminated specimens for mechanical properties studies.

This experiment indicates that the presence of deicer salts in the pore systems of concrete may require higher energy input or longer drying time to obtain a given degree of drying, as compared with noncontaminated concrete.

EFFECT ON IMPREGNATION RATE AND MONOMER LOADING

Laboratory Concrete

A series of polymer-impregnation tests, using the pressure method on slab specimens produced in the laboratory, was carried out to evaluate the effects of chloride contamination on impregnation rate and on monomer loading (11). The 24-in. x 24-in. x 6-in. (61.0-cm x 61.0-cm x 15.2-cm) concrete slab specimens were prepared from a conventional non-air-entrained 1.00:1.92:6.10:6.75 water-portland cement (type I), coarse sand-limestone aggregate (1 in. (2.5 cm) maximum) mix with a cement factor of 485 lb/yd³ (287 kg/m³) and 28-days-average compressive strength of 4750 psi (32800 Pa). The measured air content was 3 percent and the slump was 2.5 to 3.0 in. (6.4 to 7.6 cm). The slabs were given a normal trowel finish and were cured in the fog room (90- to 100-percent relative humidity) for at least 28 days before use in drying and impregnation tests. All slabs contained nominal steel reinforcement at a 4-in. (10-cm) depth to simulate the structure of the bridge deck. The slabs were dried to constant weight in an oven at 250 F (121 C). One slab was soaked in a salt solution to constant weight and redried in the same manner as described earlier; this resulted in a salt concentration in the concrete of 0.3 percent by weight. That slab and three noncontaminated slabs were subjected to vacuum-pressure impregnation using the apparatus described in Appendix C. The monomer system consisted of 90:10 methyl methacrylate-trimethylpropane trimethacrylate containing 0.5 percent azobisisobutyronitrile initiator. Various vacuum-pressure levels were used and the impregnation process was continued until the monomer penetrated the entire 6-in. (15.2-cm) thickness of the slabs. The results are given in Table F-2.

The predicted time for impregnation is based on the relationship discussed in Appendix D. It is evident from Table F-2 that the salt-contaminated slab took longer to impregnate than predicted by the equation in Appendix D, whereas the three noncontaminated slabs gave results that

TABLE F-2
IMPREGNATION OF 24-IN. x 24-IN. x 6-IN. SLABS

Slab No.	Salt Content %	Vacuum Treatment	Impregnation		Predicted Polymer Loading	
			Pressure psi (kN/m ²)	Time hr	Time hr	%
1A	0.0	None	30 (210)	17-24	18	5.5
1	0.0	2 hr @ 25 in. (63.5 cm) Hg	40 (280)	7.0-8.5	7-10	5.5
2	0.3	1.5 hr @ 28 in. (71 cm) Hg	60 (410)	5.0-7.5	4.0-5.5	5.0
8	0.0	1.5 hr @ 28 in. (71 cm) Hg	80 (550)	2.0-3.5	2-3	5.5

Unit Conversion: 1 kN/m² = 1 Pa

closely agreed with predicted values. Also, it can be seen in Table F-2 that the monomer loading in the salt-contaminated slab was less than it was in the noncontaminated slabs (5.0 vs. 5.5 percent). Therefore, it can be concluded that salt contamination reduces the rate of impregnation and polymer loading, although not to an appreciable extent.

Field Concrete

For this study (47), concrete cores were taken from three 7-year-old bridge decks with an ADT (average daily traffic) of 5160 in 1969. The three decks were in excellent condition and did not display the presence of large cracks, spalled areas, or potholes. The concrete used in the construction of the three decks was required to meet the PennDOT specifications for Class AA reinforced vibrated concrete. Portland cement (type I) was used, and glacial sand and crushed limestone were the aggregates. The average slump, air content, and flexural strength for the concrete used in these decks are given in Table F-3.

The impregnation system consisted of methyl methacrylate (MMA), trimethylpropane trimethacrylate (TMPTMA), and azobisisobutyronitrile (AZO) mixed in the ratio of 100:10:0.5 parts by weight, respectively.

A total of 26 cores was taken from the three bridge decks. The coring positions represented the lateral range of the different usage areas (water tables and the truck and passing lanes) on a bridge deck. Duplicate cores were taken from these areas in order that chloride determinations could

TABLE F-3
AVERAGE CONCRETE CONTROL PARAMETERS

Bridge Structure	Slump	Air Content	Flexural Strength
Number	(in.)	(%)	psi @ 7 days
6254NB	2.2	6.5	769
6254SB	2.2	6.5	641
6258NB	2.2	6.2	956

be made. Figure F-1 shows the positions from which the cores were taken.

The bottoms of the cores were trimmed with a diamond saw to provide specimens that were 4 in. (10 cm) in diameter by approximately 5 in. (13 cm) in height. The cores were then dried in a forced draft oven at 239 F (115 C) for 72 hr followed by 24 hr at 239 F (115 C) in a vacuum oven at 29 in. (98 kPa) Hg vacuum. After cooling under vacuum, the sides of the cores were painted with a coat of epoxy. A metal ring, 1 in. (2.5 cm) in height and 4 in. (10 cm) in diameter, was bonded to the top of each core with epoxy to provide a reservoir for ponding the monomer during the impregnation of the cores.

To determine the quantity of deicer salts present in the cores, the Berman (24) chloride titration procedure was employed. Chloride analyses were performed on cores 1-2, 1-4, 1-6, 2-2, 2-4, 2-6, 3-5, 3-6, and 3-8. To provide the cement paste sample used in the titrations, the cores were first split using the tensile splitting method. The cement paste was then extracted as a fine powder by drilling on the

split face with a 3/16-in. (0.48-cm) carbide drill bit. The positions drilled were in the cement paste areas, and care was taken to avoid any large aggregate particles. Cement paste samples were obtained from four areas on each core (0 to 1/4 in. (0.6 cm), 1/4 to 3/4 in. (0.6 to 1.9 cm), 3/4 to 1 3/4 in. (1.9 to 4.5 cm), and 1 3/4 to 3 3/4 in. (4.5 to 9.5 cm) in depth from the wearing surface).

The impregnation of the dried cores with the MMA system was accomplished by allowing the monomer to soak through the cores from the wearing surface only with an evaporation barrier provided above the free monomer surface. The rate of impregnation was determined by periodic weighing of the specimens during impregnation. Completion of impregnation was assumed to occur when the monomer exuded uniformly from the bottoms of the specimens.

It was assumed that the heaviest traveled areas would have the greatest amount of surface contamination. Therefore, six cores were taken from the truck lane, three from the right-wheel path, and three from between the wheel paths. The surfaces of these cores were cleaned by three methods (detergent, lye, and sand blasting). Cores 1-7 and 2-7 were scrubbed for 5 min with a 20 percent by weight detergent (Biz) solution; cores 2-7 and 2-8 were scrubbed for 5 min with a 20 percent by weight lye (NaOH) solution; cores 1-9 and 2-9 were cleaned by sand blasting at a pressure of 75 psi (0.66 MPa) for a period of 10 min.

Typical results of the chloride analyses for the nine bridge deck cores are shown in Figure F-2. The concentrations of the chlorides appear to decrease linearly as a function of depth. This agrees with the results for sound concrete found in other research on the durability of concrete bridge decks (49). In general, the degree of contamination by chlorides was determined to be approximately the same for the areas

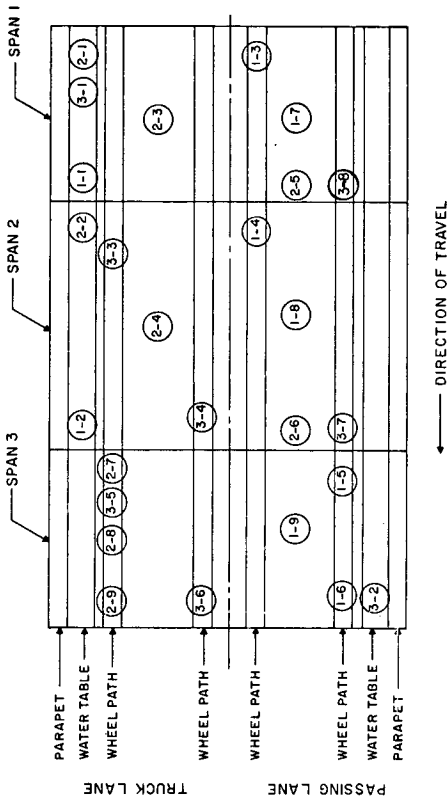


Figure F-1. Coring positions of bridge deck 6254 NB (1-1 to 1-9), 6254 SB (2-1 to 2-9), and 6258 NB (3-1 to 3-8).

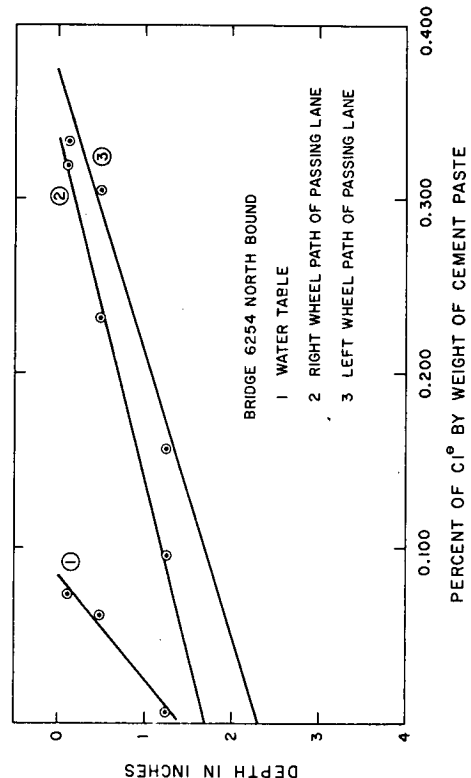


Figure F-2. Chloride content of bridge 6254 northbound.

investigated except for the areas not used by traffic where the concentrations were lower.

The lateral position of the cores on the decks was matched with the closest lateral position of the cores used for chloride analyses. The values of chlorides present in the top ¼ in. (0.6 cm) were then assigned to the respective impregnated cores. These chloride values and the impregnation data are given in Table F-4.

Correlation coefficients were calculated for the chlorides in the top ¼ in. (0.6 cm) versus the percent MMA at 96 hr and versus the rate of impregnation (slope). Both correlation coefficients were significant at the 95-percent confidence level.

Because of the small sample sizes of the cores subjected to the various cleaning processes, no statistical analyses were performed. However, by observing the percent MMA gained in 96 hr for the six cores that were cleaned (1-7, 1-8, 1-9, 2-7, 2-8, and 2-9) with the remaining cores from the same two bridge decks (Table F-4), it is concluded that contamination from materials considered here had no significant effect on polymer loading. However, the presence of deicer salts in the concrete clearly retards the impregnation rate, as shown earlier for mortars (15).

EFFECT ON POLYMERIZATION

It has been reported in the literature (50) that 90 percent of polymerization is achieved at the peak of the exotherm for the MMA-TMPTMA monomer system. Therefore, it was decided to investigate the effect of contaminants on polymerization by measuring the time required to reach the exothermic peak. The need for the determination of the warm-up time was eliminated by measuring the difference in time to peak exotherm between a control and the contaminated specimens.

Since the exotherm of the polymerization reaction can be dependent on specimen size, a constant volume was chosen. A specimen size of 0.88 oz (25 g) was used, because the specimen had to be large enough to overcome the effects of the temperature of the oil bath but small enough so that the oil bath temperature remained essentially constant during polymerization.

It has been shown that the rate of polymerization (47) is dependent on the activation temperature. It was also expected that the level of contamination would alter the polymerization time. Therefore, polymerization time studies were conducted at 131 F (55 C), 149 F (65 C), and 167 F (75 C) with contaminant levels of 0.5, 1.0, and 2.0 percent by weight. The exotherm of reaction was measured by means of a copper-constantan thermocouple. The depth of the thermocouple in the specimens was kept constant. The culture tubes containing the specimens were placed in the oil bath; care was taken to prevent the oil from the bath from entering the specimens. The contaminants investigated were sodium chloride, calcium chloride, linseed oil (used as a sealant on bridge decks), motor oil, automobile lubricant (grease), and asphalt cement (used in patching and sealing cracks and joints).

The effects of the various contaminants on polymerization are given in Table F-5. It can be seen that the effects of all contaminants decrease sharply with increasing po-

TABLE F-4

BRIDGE DECK CORE IMPREGNATION DATA

Core No.	Slope (g/hr ^{1/2})	Monomer gained in 96 hr (g)	Total Monomer gained ¹ (g)	Percent at 96 hr	Percent Cl at 1/4 in. (.6 cm)	Total Soak Time (days)
1-1	7.4	81.5	98.5	82.7	0.074	7
1-3	6.7	71.1	87.6	81.2	0.333	7
1-5	5.6	54.8	87.9	62.3	0.319	11
1-7	5.0	54.0	81.7	66.1	0.319	11
1-8	4.7	50.4	68.9	73.1	0.319	9
1-9	5.9	58.8	84.0	70.0	0.319	9
2-1	5.0	53.0	74.6	71.0	0.163	9
2-3	5.0	52.7	81.8	64.4	0.355	11
2-5	5.1	56.1	84.2	66.6	0.377	11
2-7	5.9	65.2	86.8	75.1	0.355	9
2-8	5.1	50.0	81.2	61.6	0.355	11
2-9	5.8	68.1	93.9	67.2	0.355	11
3-1	8.7	87.5	87.5	100.0	0.020	4
3-2	7.7	78.2	93.7	83.5	0.020	6
3-3	7.6	76.0	82.7	91.9	0.298	5
3-4	5.6	60.9	76.5	79.6	0.192	7
3-7	5.4	58.8	72.5	81.1	0.020	7

Unit Conversion: 1 oz = 28.35 g.

1. At complete penetration.

lymerization temperature, becoming essentially nil at 167 F (75 C). In fact, at 149 F (65 C), only the asphalt cement significantly affected polymerization. At 131 F (55 C) all contaminants, except sodium chloride, significantly reduce the polymerization rate. This suggests that the activation temperature should be kept above 149 F (65 C) in order that polymerization be achieved. Also, asphalt cement should be removed to the extent practical from the surface prior to impregnation.

EFFECT ON MECHANICAL PROPERTIES

The same group of concrete specimens described earlier in this appendix (at the beginning of the section entitled "Effect on Drying") was used to study the effect on mechanical properties (10). After the drying tests, half of the specimens (4) from each group were cooled down, placed in the impregnation vessel (Appendix D), and subjected to both vacuum and pressure. Air was removed from the specimens by a vacuum pump at 29 in. (100 KN/m²) of mercury for 1½ hr before MMA containing 0.5 percent by weight azobisisobutyronitrile was induced into the vessel. The vessel was then pressurized with nitrogen at 60 psi (0.41 MPa) for 1½ hr to speed up the penetration of monomer. After removal from the vessel, the specimens

TABLE F-5
EFFECTS OF ROAD CONTAMINANTS ON
POLYMERIZATION OF MMA-TMPTMA-AZO SYSTEM

Level of Contaminant (% of MMA System Wt.)	Type of Contaminant	Increase in Polymerization Time ¹ (min)			Number of Exotherms		
		55°C	65°C	75°C	55°C	65°C	75°C
0.5	NaCl	7	2	0	1	1	1
1.0	NaCl	3	1	0	1	1	1
2.0	NaCl	5	7	0	1	1	1
0.5	CaCl ₂	30	5	0	2	1	1
1.0	CaCl ₂	26	3	0	2	1	1
2.0	CaCl ₂	39	10	0	2	1	1
0.5	Linseed Oil	47	2	0	2	1	1
1.0	Linseed Oil	45	1	0	2	1	1
2.0	Linseed Oil	88	8	0	2	1	1
0.5	Motor Oil	44	3	0	2	1	1
1.0	Motor Oil	30	3	0	2	1	1
2.0	Motor Oil	68	13	2	2	1	1
0.5	Grease	52	4	0	2	1	1
1.0	Grease	56	6	0	2	1	1
2.0	Grease	81	15	2	2	1	1
0.4	Asphalt Cement	138	27	2	2	1	1
1.2	Asphalt Cement	273	81	2	2	1	1
2.0	Asphalt Cement	470	120	3	3	2	1

Unit Conversion: °F = $\frac{9}{5}$ °C + 32.

1. Polymerization time is 67 percent of the time (after the system attains bath temperature) it takes the system to reach its peak exotherm temperature. This time for the MMA system is only 108 ± 8 minutes at 55°C and 32 ± minutes at 65°C.

were polymerized under hot water at 160 F to 175 F (70 C to 80 C) for 4 hr. The polymer loading of the specimens after polymerization was calculated as the increase in weight after polymerization in percent of the initial dry weight.

The remaining one-half of the specimens from each group were used for controls in the mechanical properties determinations. A modification of the standard splitting tensile test (ASTM C496-66) was used. The setup has the advantage that the lateral strain can be automatically recorded as a function of load. A strain gauge was glued to the bottom plane surface of each specimen, horizontally in the center of the specimen.

The specimens used for compression tests (ASTM C39-66) were capped with high-strength gypsum plaster to assure plane parallelism of the ends. Two clip-type extensometer were fixed on either side of the specimen between two rings. The load-strain relationships were recorded automatically on an X-Y plotter for both the tension and compression tests.

Essentially, uniform impregnation and complete conversion to polymer were achieved for all of the PIC specimens, as shown by visual and microscopic examination, and by

the observation of at most a faint odor due to unreacted monomer (in only a few specimens on freshly broken surfaces). The results of the mechanical properties determinations are given in Table F-6 and are shown in Figures F-3 and F-4.

