

NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT

257

LONG-TERM REHABILITATION OF SALT-CONTAMINATED BRIDGE DECKS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT

257

LONG-TERM REHABILITATION OF SALT-CONTAMINATED BRIDGE DECKS

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AREAS OF INTEREST:

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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.

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FOREWORD

*By Staff
Transportation
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The research covered herein was conducted to find effective methods of rehabilitating salt-contaminated, reinforced concrete bridge decks. Existing methods having the potential to provide long-term inhibition of salt-induced corrosion of reinforcing steel were reviewed, and certain ones were subjected to laboratory investigations to compare effectiveness and predict costs. They consisted of deep grooving or scarification of bridge deck surfaces to facilitate "deep polymer impregnation" (i.e., to encapsulate the top level of reinforcing steel), water displacing monomers to facilitate deep polymer impregnation, hydrophobic sealants, hot impregnants, corrosion inhibitors, and electrochemical removal of chlorides. Most of the techniques were evaluated in conjunction with the placement of low-permeability-type bridge deck overlays. As a result, field trials have been recommended that should be of interest to maintenance, construction, bridge, and materials engineers. Researchers will benefit from the results of the review of existing information and the laboratory studies themselves.

The feasibility of "deep polymer impregnation" of reinforced concrete bridge decks to depths sufficient to encapsulate the top level of reinforcing steel was demonstrated under a previous NCHRP project, and the results were published in NCHRP Report 190, "Use of Polymers in Highway Concrete." Impregnation to these depths was expected to ensure long-term protection of the reinforcing steel against corrosion, particularly corrosion from concrete contaminated with chlorides from deicing chemicals or salts from a marine type environment. However, impregnating the selected monomer system (methyl methacrylate and trimethylolpropane trimethacrylate (MMA/TMPTMA)) into a bridge deck and subsequent polymerization were recognized as a difficult process, and initial costs were predicted to be high. If the process could be simplified, its acceptance as an effective long-term rehabilitation technique would be enhanced.

Under the NCHRP Project 18-2(3), "Long-Term Rehabilitation of Salt-Contaminated Bridge Decks," Lehigh University along with The Pennsylvania State University conducted research to identify and evaluate promising methods to simplify polymer impregnation. Other methods to arrest or inhibit corrosion of salt-contaminated bridge decks were also investigated. A basic, though not universal, premise considered for a majority of techniques was that a bridge deck would be scarified to a level immediately above the reinforcing steel; the selected treatment would then be applied; and a low-permeability overlay would be placed.

The findings of the research are summarized in this report together with an appendix detailing the deep grooving process used to facilitate the polymer impregnation of sound, but chloride-contaminated concrete bridge decks. Other appendixes providing details of the laboratory work and the development and use of an economic model for comparing techniques are available in an agency document titled, "Supplement to NCHRP Report 257, Long-Term Rehabilitation of Salt-Contaminated Bridge Decks." The agency document has been provided to all

NCHRP sponsors. It is available to others on a loan basis, or on a purchase basis for the cost of reproduction, on written request to Cooperative Research Programs, Transportation Research Board, 2101 Constitution Avenue, NW, Washington, DC 20418.

When reviewing the research findings in either report, readers must realize that the work conducted is still preliminary to full implementation. Development of the more promising techniques identified during this research will require further effort. Many will require additional laboratory investigations before advancing further or justifying field trials. However, in the case of deep polymer impregnation, methods of performing this operation do appear ready for actual field trials and recommendations are made accordingly.

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Dr. John A. Manson, Professor of Chemistry, Lehigh University, was the principal investigator. The work undertaken by The Pennsylvania State University was performed under the direction of Dr. P. D. Cady, Professor of Civil Engineering. The other authors of the report are: Drs. J. W. Vanderhoff and R. Slutter, of Lehigh University; and Mr. R. E. Weyers, Drs. D. E. Kline and G. R. Moore, and Messrs. D. T. Wilson and K. H. Wong, of the Pennsylvania State University.

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LONG-TERM REHABILITATION OF SALT-CONTAMINATED BRIDGE DECKS

SUMMARY

This report covers critical review and experimental work conducted on new methods for the rehabilitation of salt-contaminated bridge decks. Emphasis was given to improving techniques for the impregnation of concrete with poly(methyl methacrylate), and to the concept of scarification to remove the top layer of concrete, followed by impregnation with a polymer or corrosion inhibitor, and overlaying with a low-permeability concrete. Exploratory research with the electrochemical removal of salt was also conducted.

Resistance to freezing and thawing and to corrosion (measured by the polarization resistance technique (App. F)) was determined for several combinations of substrate treatment and overlay (latex-modified concrete, low-slump dense concrete, and polymer concrete) after scarification was simulated. Treatments of the concrete with methyl methacrylate consistently gave superior performance with respect to durability under freezing and thawing conditions and corrosion resistance provided the concrete was dry prior to impregnation. Two impregnated inhibitors (calcium nitrite and a commercial rust inhibitor) improved corrosion resistance, but durability was decreased. Sulfur gave variable or poor results, whereas a hydrophobic silane improved corrosion resistance but greatly decreased durability. A new technique for impregnation was also developed, based on deeply grooving the concrete to facilitate drying and the impregnation process.

Using a model developed to compare cost-effectiveness, it was found that treatments with poly(methyl methacrylate) should lead to minimum capitalized costs. The concept of treatment with methyl methacrylate without scarification appears more cost-effective than the current, common rehabilitation procedure (patching spalls with bituminous concrete until spalling becomes too extensive, requiring the removal of all deteriorated concrete and bituminous patches; scarifying over the remainder of the deck; and installing a latex-modified concrete overlay). In particular, the deep-grooving approach appears to offer minimum cost. The use of polymer impregnation following the electrochemical removal of salt also appears cost-effective. The concept of scarification followed by impregnation with a polymer and placement of a low-permeability overlay is valid, but probably less cost-effective than the current rehabilitation procedure, at least at the present time. The deep-grooving technique could probably be used to advantage with liquid impregnants other than methyl methacrylate, although improvement in the durability of such systems is required. The concept of impregnation with a corrosion inhibitor appears to be valid with respect to the improvement of corrosion resistance; however, inhibitors are needed that do not adversely affect durability of the concrete.

It was also concluded that a field trial of at least the deep-grooving method should be conducted; trials of the scari-

fication/inhibitor method, and of the electrochemical method followed by impregnation with poly(methyl methacrylate), would be valuable as well. A search for corrosion inhibitors that do not decrease durability of the concrete would also be worth additional study.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

Problem Statement

It was recently reported that nearly one-third of all highway bridge decks in the United States are seriously deteriorated because of corrosion of reinforcing steel. This corrosion is usually caused by chloride ions that have penetrated the concrete as a result of repeated application of de-icing salts. Accumulation of corrosion products around the reinforcing steel causes cracks to develop in the concrete cover. This allows intrusion of additional chloride solution, thereby accelerating corrosion and causing spalling of the deck.

Considerable research has been directed to the problem of prevention of corrosion in new bridge decks and several promising methods are available. However, restoration of existing decks is a more difficult and pressing problem. The cost of restoring deteriorated decks has been estimated at \$6.3 billion or more.

Clearly there is a need for treatments that are cost-effective, and, if possible, more cost-effective than current methods.

Current Ameliorative Techniques

Low-permeability overlays have been applied to hundreds of deteriorated bridge decks during the past fifteen years. The overlay is normally preceded by spot repair, involving removal of all deteriorated concrete. In most cases, however, large areas of chloride-contaminated concrete remain in place. Although field experience has shown such procedures to be cost-effective in extending the usable life of decks by ten or more years, the presence of large areas of new delaminations and corroding reinforcing steel in contaminated decks that have been overlaid from five to fifteen years previous indicates that detrimental corrosion was not completely arrested by these procedures. Thus, there is a need for long-term rehabilitation procedures.

As part of the rehabilitation process, the top surface of the deck is sometimes scarified prior to application of the overlay. Scarification to a level within 1/2 inch of the top reinforcement disposes of a large volume of contaminated concrete and can facilitate impregnation of the concrete around the steel. If an economical method were found to nullify the effects of chlorides in concrete around reinforcement under shallow cover, an alternative restoration procedure promising long-term effectiveness

could be available.

Polymer impregnation to a depth sufficient to encapsulate the reinforcement is generally expected to ensure long-term protection. However, costs and difficulty of application were believed to limit widespread use of this procedure. There is a need for simpler treatments (e.g., water-tolerant monomers or corrosion inhibitors that can readily impregnate concrete around the reinforcing steel) that are capable of arresting corrosion of reinforcement in sound but salt-contaminated concrete, without necessarily enhancing other concrete properties such as strength, permeability, resistance to freezing and thawing, and wear resistance.

OBJECTIVES AND SCOPE

The feasibility of impregnating a salt-contaminated, but structurally sound, bridge deck with poly (methyl methacrylate) to a depth of 4 inches was demonstrated in the field under the original NCHRP Project 18-2 study. Although the treated area has experienced no subsequent deterioration, concern over possible costs and difficulty of application of the procedure led to the initiation of NCHRP Project 18-2(2), which reviewed potential alternative methods for rehabilitation and recommended what new research needed to be undertaken in the study of the durability and corrosion resistance of several treatments. Following this review, NCHRP Project 18-2(3) was developed to provide the additional information needed in this area, to recommend further research studies, and to conduct research in preparation to field evaluation of the most promising candidate procedure.

In particular, the objective of this study was to develop and evaluate materials and procedures that can be used in conjunction with a low-permeability overlay to prevent continued corrosion on a long-term basis in shallow-depth reinforcement surrounded by chloride-contaminated concrete. The study addressed polymer impregnation as well as other chemical treatments that might arrest corrosion when used in conjunction with the previously mentioned rehabilitation technique involving scarification and placement of a relatively impermeable overlay.

The evaluation of materials and procedures reflected consideration of: (1) economic feasibility, including both materials and application costs; (2) long-term effectiveness; (3) compatibility including substrate, repaired areas, and overlay; (4) durability; (5) pollution problems; and (6) potential safety hazards.

Particular emphasis was given to (1) the possible combination of impregnation of monomers of corrosion inhibitors with prior scarification to remove salt-contaminated concrete and thus simplify the impregnation procedure, and (2) impregnation with a polymer.

RESEARCH APPROACH

The initial 10 months of the research project were spent on a critical review of the state of the art and the development of

recommendations for further research. The remaining contract period was devoted to research on processes and materials, as well as the evaluation of durability, corrosion resistance, and figures-of-merit for probable cost effectiveness.

To accomplish these goals, the following tasks were executed:

Task 1. Identification of current and potentially available methods, materials, and concepts that may hold promise for arresting, and long-term prevention of, corrosion under the previously described conditions. Emphasis was given to polymer impregnation, but consideration was not limited to the study of conventional monomers that require drying of the concrete and subsequent polymerization using catalysts and heat. Corrosion inhibitors, chloride and oxygen-scavengers, and other chemical treatments that increase pH or otherwise stop corrosion were also considered. This task involved a review of the literature, research in progress, manufacturers' information, and other appropriate sources.

Task 2. Preliminary analysis of methods, materials, and concepts identified in Task 1. Particular attention was given to evaluation criteria related to ease of application and probable long-term effectiveness.

Task 3. An interim report that describes the various treatments and the reasons for their rejection or selection for further study, including as well an updated working plan for laboratory evaluation of promising treatments. The required interim report (1) was submitted and approved by the NCHRP before initiation of Task 4.

Task 4. Laboratory evaluation of treatments for the purpose of establishing feasibility based on the desired characteristics outlined earlier.

Task 5. Preparation of a final report that includes all research findings and recommendations for possible field evaluation of selected treatments.

Identification of Processes, Materials, and Problems

A summary of the processes and materials evaluated as candidates for research follows in Table 1; this table also identifies major potential problems anticipated (for more details, see Ref. (1)).

These various possibilities were evaluated with respect to demonstrated or potential technical and economic feasibility and expected long-term effectiveness, compatibility of the various elements involved, state of the art, and expected pollution or safety problems. On the basis of these evaluations an assessment was made of probable success within the subsequent contract period.

Rationale for Selection

The rationale for the selections made is summarized in the following and is discussed in more detail in Ref. (1).

Table 1. Identification of processes, materials, and problems.

PROCESSES

Drying

- (a) improved drying methods
- (b) elimination of drying

Scarification

Impregnation

- (a) re-analysis of impregnation operation
- (b) further analysis of surface chemistry and of energies needed for penetration into water-wet pores
- (c) mechanical impregnation (pressure mat)
- (d) deep grooving of original deck (in lieu of scarifying, and to aid impregnation)

Polymerization

- (a) ambient-temperature polymerization
- (b) catalysis by the concrete
- (c) anaerobic polymerization

Chloride-ion removal by electrochemical means

MATERIALS

Monomers

- (a) conventional monomers
- (b) water-displacing and water-tolerant monomers
- (c) low-temperature active monomers
- (d) anaerobic monomers
- (e) monomers initiated by contact with hydrated cement paste
- (f) monomers initiated by ionic catalysts

Inhibitors

- (a) organics
- (b) calcium nitrite
- (c) other inorganics

Scavengers

- (a) for chloride
- (b) for oxygen

pH Controllers (buffers)

Other Penetrants

- (a) hot liquids
- (b) inorganics
- (c) hydrophobic sealants

Overlay Systems

- (a) latex-modified concrete
- (b) low-slump dense concrete
- (c) polymer concrete
- (d) wax-bead systems

HAZARDS

Major Problem Areas

- (a) debonding of overlays due to Δ permeability (freezing and thawing)
- (b) cracking of overlays
- (c) damage induced by scarifying and other delaminations
- (d) transference of areas of cathodic activity to lower rebar mat
- (e) uniform penetration of corrosion inhibitors to prevent the setting up of new corrosion cells
- (f) evaluation of cost-effectiveness

Drying

Because no evidence was found for the development of suitable methods for the large-scale drying of decks (e.g., by microwave techniques), it was concluded that infrared heating is probably the most effective method at this time, assuming that a temperature of 105 C is reached at the depth of impregnation desired. The drying units are readily available to contractors, and they have been successfully used in a number of field trials (2,3). Moreover, although some evidence has been obtained which shows that drying at high temperatures may result in cracking of the concrete that was not healed by polymer treatment (4), earlier studies under NCHRP 18-2(2) indicated that damage due to high temperatures was repaired by such treatment. Also, there is as yet no sign of spalling in the bridge deck treated with poly(methyl methacrylate) under NCHRP project 18-2.

Elimination of Drying

The elimination of drying was estimated to lead to a reduction in treatment cost by about \$1.00 per square foot. Thus consideration of methods for doing so was judged to be useful (e.g., by the use of water-displacing monomers or other liquids).

Scarification

Scarification to remove much of the salt-contaminated concrete above the reinforcing steel was thought to be worthy of consideration as a means of reducing the depth of impregnation by a liquid. Care must be taken to avoid subsequent delamination of the overlay that is placed afterwards; however, disposal of the rubble appears to be an acceptable problem in practice. No special problems with safety or environmental pollution are evident. The greatest disadvantage of scarification appears to be an unexpectedly high cost per unit area, as estimated in both preliminary and final evaluations. Nevertheless, because scarification is such a common technique, and because costs could conceivably become lower, it was concluded that the combination of scarification with a treatment (a pore sealant or a corrosion inhibitor), followed by overlaying with a relatively impermeable concrete, should be evaluated.

Impregnation

The physical chemistry of impregnation of a porous body with a liquid was reviewed. With a dried concrete the rate of impregnation in a given pore is directly proportional to the square root of the ratio of surface tension to the viscosity of the liquid, and to the square root of the cosine of the contact angle, and, approximately, to the applied pressure. It turns out that methyl methacrylate has a very favorable combination of these properties (1).

The case of impregnation of a water-containing concrete poses difficulties. Displacement of water by another liquid or by a gas appears to be problematic: the

pressures required were estimated to be very high, and the displacement was predicted to follow the line of least resistance, with channeling through the larger pores or microcracks. Use of a water-soluble liquid would be feasible in principle; however, a cost advantage was not obvious. Pressurization with a water-immiscible monomer would be preferable, but the relevant surface-chemical data were not available for possible candidates. Similarly, a solution of a suitable polymer or emulsifying agent in a monomer or other liquid could also serve in principle as an impregnant under pressure. Again, suitable candidates could not be readily identified; however, the use of a water-displacing corrosion inhibitor is recommended for study (see discussion under "Inhibitors" below).

