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16. Abstract

Polymer-impregnated surface treatments have been developed to improve durability of bridge decks. Several monomer systems have been identified that, after soaking into concrete, can be polymerized at temperatures of 125°F or higher. The strength and stiffness of the polymer-impregnated concrete are increased by several times.

Surface treatment evaluations were performed to determine the effectiveness of the treatments. Freeze-thaw tests indicated that field treated slabs were more durable than non-air-entrained control slabs. Air-entrained control slabs were quite durable but were less resistant to scaling than treated slabs. Treated slabs resulted in improved water tightness in all cases. After undergoing freeze-thaw tests, many impregnated slabs maintained a relatively watertight concrete surface.

In wear track tests, 8 of 9 polymer treatments provided significantly higher skid resistance than control slabs. After grit and water were applied, the skid resistance of all treated specimens decreased; however, at the termination of the test all treated specimens had a skid resistance equal to or slightly higher than the control specimens had. Surface wear was about equal for treated and untreated slabs. Wear measured by sandblast tests showed a higher abrasion resistance for treated slabs.

Tests on surface-treated reinforced beams indicated a 22% higher strength than for untreated beams. Under cyclic loading, no spalling of the surface has been observed to date. Unreinforced beams broken in flexure have been repaired successfully with monomer systems that yield approximately the original flexural strength.

Significant savings are likely if the surface treatment procedures are implemented.

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POLYMER-IMPREGNATED CONCRETE FOR HIGHWAY APPLICATIONS

by

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PREFACE

The research on "Polymer-Impregnated Concrete for Highway Applications" began September 1, 1970, and is in the third year. This is the first formal report issued on the research and summarizes the results of the study through the first two and one-half years.

Polymer-impregnated concrete was developed less than ten years ago; the first public mention was about five years ago. When this study began, nearly all related research had been conducted in laboratories under idealized conditions. Concrete had been fully impregnated using an initial vacuum, immersion in monomer baths, and curing by either cobalt-60 irradiation or elevated temperatures. These techniques were simply not adequate for large scale use in treating the surfaces of bridges. But the excellent improvement in strength and durability properties made the effort to develop practical surface treatments worthwhile.

While the purpose of this investigation was to determine if polymer-impregnated surface treatments were effective in improving durability, the major problem was in developing practical surface treatments. The obstacles encountered have been numerous and challenging, but with the dedicated help of graduate research assistants Jimmie Henze, Michael

McNeil, Ragan Broyles, and John Wyman, and the fine work of Robert Garcia, project technician, practical surface treatment techniques have been developed that have proven to be effective in improving slab durability. Significant savings should result from the expected implementation of these findings. Many other applications of polymer-impregnated concrete for highway uses also appear probable.

The project would never have been initiated, however, without the vision, faith and support of the Texas Highway Department and the Federal Highway Administration. The continued patience, encouragement, and helpful suggestions of these agencies have been greatly appreciated. In particular the study supervisors are indebted to Donald O'Connor and M. U. Ferrari, contact representatives of the Texas Highway Department, and Jerry Bowman and Robert Pike of the Federal Highway Administration.

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ABSTRACT

Polymer-impregnated surface treatments have been developed to improve durability of bridge decks. Several monomer systems have been identified that, after soaking into concrete, can be polymerized at temperatures of 125°F or higher. Several methods of obtaining the required temperature are available. The strength and stiffness of the polymer-impregnated concrete are increased by several times.

Surface treatment evaluations were performed to determine the effectiveness of the treatments. Freeze-thaw tests indicated that field treated slabs were more durable than non-air-entrained control slabs. Air-entrained control slabs were quite durable but were less resistant to scaling than treated slabs. Treated slabs resulted in improved water tightness in all cases. After undergoing freeze-thaw tests, many impregnated slabs maintained a relatively watertight concrete surface.