TABLE F-6
EFFECTS OF SALT CONTAMINATION ON MECHANICAL PROPERTIES

Specimen Series	% Salt Loading, %	Tensile		Compressive		Young's Modulus ksi x 10 ³
		Polymer Loading, %	Strength ksi	Strength ksi	Strength ksi	
D	0.0	7.7	1.45	19.6	6.7 ^a	
D Control	0.0	0.0	0.39	4.2	2.3 ^a	
Difference	0.0	7.7	1.06	15.4	4.4	
DI	0.5	7.7	1.40	15.8	5.8	
DI Control	0.5	0.0	0.42	4.5	2.9	
Difference	0.0	7.7	0.98	14.3	2.9	
DII	1.0	7.1	1.38	19.9	6.3	
DII Control	1.0	0.0	0.47	4.8	3.6	
Difference	0.0	7.1	0.91	15.1	2.7	

^aTangent Modulus.

^bSecant Modulus.

¹Conversion Factor: 1 ksi = 6.89 kPa

In looking at the differences between the control specimens and the impregnated specimens in Table F-6, it appears that tensile strength and Young's modulus tend to

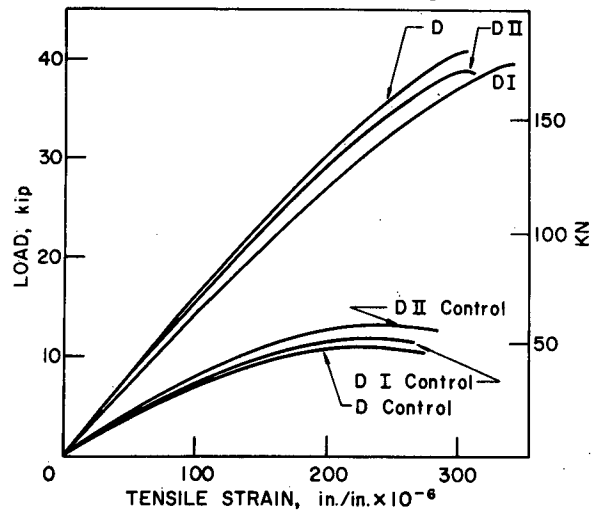


Figure F-3. Tensile load-strain curves for salt-contaminated concrete impregnated with MMA.

decrease slightly with increasing salt content. The compressive strength, on the other hand, appears to give a minimum value at the intermediate salt-content value.

However, for the salt contents used in this experiment (up to 1.0 percent), the effect on mechanical properties is relatively insignificant. The tendency of polymer impregnation to mask initial differences in different concretes by producing composites that have very nearly the same mechanical properties may imperil any meaningful comparison of differences between controls, impregnated specimens, and salt content. In other words, the best comparison may be between the impregnated specimens and the salt content irrespective of the controls. This comparison yields no consistent evidence of a relationship between salt content and mechanical behavior, at least in well-dried specimens.

EFFECT ON FREEZE-THAW RESISTANCE

As described under "Freeze-Thaw Tests" in Appendix E, salt contamination reduced the freeze-thaw resistance of nonimpregnated concrete, but had no apparent effect on the durability of polymer-impregnated concrete. Both salt-contaminated and non-salt-contaminated polymer-impregnated specimens showed outstanding resistance to freeze-thaw action.

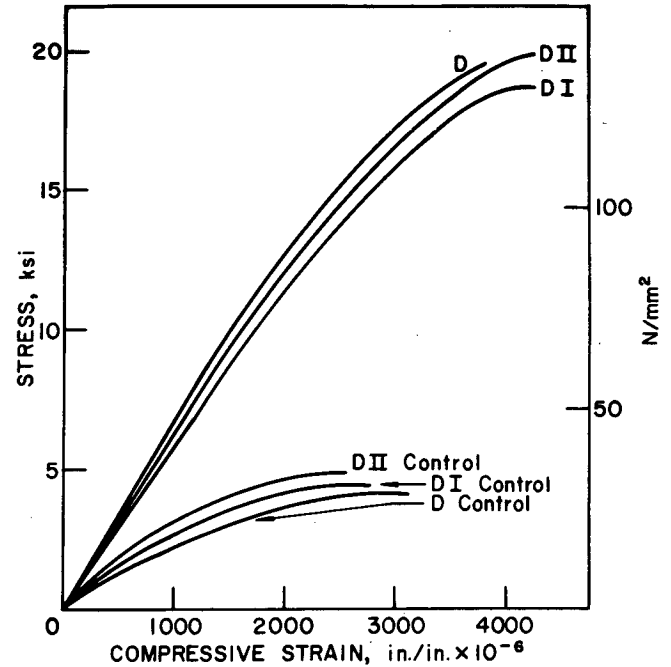


Figure F-4. Compressive stress-strain curves for salt-contaminated concrete impregnated with MMA.

APPENDIX G

METHODS FOR POLYMER IMPREGNATION

Prior to moving to preliminary small-scale field tests using the PTI test track bridge, experiments were conducted on large slabs in the laboratory (see also Appendix C). Two combinations of drying, impregnation, and polymerization were used: (1) gas-fired infrared drying, ponding, and hot-water-heated polymerization; and (2) torch-drying, pressure impregnation, and steam-heated polymerization.

For the preliminary field trials, a site in the water table area on span 2 of the PTI test track bridge (discussed earlier) was selected, as shown in Figure G-1. At this location, the deck was 7.5 in. (19 cm) thick with #5 reinforcing bars on 6-in. (15-cm) centers and #4 temperature steel on 12-in. (30-cm) centers. Both laboratory and field tests are described as follows.

IR DRYING, SOAK IMPREGNATION, HOT-WATER POLYMERIZATION

Laboratory Studies

Large slabs were constructed in the laboratory to investigate infrared drying techniques, temperature distribution during drying and polymerization, soak-impregnation techniques, and polymerization using hot water bath. These slabs were constructed to simulate bridge decks in the laboratory and to evaluate laboratory data acquired on cores and cylinders (Appendixes B, C, D, and F) on a larger scale.

A 6-ft x 6-ft x 6-in. (1.83-m x 1.83-m x 0.15-m) slab with one layer of reinforcing steel was constructed to investigate the temperature distribution during drying in a large slab. Copper-constantan thermocouples were placed in the slab at depths of ½ in. (1.3 cm), 1 in. (2.5 cm), 2½ in. (6.4 cm), and 4 in. (10.2 cm) from the top at five different locations in the slab. Figure G-2 shows the general design of the large slabs. Numbers 1 through 5 in Figure G-2 are the thermocouple positions for the 6-ft x 6-ft x 6-in. (1.83-m x 1.83-m x 0.15-m) slab. Table G-1 gives the mix design for the 6-ft x 6-ft x 6-in. (1.83-m x 1.83-m x 0.15-m) slab.

A second slab 6 ft x 6 ft x 8 in. (1.83 m x 1.83 m x 0.20 m), with two layers of reinforcing steel, was constructed using the general design similar to the design of bridge decks constructed in Pennsylvania, as shown in Figure G-2. Letters A and B (Figure G-2) indicate the thermocouple positions for this slab. The thermocouples in this slab were embedded at 2½ in. (6.4 cm) and 4 in. (10.2 cm). Table G-1 gives the mix design.

After the slabs were hydrated for 28 days (wet burlap placed over the surfaces), each slab was subjected to a series of drying tests. These tests were performed to understand the drying technique beyond the overdrying used in cylinder studies. There are several methods being investigated for drying bridge decks in the field, and infrared drying represents one of the more promising techniques.

TABLE G-1
CONCRETE MIX DESIGN (9)

Material	Amount		PSU Test Track Bridge Deck
	6' x 6' x 6" Slab	6' x 6' x 8" Slab	
Cement (Type 1) - lb	588	588	588
Fine aggregate (silica sand) - lb	1099	1099	1075
Coarse Aggregate (limestone) - lb	1920	1920	1986
Water/cement - gal/sack	5.3	5.3	5.0
Air entraining agent - oz	10	10	10.5
Air content - %	6.5	5.4	6.5
Slump - in.	2.5	2.0	2.5
Compressive strength - psi average 3 cylinders (28 days)	3519	4110	3980

Unit Conversions: 1 in. = 2.54 cm

1 ft = .305 m

1 psi = 6.89 kN/m² (Pa)

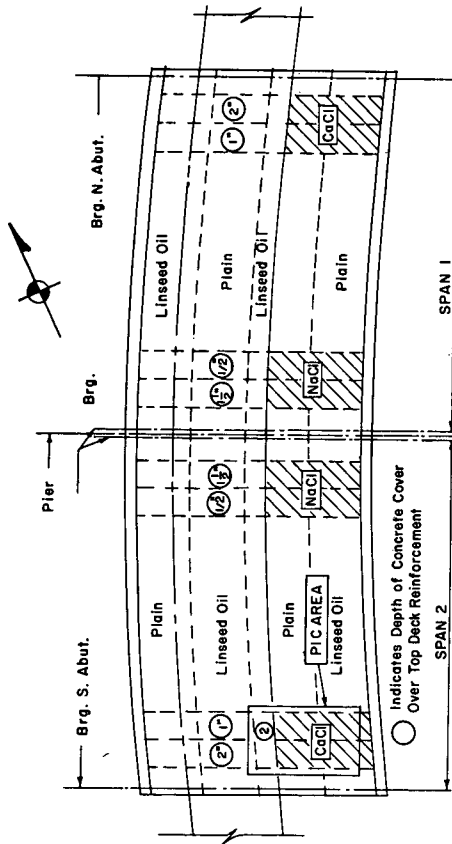


Figure G-1. Location of field trials on PTI test track deck (infrared drying-ponding method, torch-drying-pressure impregnation; large-scale tests, shaded area).

Gas-fired infrared heaters were applied to the slabs over a surface area of 1½ ft x 2½ ft (4.57 m x 7.62 m). This simulates point drying on a bridge deck, since at present it does not seem feasible to dry the whole bridge deck at once. Gas-fired infrared heaters were chosen for the drying experiments because of their relative efficiency and low consumption of propane or natural gas. The infrared heater (Pavement Reclaiming Corp., Buffalo, N.Y., Model TPRC JH2 Joint Heater) used burned about 2.9 lb (1.32 kg) propane/hr, and it produced 60,000 Btu (63.3 MJ).

It became evident in the drying studies using infrared heat (Appendix C) that one can either maintain a constant surface temperature (as in oven drying) or maintain the heater at a constant distance above the concrete. If a constant surface temperature is desired, the surface temperature of the concrete must be continually monitored and the heater distance above the surface adjusted accordingly. This method may decrease the drying rate, and it was decided for these tests to maintain a constant heater distance between the concrete and heater because of faster drying rates and less monitoring (9).

Temperature profiles obtained during IR drying of the 6-ft x 6-ft x 6-in. (1.83-m x 1.83-m x 0.15-m) and 6-ft x 6-ft x 8-in. (1.83 m x 1.83-m x 0.20-m) slabs were presented in Appendix C. Many drying tests were conducted, and the temperature profiles reported are considered to be typical. During some of the slab drying tests, severe cracking was observed. The drying curve profiles agree with a discussion of moisture movement in concrete presented by Harmathy (20), as mentioned in Appendix C. In the first period (constant rate period), the average moisture content decreases fairly fast and the temperature in the concrete rises, after which it remains fairly constant. Capillary flow is believed to be the principal mechanism of migration in this period. When the concrete temperature begins to increase, this period ends. The second period is called the falling rate period, and moisture movement is mainly by an evaporation-condensation mechanism. During this period, the rate of temperature rise throughout the concrete steadily decreases until equilibrium with the surroundings is reached. The data presented agree with this discussion.

As previously discussed in Appendix C, in order to predict if the concrete is dry enough for impregnation at 4 in. (10.2 cm), using the temperature as an indication, one can insert a thermocouple to a depth of 4 in. (10.2 cm) and read the temperature, or one can use the surface temperature as an indication of the temperature at 4 in. (10.2 cm). It was found that the best indication is to observe the rate of surface-temperature change once per hour, and when the rate of increase per hour is 10 F (5.5 C), or less, the temperature at 4 in. (10.2 cm) is approaching equilibrium. In all drying tests, including some on the bridge decks, this rate (≤ 10 F/hr (≤ 5.5 C)) occurred about 2 hr after the temperature at 4 in. (10.2 cm) reached about 212 F (100 C). Hence, there appear to be two ways of expressing the same criteria: (1) when the rate of temperature change at the surface is 10 F (5.5 C)/hr or less, drying equilibrium is nearly attained at 4 in. (10.2 cm); or (2) when the temperature at 4 in. (10.2 cm) is above 230 F (110 C), drying equilibrium is practically attained.

After drying the concrete slabs until the temperature at 4 in. (10.2 cm) was above 230 F (110 C), a metal impregnation box (2½ ft x 1½ ft x 1 ft (0.76 m x 0.46 m x 0.31 m)) was immediately secured over the dried area. This box was secured to the concrete surface using a Silastic rubber compound. The concrete was allowed to cool to ambient conditions (~12 hr) and the monomer (MMA-TMPTMA-AZO, 100:10:0.5 by weight) system was placed in the box. The top of the box was enclosed with a clear polyethylene sheet completely taped around the sides of the box. This totally contained system helps to keep the evaporation of the monomer system to a minimum. The monomer system was allowed to soak for 4 days, based on results from cores and cylinders discussed in Appendix F. There is some indication at present (Appendix B) that the ponding time could be reduced to 1 to 2 days.

At the end of the impregnation time, the excess monomer was removed from the surface. At the same time, water ≥ 185 F (85 C) was placed in the impregnation box. This water was at a minimum depth of 7 in. (17.8 cm). Immersion heaters (1000 to 2500 watts (3600 to 9000 kJ/hr)) and a stirrer were placed in the water to maintain the bath temperature at ≥ 185 F (85 C). The immersion heater wattage was varied in order to maintain the desired bath temperature. During the polymerization the impregnation box was completely surrounded by insulation. This helped in maintaining a high bath temperature. The immediate application of hot water (≥ 185 F (85 C)) to the concrete also helps to decrease surface depletion by polymerization of the surface. The steady-state polymerization temperature at 4 in. (10.2 cm) was about 130 F (54 C), and it was maintained for 10 hr. Although immersion heaters were used during these tests, it may be impractical to generate enough electricity for them on a bridge deck. Other means of heating water, such as steam, may have to be employed.

The depths of impregnation achieved during slab tests were from 3¾ in. (7.9 cm) to 4¼ in. (10.8 cm). The results are given later in this appendix in Table G-2.

PRELIMINARY FIELD TRIALS: PENNSYLVANIA TRANSPORTATION RESEARCH FACILITY BRIDGE DECK

Field drying, impregnation, and polymerization trials were performed on the Pennsylvania Transportation Research Facility bridge deck in order to verify the results obtained on the large slabs in the laboratory. The concrete mix design for this bridge deck and a description of the bridge are given in Ref. (51). The drying data are presented in Appendix C.

Figure G-3 shows the infrared heater with a metal box enclosure during the bridge deck impregnation trial. The metal box enclosure was used to protect the heater from the wind and to act as a reflector. The other box in the figure is the impregnation box that was placed around the dried area.

After drying the bridge deck until the temperature at 4 in. (10.2 cm) was above 230 F (110 C), a metal impregnation box (2½ ft x 1½ ft x 1-ft (0.76 m x 0.45 m x 0.31 m)) was immediately secured over the dried area. This box was secured to the concrete surface using a Silastic rubber compound. The concrete was allowed to cool to ambient conditions (~12 hr), and the MMA system (MMA-TMPTMA-AZO, 100:10:0.5 by weight) was placed in the box. The top of the box was enclosed with a clear polyethylene sheet completely taped around the sides of the box (see Fig. G-4) as in the large-scale laboratory studies.

After an impregnation (soak) time of 4 days, the excess monomer was removed and hot water (≥ 185 F (≥ 85 C)) was put in the impregnation box. Immersion heaters and a stirrer were placed in the hot water and insulation was

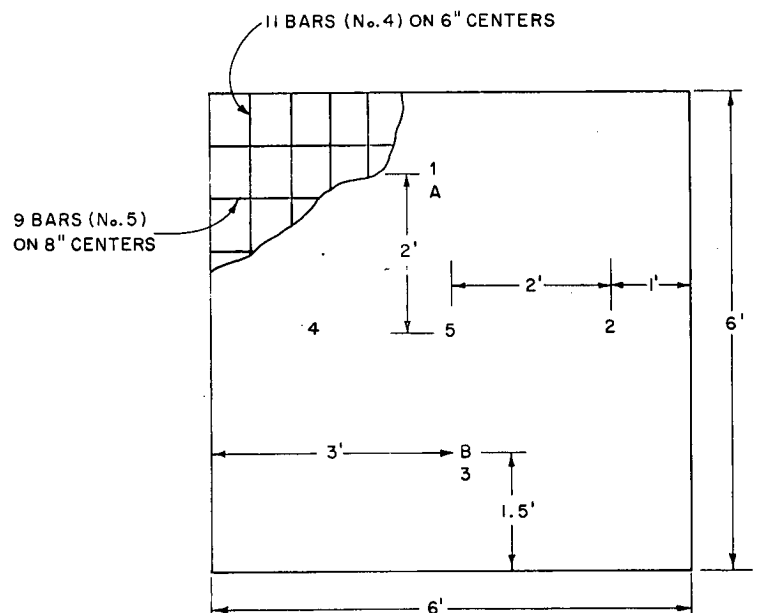


Figure G-2. Large slab design (9).