Because previous studies (2) had demonstrated impregnation of methyl methacrylate under pressure in the field, this method was considered. There are some problems with channeling, however, and methods of sealing to, and unsealing from, the bridge deck would require development.

The technique of cutting deep grooves in the concrete to increase the rate of impregnation appears to offer the simplest approach. It minimizes the lengthy impoundment of the monomer for deep impregnation, and eliminates the need for scarification or pressurization. Attention was therefore concentrated on this approach.

Monomers for Impregnation at Ambient Temperature

Of the conventional vinyl monomers, methyl methacrylate appeared to offer several advantages, specially a relatively high penetration rate and resistance of the impregnated concrete to chloride intrusion (5). Although flammable and toxic, this monomer has been used in the field without exceeding OSHA limits for vapor concentration. Though more costly and more viscous, low-viscosity epoxies were considered to have the advantage of lower vapor pressure and flammability. Furfuryl alcohol has received some attention, but recent results indicate problems with the polymerization after impregnation (6), and problems of durability with related materials. Thus methyl methacrylate still seems to be the monomer of choice for the impregnation of concrete, assuming the taking of proper safety precautions.

No evidence was found for impregnations using monomers that are more tolerant of water than methyl methacrylate. In principle, monomers that are more basic than methyl methacrylate could be candidates, but in view of the already broad scope of the project, it was concluded that the new polymerization process under study could best be studied using methyl methacrylate.

Investigation of low-temperature active and anaerobic monomers, as well as monomers sensitive to ionic catalysis, was considered to be unjustified in this study, either because of a lack of strong economic justification or because of the very specu-

lative nature of such research.

Polymerization

Polymer impregnation of concrete has generally been conducted using thermocatalytic initiation. Thus one separates the impregnation from the polymerization step, avoiding premature polymerization using initiators that require heating for their activation. On the other hand, oxidation-reduction systems that operate at room temperature are commonly used in the casting of polymer concrete. However, such initiators (as well as ionic initiators) have been less predictable in their behavior than thermocatalytic initiators. Although better control appears to be possible now (7), it was decided to stay with the well-tested thermocatalytic system, especially because the program already involved much investigation of new processes and electrochemical testing.

The possibilities of using the concrete itself as an initiator, or of using a monomer that would polymerize under anaerobic conditions, were judged to be too problematic for the purpose of this study.

Chloride-Ion Removal by Electrochemical Techniques

This process involves the application of a direct current between a reinforcing steel mat and a metal electrode on top of the deck in order to drive the chloride ions to the surface electrode where they react to form chlorine (in the case of an inert electrode) or metal chloride (in the case of a reactive metal) (6,8,9). Costs should be relatively low, and tests in the laboratory and the field indicated decreases in chloride content to amounts close to the threshold value for the initiation of corrosion (8). A problem may exist, however, because the permeability of the concrete was increased about five-fold. Of course, one approach to this problem would be impregnation with a monomer such as methyl methacrylate. This combination of chloride removal with subsequent impregnation and polymerization was judged to be worthy of attention because the increased permeability would probably increase the rate of impregnation.

Inhibitors

The use of inhibitors to protect steel against corrosion is, of course, well established. Some of these block the anodic process, some block the cathodic process, and some are effective both cathodically and anodically (10). Some, for example, alkaline-earth petroleum sulfonates, can also displace water from a metal surface (11).

The selection of candidates within the time period of this project was difficult because of the large number of corrosion inhibitors that exist, and the range of conditions within which inhibition occurs varies widely. However, many can be eliminated on the grounds of toxicity (e.g., chromates) and some are known to decrease

the strength of concrete (e.g., chromates and sodium nitrite) (12). Of all the inhibitors considered, several seemed potentially suitable for impregnation, even though evidence for impregnation had not been published: aqueous calcium nitrite (12), alkaline-earth petroleum sulfonates, and organic ammonium nitrites. From this group, the first two were selected for study in view of the current use of aqueous calcium nitrite as a concrete admixture (12), and of alkaline-earth petroleum sulfonates as a common water-displacing corrosion inhibitor.

Scavengers

The possibility of controlling corrosion by controlling pH or by use of a scavenger for chloride ion or oxygen was considered, but promising leads were not found.

Other Penetrants

In earlier studies it was found that molten sulfur could displace water in concrete pores and yield a strong and relatively impermeable composite (2). Although the long-term stability with respect to water was not fully established (see App. F), it was concluded that molten sulfur should be tried as an impregnant. A low-viscosity epoxy was also selected. Molten waxes and asphaltic liquids were also candidates, but it was thought that the ability to confer some mechanical strength might be advantageous (as with sulfur or methyl methacrylate). Inorganic penetrants have been tried, but without promising results (13,14).

Considerable evidence was found to support the use of solutions of certain silanes, which were shown to reduce significantly the penetration of chloride ions (15). The most promising of these, an alkylalkoxy silane, was selected for study.

Overlay Systems

Three types of overlay systems for partial-depth replacement of deteriorated concrete bridge decks have been in use for over 10 years. They are: latex-modified mortar (LMM), latex-modified concrete (LMC), and low-slump dense concrete (LSDC), sometimes called "Iowa mix." In general, these have performed satisfactorily, and although they do not completely halt corrosion, they are believed to extend the service lives of bridge decks by 10 or more years (15). To be sure, some problems have been encountered; these are addressed under "Major Problem Areas," below.

Test installations of polymer concrete (PC) overlays consisting of 1/8 inch (3-mm) layers of polymer and sand built up to total thicknesses of 1/2 to 3/4 inch (1 to 2 cm) have displayed excellent resistance to the penetration of chloride ions, although some problems have been encountered. More recently, thin (1/4 to 1/2-inch (6 to 10-mm)) and thick (1-1/4 to 1-1/2-inch (3 to 4-cm)) single-layer PC overlays have been placed (7,22).

Concrete overlays containing wax beads have also been developed (16); with these a heating stage is required to melt the wax and allow it to seal the pores. It was concluded that any of the foregoing overlay systems would probably be satisfactory for use in this study; however, the LMM, LMC, LSDC, or PC systems would have the advantage of greater simplicity because the heating stage needed for the wax-bead type would not be necessary.

Hazards

Hazards were considered case-by-case; perceived special hazards are discussed under the relevant individual topics, as well as in Chapter Three. None of the systems selected was judged to pose unusual problems requiring more than the usual precautions in dealing with flammable and toxic materials and with mechanical and electrical equipment.

Major Problem Areas

Debonding of Overlays. It was found in earlier studies (1) that LMC overlays tended to debond during freeze-thaw tests from a polymer-impregnated substrate, although the tendency was reduced by use of a latex slurry as a bonding agent. Because this could be a potential problem with substrates treated with other materials (e.g., silanes or hydrophobic corrosion inhibitors), it was concluded that debonding tendency should be evaluated with all systems studied.

Delamination of Overlays Due to Other Causes. Delamination of overlays by failure through the substrate has been noted in many cases (17,18,19). Because the failures were generally attributed to poor inspection or scarification practices, this problem was considered to be outside the scope of this project and was, therefore, not investigated.

Surface Cracking of Overlays. Problems with surface cracking have been reported with LMM and LMC overlays (20,21). Because surface cracking is believed to be related to such factors as curing procedures, structure type, and traffic conditions, study appeared to be unwarranted. However, it was decided to observe closely the performance of all overlay/substrate systems in freeze-thaw tests.

Transferral of Areas of Cathodic Activity to the Lower Reinforcing Steel Mat. Although it seemed unlikely that this potential problem would exist when treatment consisted of sealing the concrete around the top reinforcing steel mat (e.g., by polymer impregnation), other treatments that did not physically seal the pores were thought to be more favorable. Thus it was decided that measurements of corrosion potential should include suitable tests to establish whether or not a problem might exist (see App. F).

Uniform Penetration of Corrosion Inhibitors. Unless the reinforcing steel bars receive a uniform exposure to a corrosion inhibitor, corrosion cells may be set up. Thus variability in corrosion resistance may well be common and might be observable in the electrochemical tests planned.

Evaluation of Cost Effectiveness

Unless a common basis is used for comparing the effectiveness of treatments and their estimated costs, clearly no conclusions can be drawn. A model was developed, therefore, that would take into account technical and economic factors -- specifically, the relative improvement in durability and corrosion resistance, initial costs, maintenance, and the time value of money.

Selection and Evaluation Treatments

Selection

The following approaches in the treatment of reinforced, salt-contaminated concrete were selected as the most promising with respect to their effectiveness in inhibiting the corrosion process and in terms of their potential economic and technical feasibility:

1. The impregnation process.
2. The simplification of the impregnation process by limiting the depth required (by deep grooving to provide monomer impoundment below the nominal surface, by mechanical pressurization using a cellular mat, and by removal of the top layer of salt-contaminated concrete by scarification).
3. The simplification of the impregnation process by the use of water-displacing liquids, nonpolymeric sealants, and corrosion-inhibiting liquids (especially solutions of calcium or organic nitrites).
4. Combination of scarification (to remove salt-contaminated concrete) with the processes and materials mentioned, followed by overlaying with polymer-concrete, or with a latex-modified or low-slump concrete.

The electrical removal of salt coupled with subsequent polymer impregnation was also judged to be worthy of research. However, because electrochemical removal of salt has been demonstrated in the laboratory and in the field (6,8,9), and because durability and corrosion resistance should parallel that found for polymer-impregnated concrete, it was decided that more attention should be given to the other approaches, including the development of corrosion tests. Similarly, it was decided to delay studies of mechanical pressurization, the feasibility of which has already been shown in the laboratory (2).

Evaluation

Specifically, the following systems were studied and evaluated for durability, compatibility with overlays (where

appropriate), corrosion resistance, and probable cost effectiveness:

1. Deep (up to 4-inch) impregnation with poly (methyl methacrylate) (PMMA) and with a commercial corrosion inhibitor.
2. Deep grooving of concrete to facilitate impregnation with PMMA to below the top rebar mat.
3. Simulated scarification to remove the top layer of salt-contaminated concrete, followed by impregnation with a pore sealant or corrosion inhibitor, and overlaying with a concrete suitable for resisting the subsequent intrusion of salt.

Impregnants for the latter system included (1) pore sealants (methyl methacrylate, sulfur, an epoxy, and a silane to render the pores hydrophobic); and (2) corrosion inhibitors (aqueous calcium nitrite, calcium and barium petroleum sulfonates, and a commercial corrosion inhibitor said to be water-displacing).

Durability and Compatibility. Freeze-thaw tests (ASTM C 666, Method A) were conducted on concrete deeply impregnated with poly(methyl methacrylate), and on concrete treated by the simulated scarification approach. Durability was estimated based on weight loss and visual observation, and compatibility was evaluated on the basis of pulse velocities normal to the interface and observation of debonding. Tests were run for 300 to 500 cycles, or until failure occurred. In all cases, figures-of-merit relative to nontreated concrete were obtained. (For details, see App. E.)

Corrosion Resistance. Most of the systems whose durability was studied, using specially designed specimens, were examined to obtain figures-of-merit for corrosion resistance in comparison to controls. The effect of drying prior to methyl methacrylate impregnation was also studied. For these tests, a linear polarization method for estimating polarization resistance, a measure of corrosion current, was adapted; the test was found to be simple and convenient, and was judged to be reliable. Rankings were based on the relative polarization resistance of a treated sample with respect to its value before treatment. Because in all cases the polarization resistance varied with the environmental conditions, values before and after treatment were averaged; values after removal of the top level of concrete to within 1/2 inch of the reinforcing steel were included in the average before treatment. (For details, see App. F.)

Cost Effectiveness. An economic model was developed to evaluate the life-cycle cost of various alternatives. This model takes into account all costs involved in rehabilitation, cost of subsequent maintenance, anticipated service life, and time value of money expressed in terms of present worth. (For details, see App. G.) Figures-of-merit based on the results of the durability, compatibility, and corrosion tests were used to estimate nominal service lives.

CHAPTER TWO

RESEARCH FINDINGS

SPECIFIC FINDINGS

New Impregnants

Impregnations of 1-inch x 2-inch portland-cement mortar specimens (W/C=0.4) were successfully achieved with the following corrosion inhibitors: 10 percent aqueous calcium nitrite, a corrosion-inhibiting and water-displacing penetrant (WD-40), and dispersions of calcium and barium petroleum sulfonates in oil and mineral spirits. All of these impregnants were more viscous than water or methyl methacrylate, with penetration rates of ~0.2 inches/√hour for the nitrite and WD-40, compared to ~0.4 to 2 inches/√hour for methyl methacrylate and ~0.3 inches/√hour for the sulfonate dispersions. It should be noted that these rates are based on observations of penetration by the liquid generally; it was not possible to determine the distribution of the active ingredient, which was not identified in the case of WD-40. At least with WD-40 and calcium nitrite, splitting tensile strengths were not significantly affected by the treatment. (For details, see App. C).

Because treatment with silane has been reported to give promising results in tests of corrosion resistance in bridge-deck slabs (23), an extended study was conducted on previously dried concrete using a commercial silane formulation as the impregnant (see App. D). An impregnation rate of ~0.4 inches/√hour was found. Preliminary tests of electrolysis using concrete specimens containing a reinforcing bar as one electrode and immersed in saltwater containing another rebar electrode indicated a significant (2 orders of magnitude) reduction in electrolysis current in treated samples (see also "Corrosion Testing," below).

Because the impregnation of concrete with epoxy resins (without a chemical curing agent) followed by thermal polymerization had been previously shown to give good sealing of concrete pores (24), an extended study was also made using two bisphenol-A-based epoxy resins (see App. B). As expected the impregnation rate depended on the temperature; rates were approximately 1 and 0.8 inches/√hour at 135C and 105C, respectively -- values judged to be feasible in practice, though a possible problem may exist with respect to decomposition at the high curing temperatures used.

Preliminary tests on 1-inch x 2-inch cylinders indicated that methyl methacrylate could displace a significant fraction of water in water-saturated portland-cement mortar specimens, at least under pressure. However, subsequent tests without the application of pressure resulted in displacements of ~10 percent of the water in specimens containing 1.1 and 8.0 percent water. Results of splitting tensile strengths indicated that 1.1 percent water had little effect, whereas 8.5 percent water resulted

in strengths close to those of the controls.

The impregnation of concrete with molten sulfur has been discussed in an earlier report and shown to be feasible. Details are given in Appendix E, Ref. (2); the references contained therein describe studies by others as well.

DEEP GROOVING TECHNIQUES

As mentioned earlier, deep impregnation with methyl methacrylate has been shown to be feasible in the field, but to be costly in terms of time; the time required for penetration to a given depth varies with the square of the depth desired (2). In an attempt to minimize the time required, grooves were cut into the concrete so that the impregnant could move laterally as well as vertically, thus facilitating the process.

Experiments indicated that a groove width and spacing of 3/4 inches and 2-1/4 inches, respectively, and a groove depth of 1-1/2 inches (1/2 inch above the top rebars) made it possible to obtain impregnations to a depth of at least 3-3/4 inches (i.e., below the top reinforcing steel mat) in 16 hours. In comparison, with impregnation of similar specimens by ponding of methyl methacrylate, an impregnation time of ~45 hours would have been needed.

Drying and polymerization times and temperatures were also optimized. It was found that minimum energy consumption was attained at a surface temperature of ~310C and a drying time of ~17 hours. Although an edge crack developed during each test, the crack appeared to be associated with the test set-up; cores taken after drying revealed no sign of internal cracking when observed at a magnification of 100X. For optimum polymerization, a polymerization time of 6 hours at a steady state temperature of ~50C is recommended; this temperature was reached after 16 hours of heating with a hot-water pond to a surface temperature of 98C.

ELECTROCHEMICAL REMOVAL OF SALT

Preliminary experiments confirmed reports by others (6,8,9) of the successful removal of salt from concrete by electrochemical means.

The use of an electrochemical method (sometimes referred to as "electro-osmosis") to remove a significant fraction of mobile chloride ions has been demonstrated in the laboratory and, on a small scale, in the field (8,9). The general definition of electro-osmosis is the displacement of a liquid relative to a solid by an applied potential. If a potential is applied between the reinforcing steel and the surface of the concrete slab, the resultant movement of liquid can in principle carry the chloride ions in a direction opposite to their diffusion (i.e., from the interior toward the surface).