In wear track tests, 8 of 9 polymer treatments provided significantly higher skid resistance than control slabs after 140,000 wheel passes. After grit and water were applied, the skid resistance of all treated specimens decreased; however, at the termination of the test (420,000 wheel passes) all treated specimens had a skid resistance equal to or slightly higher than the control specimens had. Surface wear was approximately equal for treated and untreated slabs. Wear measured by sandblast tests indicated a higher abrasion resistance for treated slabs.

Tests on surface-treated reinforced beams indicated a 22 percent higher strength than for untreated beams. Under cyclic loading, no spalling of the surface has been observed to date.

Unreinforced beams broken in flexure have been repaired successfully with several monomer systems that yield approximately the original flexural strength.

The estimated total cost of surface treatments for bridge decks ranges from \$0.40 to \$0.90/sq ft. Significant savings are likely if the surface treatment procedures are implemented.

KEY WORDS: bridge slabs, durability, polymer-impregnated concrete, surface treatments, freeze-thaw, wear, skid resistance, abrasion, piles, cyclic loading, strength.

SUMMARY

The use of polymer-impregnated concrete for highway applications has been investigated. The primary research effort has been focused on the development of practical surface treatments for highway bridge decks to increase the durability. Several liquid plastics, called monomers, have been identified as being suitable for this purpose. A quarter-inch layer of sand on the surface of the concrete is sprayed with the monomer and it is allowed to soak into the concrete for 8 to 10 hours. The sand serves the purpose of holding the monomer on sloped bridge decks and minimizing the run-off. The 8 to 10-hour soaking interval is required to allow the monomer to fill the minute pore structure of the concrete to an adequate depth. Upon completion of the soaking interval, the slab surface temperature is increased to 125°F or higher, which causes the monomer to polymerize. The slab heating can be accomplished by one of several ways: (1) ponded hot water in plastic-lined wood frames or (2) steam or warm air blown inside a shallow canvas covered portable enclosure over the slab. The estimated total cost of the surface treatment is less than $1.00/sq ft.

The plastic-filled concrete is up to 2 or 3 times stronger and stiffer than ordinary concrete. The water tightness of treated slabs has been found to be improved over that of non-treated slabs. For example, in a 24-hour water penetration test, untreated slabs are usually penetrated to a depth of 2 to 3 inches or more while normally no water penetration is observed in the treated slabs. In tests where water was ponded on the slab and alternately frozen and thawed, untreated slabs with no air entrainment usually fail by excessive cracking after 20 to 60 cycles; several polymer treatments resulted in slabs which were durable through 120 cycles of freeze-thaw, at which point the tests were terminated. Good quality air-entrained slabs that had no surface treatment were volumetrically stable through 100 or more cycles of the freeze-thaw testing, but more surface scaling was evident than there was for treated slabs. The protection against freeze-thaw failure and water penetration is perhaps the most important advantage of polymer-impregnated surface treatments.

In wear track tests where treated slabs were placed around a 10-ft-diameter track and subjected to wear by a rotating weighted tire, 8 of 9 slab treatments provided higher skid resistance over that of untreated slabs after 140,000 wheel passes over each. When the wear was accelerated by application of grit and water to the surface, the skid resistance of the treated slabs was reduced but still equalled or slightly exceeded that of the untreated slabs. Generally the wear depth of the treated and untreated slabs was about the same. Sand blast abrasion tests showed the treated slabs to be slightly more resistant than high quality control specimens and significantly more resistant than lower quality concrete slabs.

Flexural tests on reinforced concrete slabs indicated that the surface treatment resulted in 22 percent greater strength. Slabs subjected to 2,000,000 cycles of load application showed no tendency for the surface-treated portion of the concrete to spall off.

The repair of broken small unreinforced concrete beams has been accomplished by filling the crack with monomer and allowing it to harden. Strengths equal to the original strength have been obtained.

Fully-impregnated wood and reinforced concrete piles have been subjected to long-term exposure tests in the ocean. After seven months, the treated wood piles showed severe attack by marine borers. The treated concrete specimens, however, showed no evidence of corrosion on the reinforcing whereas some corrosion had begun in the untreated piles.