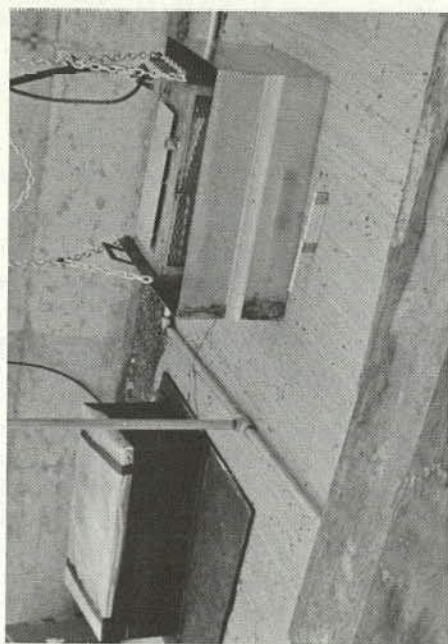


Figure G-3. Infrared heater during bridge deck impregnation trial (9).

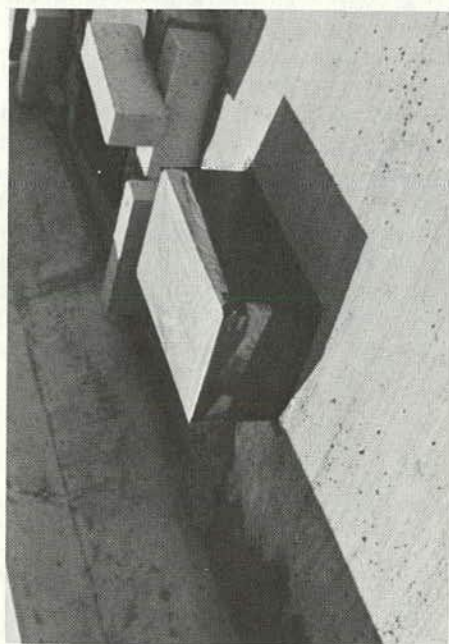


Figure G-4. Impregnation box during bridge deck impregnation trial (9).

placed around the bath. A steady-state temperature of 130 F (54.4 C) at 4 in. (10.2 cm) was achieved. Figure G-5 shows some of the investigators adjusting the hot water bath during polymerization on the bridge deck trial.

Table G-2 summarizes the drying, impregnation, polymerization, and results of some of the slab and bridge deck tests conducted. Cores cut from the impregnated areas show heavy loadings from 3½ in. (8.9 cm) to 4 in. (10.2 cm) from the top. These heavy loadings (based on monomer density) are estimated to be between 7.3 and 9.8 percent of the concrete volume (17). In addition to the heavily loaded area, a depth below that area of 1 in. (2.5

cm) to 1½ in. (3.8 cm) is also impregnated. This area became evident during acid-etch studies of part of the slab and bridge deck cores and may be a result of a monomer evaporation-condensation mechanism. This is reasonable, since the MMA vapor pressure at room temperature is about double that of water. Figure G-6 shows part of a core from the bridge deck field trial. In this test, one section was placed in HCl, and the HCl was changed until the reaction was complete. The results indicate that the total penetration was over 4 in. (10.2 cm) deep on the bridge deck; exposed limestone aggregate has been destroyed, but the polymer-impregnated areas remain intact.

In summary, criteria for drying concrete slabs and bridge decks to a 4-in. (10.2-cm) depth using infrared heaters can be proposed. These criteria are either to measure the temperature at 4 in. (10.2 cm) and to stop drying when it reaches ≥ 230 F (110 C) or to stop drying when the rate of temperature rise on the surface is less than 10 F (5.5 C)/hr. Impregnation by ponding to achieve a depth of 4 in. (10.2 cm) required about 4 days. This time may possibly be reduced to 1 to 2 days if a depth of 3 in. (7.6 cm) to 3½ in. (8.9 cm) instead of 4 in. (10.2 cm) is required. Polymerization using a hot water bath was successfully completed at 4 in. (10.2 cm) when the temperature at 4 in. (10.2 cm) was maintained at ≥ 130 F (54 C).

FLAME DRYING, PRESSURE IMPREGNATION, STEAM POLYMERIZATION

Laboratory Studies

A test of this combination of processes was conducted using a 6-ft x 6-ft x 8-in. (1.83-m x 1.83-m x 0.20-cm) slab of the type described earlier (11, 12). As before, the slab was fitted with thermocouples to permit the measurement of temperatures at various depths. Drying was effected using the propane torch assembly described in Appendix C and shown on Figure G-7. A ½-in. (1.3-cm) layer of sand was used to minimize thermal stresses at the surface. Temperature profiles were similar to those obtained with the IR heater (see Appendix C). No serious problem with cracking was encountered.

Impregnation was effected using the pressure impregnation unit used in small-scale tests (Figs. G-8 and G-9). Polymerization was effected using steam provided by a pressure cooker (10 psi (70 kPa) to 13 psi (90 kPa)) for 10 hr.

As shown in Figures G-10 and G-11, examinations of a core revealed a dense impregnation to a depth of 3 in. (7.6 cm) (excluding the sand cover) with a less dense impregnation for an additional 1 in. (2.5 cm) to 1.5 in. (3.8 cm).

Preliminary Field Trial: Pennsylvania Transportation Research Facility Bridge Deck

The drying, impregnation, and polymerization were carried out in the following sequence: (1) an area of the bridge deck was dried for 10 hr using the propane torch assembly (Fig. G-7); (2) the pressure impregnator (Figs. G-8 and G-9) was used to impregnate an area 16 in. (0.41 m) in diameter for 8 hr at a pressure of 15 psi to



Figure G-5. Investigators adjusting polymerization bath during bridge deck impregnation trial (9).

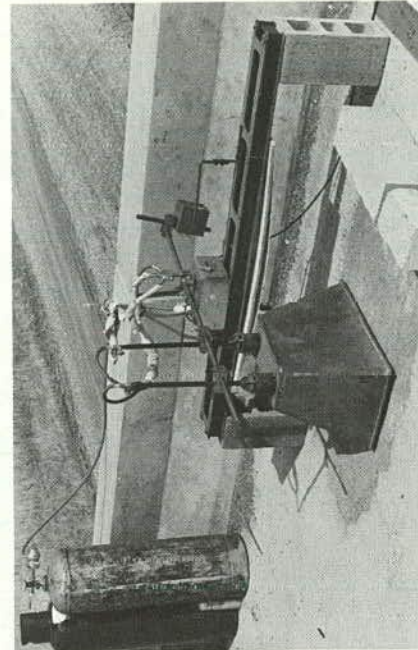


Figure G-7. Propane torch assembly used in fast drying of concrete slabs and bridge deck.

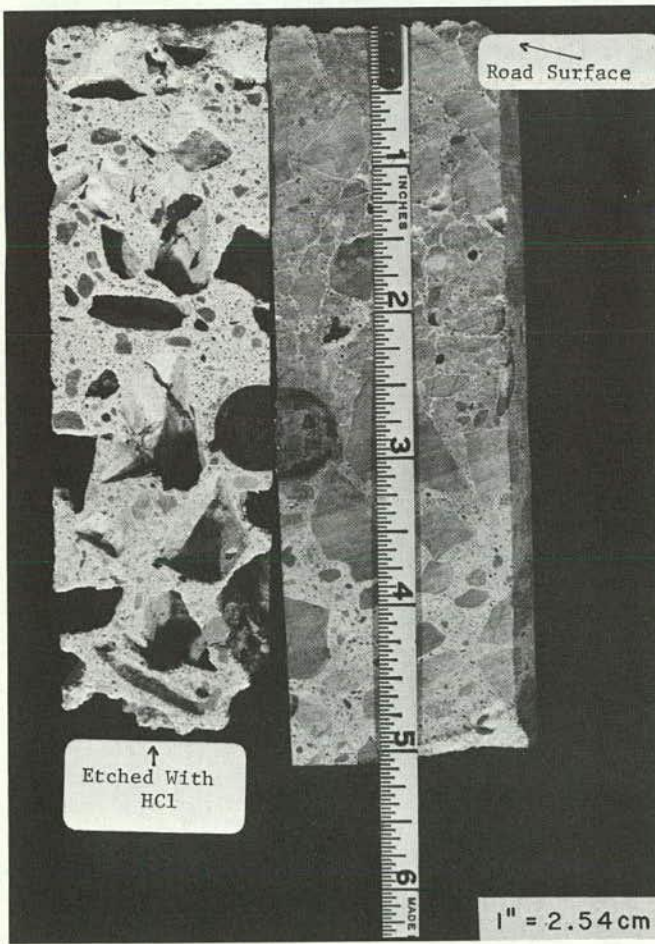


Figure G-6. Core from impregnated area of bridge deck using soak technique (9).

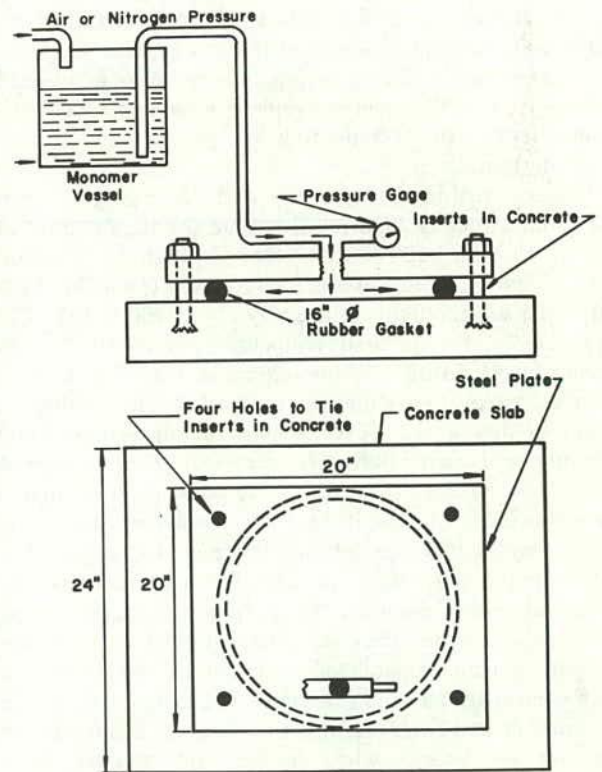


Figure G-8. Schematic representation of pressure impregnation device.

TABLE G-2
SUMMARY OF SOAK IMPREGNATION TESTS (9)

A. Drying and Impregnation		Temp (°F) at End of Drying ¹		Monomer ²
Test	Ambient ⁴ Temp (°F)	Surface		Soak Time
		2.5"	4"	
6' x 6' x 6" Position 3	70	623	325	251 4 days
6' x 6' x 8" Position A	69	630	317	267 4 days
PSU Test Track Bridge	31	671	280	231 4 days ₅ , 10 hr

B. Polymerization and Penetration						
Test	Steady State Polymerization Temp (°F)	Time (hr) at Steady State	Depth of Penetration ³ (in.)			
				Bath 2.5"	4"	
6' x 6' x 6" Position 3	185	145	129	21	20	3-1/4 - 4-1/4
6' x 6' x 8" Position A	202	156	141	10	10	3-1/8 - 4
PSU Test Track Bridge	203	140	131	10	10	3-3/8 - 4-1/2

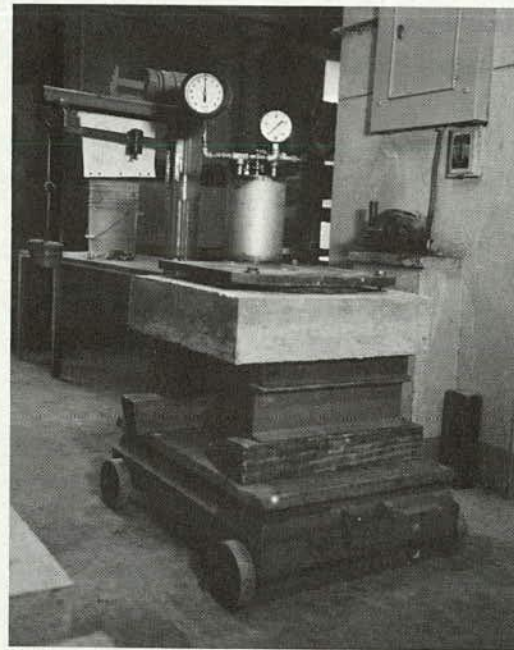


Figure G-9. Prototype pressure impregnation device bolted to concrete slab and mounted on supports.

20 psi (100 kPa to 140 kPa); (3) the impregnated concrete was polymerized by feeding steam from a pressure cooker (10 psi to 13 psi, or 70 kPa to 90 kPa) into the impregnation chamber and also over the surface of the deck for 10 hr. Thermocouples were installed in the bridge deck to monitor the temperature during drying. The monomer consisted of the 90:10 methyl methacrylate-trimethylolpropane trimethacrylate mixture containing 0.5 percent azobisisobutyronitrile initiator.

The deck was dried thoroughly in 10 hr, using the propane torch assembly. During this time the temperature at the 4-in. to 5-in. (10-cm to 13-cm) depth reached 250 F (121 C). No cracking of the surface was observed, even though the surface temperature was about 700 F (372 C). Unexpectedly, the ambient temperature dropped to sub-freezing levels during the impregnation (see Fig. G-12); this hindered proper sealing of the gasket and resulted in leakage of monomer. Nevertheless, the impregnation and subsequent polymerization were successful. Examination of a 4-in. (10-cm) core taken from the polymer-impregnated area followed by etching in 18.5 percent hydrochloric acid showed that the impregnation was complete to a depth of at least 5 in. (13 cm) (see Fig. G-13). In some areas, the impregnation was complete throughout the entire 7.5-in. (19-cm) depth of the deck, as indicated by the appearance of a dark spreading patch of monomer on the underside, which eventually covered an area equal to one-half of the area impregnated from the upper surface. A slight odor of monomer was detected when the core was removed; however, the polymer loading at the 5-in. (13-cm) depth was sufficient to give fracture *through* rather than *around* the aggregate particles. Also, the large air voids were completely filled with polymer to the 4-in. (10-cm) depth.

Thus, this first field trial demonstrated that practical impregnations can be attained within a reasonable time by pressure impregnation at 15 psi to 20 psi (100 kPa to 140 kPa). It may also be noted that preliminary tests of skid resistance after 13 months of service indicated no significant effect of impregnation.

1. The distance between the gas-fired infrared heater (60,000 BTU) and the concrete surface was about 11 in.

2. The monomer system used was 100 parts MMA, 10 parts TMPTMA, and 0.5 parts AZO.

3. The first depth is the depth of the heaviest loading (7.3-9.8% by volume). The second number is the total depth including depth of the lesser loaded area (<10% by volume).

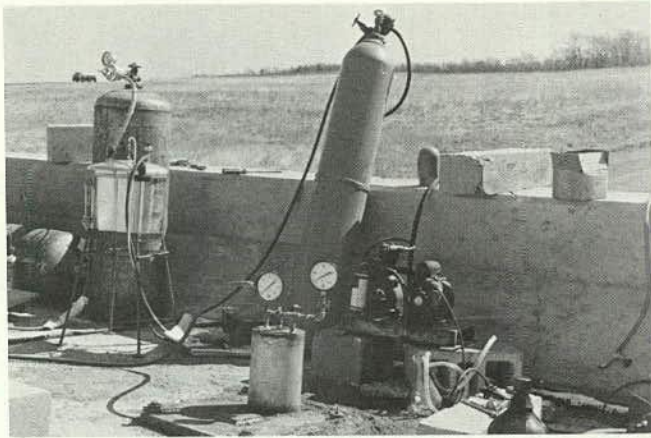


Figure G-12. Pressure impregnation unit in operation on bridge deck.

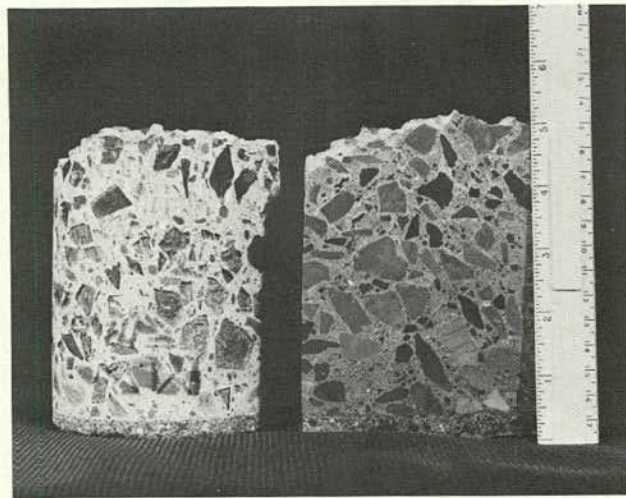


Figure G-13. 4-in. core from polymer-impregnated bridge deck (pressure process): acid-etched and polished section (note limestone aggregate particles are eaten away, but cementitious matrix is unaffected).