In one well-documented study (9), direct current was applied between the reinforcing steel and a copper screen on top of the deck. The copper screen was used as an electrode to eliminate the production of gas bubbles. Reductions in salt concentration

of 10-20 lb/yd³ (6-12 kg/m³) from initial concentrations ranging up to 21 lb/yd³ (7.9 kg/m³) were obtained after times of up to ~100 hr. Significant reductions in chloride content to values close to the threshold value for the initiation of corrosion were also observed in a second detailed study (8). However, the removal of chloride ion by this method increases the permeability of the concrete about fivefold. Thus the reapplication of de-icing salts to a concrete slab treated in this manner would give more rapid diffusion than before. One approach to offset this more rapid diffusion is polymer impregnation of the now more porous concrete; of course other waterproofing methods could be used as well.

For purposes of this research, concrete cylinders (3-inch x 6-inch) were used, each containing an embedded steel rod as the electrode. Power was supplied by a unit with a capability of 200 amperes and 500 volts. Temperature was monitored using a thermocouple and strip-chart recorder.

Salt was administered (at a level of 15 lb/yd³) to the concrete cylinders in two different ways: (1) addition of powdered salt to the concrete mix followed by molding and curing; and (2) impregnation of cured cylinders using salt water.

A copper screen was fixed around the cylinder; after good contact between the cylinder and the screen was assured, the specimen was wrapped with a wet cloth.

The migration of chloride ions was readily demonstrated by the deposition of green material at the surface of the cylinder. In experiments with cylinders impregnated with salt solution, 80 percent of the copper screen was destroyed due to the attack by chloride ions and subsequent formation of copper chloride. On the other hand, with cylinders whose mix contained salt, the migration was slow and random, leaving most of the copper screen intact. In the practical case, the situation would be similar to the samples impregnated with the salt solution and thus other reports of success with such electrochemical techniques are confirmed (31,32).

It was hoped to obtain a quantitative evaluation of the distribution of salt using an electron microprobe technique. However, because of difficulties with the instrument, this proved not to be possible within a reasonable time. Since measurements of the salt distribution within a bridge deck (before and after electrochemical treatment) have already been obtained (31,32), and since other work on as yet untried treatments remained to be done, the experiments were terminated.

Thus, the electrochemical process has been demonstrated in both the laboratory and in the field. The increased porosity may be advantageous to subsequent impregnation. One problem of scale-up is the need for containment of the electrolyte ponded on the deck; the existing system needs modification for use on decks having sharp gradients of slope. In this respect, the state of development resembles that of deep polymer impregnation -- although in the latter case the containment problem was

solved, at least on a small scale, by use of a chamber sealed to the deck. Another possible problem is whether or not the process results in a weakening of the concrete; again, polymer impregnation could alleviate such a condition.

DURABILITY AND COMPATIBILITY

Systems Studies

In this part of the study, the durability of substrates and overlays with respect to freeze-thaw behavior was examined for the combinations of treatments and overlays indicated in Table 2. Because of the emphasis on scarification followed by treatment and overlaying, compatibility between the treated substrate and overlay was also of obvious interest. A totally factorial evaluation of all combinations was not possible because of the time, equipment, and funding limitations of the project.

Substrate Durability

Untreated concrete controls exhibited surface scaling and a progressive loss of integrity of the aggregate-matrix bond; by 400 cycles some coarse aggregate had been lost.

All substrates treated with methyl methacrylate exhibited exceptional resistance to freezing and thawing, retaining integrity throughout the whole 500 cycles. In a separate test, cylinders containing holes to simulate deep grooving showed no signs of distress at 304 cycles (at which time equipment malfunction required termination of the test).

Epoxy treatment also yielded generally satisfactory results (up to 304 cycles).

In contrast, silane-treated substrates exhibited severe deterioration in the form of bulging, matrix cracking, and pull-out of aggregates; the extent of damage increased as the number of cycles increased. For unknown reasons, the damage was much more severe than in the untreated controls. Similar extensive deterioration was also noted with sulfur-impregnated substrates.

The substrates treated with corrosion inhibitors showed varying levels of damage, ranging from slight surface deterioration to nearly complete disintegration; all showed a tendency towards spalling to some degree. The extent of damage increased in the following series (the numbers in parentheses indicating the number of the four specimens tested that exhibited severe deterioration):

Barium petroleum sulfonate (1/4) ~ calcium nitrite (1/4) < calcium petroleum sulfonate (3/4) < WD-40 (4/4)

Overlays

In general the latex-modified concrete (LMC) and polymer concrete (PC) overlays performed well. The low-slump dense concrete exhibited greater surface mortar deterioration than the other two overlays; all overlays performed better than the normal air-entrained concrete controls.

Compatibility

All specimens treated with methyl methacrylate or hot epoxy generally exhibited satisfactory compatibility between

Table 2. Substrate treatment/overlay systems.

Substrate Treatments		Overlays ^a		
Type	Material	LMC	LSDC	PC
Inhibitors	Barium Petronate	X		X
	Calcium Petronate	X		X
	Calcium Nitrite	X		X
Hydrophobic	Alkyl-Alkoxy Silane ("ChemTrete")	X	X	X
Hot	Epoxy (175C Cure) ("Epon 828")	X		X
	Epoxy (125C Cure) ("Epon 828")	X		
	Sulfur	X		
Ambient	Methyl Methacrylate (soak)	X	X	X
	Methyl Methacrylate (pressure)	X	X	X
Water Displacing	WD-40 Corrosion Inhibitor	X		
Control	None	X	X	X

^aLMC = latex modified concrete; LSDC = low-slump dense concrete; PC = polymer concrete

the substrate and overlay, although values of relative pulse velocity implied a tendency to debond in the case of a portland cement overlay on epoxy-impregnated concrete (not with LMC or LSDC overlays, however).

In contrast, severe debonding was observed for all three overlays cast on silane-treated concrete using the following bonding agents: a neat cement grout (LSDC), activated acrylic monomer (PC), and a latex slurry (LMC). The debonding was associated with matrix cracking, primarily in the substrate.

A tendency towards debonding was observed with barium petroleum sulfonate (1 of 4 specimens), sulfur (1 of 2 specimens), and WD-40 (1 of 2 specimens), but the tendency was not as clear-cut as in the case of silane-treated substrates. With calcium nitrite, the relative pulse velocity was similar to that of normal concrete on normal concrete.

Durability Factor

To obtain a figure-of-merit for freeze-thaw resistance, a durability factor was defined as:

$$\frac{\text{No. of freeze thaw cycles}}{\text{average \% weight loss}}$$

This factor reflects the fact that the weight loss increases with the number of freeze-thaw cycles, and takes account of differences in the number of cycles from system to system.

Values of the durability factor (given in parentheses) ranged widely, and increased in the following series:

Sulfur (7) ~ WD-40 (7) < calcium petroleum sulfonate (16) < silane (13) < barium petroleum sulfonate (25) < calcium nitrite (25) < epoxy (40) < overlaid normal concrete (50) < MMA (420)

For further details, see App. E.

CORROSION RESISTANCE

Resistance to corrosion was evaluated conveniently by determining the polarization resistance, E_p , in a test based on the well-established "linear polarization" method. Thus a polarizing potential (~ 100 mV) was applied to a circuit comprising a desired pair of reinforcing bars, and the response potential, E_1 , and current, i_1 , were measured (with respect to a standard calomel half-cell) after a fixed time. The polarizing potential was then reversed and the response potential, E_2 , and current, i_2 , were measured after the same time. The polarization resistance, R_p , was then calculated as $\Delta E/\Delta i = (|E_1 - E_2|)/(|i_1 - i_2|)$.

This ratio approximates the slope of the potential-current curve in the region of the corrosion potential, which is bracketed by E_1 and E_2 ; the corrosion current is inversely proportional to E_p . It should be noted that polarization resistance is inversely proportional to the corrosion current. For further details see App. F.

As with durability, the effects of treatment varied widely, with values of relative resistance ranging from below those for untreated specimens to significantly above. The actual numbers may vary from time to time because of variations in the environment; nevertheless, clear trends in relative performance were obtained.

Simulated scarification and placement of an overlay gave a significant but variable improvement in polarization resistance (2 and 980). Even higher values were obtained when this treatment was coupled with impregnation with a polymer or corrosion inhibitor.

Impregnation with methyl methacrylate, whether to a depth of 4 inches or to a lesser depth in the case of simulated scarification, gave the most consistently high values (from 37 to >1900). The impregnation of undried surfaces gave more variable results before placement of the overlay, but high values thereafter (>1900 and >1300).

Silane treatment also resulted in high values of relative polarization resistance (22 and >480), whereas WD-40, a penetrating corrosion inhibitor, yielded even higher values (from 80 to 2000). Treatment with aqueous calcium nitrite gave a significant increase in resistance, at least after placement of the overlay (68 and 980). (As noted earlier, unfortunately treatment with silane and WD-40 resulted in problems with durability and compatibility.) Treatment with sulfur tended to give low and erratic values (from 0.5 to 14).

Additional details are contained in Appendix F.

COST EFFECTIVENESS

The purpose of developing this model was to translate each technical alternative to an equivalent monetary value. Although the numbers developed may vary in magnitude in individual cases, the numbers should still yield a relative comparison of probable costs.

Scenario Used

It was assumed that the hypothetical deck considered was one in which half of the top layer of rebars was embedded in concrete containing sufficient chloride ion to promote corrosion, and that the average clear cover of concrete was 2 inches thick. By taking into account common salting procedures and diffusion characteristics of chloride ion in typical bridge decks, it was estimated that the average time for such a deck to reach the threshold chloride ion concentration for corrosion (0.2 percent) (23,25), affecting half the top rebars, was 13 years. This age was taken as the age at the beginning of the planning horizon (i.e., the period of time over which the alternatives are evaluated).

The planning horizon itself was taken as infinite. Although planning horizons from 50 to 100 years are commonly used, there is convincing evidence (26) that use of an infinite horizon is preferable. In

any case, the difference obtained by using 50 years or infinite life is small.

With respect to maintenance, it was assumed that spalling would occur to the extent of one-fourth of the deteriorated area of the deck and that the rate of deterioration would be linear in time. (Deviations from linearity would not significantly affect the results.) Hot-bituminous patching of the deck was assumed until 40 percent of the deck area had been affected by spalls and fracture planes; the value of 40 percent is recommended as a practical limit (27).

At this point, it was assumed that the deck would be rehabilitated by scarification and overlaying, and that rehabilitation would continue until the deck age reached 50 years (i.e., 37 years into the planning horizon). Now, the scenario calls for replacement of the deck with one having epoxy-coated reinforcing steel (a system that is believed to offer the most cost-effectiveness for new construction (28)). Subsequently such replacements each 50 years thereafter were assumed. All cost data were considered in terms of average 1981 values. Costs for traffic control and road use were not included because of inability to estimate average values.

Criteria for Alternatives

Analysis of the various alternatives required development of criteria for durability, compatibility of substrate with overlay, and corrosion resistance. Thus estimates of service life as determined by these life-limiting factors were required.

It was assumed that an average value for service life exclusive of deterioration by corrosion of the reinforcing steel was 50 years, and an average time for failure due to such corrosion was estimated to be 22 years. The latter value was based on an analysis of condition data for 169 decks.

Thus the criterion for acceptability of a treatment in terms of corrosion resistance for a deck failing of the reinforcing steel was taken to be: corrosion parameter (treated) \geq corrosion parameter (control); in this case, the parameter used was the polarization resistance. The expected service life with respect to corrosion would, of course, equal 22 times the resistance ratio. The criterion for acceptability in terms of durability was taken to be: durability parameter (treated) $>$ 22/50 times durability parameter (control), the durability parameter being the number of freeze-thaw cycles per unit weight loss.

Comparisons

Cash flow diagrams were developed for each of the alternatives, and capitalized present worth costs (interest rate, 6 percent) were calculated. Details of the calculations are given in Appendix G. The following values were found for treatments that pass the acceptability criteria:

1. Present method of rehabilitation (patching, shallow scarification, and

overlay)	\$12.80/square foot
2. Deep impregnation with methyl methacrylate (soaking)	\$10.20/square foot
3. Deep impregnation with methyl methacrylate (pressure)	\$9.46/square foot
4. Scarification/methyl methacrylate treatment/overlay	\$18.28/square foot
5. Scarification/nitrite treatment/overlay	\$21.87/square foot
6. Deep grooving/impregnation with methyl methacrylate	\$7.96/square foot

Calculations for a combination of calcium nitrite with deep grooving plus filling of the grooves with polymer concrete yielded a value of \$14.29, a value that would be reduced to \$13.23 if impregnation could be achieved without prior drying of the substrate. For a hypothetical corrosion costing no more than calcium nitrite, and having no adverse effect on durability, a value of \$9.38 would be obtained. Although cost figures for the electrochemical removal of salt (8,9) followed by polymer impregnation (9) to seal the pores are difficult to estimate, preliminary calculations suggest that this approach may lead to costs of the order of those for the deep-grooving approach.

Sensitivity analyses were also conducted to examine the effects of variations in interest rate, service life, and length of the planning horizon.

The capitalized cost of the deep-grooving method was only slightly sensitive to interest rate, whereas the cost of the present method was strongly sensitive. Thus between interest rates of 4 and 10 percent the costs per square foot for the present method change from \$19.58 to \$6.98, whereas those for the deep-grooving method change from \$8.13 to \$7.87. For the scarification method the corresponding ranges were from \$28.17 to \$17.25 (with methyl methacrylate) and from \$27.24 to \$17.56 (with calcium nitrite).

Service life had a minor effect on capitalized costs. If, for example, methyl methacrylate treatments yielded service lives of only 50 years, the cost would increase to \$10.50 (deep grooving), and \$19.05 (scarification method), but the ranking would be unchanged.

The effect of changing the planning horizon was trivial; choice of a 50-year period decreased the costs as follows: 2 percent for calcium nitrite and the present method, 4 percent for the scarification/methyl methacrylate/overlay system, and 0.4 percent for the deep-grooving method.

POTENTIAL HAZARDS

No extraordinarily hazardous situations appear to exist with the methods and processes described in this report. The potential fire or explosion hazards associated with methyl methacrylate monomer in concrete impregnation are well known and recommendations for handling have been made (29). Vapor concentrations should be determined to ensure that exposure standards are followed; a closed system would be preferred, if possible. It should be pointed out that the deep-grooving impreg-

nation method would reduce fire hazards by decreasing both the free surface area of the monomer and the volume of monomer present on the surface of the concrete. The use of hot epoxy as an impregnant in lieu of methyl methacrylate would also considerably reduce fire hazards because of its lower volatility and higher flash point.

Flammability is also of concern with several other potential sealants, for most sealants for concrete contain flammable organic solvents such as alcohols or petroleum distillates. Thus care must be taken in handling solutions of silane such as the petroleum sulfonates or commercial corrosion inhibitors. Again, exposure to vapors must be kept to within acceptable limits; this should not be difficult, for the evaporation of liquid from the concrete pores may be expected to be slow. It may be noted that silane solutions and petroleum sulfonates are commonly used in the commercial treatment of concrete or stone, and steel, respectively. Similar recommendations would hold for experimentation with any new sealant or inhibitor.

While calcium nitrite itself is toxic, and a reducing agent, dilute aqueous solutions are commonly used as an admixture for concrete.

Drying by means of gas-fired infrared heaters involves no special problems; normal precautions in storing and handling the large quantities of propane required should suffice. The electrochemical removal of salt would also require normal precautions with respect to the handling of electrical equipment; in addition, caution should be exercised to ensure that impermissible concentrations of chlorine gas do not develop.

With any of these materials or processes, the user and all associated personnel should be familiar with any specific recommendations of the supplier concerning safety and with the standards of the OSHA.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATIONS

This chapter covers interpretation of the findings summarized in Chapter Two and discusses the implications with respect to possible application.

MATERIALS FOR TREATMENT

Methyl Methacrylate

The impregnation of dried bridge-deck concrete has certainly been amply demonstrated using either a soaking or pressurized technique (see Refs. (2,5), which also cite related studies). Although methyl methacrylate can displace some water, the effect of what water remains on freeze-thaw and corrosion resistance is problematic. Thus it seems prudent to ensure that most (say, 90 percent) of the evaporable water in the pores be removed prior to impregnation.

A detailed discussion is given in Appendixes A, C, E, and F.

Inhibitors

Bridge-deck concretes can certainly be impregnated by typical inhibitors such as the alkaline-earth petroleum sulfonates, calcium nitrite, and the commercial penetrant WD-40. However, because the viscosities are higher than that of methyl methacrylate, the rate of penetration is lower than with methyl methacrylate. More detailed study of the concentration and distribution of the active inhibitor component would be desirable. This question is complicated by the fact that several of these inhibitors are in the form of dispersions in a petroleum-based carrier, which could also play a role in the inhibition of corrosion. (See Appendixes C, E, and F for details.)

It would be useful to examine the penetration of the petroleum sulfonates obtained in a pure form and dissolved in, for example, low-viscosity mineral spirits. A suitable low-viscosity solvent for calcium nitrite could also be considered. The causes of problems with durability should be of interest.

In any case, caution must be exercised in treatments with inhibitors because unless the concentration around the rebars is reasonably uniform, corrosion could be activated rather than inhibited due to the formation of concentration cells.

Sulfur

As with methyl methacrylate, the use of liquid sulfur as an impregnant has been demonstrated previously (2,5). Impregnations used in this study are described in Appendixes E and F. A specific problem with durability and corrosion resistance is discussed below and in Appendixes E and F.

Epoxy

The feasibility of impregnating concrete with an epoxy that does not contain a curing agent, and polymerizing the epoxy thermally, was demonstrated earlier (see Ref. (2) and references contained therein), and confirmed in this study. While the impregnation rates at the temperatures used (App. D) are reasonably high, there is a question of stability of the cross-linked network and the effects on durability (App. E).

Hydrophobic Silane

Again, this study confirmed the reported feasibility of impregnating concrete with a hydrophobic silane (App. B). As with the inhibitors, the precise concentration of the silane in the pores and the optimum concentration for good performance are not known, nor is the role of the residual liquid carrier known.

Difficulties with respect to durability of the concrete are discussed below and in Appendix E. The cause of the difficulty should be investigated in view of the fact that corrosion resistance is greatly increased by the presence of silane.

PROCESSES

Normal Impregnation with Methyl Methacrylate

As mentioned previously, drying of the concrete prior to impregnation to remove most of the evaporable water is probably desirable in conservative practice, unless further studies can demonstrate consistently good results. In any case (see App. G), the drying cost is a relatively small component of the total cost, especially for shallow impregnations. It is also noteworthy that the drying cost can be minimized by appropriate selection of conditions (see App. A).

Scarification/Impregnation/Overlaying

The concept of scarification followed by impregnation with a monomer or corrosion inhibitor and overlaying with a relatively impermeable cover of low-slump dense concrete, latex-modified concrete, or polymer concrete, would certainly be feasible in practice.

One possible problem could occur. If a treatment is applied that does not increase strength (e.g., use of a typical non-polymeric inhibitor), scarification might induce small cracks in the substrate that could weaken the concrete. At the same time, because only a shallow impregnation is required, the surface temperatures required for drying would be significantly less than with deeper impregnations (2).

Durability of specific systems is discussed later in this chapter and in Appendix E.

Electrochemical Removal of Salt

The preliminary studies of this project confirm the demonstration by others that chloride ion can be removed electrochemically (6,8,9). The concept of subsequent impregnation with methyl methacrylate also seems valid (9).

At present, costs are not well established. For example, the use of a platinum electrode mentioned in Ref. (8) would be expensive but non-consumable. In this case an ion-exchange resin can be used to trap the chlorine by-product. The use of a copper mesh would also be costly because the mesh would be consumed by reaction with the chloride.

Nevertheless, the process appears to be worth additional field study, as well as detailed and long-term study of the corrosion resistance conferred.

Impregnation by Deep Grooving

The feasibility of facilitating the impregnation process by cutting deep grooves into the concrete to facilitate penetration of impregnant has been clearly demonstrated. Although the process was studied using methyl methacrylate as the impregnant, other impregnants could also be used. The process should be especially useful with high-viscosity materials; however, with liquids other than monomers the grooves would have to be filled (e.g., with polymer concrete) after impregnation.

An advantage of this process stems from the fact that the grooves permit in effect an internal impregnation; the impregnation proceeds laterally as well as vertically, thus saving time. Also by using a monomer, such as methyl methacrylate, the grooves (filled with sand) are automatically filled with a polymer concrete during the process.

Grooves that are shallower than those used here could well be useful in the shallow impregnation of relatively viscous impregnants.

DURABILITY

Overlays

With the freeze-thaw tests used, it is clear that all the overlays (latex-modified concrete, polymer concrete, and low-slump dense concrete) performed as well as normal air-entrained concrete, though low-slump dense concrete exhibited a somewhat greater degree of surface mortar deterioration than the others. This is not surprising because one would expect systems containing polymer to be less sensitive to freezing and thawing. In LMC, the mortar is essentially protected by a film of polymer, and the growth of microcracks is inhibited. With a PC based on PMMA, the matrix itself contains no portland cement and is inherently stable to freezing and thawing. (Many exterior applications of poly(methyl methacrylate) involve such environmental conditions.)

Substrates

Polymer-Containing Systems

The findings with the poly(methyl methacrylate) containing substrates confirm earlier reports of excellent freezing and thawing behavior (see Ref. (2) and the references contained therein). The polymer fills a significant fraction of the pores and bonds well to the cementitious substrate, thus distributing stresses more uniformly and minimizing penetration by salt and water (2,30). Epoxy also performed well, although not quite as well as poly(methyl methacrylate), perhaps because the polymer network is not as efficient due to some degradation at the high polymerization temperatures used. It is also possible that the epoxy (which contains acidic hydroxyl groups) does not bond to the acidic silicate as does an acrylic polymer (which contains basic ester groups). Even though all of these polymers are brittle, their fracture energies are far higher than those of portland cement concretes.

Thus polymer-containing substrates offer by far the best resistance to freezing and thawing.

Other Systems

Surprisingly, the silane-treatment substrates behaved very poorly indeed. Although the reason is unknown, some reaction between the silane and the cement was evident (see App. B); a whitish material was

observed to form. It is also possible that water vapor could condense in the pores, which are presumably only lined with the silane, and result in undesirable internal stresses during freezing and thawing. Further research would be required to determine the mechanism of failure and to see if another concentration of silane or treatment method would yield better results.

As noted earlier, the inhibitors resulted in a wide range of damage, from a relatively slight degree (barium petroleum sulfonate and calcium nitrite) to a clearly unacceptable degree (WD-40). However, even with the less severe cases, the expected lifetime was lower than that of untreated concrete. Although the cause is unknown, it may be related to the compatibility of at least these inhibitors with water; indeed, calcium nitrite is deliquescent and forms a mono and a tetrahydrate. Again, significant stresses may develop on freezing and thawing. (In any case, the inhibitors used were not formulated for the use studied in this project.)

It may be noted that the distribution of the inhibitors must be quite nonuniform. In contrast to the case of concrete containing calcium nitrite as an admixture, here the pores are filled with a material that cannot contribute to strength (or, presumably, stiffness) but that may attract water in a localized fashion. It would be useful to investigate the mechanism of failure in such cases and to see if inhibitors can be found that do not affect strength adversely. (There are many possible inhibitors that could be tested.)

Compatibility

As mentioned earlier, debonding was an especially severe problem with the silane treatment, with all overlays. Therefore, although it had been expected that a polymer concrete overlay might be compatible with a surface containing a hydrophobic silane (silanes do mix with methyl methacrylate), the silane is bonded too strongly to the cement and aggregate to compete with the monomer. It is possible that a suitable treatment might be found; however, the overall durability of the silane-treated material was so low that further study is judged to be of doubtful value (unless a better mode of application is available).

Debonding appears to pose no problem with the polymer-containing and nitrite-containing substrates; however, a significant tendency towards debonding was observed in the case of sulfur, and a lesser tendency with the petronates and WD-40. It seems likely that a wash with mineral spirits coupled with a roughening of the surface would be advantageous in the latter cases in order to remove the oily components.

Corrosion Resistance

General

As mentioned above, polarization resistance, R_p , was used as a measure of resistance to corrosion. Specimens were prepared by embedding equally spaced reinforcing

bars as electrodes in rectangular blocks of concrete. The blocks were cast so that one bar (bar 1) was surrounded by a chloride-rich concrete, while the remaining 3 bars were surrounded by plain concrete; one pair of bars surrounded by plain and chloride-rich concrete was designated as the "upper" pair. (For further details, see App. F.) Treatments were then applied to the upper portion of the specimen for comparison with control specimens.

In this way, it was hoped to simulate a bridge-deck configuration. Thus tests of polarization resistance across the top 2 bars (bars 1 and 2) should reflect the effects of development of both anodic and cathodic areas in the upper mat of reinforcing steel, while tests across bars 1 and 3 or 1 and 4 should reflect the development of cathodic areas in the lower mat (assuming a conductive pathway between the bars).

It is believed that the 3-electrode system used here (i.e., 2 reinforcing bars as electrodes plus a standard calomel electrode as reference) did yield a reasonably accurate ranking of corrosion resistance in the various specimens. Indeed the range of behavior was unexpectedly broad.

To be sure, a more refined system that would take account of variations due to such factors as the presence of moisture would be desirable in any future experiments. It would also be desirable to separate screening tests to evaluate the effectiveness of treatments from tests to determine the behavior of reinforcing steel bar pairs (in the type of specimen used here) or reinforcing steel mats. Finally, clearly longer term tests would be in order.

The question of applicability to measurements on actual decks in field trials also arises. Such consideration was beyond the scope of this project. However, in any field trials, the state of the art with respect to the evaluation of corrosion in the field should be critically reviewed.

Mechanisms of Protection Against Corrosion

Two major protective mechanisms are: (1) the physical isolation of the elements of the electrochemical involved in corrosion, and (2) specific chemical reactions or interactions between an added compound (a corrosion inhibitor) that results in passivation of the steel. Although this study was not designed to investigate the mechanisms of protection, clear differences were found between treatments that filled the pores in the concrete (e.g., impregnation with methyl methacrylate) and inhibited the intrusion of water, and treatments that presumably did not seal the pores (silane) or that involved compounds believed to act as specific corrosion inhibitors (e.g., WD-40). With treatments that filled the pores, the values of ΔE , the difference in polarization response potentials, tended to increase significantly, while with treatments using corrosion inhibitors, the values tended to decrease or remain nearly unchanged. This observation supports the earlier conclusion that the polarization tests did in fact measure

relevant phenomena.

It should be noted that treatments which improved the corrosion resistance between the upper steel bars also improved the corrosion resistance when measured between an upper and a lower bar.

Specific Systems

Clearly poly(methyl methacrylate) systems in which the concrete was dried prior to treatment exhibit outstanding resistance to corrosion, at least over the period of study involved (several months). As mentioned earlier, inconsistent results were found with systems that were not so dried prior to overlaying; at least for the present, prior drying is recommended.

The concept of partial pore sealing using the hydrophobic silane is certainly valid with respect to improving corrosion resistance, but not yet with respect to durability. Whether or not a satisfactory balance between corrosion resistance and durability can be obtained with this system or with another hydrophobic sealer is not known at this time.

The concept of treatment with a corrosion inhibitor appears to be valid, at least over a short test period. Additional research would be needed to see if the short-term benefits are sustained over a long period of time.

A study of calcium petronate, either in its present form or in a solution of the neat material in a nonoily liquid, would be valuable, as would additional research on calcium nitrite and other inhibitors. Again, the question of durability must be coupled with the question of corrosion resistance.

A study of the effectiveness of impregnation with methyl methacrylate following the electrochemical removal of salt would also be useful.

A more detailed discussion of the foregoing issues is contained in Appendix F.

COST EFFECTIVENESS

The Model

While various scenarios other than the one selected can be envisaged, the model offers a reasonable approach to ranking the probable cost effectiveness of different rehabilitation procedures. The ability to examine the sensitivity of cost effectiveness to the several factors involved (e.g., the durability of the components of a system as well as the first costs) should be advantageous in identifying the most critical parameters.

Of course, the model can only offer guidelines; the specific numbers obtained should not be construed as absolute costs for a specific system. Actual costs will depend very much on the details of the particular deck involved, as well as on refinement of estimated costs for novel treatments.

Specific Systems

Use of the model leads to results that

are somewhat surprising. All the treatments that involved the use of methyl methacrylate without prior scarification lead to predicted capitalized costs that are lower than those of the present method of rehabilitation, which comprises the following steps: (1) patching spalls with hot-mix bituminous concrete until spalling extends to 10 percent of the deck surface; (2) removing the deteriorated concrete and bituminous patches, scarifying (1/4-inch deep) over the remainder of the deck, and installing a 1-1/2-inch-thick latex-modified concrete (LMC) overlay; (3) patching the overlay (and deck) as necessary throughout the estimated 15-year life of the overlay; (4) repeating steps (2) and (3) until the original deck is 50 years old; and (5) replacing the entire deck with a deck having epoxy-coated reinforcing steel.

The most cost-effective of these methods is predicted to be the deep-grooving method, although even the soak-impregnation method exhibits a reasonable cost-effectiveness. Deep grooving might also be advantageous with nonpolymeric impregnants. The electrochemical removal of salt followed by polymer impregnation is also worth further attention because the method should be relatively cheap and has been demonstrated in the field. In contrast, the case of scarification prior to treatment leads to predicted capitalized costs that are invariably higher than for the present method.

Inspection of the calculations (App. G) and of the data on durability (App. E) and corrosion resistance (App. F) reveals an interesting point. The factor limiting the useful life of the various systems is often, if not always, durability, not corrosion resistance. In this respect, treatment with methyl methacrylate has a major advantage because it has a very beneficial effect on strength. In addition, the deep-grooving method is an especially cheap process in comparison with the others.

This is not to say that there is no room for a lowering of costs of the more expensive systems. If the cost of scarification can be decreased, if the durability of inhibitor-impregnated systems could be increased to that of plain concrete, or if the durability of overlays could be increased, significant savings could be effected.

RECOMMENDED PROCEDURES

On the basis of all the factors considered, treatment with methyl methacrylate is recommended for further field evaluation. In particular, the deep-grooving method should be examined; further evaluation of the soaking or pressure technique would also be valuable. The electrochemical method should receive attention if coupled with polymer impregnation.

It would also be useful to evaluate the use of an inhibitor, especially calcium nitrite (e.g., using prior scarification). Although the predicted costs seem high, it would be useful to determine long-term effectiveness as a guide to possible future development.

In all cases, the state of corrosion should be monitored over a long period of time. The method to be used should be selected in the light of a critical review of current measuring techniques and discussion with the FHWA.

POTENTIAL HAZARDS

All of the materials recommended (methyl methacrylate, calcium nitrite, and commercial corrosion inhibitors) are or have been used in commercial practice, and the essential elements of all the processes described have been demonstrated in the field (impregnation with methyl methacrylate, scarification, overlay placement, and the electrochemical removal of salt). Provided that standard precautions are adopted (in consultation with suppliers) with respect to the handling of flammable and toxic materials, and of electrical equipment used outdoors, no unusual hazards are anticipated with the systems recommended in this report.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The following general conclusions have been drawn:

1. The cost-effectiveness model developed is useful in comparing probable cost-effectiveness and in identifying limiting factors in predicting useful life.
2. The linear polarization method is convenient and sensitive for the ranking of corrosion resistance; the freeze-thaw method used is also sensitive to the nature of rehabilitation treatments applied.
3. The concept of treatment with methyl methacrylate without scarification is probably more cost-effective than the current rehabilitation procedure. In particular, the deep-grooving approach appears to offer minimum cost. The use of polymer impregnation following the electrochemical removal of salt is also probably cost-effective.
4. The concept of scarification followed by impregnation with a polymer and placement of a low-permeability overlay is valid, but probably less cost-effective than the current rehabilitation procedure, at least at the present time.
5. The deep-grooving technique could probably be used to advantage with impregnants other than methyl methacrylate; however, improvement in the durability of such systems is required.
6. The concept of impregnation with a corrosion inhibitor also appears to be valid with respect to the improvement of corrosion resistance; however, inhibitors are needed that do not adversely affect durability of concrete.
7. Durability of substrates and overlays tends to be a limiting factor in determining useful life.

SUGGESTED RESEARCH

The following research is recommended:

1. Longer term studies of corrosion resistance in all systems examined or suggested as candidates in this study. Refinement of the test technique would also be desirable.
2. Extension of corrosion studies to examine in more detail electrochemical effects between steel reinforcing bars or reinforcing mats.
3. Extension of corrosion studies to identify inhibitors that do not decrease durability of concrete.
4. Further use of the economic model with other scenarios to identify critical elements in the cost that would merit investigation.
5. A field trial with at least the deep grooving/methyl methacrylate system. A trial of the scarification/inhibitor approach would also be useful, as well as a trial with the electrochemical method. In all cases, the progress of corrosion should be monitored over a long period of time by the best technique available.