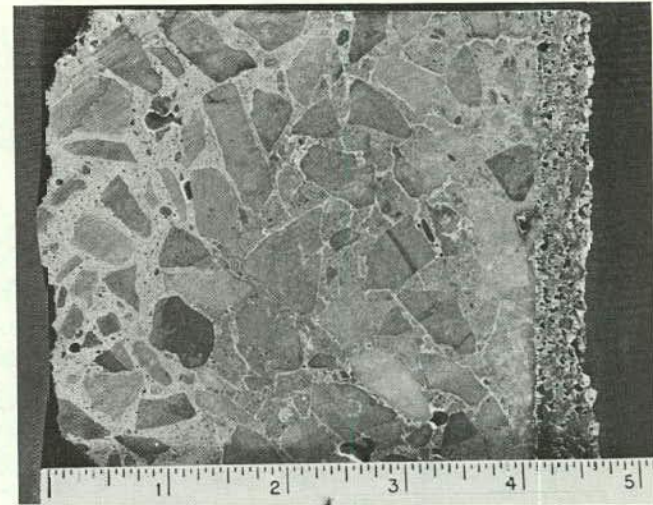


Figure G-10. Slab core, pressure impregnated with MMA.

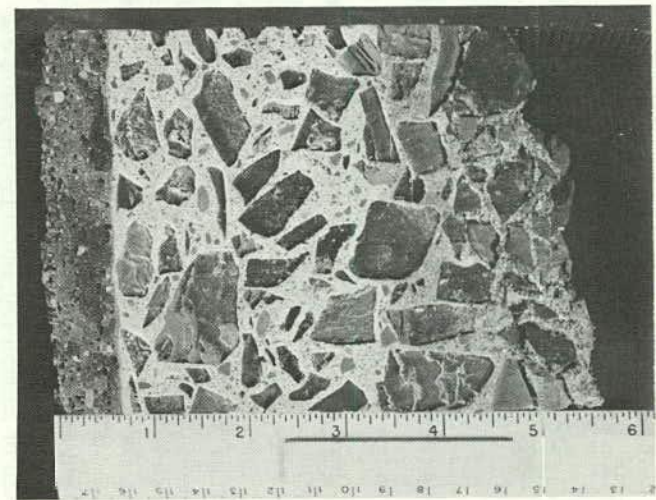


Figure G-11. Slab core, pressure impregnated with MMA and etched with dilute HCl.

APPENDIX H

LARGE-SCALE FIELD TRIALS

PENNSYLVANIA TRANSPORTATION RESEARCH FACILITY

Description of Site and Bridge

Field impregnations were conducted using a bridge deck at the transportation research facility constructed by PennDOT near the campus of The Pennsylvania State University. This facility provides, for research purposes, a pavement surface subject to controlled wear from traffic (nonpublic) with full exposure to weather, and consists of a track approximately 1 mi (1.61 km) in length and one lane in width. The configuration of the track is that of a lopsided oval, with one curve larger than the other, and with two straight sections connecting the curves. This arrangement allows test vehicles to traverse all but the small curve at a speed of 50 mph (80 km/hr). The entire track is designed at zero grade. Each of the straight sections—one in cut, the other in fill—is divided into three structural test sections, each test section being approximately 400 ft (122 m) in length. The large-radius curve contains special study sections, the majority of which will deal with environmental factors. Loading is applied through conventional truck axles.

The research facility bridge (Figs. H-1 and H-2) consists of a two-span, two-lane structure with span lengths of 60 ft (18.3 m) center-to-center of bearings for each of the simple spans. The width of the bridge comprises two 15-ft (4.57-m) traffic lanes and a 6-ft (1.83-m) shoulder. The bridge is on a 547.67-ft (166.9-m) radius curve and has a uniform superelevation of 10.40 percent from gutter to gutter. One span of the structure is decked with precast, prestressed concrete planks with a composite cast-in-place concrete topping. The other span has a conventional cast-in-place deck formed on removable wood forms in one half (including the area selected for impregnation in span 2), and on stay-in-place forms in the other half. Concrete mix data are given in Appendix C. Safety curbs and parapets for the bridge are precast, prestressed composite I-beams. Further details of the bridge are given in one of the reports of the Commonwealth of Pennsylvania Research Project No. 71-8 (51).

The following studies have been conducted on the bridge by other investigators:

1. The behavior of two types of bridge decks under controlled loading conditions.
2. The effect of different environmental and maintenance variables on the deterioration of the bridge deck surface.
3. The behavior of the superstructure components under dynamic and static loading conditions.
4. Design, fabrication, and construction as related to behavior under load.

In this study, the structure was loaded with one million cycles of variable axle loads equivalent to one million cycles

of an 18-kip (80-kN) axle. At various locations in the bridge deck, the top reinforcement was placed at depths varying from ½ in. (1 cm) to 2 in. (5 cm) and deicers (NaCl and CaCl₂) were applied during the winter months to study the modes of deck deterioration. The bridge was instrumented with strain gages and deflectometers to determine load responses. In addition to repetitive dynamic loadings, the bridge was also subjected to static loadings, including a load to failure at the end of the bridge test project.

Impregnation Area

The trial itself was conducted on a 12-ft x 6-ft (3.7-m x 1.8-m) area of the facility's bridge deck (Fig. H-1), using two adjacent 12-ft x 3-ft (3.7-m x 0.9-m) sections. At this

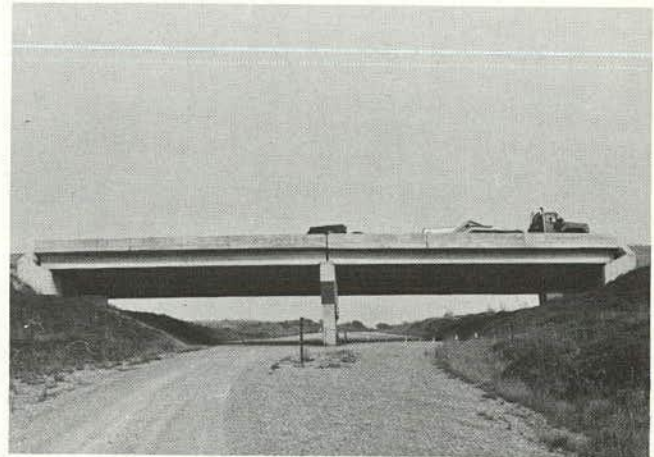


Figure H-1. General view of PTI test track bridge.

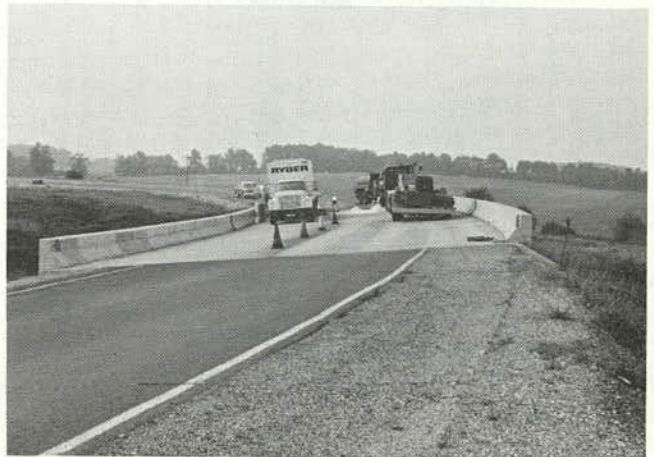


Figure H-2. Close-up view of PTI test track bridge.

site (water table area on span 2), the deck was 7½ in. (19 cm) thick with reinforcing bars (#5) on 6-in. (15.-cm) centers and temperature steel (#4) on 12-in. (30.-cm) centers.

Chloride Distribution

The total application of the CaCl₂ deicing agent to the impregnation area during the 2-year bridge deck testing period amounted to about 0.4 lb/ft² (2 kg/m²). Chloride determinations were made on a test core using the Berman (FHWA) method (52).

As given in Table H-1, chloride ion concentrations by weight in the paste phase ranged from about 0.05 percent near the surface to about 0.002 percent at a depth of from 1 in. (2.5 cm) to 2 in. (5.1 cm). These values correspond to about 0.67 lb/yd³ (0.40 kg/m³) and 0.03 lb/yd³ (0.02 kg/m³), respectively. These values are less than the concentrations believed to represent potential problems with respect to the onset of corrosion in the steel (52).

TABLE H-1.

CHLORIDE DISTRIBUTION IN IMPREGNATION AREA OF BRIDGE DECK AT PENNSYLVANIA TRANSPORTATION RESEARCH FACILITY

Depth from Surface	Percent Chloride (by Weight) in Mortar
0 - ½"	0.047
½" - 1"	0.008
1" - 2"	0.002

Drying

The impregnation area was dried with gas-fired infrared heaters. In order to dry a 12-ft x 6-ft (3.7-m x 1.8-m) area with the heater capacity presently available, three different heater positions were required. The infrared heater was shut down in each position when the temperature at 4 in. (10 cm) was ≥230 F (110 C). Curves for one of the three drying areas are shown in Figure H-3; these curves are typical of those obtained for the other two adjacent positions.

Impregnation Unit

A special impregnator (4 ft x 12 ft (1.22 m x 3.66 m) in area), as shown in Figure H-4, was designed and constructed of ⅜-in. (0.95.-cm) aluminum sheet to permit the impregnation of a 3-ft x 12-ft (0.9.-m x 3.7.-m) section, using either a soak technique or an applied pressure of 20 psi (140 kPa). The area was selected to be of a scale reasonably compatible with potential practice. For use under pressure, the unit was provided with 24, 1-in. (2.5.-cm) holes to accommodate ¾-in. (1.9.-cm) self-drilling tie-down

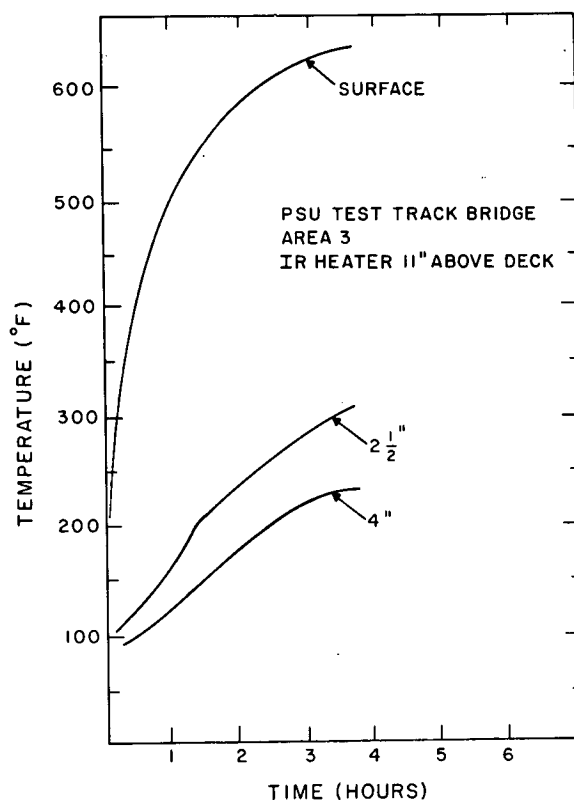


Figure H-3. Temperature profile vs. time for 12-ft x 6-ft bridge deck drying trial.

inserts in holes drilled in the deck (Fig. H-5); for use at various slopes, there were trapezium-shaped (Fig. H-6) long walls.

Impregnation of First Area

Thermocouple Insertion

To monitor temperatures during polymerization, thermocouples were inserted at depths of 2.5 in. (6.4 cm) and 4.0 in. (10.2 cm) at three different locations. The placement is shown in Figure H-7.

Attachment of Impregnation Unit

After location of the rebars using a pachometer, as shown in Figure H-8 (see also Fig. H-5), the insert holes were drilled. In spite of considerable care, one rebar was struck; drilling through it widened the hole sufficiently to cause some difficulty later with the impregnation. Epoxy resin was used to bond the insert concerned. The vessel was then placed over a dual set of silicone rubber gaskets and bolted to the deck (Figs. H-6 and H-9)—a procedure necessary only when pressurized impregnation is desired.

Impregnation

Following placement of the impregnation unit, a total of 120 lb (54 kg) of monomer (90 parts MMA + 10 parts TMPTMA + 0.5 parts AZO catalyst) was fed into the chamber and the pressure raised to 15 psi (100 kPa) over

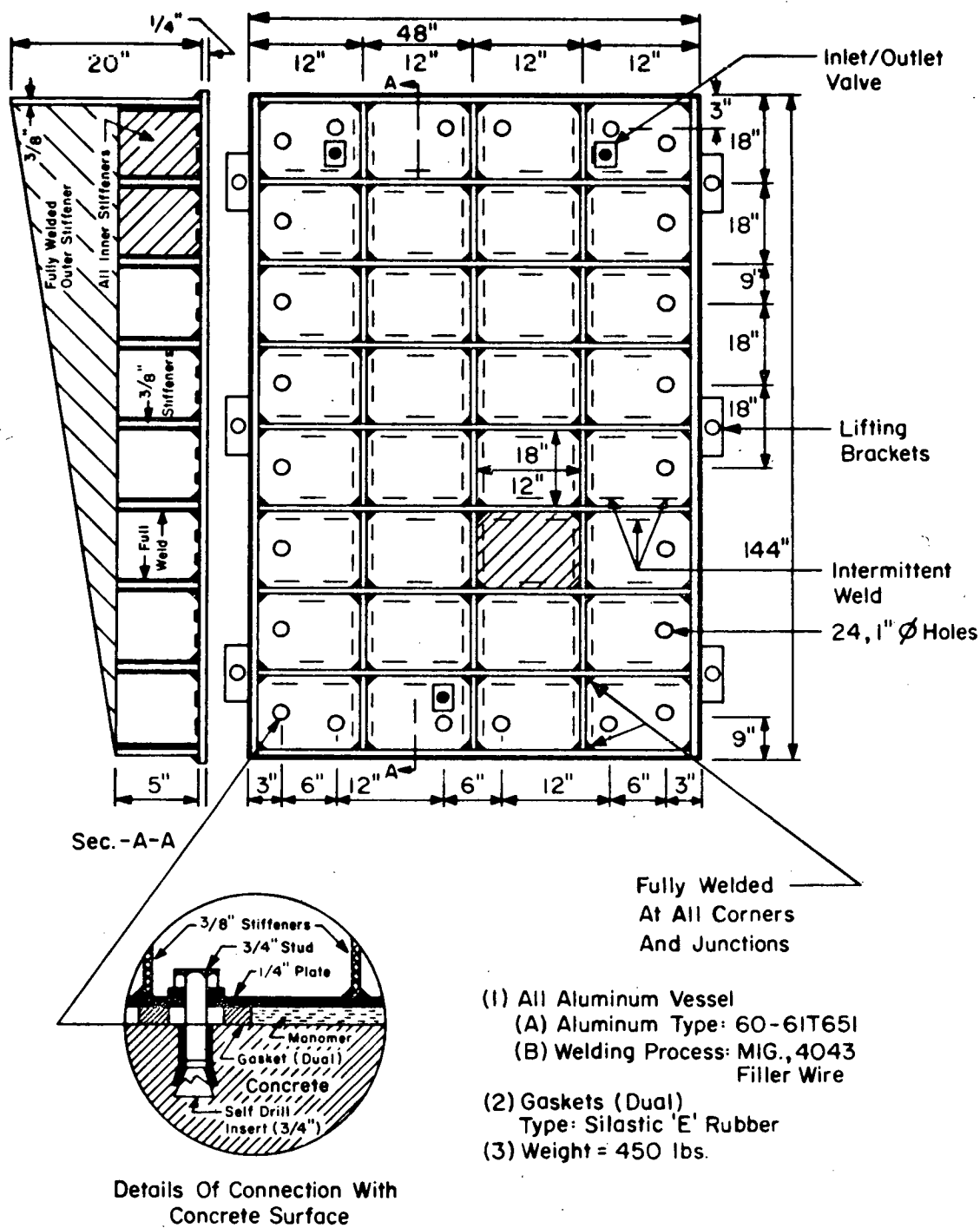


Figure H-4. Design of 3-ft x 12-ft pressure impregnator.

a period of 10 min. No leaks were observed through the gaskets, although some leakage was observed on the underside of the deck, as shown in Figure H-10. The latter leakage was ascribed to small cracks formed at the unconstrained edge of the deck section; no such cracks were observed in the next section, which was away from the edge. Since the insert in the epoxy-filled hole then worked loose, thus causing excessive leakage at 15 psi (100 kPa), the pressure was reduced to 5 psi (35 kPa) and the impregnation continued for about 7.5 hr, during which period the monomer supply was replenished twice. The residual monomer was then pumped out.

Polymerization

After covering of the adjacent, dried 3-ft x 12-ft (0.9-m x 3.7-m) area, 300 gal (1 m³) of hot water (195 F (91 C)) were introduced into the chamber; the water, which had been previously heated in oil drums using propane torches, was circulated through a heated 55-gal (0.2-m³) drum, as shown in Figures H-11 and H-12. Unfortunately, the water apparently picked up some residual monomer, because, when some water spilled, vapors were ignited, requiring the use of the fire extinguisher that had been brought along in case of such events. (This illustrates the

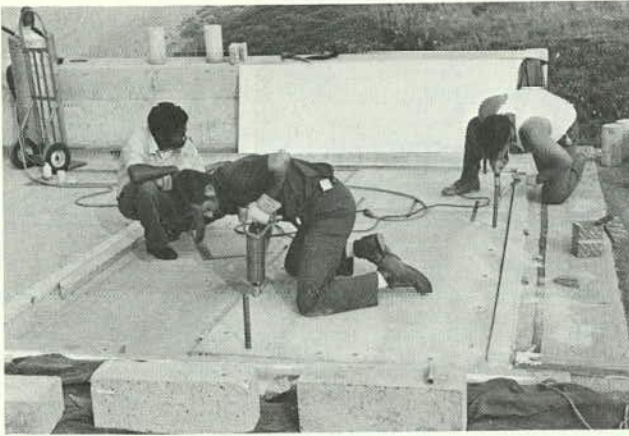


Figure H-5. Drilling of inserts in the concrete deck.