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APPENDIX A

IMPROVEMENT OF DEEP IMPREGNATION TECHNIQUES
BY DEEP GROOVING

INTRODUCTION

The deep-polymer-impregnation technique for concrete bridge decks developed under NCHRP Project 18-2 is to dry the concrete to a depth of 4 inches, allow the concrete to cool-down to 100F, impregnate the monomer mixture, (methyl methacrylate/trimethylolpropane trimethacrylate/azobisisobutyronitrile (MMA/TMPTMA/AZO), 100:10:0.5) into the surface of the deck, and polymerize the monomer using hot water or steam. A propane-fired infrared heater with a surface temperature of about 600F may be used to dry the concrete, and the concrete is considered dry when the temperature at a depth of 4 inches is equal to 230F. The impregnation process requires several days to obtain a depth of 4 inches by ponding (less for pressurization), and the polymerization equilibrium temperature of approximately 130F is maintained for a period of 25 hours.

To improve the present system, several problems must be addressed, especially the following:

1. Reducing the impregnation time.
2. Improving the drying system.
3. Sealing of pressurization systems.
4. Simplifying the present impregnation process.
5. A better understanding of the polymerization rates.
6. Minimizing the fire hazard.

While major emphasis in this project was given to a combination of scarifying and shallow impregnation, it seemed appropriate to also reexamine the deep impregnation approach, which was shown to yield excellent corrosion resistance, at least in the laboratory (1).

One approach to improve the impregnation process is to cut grooves in the deck -- say to a depth of 1/2-inch above the upper reinforcing bar -- and to use the grooves as vessels to contain the MMA monomer system. Following impregnation, the grooves can then be filled with sand and saturated with the MMA monomer system, and the monomer absorbed in the sand and concrete polymerized. The deep-grooving method would thus eliminate the need for an impregnation vessel. Further, the grooves can be cut on "contour" lines (lines of equal elevation), thereby eliminating the problems associated with grade, cross-slope, and superelevation that are encountered with the ponding method. Also, the method should reduce the impregnation time, simplify the polymerization process by eliminating the need to attach the hot-water polymerization vessel to the deck, possibly provide a more skid-resistant surface, and reduce the bridge-deck maintenance problem by upgrading the strength,

freezing and thawing durability, and wear-resistant properties of the concrete. In addition, the deep-grooving method may reduce the fire hazard associated with the impregnation process by decreasing the potential flame surface area.

Potential problems that exist with the method include: the generation of thermal stresses that might cause a shear-type failure within the concrete between the grooves; the effectiveness of the grooves in reducing the impregnation time; and possible susceptibility of the polymer-concrete filling the grooves to pop-out during freezing and thawing cycles. Also, problems common to both the earlier methods and the deep-grooving method still remain, such as improving the drying system and a better understanding of in situ polymerization rates.

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

1. To develop and optimize the deep-grooving impregnation process.
2. To optimize the gas-fired infrared drying method considering time and energy expended.
3. To optimize the hot-water polymerization method of the MMA impregnant system considering time and temperature.
4. To demonstrate the deep-grooving impregnation system in the laboratory.

EXPERIMENTAL

General

The deep-grooving impregnation method consists of the following processes:

1. Cutting the grooves of a determined depth, width, and spacing.
2. Drying the concrete to a depth of 1/2 inch below the upper reinforcing steel mat and letting the concrete cool to a temperature equal to or less than 100F.
3. Filling the grooves with a methyl methacrylate (MMA) monomer system and impregnating by the soak method to a depth that will encapsulate the upper reinforcing steel mat.
4. Placing the hot-water containment vessel over the impregnated area and maintaining the temperature of the water at approximately 205F until the monomer is polymerized.

To deeply impregnate concrete using the MMA monomer system, it is usually considered that the concrete must be dry (1). If unreasonable problems occur in the drying of a grooved surface, the deep-grooving method is not feasible. Therefore, a preliminary study was first conducted to estimate an optimum groove spacing and to determine the effects of drying on the grooved surface. Following the preliminary study, the horizontal and vertical impregnation rates were determined to aid in the evaluation of the optimum groove spacing, width, and depth. Then the effects of groove width on the rate of impregnation were determined and the effect of time on

the optimized groove width, depth and spacing were evaluated. The rate of polymerization and drying was investigated and laboratory demonstrations of the deep-grooving impregnation system were performed. Figure 1 presents a flow diagram of the experimental design.

Casting of Slabs

The concrete mixture design used to cast laboratory specimens and the average measured quality control parameters are given in Table 1. The mixture design quantities were calculated in accordance with PennDOT specifications in effect in the late 1960's and early 1970's when most of the Interstate system was being constructed. The water to cement ratio was increased from 0.47 (maximum allowable) to 0.49 to increase the workability as measured by slump to a consistency that was most likely used in the construction of bridge decks at that time. The laboratory-cast specimens were moist-cured for a period of 40 days because it has been shown that the permeability of concrete decreases to an approximately constant value at this age (4).

The reinforced-concrete laboratory-demonstration slab was cast June 25, 1976. Class AA concrete was specified and delivered by a local supplier. Table 1 also gives the concrete batch quantities supplied by the concrete supplier and the measured quality control parameters. The slab, 6-feet and 8-inches thick, was constructed with 2 inches of clear cover top and bottom, and 2 reinforcing mats (1 top and 1 bottom) with #5 bars 8 inches on center in one direction and #4 bars 6 inches on center in the other direction.

Grooving Studies

Preliminary Investigation

As previously stated, for the deep-grooving impregnation to be feasible, the concrete between the grooves must not fail in shear due to thermal stresses induced during drying. Therefore a preliminary investigation was conducted to determine whether one should be concerned with the speculated failure mechanisms. The investigation consisted of first estimating an optimum groove spacing and then cutting grooves in a slab and drying the grooved area with an IR heater.

To estimate an optimum groove spacing, two 6-inch by 6-inch by 21-inch beams were cast, moist-cured, and dried to constant weight in a forced-air constant-temperature oven set at 230F. The beams were then allowed to cool at room temperature and a series of 1/2-inch diameter holes, 1-1/2 inches deep were drilled in the finished surface as shown on Figure 2. In addition, a metal containment vessel 5 inches square (interior) was attached to the beam's finished surface using a silicone rubber adhesive. Impregnation time was approximately 48 hours for beam B-1, and 24 hours for beam B-2. The beams were placed in a constant-temperature water bath set at 200F for a period of 24 hours after the holes

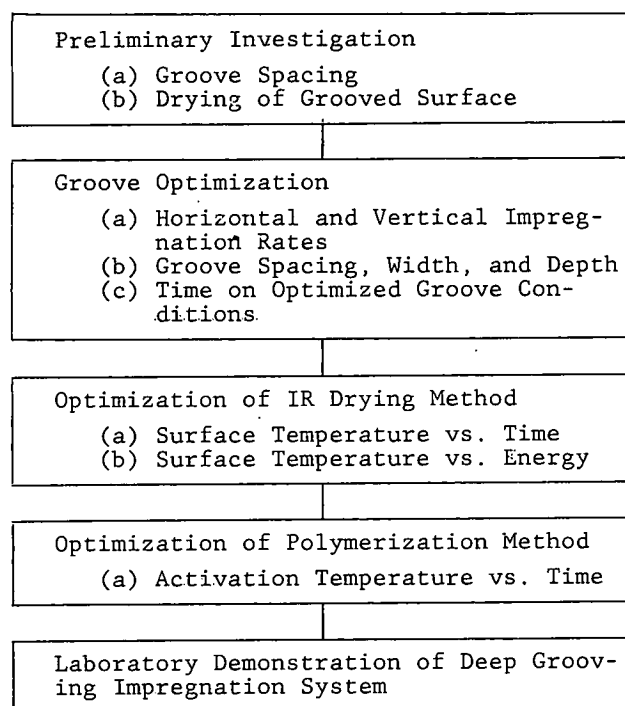


Figure 1. Experimental design flow diagram.

Table 1. Concrete batch quantities (one cubic yard).

Item	Lab Specimens S.S.D. Wts (lb)	Rein. Slab S.S.D. Wts (lb)
Cement	596	598
F.A. ^b	1129	1095
C.A. ^b	1914	1922
Water	292	312
Total	3931	3918
w/c	0.49	0.53
Slump (in.)	4½	5
Air (%)	5.0	5.6
Unit Wt. (pcf)	145.4	145.1
Comp. Str. (psi)		
7 day	--	3280
28 day	4230	--
40 day	4390	--

^aConversion: 2.2 lb - 1 kg.

^bF.A. = fine aggregate; C.A. = coarse aggregate.

were filled with sand and saturated with MMA. To determine the depth of impregnation, saw-cut surfaces were acid-etched. The drying, impregnation (soak method), polymerization, and determination of depth of impregnation were the same for all the laboratory-prepared specimens.

The reinforcing schedule for the slab and location of the 12-inch long grooved area are shown in Figure 3; the grooves

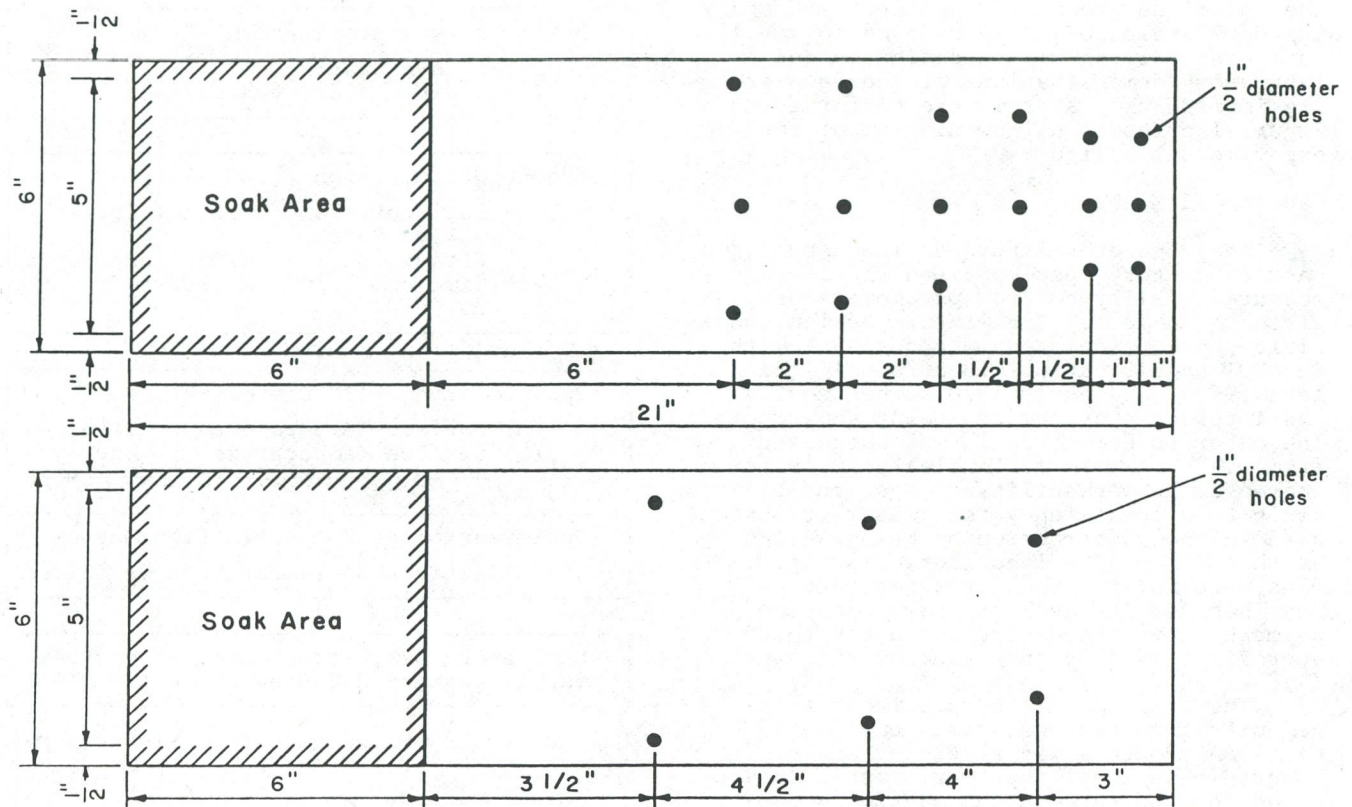


Figure 2. Design of preliminary groove investigation beams (Top B-1 and Bottom B-2).

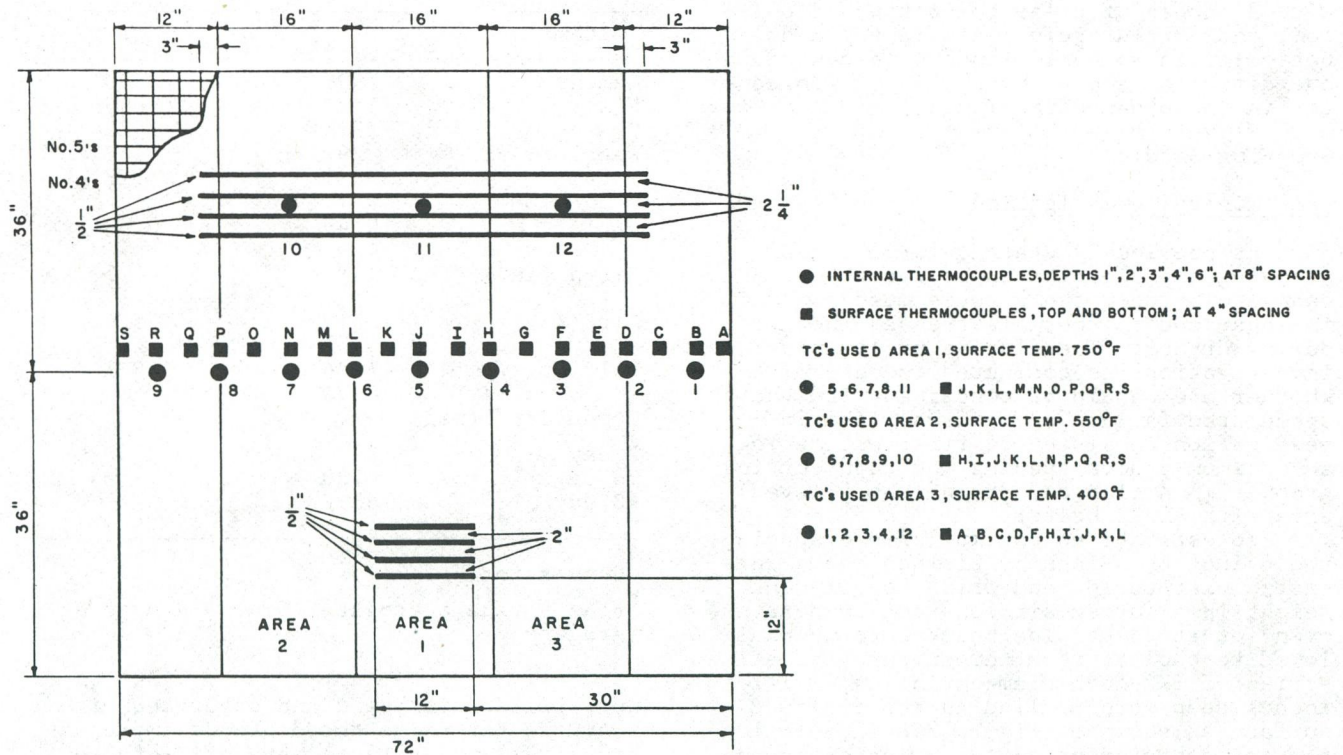


Figure 3. Design of reinforced concrete slab for grooving study.

are shown at the bottom center. Ceramic-shielded, copper-constantan thermocouples were used to measure the surface and interior temperatures during drying. Holes were drilled and thermocouples were set at depths of 1-3/4 and 4 inches from the surface at the centerline of the groove and midway between the grooves, in addition to the surface probe. Four grooves about 1/2-inch wide, 1-1/2 inches deep, and 1 foot long were cut in the slab using a gasoline-driven, walk-behind, water-cooled, concrete saw with Carborundum blades. A 1-foot by 2-foot propane-fired IR heater was placed 12 inches above the grooved area in order to maintain a surface temperature of approximately 600F. The drying criterion was the attainment of a temperature of 230F at a depth of 4 inches (1). A metal shield encompassed the IR heater in order to prevent blow-out (flame-out of the burner). Visual observations of slab cracking were made during the heating and cooling cycle.

Horizontal and Vertical Impregnation Rates

To evaluate the horizontal and vertical impregnation rates, six 6-inch by 6-inch by 21-inch beams were cast, moist-cured, and cut into 6-inch cubes with a diamond blade, water-cooled slabbing saw.

The cubes were dried, the sides coated with epoxy, and impregnated. The horizontal impregnation cubes were turned on edge and impregnated perpendicular to the cast direction. The top 1/4-inch of the vertical impregnation cubes was cut off and the specimens were impregnated parallel to the cast direction. During impregnation, the methyl methacrylate was contained as in the preliminary impregnation study. The impregnation times were 9, 25, and 49 hours. After impregnation, the cubes were cut in half and the depth of impregnation measured at the center of the impregnated area.

Optimization of Groove Width and Spacing

A 6-inch section was cut from six additional 6-inch by 6-inch by 21-inch beams. The six 6-inch cubes were dried, sides were coated with epoxy, and they were impregnated for a period of 24 hours. The 24-hour impregnation time was selected based on the depth of impregnation measured in the vertical-horizontal impregnation rate phase of the investigation. The depth of impregnation was measured for each cube specimen and two of the remaining portions of the beams (15 inches in length) were selected for impregnation at the estimated optimum groove spacing of 3 inches. Groove spacing is measured from edge of groove to edge of groove. The optimum groove width is based on a groove cross-sectional area equal to 10 percent of the area to be impregnated by a single groove with a groove depth equal to 1-1/2 inches. The 10 percent value is based on an average calculated 10 percent volume loading rate for methyl methacrylate soak-impregnated concrete. The 1-1/2-inch depth was selected on the basis of a clear cover of 2 inches of concrete and the grooves being cut to a depth of 1/2 inch above the upper rebar. The estimated optimum groove width was

calculated to be 1-1/8 inches wide. The beams were grooved by cutting a groove 1/8-inch perpendicular to the beam length and on the edge lines of the groove. The concrete between the two cut grooves was then removed with a hammer and cold chisel. Four grooves were made in 2 beams with a 3-inch grooving spacing. The beams were dried, the sides were coated with epoxy, the ends of the grooves were sealed with epoxy putty, were impregnated, and were polymerized; the depth of impregnation was then measured at the centerline of the grooves and at the centerline between the grooves. To make the depth measurements, the beams were first cut along the centerline of the grooves, and then perpendicular to the grooves along the centerline of the beam. Figure 4 shows a grooved beam prior to impregnation.

In light of the results for the 2 beams with a 3-inch spacing, the sample size of the grooved beams was reduced to 1 and the groove spacing was increased to 4 and 5 inches. Three grooves were cut in each beam, and the depth and width of the grooves were held constant. The 2 beams were impregnated and the depths of impregnation were measured to verify the optimum groove parameters at an impregnation time of 24 hours.

Next, the effect of groove width was investigated by decreasing the groove width to 7/8 and 5/8 inches with a groove spacing of 4 inches and groove depth of 1-1/2 inches. The 4-inch spacing was chosen because it was believed that if groove spacing had an effect, the effect would be more pronounced at a spacing greater than the optimum.

The effect of time of impregnation was examined by first determining the vertical rate of impregnation for a set of six 6-inch by 8-inch by 22-inch beams. A 6-inch section was cut from each of the 6 beams, and 2 sections were impregnated at times of 9, 16, and 27 hours. Based on a requirement of a minimum depth of impregnation equal to 2-1/4 inches (1/2 inch above and below the upper rebar mat plus two #5 reinforcing bars), a 16-hour impregnation time was selected. With a groove depth of 1-1/2 inches, optimum groove para-

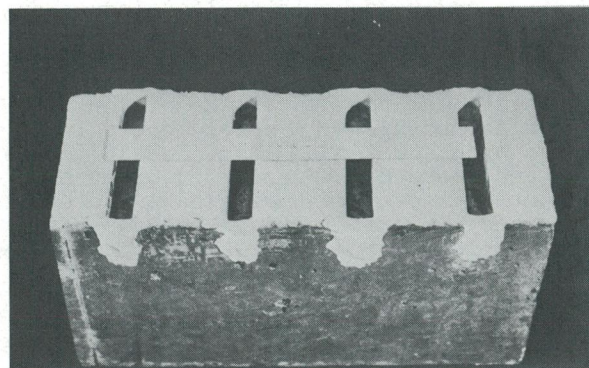


Figure 4. Grooved beam prior to impregnation.

meters were calculated (groove width equal to 2-1/4 inches). In addition to a beam with optimum parameters and an impregnation time of 16 hours, a beam was impregnated with a groove spacing greater than the optimum, but with all of the other parameters held constant (groove spacing equal to 3 inches). The depths of impregnation were determined for the beams, and the groove depths were compared with the surface pond depths, as was done for all the grooving studies.

Optimization of Polymerization Time

The effects of temperature on the time of in situ polymerization of the methyl methacrylate system in concrete was investigated by impregnating 2-inch mortar cubes. The cubes were cast with a thermocouple set in the center of each cube, moist-cured for 3 days, dried, and impregnated for 4 days to achieve a uniform weight gain of methyl methacrylate. The cubes were wrapped in aluminum foil and placed in a constant-temperature water bath. The internal temperature of the cubes was monitored in an effort to measure the temperature rise due to the polymerization exotherm. Periodically, 2 cubes were removed from the bath and tested in compression. The time of in situ polymerization of the methyl methacrylate system was investigated at polymerization temperatures of 114F, 122F, 130F, and 148F.

Optimization of the IR Drying Method

In this study, the simply supported slab used in the preliminary drying study was employed. Although no analysis of thermal cracking was made, the deflection of the slab was measured with a dial gage with the smallest division equal to 1 thousandth of an inch and recorded at the centerline of the slab during each drying cycle. Visual observations for evidence of thermal cracking were made, and a 4-inch diameter core was taken from each test area after impregnation and polymerization and examined under a reflective light microscope at a magnification of 100X.

Three areas of the slab were dried with a 1-foot by 4-foot IR heater. The internal temperatures were measured and recorded at depths from the surface of 1, 2, 3, 4, and 6 inches at 4 locations along the centerline of the slab. The surface temperature under the center of the heater, at the edge of the shield, and at 4-inch spacings along the centerline of the slab were also measured. A metal shield 16 inches wide, 60 inches long, and 36 inches high encompassed the heater in order to prevent blow-out and to increase the drying efficiency. In addition, 3 inches of fiberglass insulation was placed on top of the slab outside of the shielded area to also aid in the drying efficiency. The insulation was also placed inside the shielded area at the completion of the heating cycle. The insulation remained in place until the end of the cooling cycle in order to help reduce the thermal stresses during the cooling cycle. The location of the thermocouples and drying areas are

shown in Figure 3.

Area 1 was dried using a constant surface temperature of 750F, area 2 at 550F and area 3 at 400F. The constant surface temperatures were achieved by varying the distance the heater was placed above the slab and reducing the flow of propane. For a surface temperature of 750F, the heater was placed 14 inches above the slab, 20 inches for 550F and 27 inches for 400F. The test area was considered dry when the temperature at a depth of 4 inches was equal to 220F for the three drying cycles. Figure 5 shows the slab and an investigator recording visual observations during the 550F surface-temperature drying test. The propane tank was weighed before and after each drying test to determine the amount of propane used.

Laboratory Demonstration of Deep-Grooving Impregnation Method

Cores were taken from the slab prior to the drying tests. The cores were dried, sides coated with epoxy, impregnated, polymerized, and cut in half to determine the rate of impregnation for the slab. The impregnation times used were 9, 16, and 40 hours. Based on an impregnation time of 16 hours to obtain a depth of impregnation of 1/2 inch below the upper reinforcing steel mat, the optimum groove spacing was determined to be 2-1/4 inches. Four grooves about 1-1/2 inches deep, 1/2 inch wide, and 4-1/2 feet long spaced at 2-1/4 inches apart were cut in the slab using the Milwaukee "walk-behind" slab saw. The location of the grooves is also shown in Figure 3.

Thermocouples were placed at depths of 3 and 4 inches below the top surface in the center of each of the grooved impregnated areas. For areas 1 and 2 the IR heater was turned off when the temperature reached 230F at a depth of 4 inches and when the temperature was 220F for area 3 (the steady state temperature at a depth of 4 inches using a 400F surface temperature).

The slab was allowed to cool down to approximately 100F, impregnated for 16 hours, and the grooves were filled with sand and saturated with methyl methacrylate.

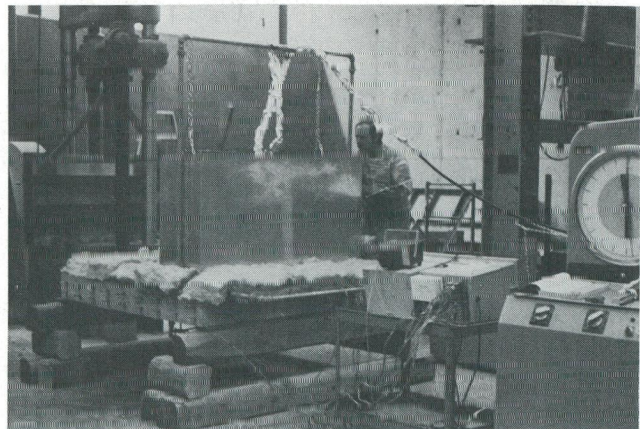


Figure 5. IR-drying of slab (Area 2).

During the impregnation, the area was covered with a sheet of polyethylene to reduce the evaporation rate and fire hazard. After the sand was saturated with methyl methacrylate, a sheet of aluminum foil was placed over the impregnated area. A 12-inch by 14-inch by 6-inch, 4-sided aluminum containment vessel lined with 4-mil-thick polyethylene was placed over the impregnated area and boiling water was placed in the vessel. A piece of aluminum sheet metal with two 500-watt immersion heaters penetrating through the aluminum sheet was set on top of the vessel. The polymerization vessel was then covered with 6 inches of fiberglass insulation and the temperature of the water was maintained at 208F. After the polymerization, a 4-inch diameter core was taken from each impregnation area and the depth of impregnation was determined. Figure 6 shows the grooves cut in the slab and Figure 7 shows the slab polymerization of area 1.

EXPERIMENTAL RESULTS

Preliminary Investigation

Table 2 gives the results of the preliminary impregnation study. The data indicate that dry concrete can be impregnated by grooving and that the time to impregnate to a specified depth can be reduced relative to ponding impregnation. The impregnation depth gained was 1/2 inch to 1-1/4 inches. The variability may be related to the percent of cross-section of the bottom of the hole taken up by the coarse aggregate. The coarse aggregate at the hole bottom would reduce the flow area since the flow of methyl methacrylate through dry concrete is confined to the capillary system in the cement paste.

Visual observations during the drying cycle revealed that no macrocracking of the concrete occurred between the grooves. These results are most probably related to small temperature differential between the groove centerline and spacing centerline at a depth of 1-3/4 inches below the surface (1/4 inch below the bottom of the groove) (see Table 3). At a depth of 4

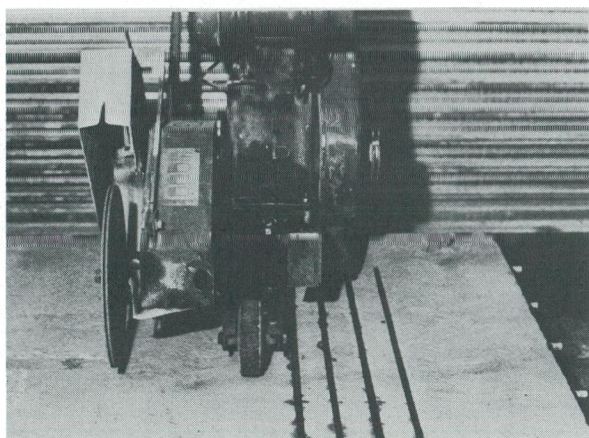


Figure 6. Grooved slab.

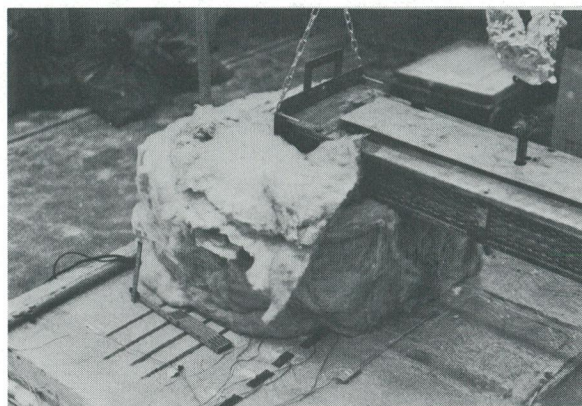


Figure 7. Polymerization of methyl methacrylate in slab (Area 1).

inches, the temperature differential increased from a maximum of 8F at 1-3/4 inches to 20F. Because the surface temperature changes very rapidly in both the heating and cooling cycles, stresses large enough to crack the concrete might be expected. However, no cracking was observed within the heated area, although one crack did occur outside of the heated area. This crack extended through the full depth of the concrete and ran from the edge of the

Table 2. Impregnated depths for preliminary investigation.

Depth at Center of Hole (in.)	Depth at Between Holes (in.)	Depth at Center of Hole (in.)	Depth at Center of Pond Area (in.)	Depth Gained (in.)
<u>Beam B-1, 48-Hour Impregnation Time</u>				
1-inch hole spacing				
4-7/8	4-7/8	4-7/8	3-5/8	1-1/4
1½-inch hole spacing				
4-7/8	4-7/8	4-7/8		1/1/4
2-inch hole spacing				
4-7/8	4-7/8	4-7/8	1-1/4	
<u>Beam B-2, 24-Hour Impregnation Time</u>				
3-inch hole spacing				
3-1/4	2-3/4	3-1/4	2-3/4	1/2
4-inch hole spacing				
3-1/4	2-1/2	3-1/4		1/2
4½-inch hole spacing				
3-1/2	2-1/2	3-1/2	3/4	

Table 3. Temperature ($^{\circ}\text{F}$) measurements for preliminary drying investigation

Time Hours	Surface	Position		4 in. at ¢ of Groove	4 in. at ¢ of Space	Ambient
		1-3/4 in. at ¢ of Groove	1-3/4 in. at ¢ of Space			
0	78	70	70	70	70	78
$\frac{1}{4}$	490	88	86	70	70	--
$\frac{1}{2}$	554	128	126	74	74	--
1	600	204	198	108	98	--
2	616	248	250	162	148	--
3	622	304	304	216	202	--
4	630	334	338	240	220	--
4-3/4	640	348	352	250	230	--
End Heating Cycle						
5	384	342	350	254	234	--
5-1/2	306	326	330	256	242	--
6	204	266	262	242	236	--
7	160	218	214	216	210	84
20	88	88	88	88	88	--
21	84	84	84	84	84	70

slab to the edge of the metal shield; the crack was located approximately at the centerline of the heater and occurred at about 1 hour into the heating cycle. Nevertheless, the preliminary drying test did indicate that a grooved concrete surface can be dried using the IR heater without the occurrence of thermally induced cracking between the grooves. Thus the deep-grooving impregnation method appears to be feasible.

Horizontal and Vertical Impregnation Rates

A linear regression analysis was performed on the horizontal and vertical impregnation data using a Mini-Tab Program. The equation used to model the impregnation was $Y = B_0 + B_1 X_1$ with $B_0 = 0$ because of the physical constraint at zero time, at which the depth of impregnation is equal to zero. The best-fit line was obtained when the depth of penetration as the dependent variable (expressed in inches) and the square root of time as the independent variable (expressed in hours). This shows that the data fit the Rideal-Washburn equation for fluid flow in a porous medium as was found earlier (1,5). Table 4 gives the individual impregnation results and Table 5 gives the results of the linear regression analyses and shows that the slopes of the curves are equal. Thus the horizontal rate of impregnation is equal to the vertical.

Optimization of Groove Width, Depth, and Spacing

The data given in Table 6 show that the depth gained by grooving is approximately 72 percent of the groove depth. Also, as the ratio of groove spacing to impregnation depth below the groove bottom (impregnation ratio) increases from 1.0 at the 3-inch spacing to 1.4 at the 4-inch spacing and to 1.7 at the 5-inch spacing, the depth of impregnation at the centerline

Table 4. Depth of impregnation of the horizontal and vertical impregnation specimens.