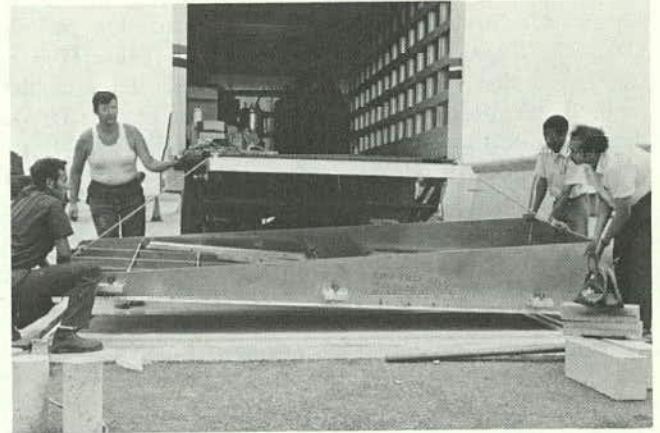


Figure H-6. Positioning vessel on area of treatment.

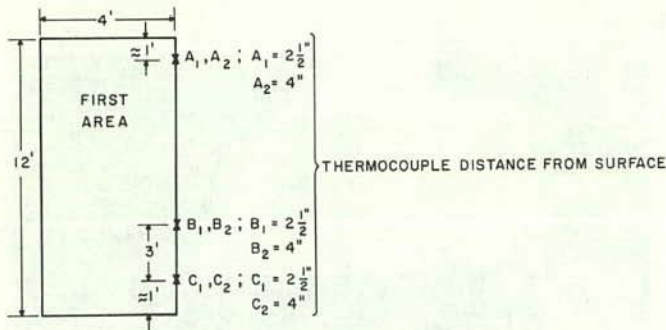


Figure H-7. Sketch showing location and depth of thermocouples for monitoring temperatures during polymerization.

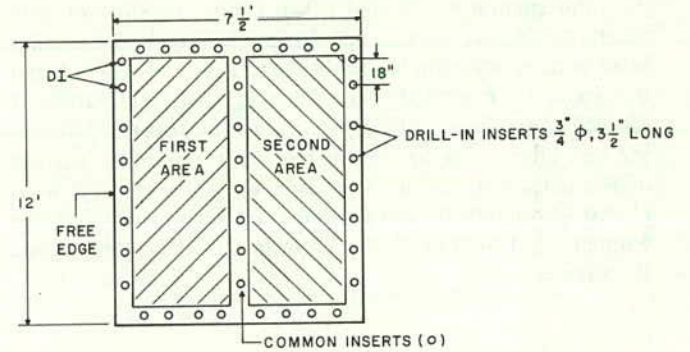


Figure H-8. Sketch showing adjacent areas for treatment and location of inserts.

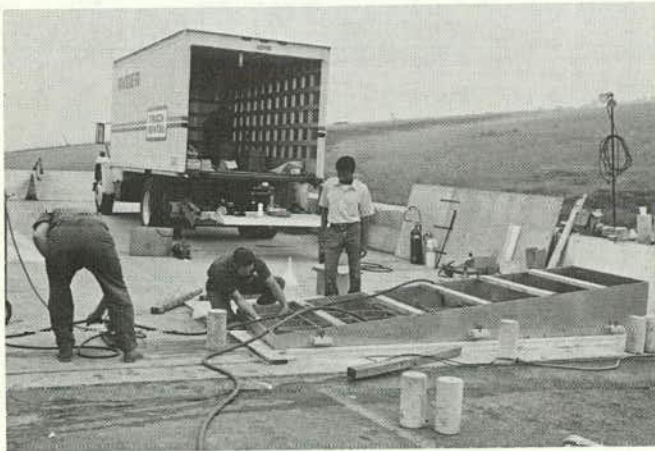


Figure H-9. Tying down vessel over gaskets with bolts.



Figure H-10. Monomer leakage from underneath slab at free edge.

hazards implicit in the use of MMA as a monomer and the need for extreme caution in handling.) To avoid possible further problems, circulation was stopped, 165 more gal (0.6 m³) of hot water were added, (heating was provided by a combination of three 2500-watt (2500 J/sec) im-

mersion heaters), and steam was produced in a pressure cooker. (Thus in one trial, experience was gained with several heating systems.) To minimize heat losses, the chamber was covered with a fiberglass insulating layer and a tarpaulin, as shown in Figure H-13; it was thus possible

to maintain a mean water temperature of 169 ± 9 F (76 ± 5 C) throughout the 12-hr polymerization period. Using the thermocouple pattern shown in Figure H-7, it was found that internal temperatures at the edge of the treated area ranged from 120 F (49 C) to 135 F (57 C), depending on the depth and location (see Fig. H-14).

In order to verify whether or not polymerization had been attained at the desired depth, a core was taken the next day from the area that had shown the lower polymerization temperature. As discussed later, satisfactory impregnation was in fact achieved.

It may be concluded that ponded water, heated electrically or with steam, should be adequate for polymerization.

Impregnation of Second Area

Preparation

After removal of the water used with the first area, the impregnator was unbolted, 16 more inserts were fitted, and the impregnator was bolted down again. In spite of care taken, two rebars were struck during drilling, and the holes filled with epoxy resin before bolting. It was also noted that the gaskets (made of Dow-Corning Silastic E rubber) showed some signs of deterioration in the form of hardening and edge cracking. Since the asperities in the surface of the deck were $\frac{1}{4}$ in. (0.6 cm) deep, the gaskets were placed very carefully and the bolts tightened using a torque wrench (to 150 ft-lb (200 J) torque) in order to balance the stresses.

Impregnation

Although a pressure test indicated that leakage was occurring through the inner gaskets, it was necessary to either proceed or cancel the trial, because the site had to be cleared by the following morning for other experimental work on the deck. It was therefore decided to proceed. After feeding in 120 lb (54 kg) of monomer, 15 psi (100 kPa) pressure was applied gradually, in the hope that the second gasket would hold. In fact, the leakage stopped, apparently because the monomer reswelled the stiffened inner gasket. However, slight leakage was noted from a small crack on the underside of the deck. After 3 hr, the valve became clogged with polymer and remained so for 4 hr, at which time another valve was used and pressurization continued for an additional 5 hr. In the latter case, the pressure was reduced to 5 psi (35 kPa) because of loosening of the two epoxy-mounted bolts. Thus, the schedule for the 12-hr period was: 3 hr at 15 psi (100 kPa), 4 hr at ambient pressure, and 5 hr at 5 psi (35 kPa).

Polymerization

In this case the same general procedure was used as in the first area, except that hotter water (210 F (99 C)) was introduced into the chambers, and the water temperature was maintained at 180 F (82 C) for 12 hr. On completion, it was found that the bottom of the heated area was 15 F (8 C) hotter than the surrounding area.

Because of the resumption of the PennDOT testing program on the deck after completion of the trial, it was not possible at that time to take a core in the section.



Figure H-11. Circulation of heater water from drums to impregnation chamber.

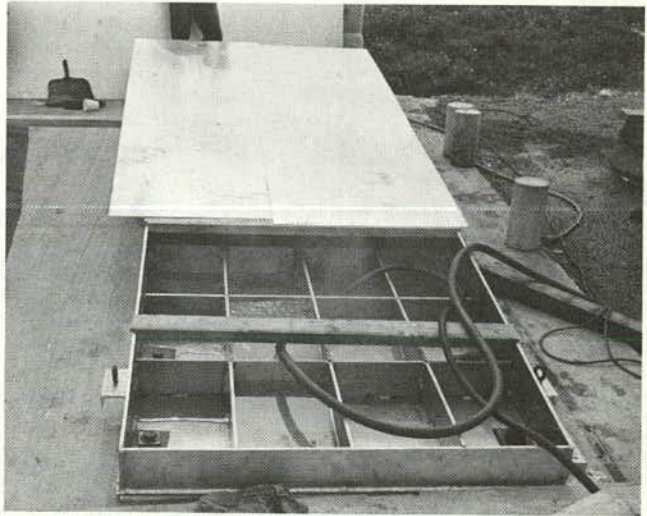


Figure H-12. Close-up view of impregnation chamber filled with hot water.



Figure H-13. View of chamber cover with insulation during hot-water polymerization.

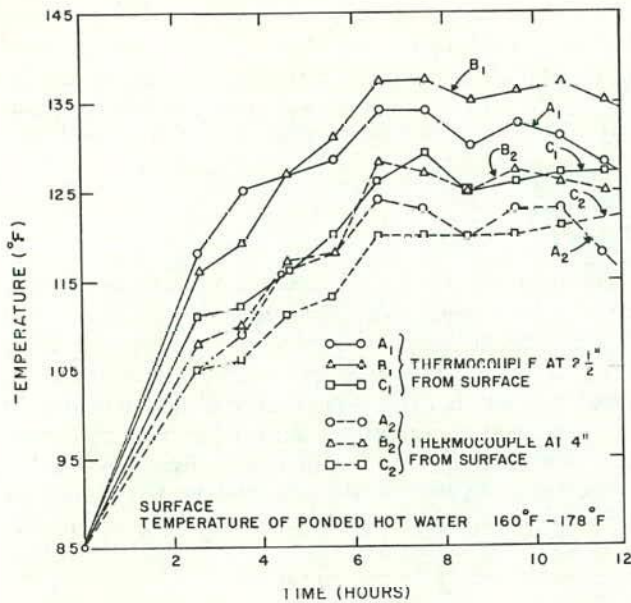


Figure H-14. Temperature distribution curves for hot-water polymerization.

Observations and Discussion

As shown in Figure H-15, on removing the chamber from the surface after polymerization, a froth of polymer was found on the surface, but was easily washed away. On close examination the surface was found to be speckled with conical beads of hard polymer, showing that effective polymerization had taken place at least on top (see Fig. H-16). A 4-in. (10-cm) diameter core taken from the first area (Fig. H-17) showed that full impregnation was obtained up to a depth of 3½ in. (8.9 cm) with an additional 1 in. (2 cm) or more of partial impregnation, thus demonstrating that the stated objective of up to 4-in. (10-cm) impregnation was essentially achieved. The results in the second area may be expected to be even better because pressurization was done at higher pressure for a longer time. Interestingly, tests of skid resistance after 13 months of service indicated no significant effect of impregnation (see Appendix E).

It may also be noted that both the drying and impregnation experience shows that it is just as easy to treat a larger area as a smaller one; indeed—heat losses, cracking, and total impregnation time are thus minimized.

Even though this was the first large-scale trial (with several minor problems), the treatment of two adjacent 3-ft x 12-ft (0.9-m x 3.7-m) sections (previously dried) was successfully accomplished during one weekend, starting at 4 p.m. on August 23 and ending at 7 a.m. on August 25. Clearly, in practice, these times should be reduced significantly.

PennDOT BRIDGE

Selection of Deck for Field Trial

With the cooperation of PennDOT (L. Sandvig, W. Gramling, R. M. Tirpak, and A. V. Cesare), several bridge

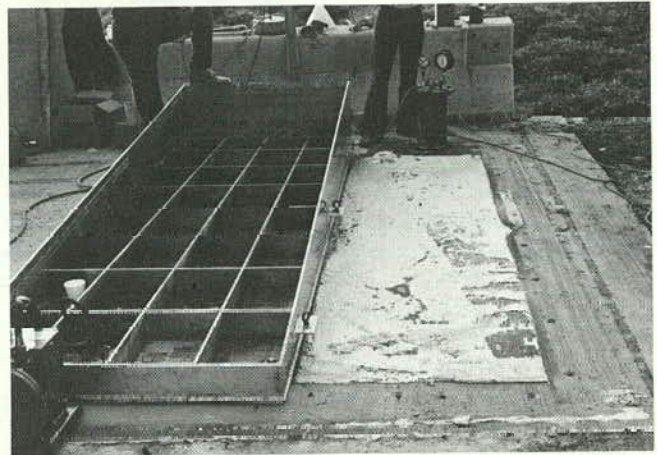


Figure H-15. Polymer froth on the surface in first area (impregnation vessel on the second area).



Figure H-16. Close-up view of impregnated surface.

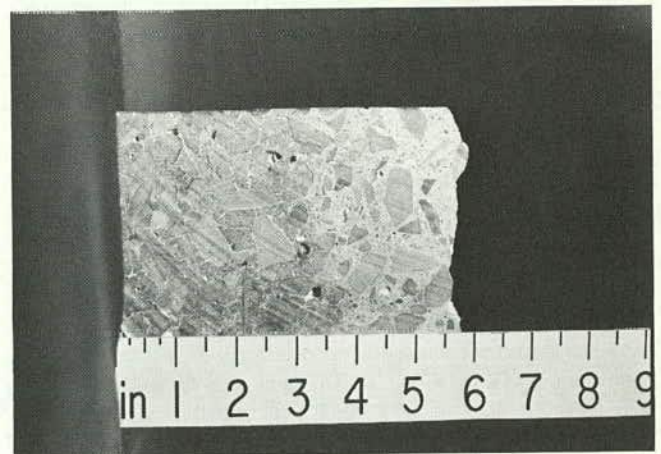


Figure H-17. Cross section through a 4-in. diameter core from the first area (note 3½ in. of full impregnation with 1½ in. band of partial impregnation).

decks were considered for our final field trial to demonstrate the impregnation of a section of a salt-laden but structurally sound deck in actual service. The best candidate was the bridge over Union Blvd. on Pa. Route 378 (formerly I-378), the spur route linking Bethlehem to U.S. Route 22 and I-78. The concrete in the deck contained slag aggregate rather than limestone. The nominal mix (type AA) was water-cement-sand-crushed slag 10.46:1:1.89:3.37, with a cement factor of 1.562 and a 2¼-in. slump. Salt analyses were received from R. M. Tirpak (District Office 5-0, PennDOT) for the cores shown in Figure H-18. Chloride contents (Table H-2) ranged from 0.8 lb/yd³ (0.47 kg/m³) to 4.6 lb/yd³ (2.7 kg/m³) for core No. 10. It was decided to impregnate the area including core No. 10, as soon as arrangements for traffic control and logistics could be made, and as weather would permit in the early spring of 1975. Since the bridge receives heavy traffic, careful planning was especially necessary.

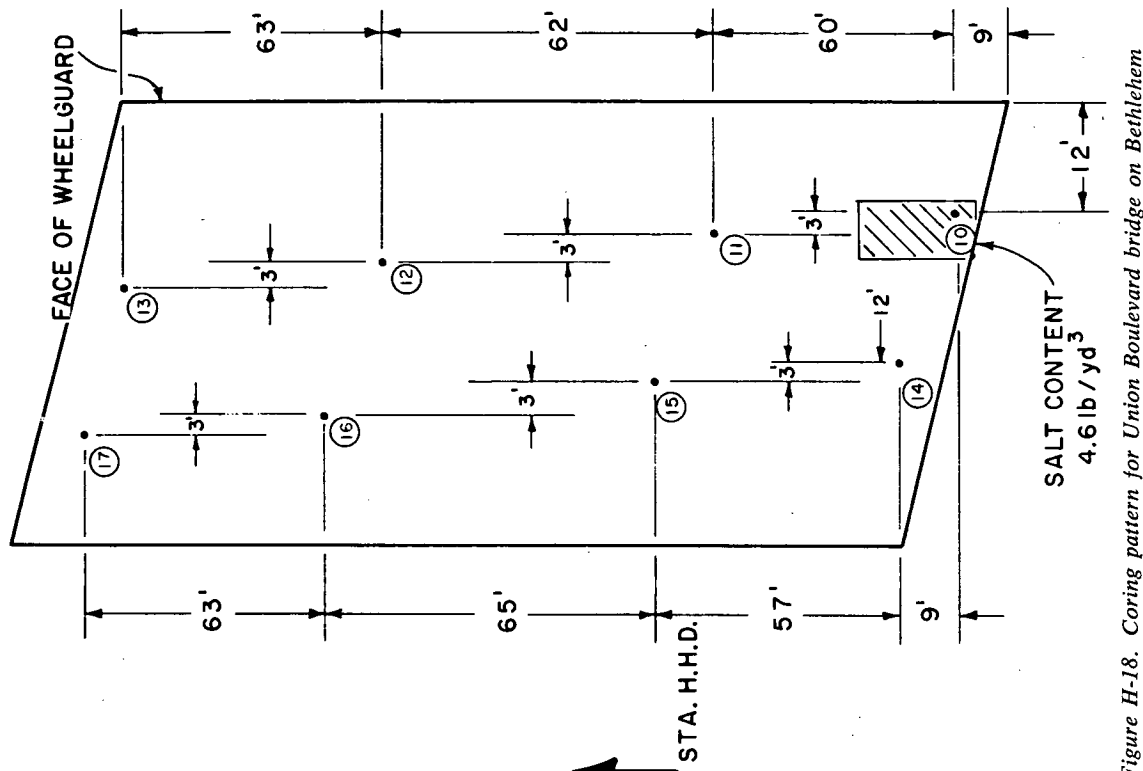


Figure H-18. Coring pattern for Union Boulevard bridge on Bethlehem spur route.

The trial was conducted over the weekend from Friday, March 21, 1975, to Sunday, March 23, 1975, with clean-up on Monday, March 24, and coring on Tuesday, March 25. During the trial the weather was spotty, with brisk winds and temperatures ranging between 35 F (18 C) and 55 F (30 C) and with showers on March 22 and 24.