Specimen	Impregnation Time (hours)	Depth of Impregnation (inches)
Horizontal		
G-1-1	9	2.02
G-1-2	9	2.49
G-1-2	9	2.49
Vertical		
G-4-1	9	2.35
G-4-2	9	2.47
G-4-3	9	2.39
Horizontal		
G-2-1	25	3.71
G-2-2	25	3.94
G-2-3	25	3.63
Vertical		
G-5-1	25	3.58
G-5-2	25	3.27
G-5-3	25	3.27
Horizontal		
G-3-1	49	4.18
G-3-2	49	5.65
G-3-3	49	5.11
Vertical		
G-6-1	49	5.30
G-6-2	49	5.30
G-6-3	49	5.18

^aConversion: 1.00 in. = 2.54 cm.

Table 5. Results of linear regression analyses.

	Slope ^a	Coefficient of Determination
Horizontal Impregnation	0.731	0.989
Vertical Impregnation	0.733	0.996

^aBased on time in $\sqrt{\text{hours}}$ and depth in inches.

between the grooves decreases for the 24-hour impregnation time. Figures 8, 9, and 10 show the effects of an increasing impregnation ratio. That is, as the impregnation ratio increases above 1.0, the boundary of the impregnation becomes more sinuous. Also, the depth of impregnation, or the shape of the impregnation boundary, appears not to be affected by reducing the groove width from 1-1/8 inches to 5/8 inch (see Table 6).

Also, as indicated in Table 6, time has no effect on the impregnation ratio. At an impregnation ratio equal to 1.0 the boundary impregnation is straight and at 1.4 it becomes slightly sinusoidal. Figure 11 shows the slightly sinuous boundary between the grooves and the straight boundary impregnation below the grooves at an impregnation time of 16 hours and a groove width and depth equal to 3/4 inch and 1-1/2 inches, respectively.

The optimum groove spacing for the 16-hour impregnation time of 2-1/4 inches was determined with the optimum impregnation ratio equal to 1.0 and the desired depth of impregnation below the groove equal to 2-1/4 inches. The time required to impregnate was estimated from the rate of

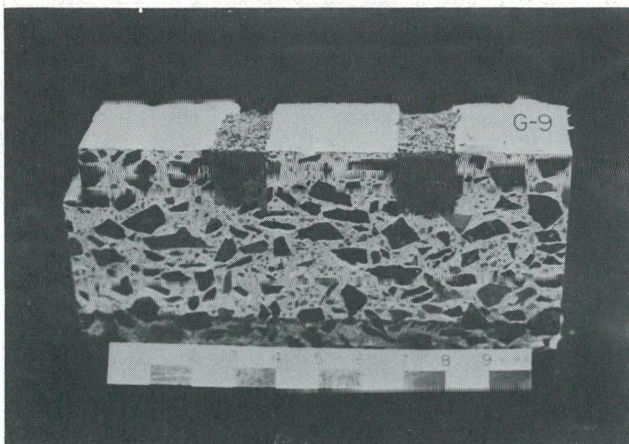


Figure 8. Grooved beam after polymer impregnation. Impregnation time, 24 hours; groove spacing, 3 inches; groove width, 1-1/2 inches; groove depth, 1-1/2 inches; impregnation ratio, 1.0.

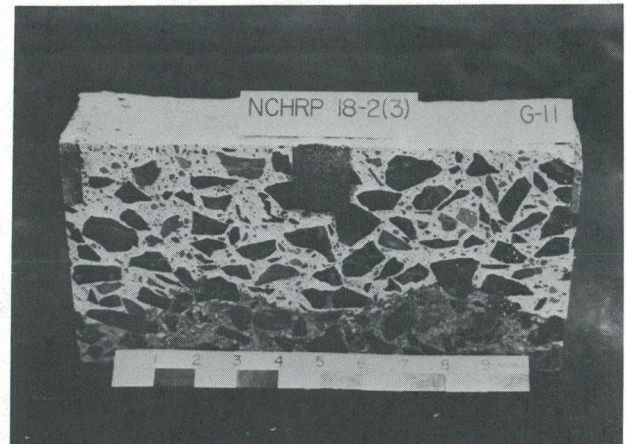


Figure 9. Grooved beam after polymer impregnation. Impregnation time, 24 hours; groove spacing, 5 inches; groove width, 1-1/2 inches; groove depth, 1-1/2 inches; impregnation ratio, 1.7.

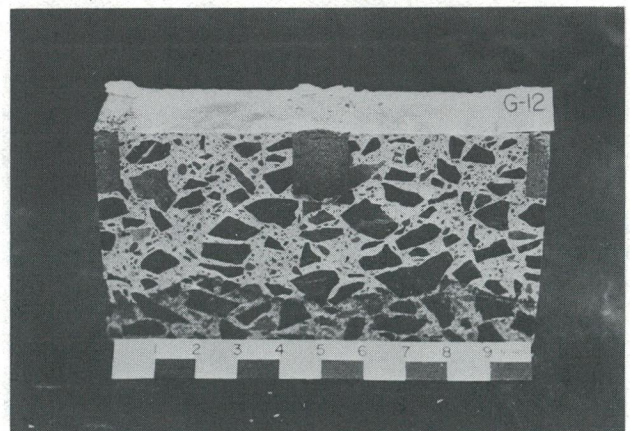


Figure 10. Grooved beam after polymer impregnation. Impregnation time, 24 hours; groove spacing, 4 inches; groove width, 1-1/8 inches; groove depth, 1-1/2 inches; impregnation ratio, 1.4.

impregnation (slope of the curve depth in inches as a function of the square root of time in hours for G-17 and G-18:

$$B_1 = 0.561, r^2 = 0.998).$$

The average depth gained for the beams presented in Table 6 is about 1-1/8 inches. This is about 75 percent of the groove depth. A possible reason for the fact that the depth gained was not equal to the groove depth is that the coarse aggregate may reduce the effective impregnation area at the bottom of the groove. However, reducing the effective impregnation area by decreasing the groove width appeared to have no effect for the groove widths that were evaluated.

Of more interest than the depth gained is the depth of impregnation below the groove (measured from the groove base) expressed in terms of the depth of impregnation by ponding (groove ratio). The groove

Table 6. Depths of impregnation for grooved beams, groove depth 1-1/2 inches.

Specimens	Depth at ¢ of Groove (in.)	Depth at ¢ Be- tween Grooves (in.)	Depth of ¢ of Groove (in.)	Depth at Pond Area (in.)	Depth Gained (in.)	Impregnation Ratio
Groove Spacing - 3 inches, Groove Width - 1-1/8 inches, Impregnation Time - 24 hours						
G-9	4-1/2	4-1/2	4-1/2	3-5/8	7/8	1.0
G-10	4-5/8	4-1/2	4-5/8	3-1/2	1-1/8	1.0
Groove Spacing - 5 inches, Groove Width - 1-1/8 inches, Impregnation Time - 24 hours						
G-11	4-1/2	3-1/2	4-1/2	3-1/4	1-1/4	1.7
Groove Spacing - 4 inches, Groove Width - 1-1/8 inches, Impregnation Time - 24 hours						
G-12	4-3/8	3-3/4	4-3/8	3-3/8	1	1.4
Groove Spacing - 4 inches, Groove Width - 7/8 inch, Impregnation Time - 24 hours						
G-13	4-1/2	4-1/4	4-1/2	3-1/4	1-1/4	1.4
Groove Spacing - 4 inches, Groove Width - 5/8 inch, Impregnation Time - 24 hours						
G-14	4-1/4	4	4-1/4	3-1/4	1	1.4
Groove Spacing - 3 inches, Groove Width - 3/4 inch, Impregnation Time - 16 hours						
G-18	3-5/8	3-3/8	3-5/8	2-1/2	1-1/8	1.4

^aConversion: 1.00 in. = 2.54 cm.

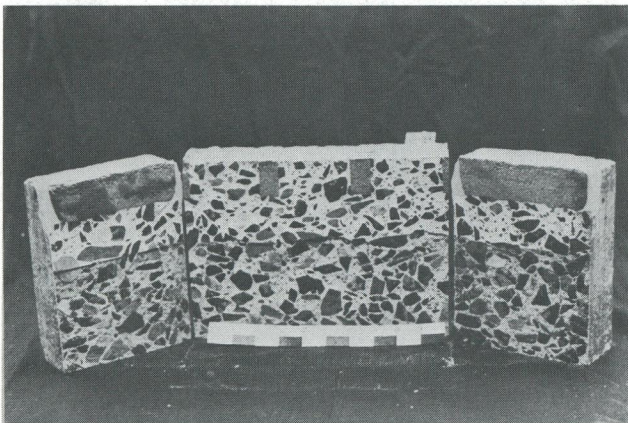


Figure 11. Grooved beam after polymer impregnation. Impregnation time, 16 hours; Groove spacing 3 inches; groove width, 3/4 inch; groove depth, 1-1/2 inches; impregnation ratio, 1.4

ratio could be used to determine the impregnation time required to impregnate to a specified depth based on the pond impregnation rate. For the grooved and ponded impregnation data given in Table 6, the mean groove ratio is 0.90 with a standard deviation of 0.05. Therefore, for a specified depth of 2-1/4 inches below the groove base, a mean depth of impregnation of 2-1/2 inches by ponding would be required.

For 99 percent of the time, the range of the depth of the impregnation below the groove base would be 1.93 to 2.63 in. for a mean depth of impregnation by ponding equal to 2.5 in. If the groove were cut to 1/2 inch above the reinforcing steel bars, an impregnation depth of 1.75 inches below

the groove base would be required to encapsulate the upper reinforcing steel mat, assuming #5 bars.

Optimization of Polymerization Time

The recorded temperatures showed an increase in the internal temperature of the mortar cubes at various times. However, the increase was no greater than 3F and occurred at regular time intervals. It is believed the observed increase in temperature is most likely due to the variation in the temperature bath and not to the exothermic heat of polymerization. Therefore, the strength data given in Table 7 were used to determine the time to in situ polymerization of the methyl methacrylate system in concrete. The data show that, as expected, the time to polymerization increases with decreasing activation temperatures. The time to polymerization was about 8 hours at 114F and decreased to 1 hour at 143F.

Figure 12 shows the polymerization temperature as a function of time using the hot-water polymerization method on the surface of the slab. With a surface temperature at 208F, an equilibrium temperature of 124F was reached at about 16 hours. A temperature of 115F was obtained after 8 hours and 120F after 12 hours. That is, the polymerization temperature after 8 hours was 115F for 4 hours and then increased to 120F for 4 more hours before reaching an equilibrium temperature of 124F.

Based on the strength-gain data, the methyl methacrylate would have polymerized before the temperature reached 124F at a depth of 4 inches. However, methyl methacrylate may penetrate to a depth of about 4.13 inches when the grooving method is employed with 2 inches of cover and a pond impregnation depth of 2-1/2 inches. In addition, it has been shown (1) that deicer

salts will increase the time to polymerization and that the effect is greater at a lower activation temperature, for example, 130F as compared to 148F. Therefore, the suggested polymerization criterion is to maintain the equilibrium temperature of about 124F for a period of 6 hours. Cores taken from the slab showed that the methyl methacrylate had polymerized.

Table 7. Compressive strength gain of methyl-methacrylate-impregnated mortar cubes as related to time and activation temperature.

Time (minutes)	Compressive Strength, psi			
	Bath Temperature, °F			
	114	122	130	148
0	1800	1800	1800	1800
15	--	--	--	3250
30	--	--	1680	6000
40	--	--	--	7200
60	2430	2330	2500	9100
120	2320	2650	8220	--
180	2750	4380	8170	--
240	3150	6310	--	--
300	5450	8540	--	--
360	--	9450	--	--
420	6830	--	--	--
480	7650	--	--	--
510	7350	--	--	--

^aConversion: 1 ksi = 6.9 MPa.

Optimization of the IR Drying Method

The flow of heat during the heating cycle extended 12 inches beyond the shield. In order to better estimate the drying energy used, the energy required to raise the temperature of the concrete beyond the shield from ambient to the temperature at the end of the heating cycles was calculated and subtracted from the total energy. The total energy was based on the weight of propane used. The energy used to increase the temperature of the volume of concrete comprised of the 8-inch slab thickness and a 12-inch wide area encompassing the heating area was calculated using a specific heat of 0.24 BTU/F/lb and a unit weight of concrete of 146 lb/ft³. Table 8 presents a summary of the drying tests and Figure 13 shows the heating and drying time and energy used as a function of surface temperature.

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

Figures 14 and 15 show the heating and cooling temperatures and the deflection of the center of the slab as a function of time for the 750F drying test. Several

points of interest are illustrated by the curves. First, the curves show three distinct slopes below, above, and at the boiling point of water; the curves tend to flatten (this trend towards a flatter curve becomes more pronounced with depth). This occurrence is due to the energy required to vaporize the water in the capillary system and thus indicates that the concrete is dry after the slope of the curve increases beyond the flattened portion.

Another observation is that the surface temperature did not drop below the interior temperature of the concrete during the cooling cycle. The slab temperatures tend to approach a narrow band when cooling. These trends are due to the insulation that was placed on the top surface of the slab. Thus, the thermal stresses should be minimized during the cooling cycle.

Of great interest is the deflection curve. Within the first hour when the temperature distribution appears to be at a maximum, the slab exhibited a maximum upward curvature. As the temperatures within the slab approach the surface temperature, the upward curvature decreases; within the first hour of cooling, the slab undergoes a complete reversal in curvature. The slab exhibited a maximum convex downward curvature after 5 hours cooling; it then rose slightly but remained in a convex downward shape after cooling to about 100F.

The upward curvature to a maximum followed by a lessening of the curvature is to be expected in light of the theory of thermally induced stresses and the reaction of the slab to relieve such stresses. However, an explanation for the observation of a complete curvature reversal during cooling is not as obvious until one realizes that the coefficient of linear expansion is a function of moisture content. At low moisture contents the correction factor is approximately zero, reaches a maximum at about 65 percent, and then decreases to zero at about 90 percent (6). The coefficient of linear expansion at a moisture content of 65 percent is about 15 percent greater than the coefficient of linear expansion at zero percent. The difference in the coefficient of linear expansion between the dry upper half and the moist lower half of the slab caused the slab to undergo a complete curvature reversal and to remain in a convex downward shape after cooling.

Visual observations of the slab during the drying cycle indicated that the slab only cracked once during each test cycle. For all 3 drying tests, the crack was at the centerline of the heater at the edge of the slab, extended through the depth of the slab and 6 inches inward along a line parallel to the centerline of the heater and ended at the outside face of the shield. The crack, which appears about 40 minutes into the heating cycle, may be related to the temperature differential created by the shield near the unsupported edge of the slab.

A microscopic survey of a polished section sawn from a core from each of the test areas showed no evidence of cracking. That is, at a magnification of 100X no cracking was visible between the paste and

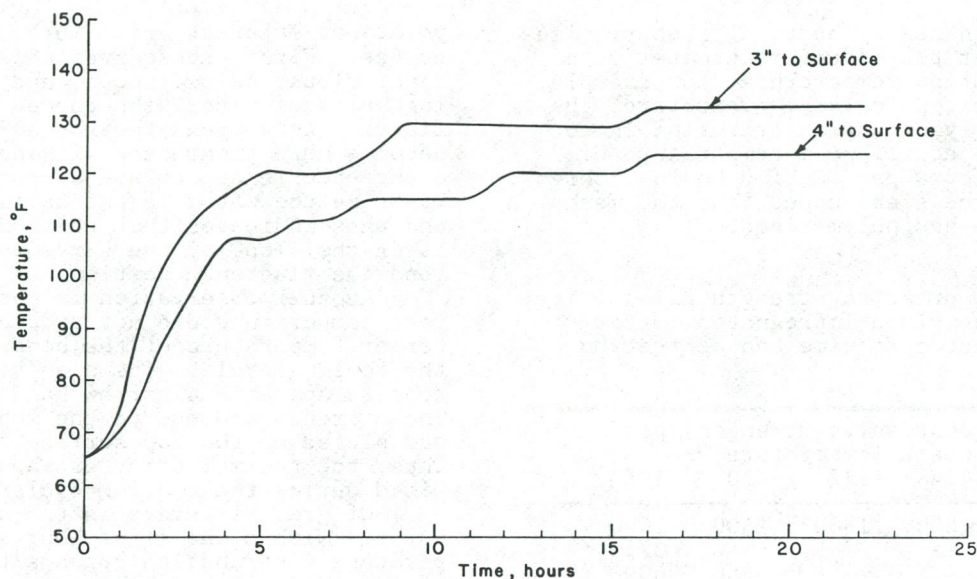


Figure 12. Slab polymerization temperature vs time (surface water at 208F).

Table 8. Summary of drying tests.

Surface Temperature (F) ^a	Heating Cycle (hours)	Drying Time (hours)	Propane Used (lb) ^b	Energy Used (BTu) ^c	Rate of Energy Use (BTu/ft ² /hr)
400	5.8	25.5	8.6	185,800	8,100
550	3.2	16.9	6.0	129,600	10,200
750	2.5	17.5	8.9	192,200	19,200

^aConversion: $0.555 (°F - 32) + 273 = K$.

^bConversion: 1.00 lb = 0.454 kg.

^cConversion: 1.00 BTu = 1.06 kJ.

^dConversion: 1.00 BTu/ft²/hr = 3.17 J/m²/s.

aggregate, within the paste, between the paste and reinforcing steel, or anywhere within all three of the examined areas.

Figure 16 shows the heating temperatures as a function of time for the 550F drying tests and shows the drying times required for depths of 2-1/4 and 3-3/4 inches.

Laboratory Demonstration of Deep-Grooving Impregnation Method

Cores taken from the slab were impregnated for 9, 16, and 40 hours. The rate of impregnation was equal to 0.579 inches per √hours with a correlation coefficient of determination equal to 0.997. The depth of impregnation was 2.5 inches at 16 hours and was determined to be sufficient for a required depth of impregnation of 2.25 inches with a groove ratio equal to 0.90 (0.90 x 2.5 in. = 2.25 in. = required depth

of impregnation below the groove base). The groove spacing was set at 2.25 inches using the optimum impregnation ratio of 1.00 (groove spacing = (impregnation ratio) (required depth of impregnation below the groove base)). The optimum groove width was calculated to be 3/4 of an inch using a 10 percent by volume methyl methacrylate loading rate. However, the grooves were cut 1/2-inch wide because of the limits of the saw.

The 3 areas dried for the optimization of the IR heating method were impregnated and polymerized using the ponded hot water method and the depth of impregnation was determined (see Table 9). The boundary of the impregnation was straight and the depth of impregnation was below the upper rebar mat for all 3 cores.

In addition, the compressive strength of the polymerized methyl methacrylate

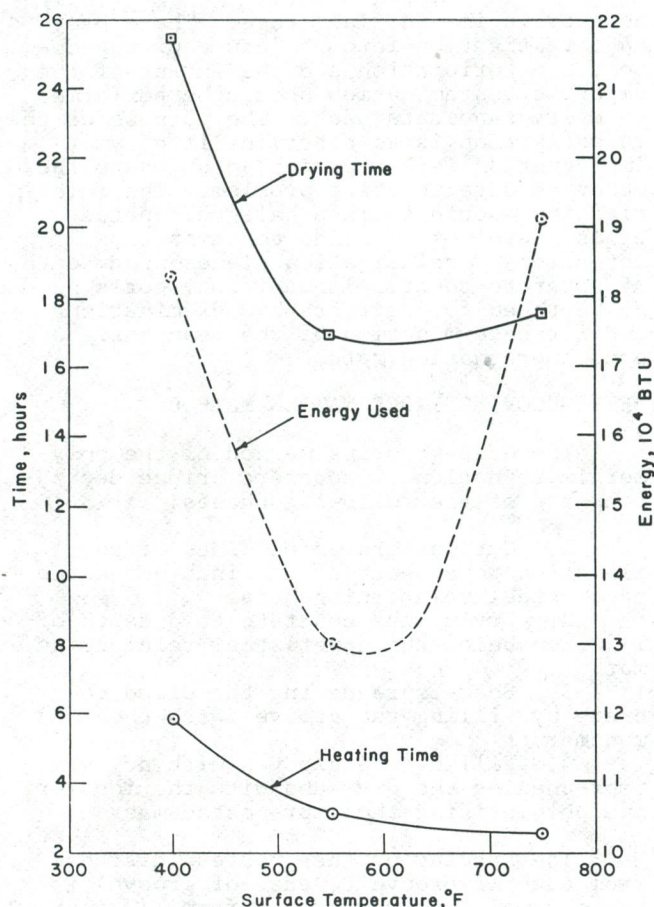


Figure 13. Drying and heating time and energy. Conversion: $K = 0.555 (^\circ\text{F} - 32) + 273$.

saturated groove sand was determined to be 7850 psi for 2 2.5-inch diameter cylinders. Impregnated 3-inch diameter cylinders with 3/4 inch diameter, 1-1/2-inch deep holes were subjected to 304 cycles of rapid freezing and thawing (ASTM C 666) and showed no evidence of pop-out problems.

CONCLUSIONS

1. It is concluded that the grooving of concrete to a depth of 1-1/2 inches prior to impregnation with methyl methacrylate can reduce the time required for impregnation; 16 hours for grooving versus 45 hours for surface ponding to obtain an impregnation depth of 3-3/4 inches. Also, the method obviates the need for the impregnation chamber needed in the case of soak and pressurized impregnation. The method would also be adaptable for impregnation with other liquids (e.g., inhibitors).

2. The optimum groove spacing is equal to the required depth of impregnation below the groove base.

3. The impregnation time required for the groove method can be determined from the surface pond impregnation rate using a groove ratio of 0.90.

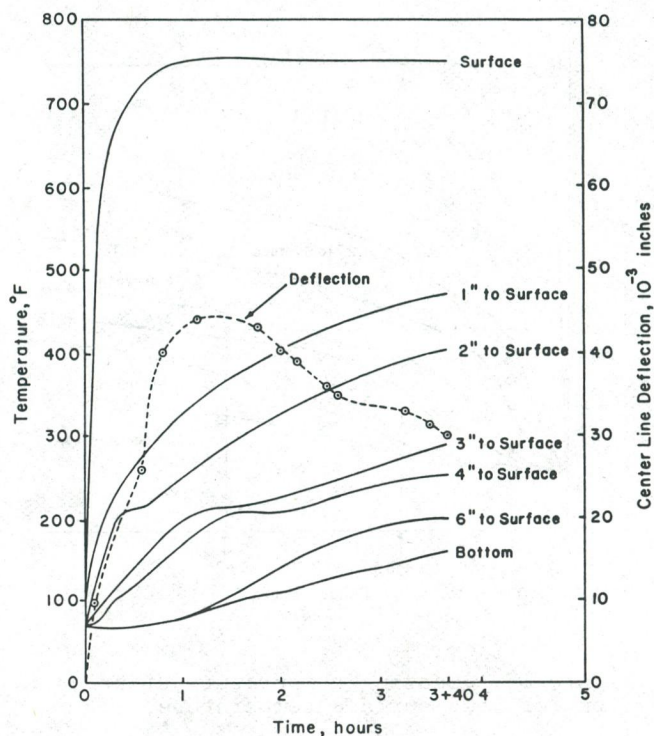


Figure 14. Heating temperatures and deflection vs. time for a surface temperature of 750F. Conversion: $K = 0.555 (^\circ\text{F} - 32) + 273$.

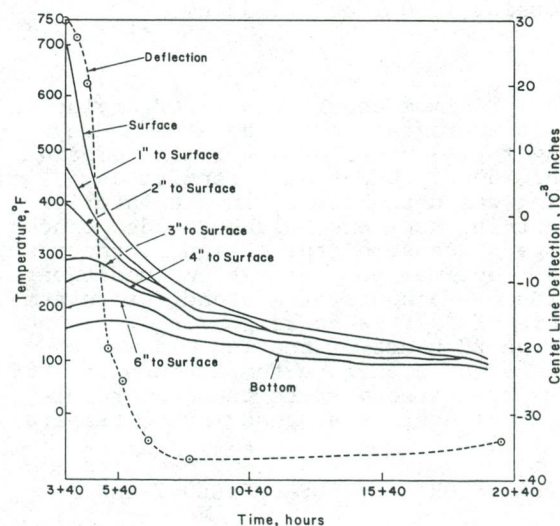


Figure 15. Cooling temperatures and deflection vs. time for a surface temperature of 750F. Conversion: $K = 0.55 (^\circ\text{F} - 32) + 273$.

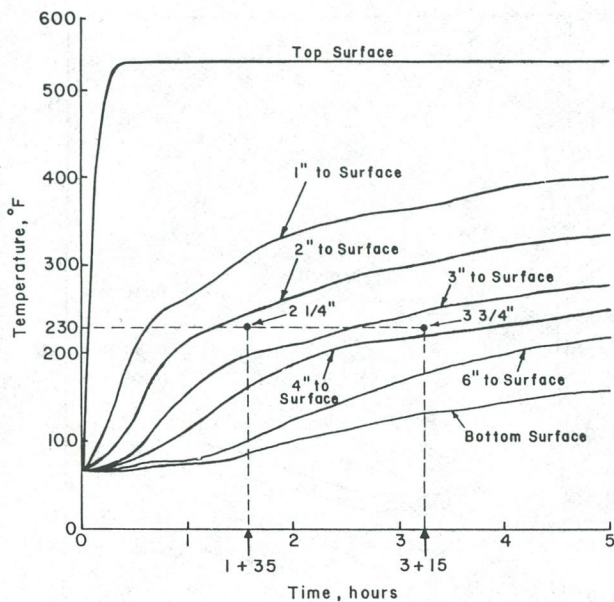


Figure 16. Heating temperature distribution for 550F surface temperature.

Table 9. Depth of impregnations for the grooved slab.

Specimen	Depth at ¢ of Groove (in.)	Depth at Between Grooves (in.)	Depth at ¢ of Groove (in.)
S-400	3-5/8	3-5/8	3-5/8
S-550	3-3/4	3-5/8	3-5/8
S-750	4-1/8	4-1/8	4-1/8

^aConversion: 1.00 inch = 2.54 cm.

4. Minimum energy costs for drying prior to impregnation can be attained by heating for ~3 hours at a surface temperature of ~600F. Under such conditions, cracking was not observed in the interior of the test specimens, although edge cracks developed because of the design of the test.

5. Optimum polymerization conditions were found: 5 hours at a steady-state temperature of 122F -- corresponding to a conservative 22 hours of heating with a hot-water pond at a surface temperature of 208F, 2 hours at a steady-state temperature of 130F, and 1 hour at a steady-state temperature of 148F.

PROCEDURES FOR A PROPOSED FIELD TRIAL

General

The polymer impregnation of steel-reinforced-concrete bridge decks is a process that will provide a long-term rehabilitation of salt-contaminated bridge decks where the corrosion of the reinforcing steel is immi-

nent or in its initial stage. Therefore, an investigation into the cause of any observed deterioration and the extent of the chloride contamination should be performed on every candidate deck. The purpose of the investigation is to determine if polymer impregnation is the proper solution to the observed deterioration problem. The investigation should include half-cell potentials, level of chloride contamination, detection of delamination planes, and depth of concrete cover. In addition, cores need to be taken for petrographic examinations and for determination of the mean surface pond impregnation rate.

DEEP-GROOVING IMPREGNATION METHOD

The deep-grooving method of the polymer impregnation of concrete bridge decks consists of the following phases:

1. Cutting grooves on lines of equal elevation to a depth of 1/2 inch above the upper steel reinforcing bars.
2. Drying the concrete to a depth of 1/2 inch below the upper steel reinforcing mat.
3. Soak-impregnating the dried concrete by filling the grooves with the monomer.
4. Filling the grooves with dry sand, impregnating the dry sand with the monomer, and polymerizing the impregnated mass.

The spacing of the grooves (distance from edge of groove to edge of groove) is to be equal to the distance from 1/2 inch above the upper steel reinforcing bars to 1/2 inch below the upper steel reinforcing mat. Example: with #5 steel reinforcing bars used in both directions, the spacing of the grooves must equal 2-1/4 inches (1/2 inch plus 2 x (5/8 inch) plus 1/2 inch). This value is also the required depth of impregnation from the bottom of the grooves. The width of the grooves is determined by dividing 10 percent of the vertical cross-sectional area of the deck to be serviced by one groove by the groove depth. Groove depth will be equal to cover depth minus 1/2 inch. Therefore

$$W = \frac{(0.10) [(W + S) (D - 0.5 + S) - (W) (D - 0.5)]}{(D - 0.5)}$$

where: W = groove width, inches;
S = edge-to-edge distance between grooves, inches; and
D = cover depth, inches.

Continuing the previous example and assuming a cover depth of 2 inches, the groove depth will be 1-1/2 inches (2 inches minus 1/2 inch), and the groove width can be determined from the preceding equation:

$$W = \frac{(0.10) [(W + 2.25) (2 - 0.5 + 2.25) - (W) (2 - 0.5)]}{(2 - 0.5)}$$

from which, W = 0.66 inches.
and the groove spacing, center-to-center, is:

$$W + S = 0.66 + 2.25 = \underline{2.91 \text{ inches}}$$

The calculation is based on a monomer loading of 10 percent by volume. Cardinal Industries has estimated the cost of a grooving machine to cut grooves 3/4 inch wide, 1-1/2 inches deep, and spaced at 3 inches c-c to be \$480,000.00. The machine would have a cutting width of 6 feet and would cut the grooves at a rate of about 300 square yards per hour. The entire deck is to be grooved before the drying phase is started.

The grooved concrete deck is to be dried with a propane-fired IR heater with a constant surface temperature of approximately 600F. The concrete is to be considered dry when the temperature at a depth 1/2 inch below the upper steel reinforcing mat is equal to 230F. A 24-inch-wide area around the perimeter of the shielded drying area should be covered with insulation with an insulating value of R-19. An area of 20 feet by 12 feet can be dried at one time. Poweray Infrared Corporation has estimated the cost of a 20-foot by 12-foot heater to be \$48,000.00. R-19 insulation is to be placed over the dried area during the cooling cycle. Thermocouples (2 per drying area) are to be placed at a depth of 1/2 inch below the upper steel reinforcing mat in order to determine when the concrete is dry and when the monomer has polymerized. The propane requirements for drying are expected to average approximately 0.331 gallons per square foot. Typically, 3 hours is the required heating time needed to achieve drying using a 600F constant surface temperature.

The time of soak impregnating by grooving is to be determined from the mean surface pond impregnation rate. Example: with a required depth of impregnation of 2-1/4 inches below the base of the groove, the surface pond impregnation depth would be equal to $2.25 \text{ inches} \div 0.90 = 2.50$ inches. The time of impregnation would then be equal to the time required to impregnate to a depth of 2.50 inches by surface ponding, typically 16 hours. Approximately 3.00 pounds of monomer is required per square foot of bridge deck (100 MMA - 10 TMPTMA - 0.5 AZO by weight). During the impregnation phase, the deck is to be covered with a 4-mil-thick sheet of polyethylene to reduce the evaporation rate of the monomer and the fire hazard.

After the impregnation phase, the grooves are to be filled with dry, compact, well-graded sand with 100 percent passing the #8 sieve and less than 2.0 percent passing the #200 sieve. About 4 pounds of dry sand is required per square foot of deck. The sand is to be saturated with monomer and the impregnated mass polymerized by placing a polymerization vessel over the impregnated area. The vessel is to be filled with several inches of water and the water temperature increased to about 205F with steam. The 205F water temperature is to be maintained with steam until the monomer is polymerized. The monomer is to be considered polymerized when the thermocouples indicate that a temperature of 200F has been maintained for 5 hours or 130F for 2 hours.

It is envisioned that the sides and top of the compartmentized vessel is to be

constructed of nonspark metal. The steam pipes would run through the vessel and the bottom of the vessel would be lined with a nylon-metal laminate. The top, sides, and a 24-inch wide are encompassing the vessel should be insulated with an insulation value of R-30. Typically, it takes 16 hours to obtain a temperature of 122F at a depth of 4 inches below the surface with hot water being maintained at about 205F. Therefore, a conservative estimate of the time to polymerize is about 21 hours.

The total time required to impregnate a bridge deck by the grooving method is dependent on site conditions. However, as an estimate, an average bridge deck of about 40 feet wide and 216 feet long can be completed in about 10 days using the grooving method. The estimate assumes one 20-foot lane to be completed at one time using one IR heater (20 feet by 12 feet) and the following time requirements: 8 hours grooving, 72 hours drying, 16 hours impregnating, and 21 hours polymerizing.

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APPENDIXES B,C,D,E,F,G

Appendixes B through G of the agency report contain more detailed treatment of the following topics:

- B. Hot Impregnation with Epoxies
- C. Innovative Treatments
- D. Impregnation with Hydrophobic Silanes
- E. Evaluation of Durability and Overlay/Substrate Compatibility
- F. Effect of Treatment on Corrosion Resistance
- G. Economic Evaluation

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