Drying

Drying of the 3-ft x 12-ft (0.9-m x 3.7-m) test area was done in two successive segments covering 4-ft x 6-ft (1.2-m x 1.8-m) areas each on March 21, 1975. A 4-ft x 5-ft (1.21-m x 1.52-m) trailer-mounted propane-fired infrared unit and a 1-ft x 4-ft (0.31-m x 1.21-m) portable unit were used at each setup. This is the same equipment that was used on the Transportation Research Facility bridge trial. Drying of the first section was started at 0955 a.m. and completed at 1600 p.m. The second sec-

General Preparations

Because of considerable wear in the wheel track (about ⅝ in. (1.6 cm) in the area selected), and the fact that salt content was high in the track area, the impregnation was conducted longitudinally along the outer wheel track of the northbound traveling lane. This also permitted safer operation since it minimized working in the open lane.

Traffic control and coring were provided through the courtesy of PennDOT. R. Brunner served as an observer for PennDOT, and J. Hoegg supervised the activities of other PennDOT personnel from District 5-0. Additional sampling for salt content was also made by Hoegg in two locations within the impregnation area; concentrations of 3.4 and 2.8 lb/yd³ (2.0 and 1.7 kg/m³) were reported.

tion was started at 1620 p.m. and finished at 2300 p.m. Table H-3 provides the drying schedule, and the time-temperature data are plotted in Figure H-19. A photograph of the drying operation in progress is shown in Figure H-20.

Drying control was achieved by monitoring surface temperatures and temperatures at a 4-in. (10-cm) depth in the centers of each of the areas. Surface temperatures were constantly recorded on a strip-chart recorder using a chromel-alumel thermocouple. Temperatures at the 4-in. (10-cm) depth were measured periodically using a portable pyrometer and a chromel-constantan thermocouple inserted into ¼-in. (0.6-cm) diameter, 4-in. (10-cm) deep thermowells drilled into the concrete from the top surface. The temperatures measured at 4 in. (10 cm) are subject to an

TABLE H-2

CHLORIDE CONTENT IN UNION BLVD. BRIDGE
(L.R. 1007, STATION 26 + 18) ON BETHLEHEM
SPUR ROUTE¹

Core No.	% Chloride (wt. % of Concrete)	Salt Content lb/yd ³
10	0.121	4.60
11	0.021	0.80
12	0.071	2.70
13	0.053	2.01
14	0.127	4.83
15	0.041	1.56
16	0.047	1.79
17	0.083	3.15

Unit Conversion: 1 lb/yd³ = 0.593 kg/m³.

1. Courtesy of Bureau of Materials, Testing & Research, PennDOT.

unknown error due to the high ambient temperatures in the vicinity of the pyrometer indicator. In previous work, the temperatures within the concrete were measured from the underside to avoid the complications of having the thermowell and the instrument in the hot zone. This was not possible in this case because of the inaccessibility of the bottom of the deck. Therefore, the surface temperatures and past experience were used to judge when drying was complete to a 4-in. (10-cm) depth. The heating rate used here was somewhat lower than that used in previous work because of the unknown characteristics of the slag-aggregate concrete used in this bridge deck.

No cracking of the slabs occurred during the heating process. However, after cooling, surface crazing developed, as shown in Figure H-21, where holes were drilled for chloride samples, thermowells, and hold-down bolts for the impregnator. Subsequent coring revealed these cracks to be usually less than ¼ in. (0.6 cm) deep, although one crack 1 in. (2.5 cm) deep was noted.

As was the case in previous work, water was observed to exude from the cold faces of the deck during the heating process. Since the test area was located near an expansion joint, an appreciable amount of water appeared at the top surface at this location (see Fig. H-22). This would indicate considerable horizontal movement of the water and might suggest the presence of a fracture plane associated, perhaps, with corrosion of the top reinforcing bars. However, subsequent coring failed to verify the existence of such a fracture plane. Water also exuded from the underside of the deck, as shown in Figure H-23, although it was not possible to ascertain quantities or exact locations of moisture exit from the concrete because of the presence of permanent steel bridge forms.

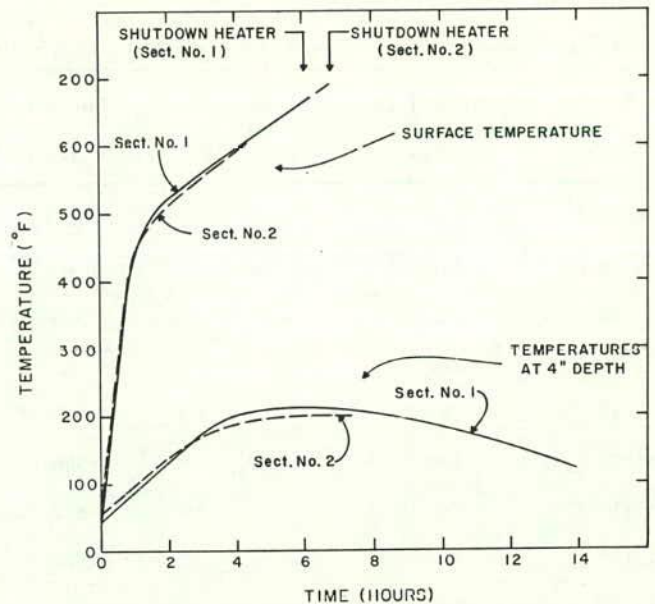


Figure H-19. Drying curves for bridge deck on Bethlehem spur route.



Figure H-20. Drying in progress.

It was estimated that the total amount of propane fuel used to dry the 4-ft x 12-ft (1.2-m x 3.7-m) area (3 ft x 12 ft (0.9 m x 3.7 m) used for impregnation) was about 220 lb (100 kg).

For protection against a light rain during the night of March 21, the dried area was covered with overlapping galvanized sheets and securely caulked with a butyl rubber sealant.

Impregnation

To prevent runoff of any leaked monomer, a dike was constructed from lumber around the impregnation area and caulked to the concrete using caulking compound or Hydrostone, depending on the size of the joint needed (Fig. H-24). The dike also served as a support for a polyethylene cover that was used for protection of the exposed surface during periods of intermittent rain (Fig. H-25).

TABLE H-3

DRYING DATA—BRIDGE DECK IMPREGNATION TEST AT BETHLEHEM, MARCH 21, 1975

Time	4-ft x 6-ft	Amb.	Surface	Temp. @	Remarks
	Section	Temp., °F	Temp., °F	4-in. Depth, °F	
9:55	1st				Start: Heater @ 11"
10:15	1st	46			
11:20	1st		513	105	
12:00	1st				Raised Heater to 16"
12:15	1st		536	150	
12:50	1st	52	540	185	
13:10	1st		572	183	
13:30	1st		572	195	
14:00	1st			210	
14:30	1st	57		205	
15:07	1st		608	200	
15:15	1st				Lowered Heater to 13½"
15:17	1st			200	
15:34	1st		658		Raised Heater to 15½"
15:42	1st		649	200	
16:00	1st	62	662	210	Shut Down Heaters
17:20	1st			210	
18:10	1st			200	
18:35	1st			195	
19:30	1st			182	
20:25	1st			172	
23:23	1st			131	
16:20	2nd	56			Start: Heater @ 16"
17:20	2nd		446	93	
18:10	2nd	43	536	135	
18:35	2nd			175	
19:30	2nd	43	536	175	Lowered Heater to 15½"
20:22	2nd		608	190	
21:00	2nd				Changed Gas Cylinders
21:35	2nd	50	622	195	
22:19	2nd		666	198	Lowered Heater to 14¼"
23:00	2nd		686	200	Shut Down Heaters

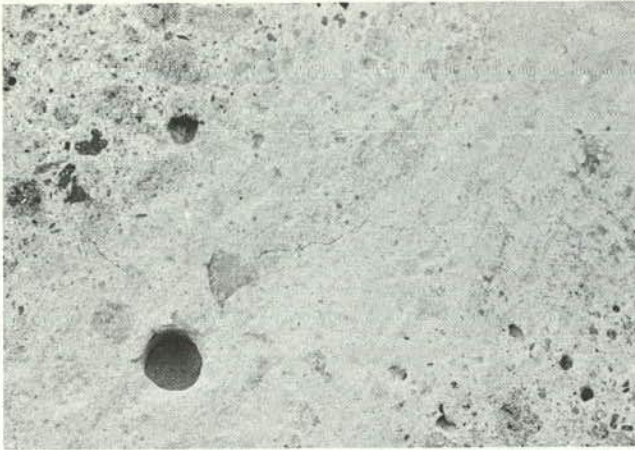


Figure H-21. Surface crazing induced by drying.

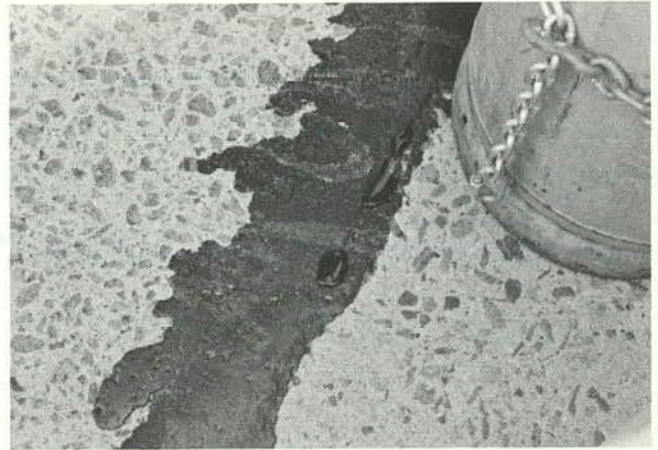


Figure H-22. Water exuding from expansion joint.

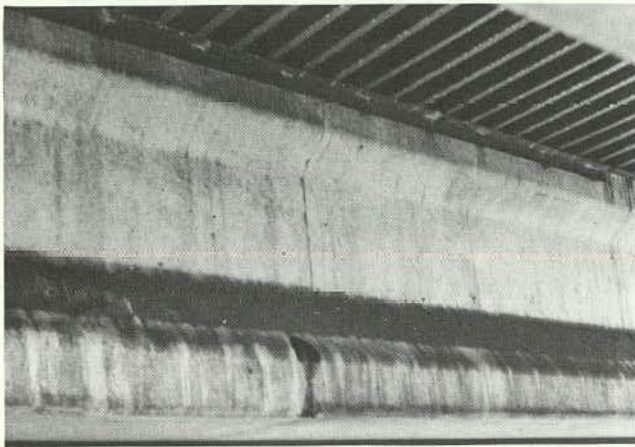


Figure H-23. Water dripping from underside of deck.



Figure H-24. Sealing dike (note prior sealing of area already dried at left).



Figure H-25. Covering of working area against rain.



Figure H-26. Drilling bolt holes for impregnation unit.

As previously mentioned, when holes were drilled (Fig. H-26) to fasten the impregnation chamber to the deck, small surface cracks appeared to open up; however, they appeared to be mostly superficial crazes (Fig. H-21), which

did not extend much below the surface. To provide a flat surface for the two $\frac{3}{4}$ -in. (1.9-cm) Silastic-E gaskets, a mixture of 50/50 Hydrostone/portland cement was brushed onto the flat areas of the roadway, and troweled and screened in the worn wheel track.

After mounting of the chamber over the dual gaskets (Figs. H-27 and H-28), the gaskets were noted to be compressed to a thickness of $\frac{3}{8}$ in. (0.9 cm). The chamber was first evacuated (to 27 in. of mercury (91 kPa)) for $\frac{1}{2}$ hr, and then pressurized at 5 psi (35 kPa) at 1630 hr on March 21. Since at this pressure considerable leakage was observed on the underside (Fig. H-29), the pressure was cut back to 2 psi (14 kPa) for $7\frac{1}{4}$ hr. At the end of this time it was possible to increase the pressure to 3 psi (21 kPa) for 1 hr and 8 psi (55 kPa) for $\frac{1}{2}$ hr, at which time the impregnation was terminated (at 0230 hr, March 22). It was estimated that, on the basis of previous experience, a 4-in. (10-cm) penetration should have been achieved.

During the impregnation, the inner gasket leaked, but not the outer one; the monomer concerned was recycled. The odor of monomer was only detectable when transfer was taking place, and then only slightly.

Polymerization

Polymerization was begun at 0315 hr, March 22, using 120 gal (0.45 m³) of water preheated to 205 F (96.1 C). The temperature dropped to the range 140 to 150 F (60 C to 65.6 C) in the chamber because of heat transfer to the chamber and concrete. Steam was therefore fed in at atmospheric pressure to three locations in the chamber for agitation, circulation, and heating. Electrical heaters (5 in number, total wattage of 2800 J/sec) were immersed in the water at 0600 hr, and 80 gal (0.30 m³) of additional water were fed in. The temperature of the water gradually increased from the range 140 to 150 F (60 C to 66 C) to the range 160 to 165 F (71 C to 74 C) by 0800 hr, and to 170 F (77 C) by 1000 hr. Heating was continued until 2000 hr (total time 17 $\frac{1}{2}$ hr), at which time the temperature was in the range of 175 to 180 F (79 C to 82 C). During the whole process, the chamber was well insulated (Figs. H-30 and H-31). The hot water was left overnight in the chamber and discarded at 0700 hr, March 23, at which time the temperature of the water had dropped to the range 110 to 120 F (43 C to 50 C).

No odor of monomer was observed at any time during the polymerization. As noted in previous field work, the deck surface was covered with a light loose froth and small nodules of polymer, and, while wet, it appeared similar to the untreated area with respect to traction.

Cores

Seven cores were taken: two outside the impregnation area (2 ft (0.6 m) away) and five within; two were drilled through the deck (8 in. (20.3 cm)), and five to a depth of 5 in. (12.7 cm), as shown in Figure H-32. One core, which contained a surface crack (but no rebar), was subjected to the split-tensile test and found to have a strength of 610 psi (4.2 MPa). All cores were etched with 15-percent HCl to reveal the impregnation pattern (Figs. H-33 and H-34).

Examination of the cores revealed the following:

1. No evidence for significant corrosion of the rebars in the control and other specimens (Fig. H-35).
2. No evidence for delamination along any fracture

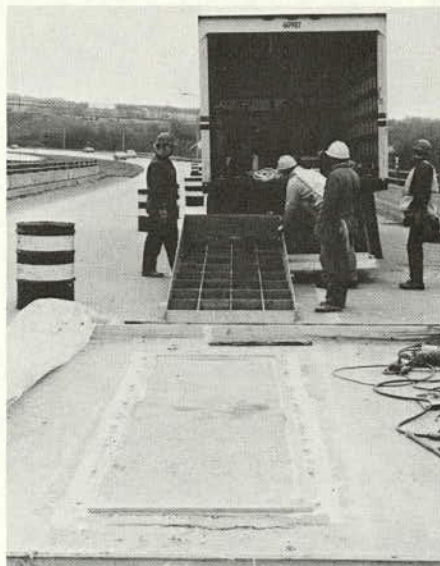


Figure H-27. Unloading impregnation chamber (note gaskets in place).



Figure H-28. Placement of chamber over gaskets.

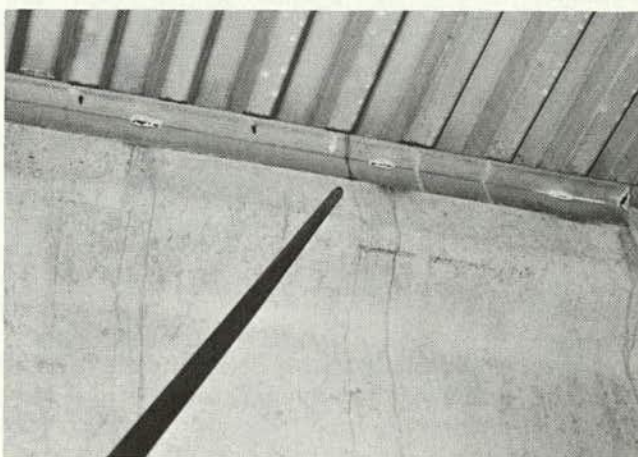


Figure H-29. Dripping of monomer on underside of deck.

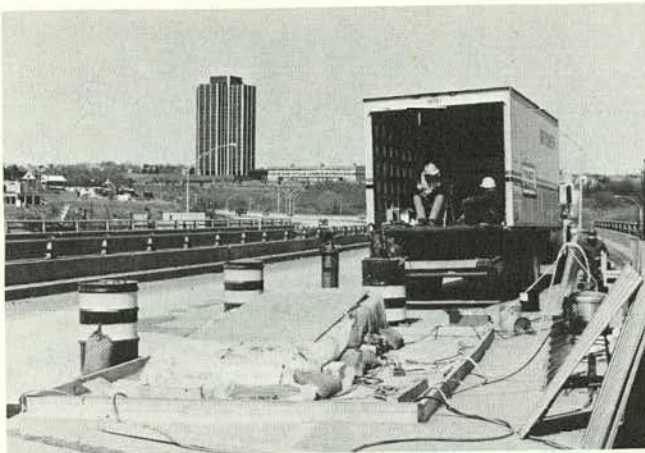


Figure H-30. Polymerization step (note insulation).



Figure H-31. Close-up of insulated chamber.

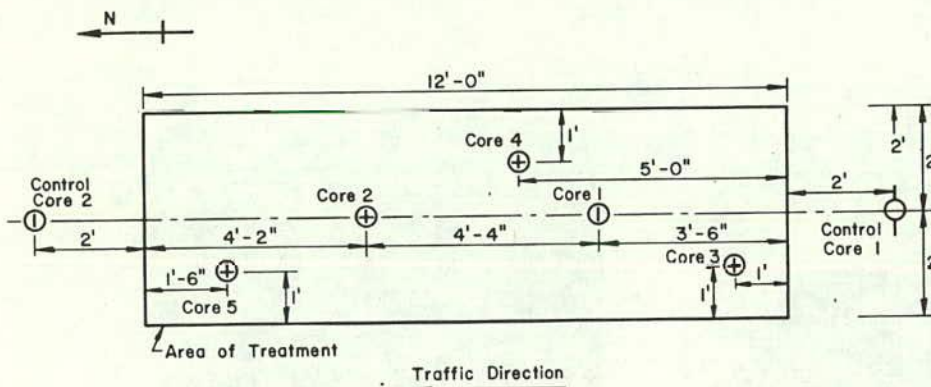


Figure H-32. Coring pattern for impregnated area of bridge deck on Bethlehem spur route.

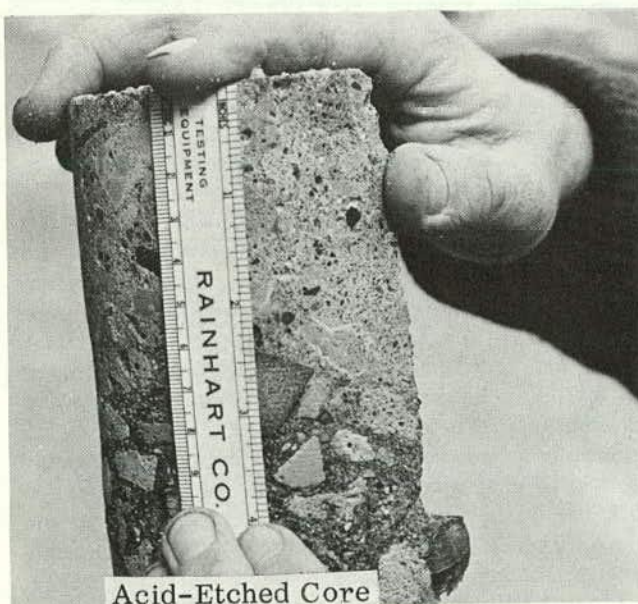


Figure H-33. Appearance of acid-etched core from bridge deck (note dense impregnation to a depth of 3 in. (7.6 cm) and less dense impregnation below).

planes generated by thermal stresses during drying or by corrosion at the rebars (Fig. H-35).

3. No evidence for significant effects due to the surface crazing. For example, in the tensile test, a craze was lined up at right angles to the platens; fracture, however, tended to occur a few millimeters away from the craze.

4. Dense impregnation to at least 3 in. (7.6 cm); less dense impregnation to 4 in. (10 cm) or more in some regions, but in most cases to below the top layer of reinforcing steel.

Conclusions

The trial was clearly successful in demonstrating the deep impregnation of a section of a deck in service under adverse weather conditions, without adversely affecting the deck by the stringent drying used. Further work is needed to define the maximum area that could be so treated at one time. Also, the impregnation procedure must be matched to the deck; this deck behaved quite differently from the test track bridge deck. Leaks, possibly around a rebar somewhere, limited the pressure that could be applied.

SCALE-UP PROCEDURES AND COSTS

General

The feasibility of deep (up to 4 in. (10 cm)) impregnation of bridge deck concrete with methyl methacrylate in

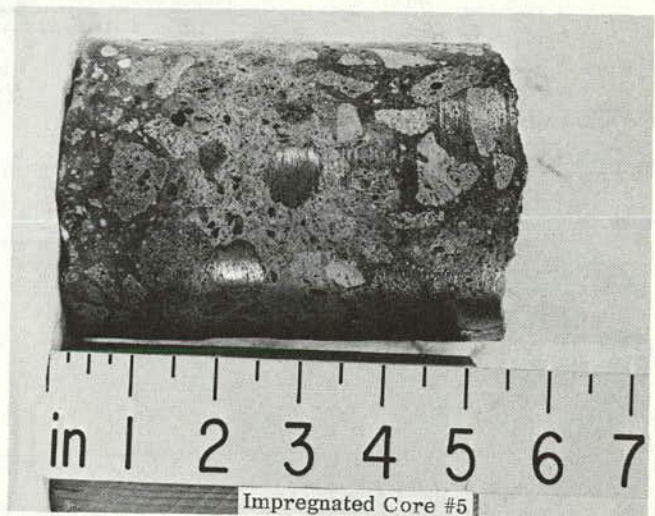
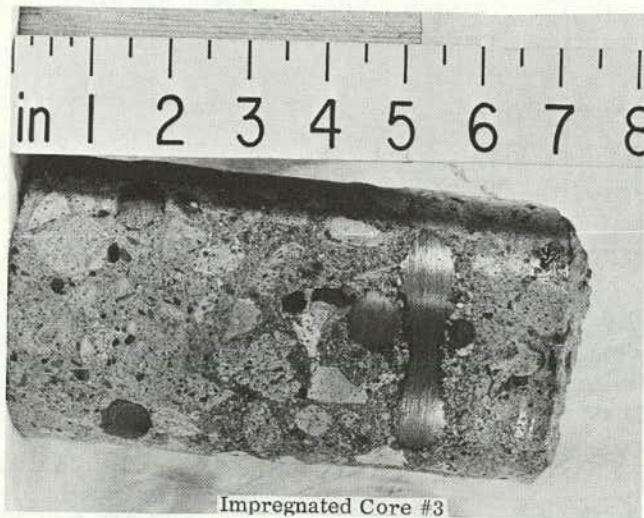
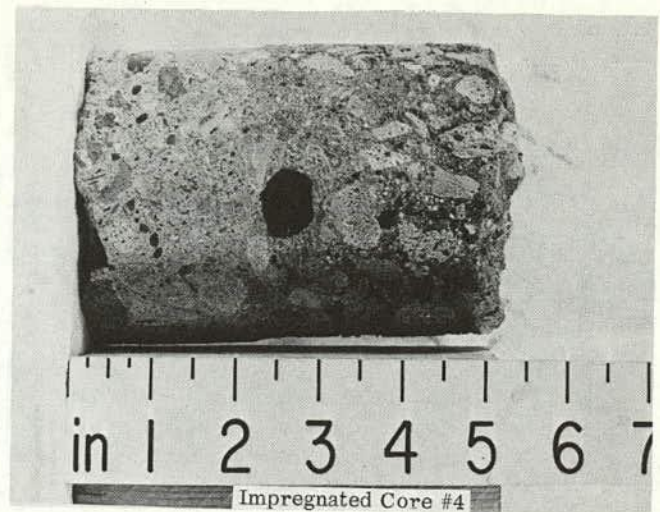


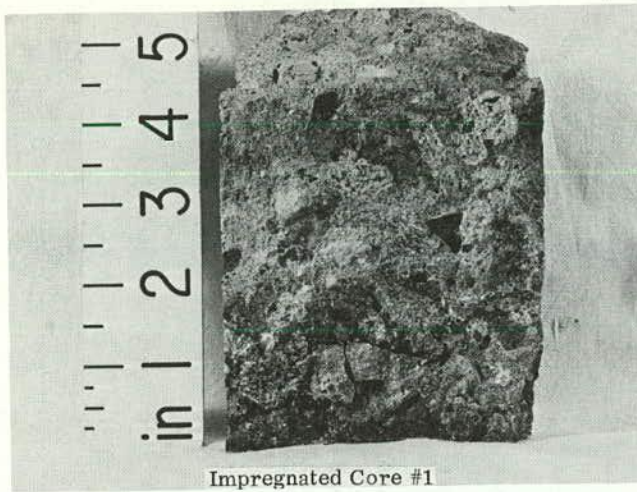
Figure H-34. Cores taken from impregnated area of Bethlehem spur route bridge deck (photographs taken after etching with 15% HCl).

the field was demonstrated in this project. Equipment and procedures commensurate with the objective of demonstrating field practicability, including equipment scale-up, were developed. However, this project did not, nor was it intended to, possess the resources to build equipment of the magnitude required for economical impregnation of bridge decks on a commercial scale.

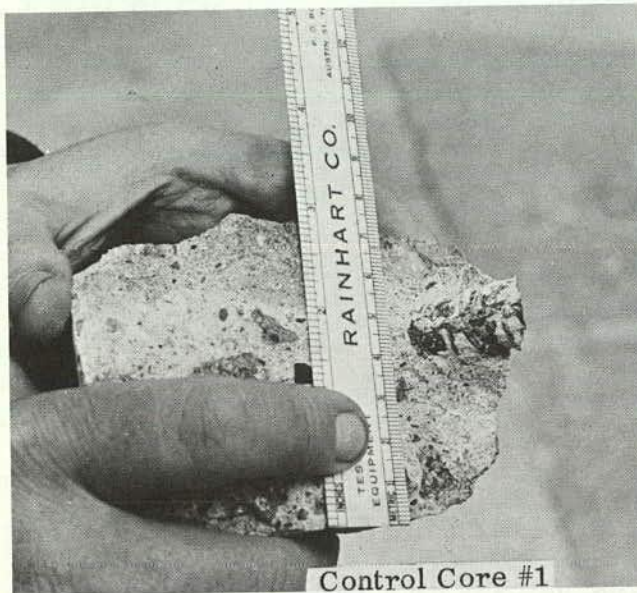
Scale-Up

The equipment and procedures used were developed with an eye toward adaptability to commercial scale through scale-up procedures. Basically, this will require only direct dimensional scale-up to units capable of handling much larger areas per setup. A number of small units, of the size used on this project, could be employed at one time on a bridge deck, but the efficiency would be low and labor costs would be prohibitive. For example, the time requirements using the equipment developed in this research will be about 2 hr/ft² (21 hr/m²) of deck surface for 4 in. (10 cm) of

impregnation at 0 to 5 psig (0 to 35 kPa). Thus, a single unit of this scale would require 70 weeks, not including downtime for equipment repair and inclement weather, to impregnate two 12-ft (3.66-m) traffic lanes on a 200-ft (60.9-m) long bridge. The time will be reduced in proportion to the number of units used simultaneously. However, each unit will require, on the average, one to two full-time workmen. Large units, say 12 ft x 40 ft (3.66 m x 12.20 m), on the other hand, would require only about 0.16 hr/ft² (1.8 hr/m²), and could impregnate a bridge of the size mentioned earlier in about 5 to 6 weeks. Note that, in both instances, it is assumed that the operation proceeds around the clock, 6 days a week; the feasibility of such round-the-clock operation, even in inclement weather, was demonstrated. There do not appear to be any technical impediments to scaling the equipment up to the 12-ft x 40-ft (3.7-m x 12.20-m) size previously mentioned. The cost estimates, presented as follows, are based on an assumed scale-up to 12 ft x 40 ft (3.66 m x 12.20 m).



Impregnated Core #1



Control Core #1

Figure H-35. Close-up of core from impregnated area of Bethlehem spur route bridge deck (after fracture during split-tensile test).

Cost Estimates

General

The cost estimates presented herein do not include amortization of capital equipment or costs for equipment maintenance, weather delays, and traffic control. Basically, they consist of direct materials and labor costs only. The costs are computed for four specified impregnation depths (1, 2, 3, and 4 in. (2.5, 5.1, 7.6, and 10.2 cm)) and two impregnation pressures (0 and 15 psig (0 and 100 kPa)).

Drying

The costs for drying are based on an assumed average ambient temperature of 70 F (21 C). Obviously, drying costs will vary inversely with ambient temperature. Other assumptions include a rated capacity of the heater of 9000 Btu/ft²/hr (100 MJ/m²/hr), use of propane gas

(heating value 20,000 Btu/lb (47 MJ/kg), cost \$0.20/lb (\$0.44/kg)), an average manpower requirement of two men full-time at \$10.00/hr each, and one half-hour needed for setting up the equipment. The resultant drying costs are given in Table H-4.

Impregnation

Costs for impregnation are computed for both pressure impregnation (15 psig (100 kPa)) and ponding (0 psig). An average manpower requirement of two men full-time at \$10.00/hr each has been assumed. Setup and take-down time is assumed to be 2 hr. Unit monomer consumption and cost figures (for 100:10 MMA:TMPTMA + 0.5% AZO) used are 0.75 lb/ft²/hr (3.66 kg/m²/hr) and \$1.00/lb (\$2.20/kg), respectively. The resultant impregnation costs are given in Table H-5.

Polymerization

The polymerization costs are based on hot-water polymerization with estimated heating costs of \$0.033/ft²/hr (0.355/m²/hr) and manpower requirements of two full-time men at \$10.00/hr each. A total time of 2 hr for setup and take-down of equipment is included in the calculations. Notice that the heating cost is an average value and may be expected to vary with atmospheric chill factor (ambient temperature and wind velocity) and with the amount of insulation used. The resultant polymerization costs are given in Table H-6.

TABLE H-4
DRYING COSTS

Specified Impregnation Depth, in.	Est. Time, hr	Propane Requirements		Labor		Total Cost	
		lb/sq ft	\$/sq ft	\$/sq ft	\$/sq ft	\$/sq ft	\$/sq ft
1	0.8	0.36	0.072	0.054	0.126		
2	1.8	0.81	0.162	0.096	0.258		
3	3.0	1.35	0.270	0.146	0.416		
4	4.5	2.03	0.406	0.208	0.614		

TABLE H-5
IMPREGNATION COSTS

Specified		Time hr	Labor \$/sq ft	Monomer \$/sq ft	Total Cost \$/sq ft
Impregnation Depth, in.	Pressure psig				
1	0	4	0.250	0.750	1.000
2	0	15	0.708	1.500	2.208
3	0	30	1.333	2.250	3.583
4	0	49	2.125	3.000	5.125
1	15	1	0.125	0.750	0.875
2	15	5	0.292	1.500	1.792
3	15	10	0.500	2.250	2.750
4	15	17	0.792	3.000	3.792

TABLE H-6
POLYMERIZATION COSTS

Specified		Time hr	Labor \$/sq ft	Heating \$/sq ft	Total Cost \$/sq ft
Impregnation Depth, in.	Pressure psig				
1	0	1.25	0.135	0.041	0.176
2	0	5.00	0.292	0.165	0.457
3	0	11.25	0.552	0.371	0.923
4	0	20.00	0.917	0.660	1.577

Total Cost

The total estimated costs drying, impregnation, and polymerization costs are given in Table H-7 for each combination of four impregnation depths (1, 2, 3, and 4 in. (2.5, 5.1, 7.6, and 10.2 cm)) and two impregnation pres-

ures of 0 and 15 psig (0 and 100 kPa). Notice again that these estimated costs are based on drying and impregnating units capable of covering a 12-ft x 40-ft (3.66-m x 12.20-m) area at each setup. These costs also do not include amortization of capital equipment, maintenance, weather delays, or traffic control.

TABLE H-7
TOTAL COSTS

Specified Impregnation Depth, in.	Drying Cost \$/sq ft	Impregnation Cost \$/sq ft.		Polymerization Cost \$/sq ft	Total Cost \$/sq ft	
		@0 psig	@15 psig		@0 psig	@15 psig
		1	0.126		1.000	0.875
2	0.258	2.208	1.792	0.457	2.923	2.507
3	0.416	3.583	2.758	0.923	4.922	4.089
4	0.614	5.125	3.792	1.577	7.316	5.983

APPENDIX I

FIELD MANUAL FOR POLYMER IMPREGNATION OF CONCRETE BRIDGE DECKS

INTRODUCTION

Purpose

The term "polymer impregnation," as used in this manual, refers to the process of saturating the top (traffic) surface of a concrete bridge deck to a specified depth with a liquid monomer, followed by subsequent polymerization (solidification) of the monomer in the pores of the concrete. Polymer impregnation increases the strength of the concrete and improves its resistance to wear. Most importantly, however, it blocks the pores of the concrete, preventing water and deicing salts from reaching and inducing corrosion of the steel reinforcement. Before the concrete can be impregnated with a monomer, it must be dried. The monomer will not enter pores that are already filled with water. After drying and impregnation, the monomer must be converted to the polymer by the process of polymerization. The basic steps then are: (1) drying, (2) impregnation, and (3) polymerization.

The purpose of this manual is to provide basic guidelines, data, and procedural instructions for the execution of these three steps in the polymer impregnation of concrete highway bridge decks. Criteria for acceptability of the completed job and safety requirements are also presented.

Scope

Although several possible techniques are available for carrying out each of the three major tasks involved, this manual will cover the only method that has been successful, to date, for deep impregnation of sound bridge deck concrete in the field. This method involves drying by means of infrared radiation, low-pressure or atmospheric-pressure impregnation, and hot-water polymerization. The sampling plan, acceptance criteria, and basis of payment presented in this manual may be varied in accordance with the practices and customs of the highway agency involved. The safety considerations cited in this manual relate only to special hazards associated with the materials and processes used in polymer impregnation of concrete bridge decks; they are intended to supplement—not to supersede—existing OSHA, state, and local safety codes.

MONOMER

Type

The monomer system should consist of a 100:10 mixture of methyl methacrylate (MMA): trimethylolpropane trimethacrylate (TMPTMA) with 0.5-percent azobisisobutyronitrile (AZO) initiator.

Handling and Storing

The three components of the monomer should be stored separately (i.e., not mixed) under security consistent with

their fire hazard potentials, in an area where storage conditions will comply with suppliers' recommendations. If any transfer of materials that may allow vapors to escape is to take place in the storage area, adequate ventilation must be afforded and explosion-proof electrical facilities provided. Mechanical equipment, as necessary, should be furnished by the contractor for safe handling of the materials.

Quantities Required

The quantity of monomer mixture required will vary with the porosity of the concrete. However, for estimating purposes, it can be assumed that the typical bridge deck concrete will require approximately $\frac{3}{4}$ lb (0.34 kg) of monomer mixture per sq ft (0.093 m²) of deck area per 1 in. (2.5 cm) of required penetration depth. An average porosity for the concrete to be impregnated should be ascertained from representative core specimens in order to provide more accurate determinations of monomer requirements. The rate of penetration should also be determined.

Mixing

Mixing of the monomer components should be carried out in a closed container in a well-ventilated area. Only the quantity of monomer required for the area to be impregnated at a given time should be batched and mixed. Batching and mixing should be carried out immediately prior to the impregnation step and in units not exceeding one drum (55 gal (0.2 m³)), and the batched material must be kept away from ambient temperatures above 70 F (21 C) to minimize the chances of the material "going exothermic." "Going exothermic" means starting to polymerize before impregnation such that the temperature of the mixture rises very rapidly, resulting in severe explosion potential.

After completion of the impregnation step, all unused monomer mixture must be safely disposed of immediately.

DRYING

Requirements

Before concrete can be impregnated with a monomer, it is necessary to remove water from the pores of the concrete. All concrete retains moisture very tenaciously. Tests have shown (53) that even after a long dry spell, the concrete deeper than 1 in. (2.5 cm) from the surface of a bridge deck will remain 60- to 70-percent saturated, and most of the time it is 90- to 100-percent saturated. In order to permit the ingress of the monomer, this water must be removed to the required depth of impregnation. This should be done by means of high-temperature radiant drying, taking care that the area heated at any one time is not so large as to produce excessive thermal stresses and buckling of the slab because of high thermal gradients.

Criteria

The basic criterion for obtaining sufficient dryness to assure impregnation to the required depth is the attainment of a temperature of 230 F (110 C) at the required impregnation depth. This can be determined in one of the following ways:

1. Drill a thermowell to the required impregnation depth and monitor the temperature with a thermocouple.
2. Measure the surface temperature with a thermocouple and stop heating when a rate of increase of the surface temperature drops below a predetermined value (see following).

The second procedure is easier from the standpoint of not having to drill thermowells. However, the rate of change of the surface temperature for a given temperature profile may vary somewhat with the composition of the concrete (principally, the aggregate type). Typically, for example, it has been found that for a limestone aggregate concrete, the temperature at 4 in. (10 cm) deep reaches 230 F (110 C) when the rate of temperature change at the surface decreases to 10 F (5.5 C)/hr. The surface temperature at this point is 620 F (327 C) (9).

In order to prevent disruption of the concrete due to excessive steam pressure or too-steep thermal gradients, the surface temperature should not exceed 500 F (260 C) 1 hr after starting, and should never be allowed to go above 675 F (357.2 C). A layer of sand up to 1 in. (2.5 cm) in thickness will be useful in minimizing surface cracking (11, 12).

The time required to carry out the drying at each setup will vary with: (1) the required depth of drying (depth of impregnation), (2) heat input at the surface, (3) the chill factor (air temperature and wind velocity), and (4) moisture content of the concrete. For a 4-in. (10-cm) drying depth, using a heat input that results in a 500 F (260 C) surface temperature after 1 hr, the drying time varied from 3.75 hr at 70 F (21 C) air temperature and zero wind velocity to 9.75 hr at 30 F (-1 C) air temperature and brisk winds. In both cases, the slabs were in nominally saturated condition (80- to 90-percent saturation). The same decks at the same conditions reached the dry state at 2.5 in. (6 cm) in approximately 2 and 6.5 hr, respectively (9).

Equipment

To carry out the drying operation, a gas-fired infrared heater with a rated output of approximately 9,000 Btu/hr/ft² (100 MJ/hr/m²) should be used. A unit consisting of supercharged, propane-fired Inconel elements was found to be satisfactory for this purpose. The heater must be capable of vertical adjustment to permit varying of the distance between the heater elements and the concrete surface. This feature is necessary to maintain temperature control in accordance with the criteria previously cited.

It is recommended that a reradiating shield constructed of galvanized steel sheet metal be used around the perimeter of the drying area to maximize drying efficiency by reducing radiant heat loss as well as conductive and convective losses.

Procedure

The initial setup of the heater must include provisions for monitoring the surface temperature and the temperature at the required impregnation depth. This can be done by means of any suitable temperature-sensing device (thermocouples, thermistors, etc.) having the appropriate temperature range and capable of withstanding the high temperatures. The sensing element on the surface must be covered with about 0.5 in. (1 cm) of sand to prevent it from being exposed to the direct radiation from the elements. The thermowell for the temperature sensor at the required level of impregnation should be drilled from the bottom side of the deck, if possible. This will reduce the possibility of erroneous readings due to conduction of heat from the surface to the sensor through the leads or sensor jacket. A ¼-in. (6-mm) diameter hole will suffice for the thermowell if thermocouples are used as sensors.

After the temperature-sensing devices are installed, the heater can be fired up. Utilizing temperature readings at frequent intervals, appropriate changes should be made in the vertical position of the heater above the deck to reach a surface temperature of 500 F (260 C) or slightly less at 1 hr. An accurate log of times and temperatures should be kept. From this point on, the temperature should be allowed to rise at a continually decreasing rate, but should not be permitted to go above 675 F (357 C). When the temperature of the deck at the level of the required impregnation depth reaches 230 F (110 C), the time and surface temperature should be recorded and the heater shut down. From the time-temperature data, the rate of change of the surface temperature during the last hour of drying should be determined. For the remaining heater setups on the deck, it will be necessary only to monitor the surface temperature, terminating the run when the temperature change during a 1-hr period is equal to or less than the final rate of change determined previously.

Cool-Down Period

After the concrete has been dried, it must be allowed to cool down to 100 F (38 C) or below, before the impregnation with monomer can be commenced. During the cool-down period, the concrete must be protected from rain or snow. A convenient means of doing this is to use large pieces of sheet metal supported on a frame made of 2 x 4 lumber. A continuous dike constructed of 2 x 4 lumber calked around the outer edge must be used around the perimeter of the dried area. It is not necessary or even desirable, to cover the dried area until near-ambient temperatures are reached. Plastic sheeting may be used *if surface temperatures are not so high as to melt the plastic*. Tenting the area with plastic or canvas sheeting can also be done during inclement weather if the tent can be constructed to prevent ingress of blowing rain and surface flow.

IMPREGNATION

Requirements

The impregnation should begin as soon as possible after

the concrete has reached ambient temperature or 100 F (38 C). Otherwise, the dried concrete will begin to re-saturate by conductive movement of water from undried areas within the concrete and by the process of capillary condensation of moisture vapor from the atmosphere. Acceptance requirements for depth of impregnation are presented later in this manual.

Equipment

Equipment should include an impregnation chamber, monomer pumps, a vacuum pump, and compressed gas suitable for pressurization. The chamber must be capable of being bolted to the deck and of withstanding pressures up to 15 psi (103 kPa). The chamber must also permit recovery of any monomer that leaks through the inner gasket. The dual gaskets for the chamber should be fabricated from a monomer-resistant grade of Neoprene or silicone rubber; a fresh gasket should be used for each impregnation.

Preparation for Impregnation

The deck should be carefully inspected for cracks, surface roughness and irregularities, and wear pattern. Visible large cracks should be filled with an epoxy patching compound.

The area where the gaskets will be located should be as level as possible to facilitate proper sealing by the gaskets. All rough or worn areas that will lie under the gasket should be made level by using a nonporous, quick-setting mortar (e.g., a 50/50 mixture of high-strength plaster, such as Hydrostone) and cement or a cement grout that will bond well to the surface and not crack during shrinkage.

The cores taken should be tested for average porosity after drying and evacuation, and also for the penetration rate of monomer. Use of the pressure-type apparatus is recommended for this purpose, so that a rate can be established at zero pressure and at 15 psig (0.10 MPa). The depth of penetration may be estimated from the porosity and the weight of monomer taken up. From the rate determined as a function of pressure, the desired operating pressure can be selected within the pressure rating of the field impregnation chamber.

Mounting of the Chamber

First, the top layer of rebars must be located using a pachometer and must be marked. It is important that the rebars be located accurately in order to avoid contact during drilling. Should a rebar be hit accidentally, the drill should be capable of cutting through the rebar to avoid enlarging the hole (which can cause leakage). However, as far as possible, hitting rebars should be prevented so as not to damage the slab structurally.

Next, positions of the insert holes should be marked on the surface of the slab. This may be done conveniently by using a template with holes corresponding to the holes in the chamber. The mounting holes in the chamber should be slotted so that a given bolt can be inserted anywhere within a 2-in. (5-cm) distance along the mounting flange in order to avoid rebars.

Self-drilling, expansion-type inserts should then be drilled in to a depth of at least 4 in. (10 cm). Driving the inserts

as deep as possible increases their carrying capacity. The size and length of the inserts should be suitable for carrying the design load for the inserts created by application of the specified pressure.

Following the drilling of the inserts, the dual gasket should be placed around the insert holes and the chamber aligned into position. The mounting bolts should then be screwed into the inserts, and the bolts tightened at a uniform torque up to a point at which a vacuum of 28 in. (95 kPa) of mercury can be held inside the chamber prior to feeding in the monomer.

Monomer can now be fed into the chamber under vacuum until the monomer chamber (within the inner gasket) is filled with the monomer mixture. The mixing and storing of monomer mixture prior to impregnation at site is described in the previous section. Extreme care must be taken to see that the chamber vessel and monomer inside it are protected from solar radiation when the impregnation is carried out during the day. Thick insulation should cover the entire chamber (to keep temperature ≤ 80 F (27.7 C)) because the monomer can polymerize, prior to impregnation, by an autoacceleration mechanism.

Pressure should now be gradually raised to the pressure selected, and the impregnation process should be continued for the required time to reach the required depth of penetration at that pressure. However, the pressure may have to be reduced if excessive leakage occurs on the underside or surface. If so, the impregnation time will have to be increased.

On completion of impregnation, the pressure is released, and any unused monomer is pumped out to a storage container and the amount measured. However, if, on estimation of the monomer materials balance (allowing for losses due to leakage and evaporation), it is found that the amount of monomer taken up does not correspond to full impregnation to the required impregnation depth, the monomer should be pumped back into the chamber and pressure reapplied for the required time.

POLYMERIZATION

Once the excess monomer is removed, the chamber is filled with hot water (200 to 210 F (93 to 99 C)) to a depth of at least 5 in. (13 cm). As the heat is transferred to the slab, chamber walls, and surrounding atmosphere during the process of feeding in the hot water, the temperature will drop quickly to the range 160 to 170 F (71 to 77 C). To keep the water temperature in the range of 175 to 185 F (80 to 85 C) during the entire process, electric heaters, steam, or a circulating water heating system may be used. In any case, the chamber should be insulated during the whole process of polymerization by covering it with 3-in. (8-cm) fiber-glass insulation and exterior-grade plywood sheets. If the temperature of 175 to 185 F (80 to 85 C) is maintained on the surface for at least 12 hr, the rise in temperature should be sufficient to polymerize the monomer to at least 4 in. (10 cm) deep.

In a continuous process, once the polymerization is completed, the water can be stored to be reused later. The chamber is unbolted after removal of the water, and poly-

mer froth and nuggets on the surface are removed. The entire process is now repeated on the adjacent section using one line of inserts already drilled.

ACCEPTANCE CRITERIA

General

In order to assure that the specified depth of impregnation has been achieved and that polymerization has been completed, an acceptance sampling program should be carried out. This program may vary in accordance with the practices of the individual highway agency.

Sampling

Depth of impregnation and degree of polymerization should be verified by obtaining core specimens of the completed job. Two core samples will be obtained from the area covered by each setup of the heater or the impregnator, whichever covers the smaller area. However, in no case shall there be less than one core per 20 lane-ft (6.1 m) of bridge deck surface. The locations for coring should be designated by the owner's representative or engineer. All coring should be done at the expense of the contractor. The core diameter should be at least two times the maximum size aggregate particles in the concrete. The cores should be drilled to a depth of 1 in. (2.5 cm) greater than the specified impregnation depth and broken off by driving wedges into the annular core-bit cut. The cores should be located so as to avoid cutting through the steel reinforcing bars in the deck. These can be located by means of a pachometer or similar device. Each core must be identified as to location. The contractor will be required to patch the core holes with a polymer-aggregate mixture.

Testing

The owner's representative or engineer should perform the necessary inspection and measurements on the cores to assure compliance with specifications. All cores that exhibit the odor of methyl methacrylate should be placed in an evacuation chamber at 70 F (21 C) and 2 cm Hg (3 kPa) for 24 hr before measurement of impregnation depth to remove nonpolymerized monomer. The cores should be etched with technical grade concentrated hydrochloric acid until the depth of impregnation becomes clearly evident. The minimum depth of impregnation observed around the perimeter of each core should be measured and recorded.

Acceptance Criteria

The criteria for acceptance of the job without penalty are as follows:

1. The average depth of impregnation for all of the cores from one bridge deck shall equal or exceed the specified value.
2. The average depth of impregnation for the two cores from each equipment setup shall equal or exceed the specified depth less 0.5 in. (1.3 cm). Two additional cores shall be taken from each area that fails to meet this criterion, and

the average of the four cores from the area must equal or exceed the criterion.

Penalties

In the event that the acceptance criteria are not met, penalties shall be applied as follows:

1. Acceptance Criterion No. 1: The contract price shall be reduced by the amount:

$$\left[\frac{\text{Specified Depth} - \text{Average Depth}}{\text{Specified Depth}} \right] \times \text{Contract Price}$$

2. Acceptance Criterion No. 2: The contract price shall be reduced for each instance by the amount:

$$\left[\frac{\text{Area of Setup}}{\text{Total Deck Area}} \right] \times \left[\frac{[\text{Specified Depth} - 0.5 \text{ in. (1.3 cm)}] - \text{Avg. Depth}}{[\text{Specified Depth} - 0.5 \text{ in. (1.3 cm)}]} \right] \times \text{Contract Price}$$

Notice that the penalties are additive. That is, if the average depth for all cores is less than the specified depth and the average depth of four cores from each of several of the individual equipment setup areas is less than the specified depth minus 0.5 in. (1.3 cm), the total penalty will be 1 plus the penalties for each of the deficient areas calculated in accordance with procedure 2.

SAFETY CONSIDERATIONS

General

All applicable national (OSHA), state, and local safety codes shall apply to protect the persons and properties of the owner and his representatives; the contractor and his employees; and the general public. Special conditions worthy of note here are high temperatures, volatile and highly flammable substances, noxious fumes, and vehicular traffic. The owner shall be responsible for traffic control.

Monomer

The highly volatile and flammable nature of the monomer (flash point = 55 F (13 C)) will require special precautions to assure that the liquid and its vapors are contained at all times. Extreme care must be exercised regarding the use of open flames, non-explosion-proof electrical gear, and smoking in the vicinity of all operations involving the monomer. Fire extinguishers suitable for Class B fires must be readily available whenever the monomer is stored or being handled or mixed and at the impregnation site. All workmen at the impregnation site should be thoroughly instructed in the use of the extinguishers. Water must *not* be used to extinguish fires associated with monomer.

Provision must be made by the contractor to safely dispose of all unused, catalyzed monomer.

Drying

The major hazards associated with the drying equipment are the high temperatures generated, which could result in

burns through carelessness, and the propane gas used for firing the heaters. Provision must be made for securely anchoring the gas containers, both while they are being used and during storage.

When drying and impregnation are going on simultaneously at different locations on a bridge deck, special precautions must be observed to assure that monomer vapor or liquid does not come within near proximity of the heating device.

Impregnation

The major hazards associated with the impregnation process are concerned with the handling of large volumes of the monomer. Every effort must be made to keep the monomer liquid and its vapors contained. Therefore, even if the impregnation is being conducted at atmospheric pressure (ponding), containment is required. Constant vigilance must be maintained for detection of monomer leakage. This includes the underside of the deck because the presence of cracks or other discontinuities that extend through the deck will permit rapid passage of the monomer to the underside, often long before the required depth of impregnation is achieved over the entire surface. If leakage occurs at gaskets, pressure must be reduced and

impregnation time adjusted accordingly. Workmen should wear chemical eye protection (goggles) when working in the vicinity of the impregnator and when the impregnation is to be carried out at pressures above atmospheric. Prolonged breathing of monomer fumes must be avoided.

For the safety of the public, the impregnator should be attended at all times. No unauthorized personnel should be permitted in the vicinity. Smoking, use of open flames, welding, and non-explosion-proof electrical gear are strictly forbidden in the vicinity of the impregnator.

Polymerization

The major potential hazard involved in the polymerization process is the possible escape of monomer vapors, especially during the initial stages. If hot water is used for the polymerization process, small, though potentially dangerous, quantities of monomer remaining on the surface may be volatilized, thus creating a potential explosion hazard. Therefore, smoking, use of open flames, welding, and non-explosion-proof electrical gear should not be permitted in the proximity of the polymerization operation. Another potential hazard associated with the polymerization step is the hot water employed to initiate and maintain the polymerization reaction. Workmen should guard against careless acts that might result in burns.

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