IMPLEMENTATION

The results of the research undertaken in this study indicate that better, more maintenance-free bridge decks are possible through the use of polymer-impregnated concrete surface treatments. The problem of bridge deck deterioration in Texas, as in nearly every state, is a most serious one, resulting in the expenditure of millions of dollars annually for repair and replacement. The surface treatments developed in this study are sufficiently practical to be used on bridge decks in Texas. Additional field testing needs to be performed to verify the simulated field tests and to refine the application techniques. Several surface treatments have been shown to be very effective in protecting the slabs against water penetration and freeze-thaw deterioration. The estimated cost, which is dependent upon several variables, ranges from $0.40 to $0.90 per sq ft. The surface treatments can be applied to both new and old bridges.

It should be possible to develop instruction manuals that will enable these treatments to be implemented routinely by either highway department personnel or independent contractors. The instruction manuals would give detailed procedures for: (1) handling of materials; (2) preparation of surface; (3) application of monomer system; (4) curing the monomer; and (5) performing quality control tests.

The polymer-impregnation of concrete has many potential applications other than surface treatments. To provide the protection against corrosion of reinforcement is suggested as a use of this material where extreme exposure conditions exist such as for reinforced concrete structures exposed to ocean spray. The high strength and stiffness also suggest the potential use of polymer-impregnated reinforced concrete for long span precast girders and slabs. The low (and in some cases, negative) creep of polymer-impregnated concrete makes it attractive in the use of prestressed components. Further research will be needed to develop these applications, however.

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CHAPTER 1.

Introduction

1.1 Bridge Deck Deterioration

The deterioration of concrete bridge decks in many parts of the United States and foreign countries has received much attention from various research groups. A large number of research reports dealing with the various parameters influencing bridge deck deterioration have appeared, mostly in the last ten to fifteen years.(1-19)*

A review of the published reports reveals that, by far, the most prominent parameters affecting the durability of bridge decks are the permeability, volume change characteristics and wear strength of the hardened concrete. Almost all mechanisms of observed deterioration of bridge deck concrete can be related to one or more of these parameters. For example, evidence of unsatisfactory performance of bridge decks has been noted in high rates of surface wear and surface polishing, shrinkage cracking, corrosion of reinforcement, surface spalling or scaling, and chemical attack.

The corrective measures offered by researchers of bridge deck durability and skid resistance problems can generally be classed as (1) proper

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*See list of references, which follows the appendix.

concrete mix design, (2) proper placement, finishing and curing, and (3) overlays or systematic surface treatments. This suggests either the revision of those specifications and construction practices employed or the requirement of more rigid adherence to the existing specifications. It also suggests that the normal variation in the quality of in-place concrete may continue to result in bridge deck durability problems which, unfortunately, tend to require expensive corrective measures. For example, efforts to salvage badly deteriorated bridge decks have included such methods as application of portland cement concrete, asphaltic concrete and epoxy composite overlays. Efforts to inhibit corrosion of reinforcement include use of protectively coated reinforcing bars and such extremes as externally impressing electrical current to the reinforcement system. Where skid resistance of bridge decks is dangerously low, surface grooving or high friction overlays have been employed. Another skid preventive measure currently being used with some success is the systematic spraying of bridge decks with linseed oil.

1.2 Application of Polymer-Impregnated Concrete

Polymer-impregnated concrete (PIC) is a relatively recent development which involves the polymerization of a liquid monomer which has partially or fully saturated the pores of hardened concrete. Tests indicate that the mechanical and durability properties generally are improved significantly by this technique.(20-24) For example, tensile and compressive strengths of the PIC range up to four or five times larger than those of control specimens;

resistance to abrasion, acid attack, water penetration, and freeze-thaw deterioration are increased significantly. These improvements in properties suggest that one potential application of PIC is for highway bridge decks.

Most of the laboratory tests reported have been on fully-impregnated specimens. The dried concrete is placed in a vacuum to evacuate air from the pores; the evacuated specimens are then immersed in a bath of liquid monomer and permitted to soak until the concrete voids are filled. Polymerization is accomplished by either irradiation or thermal-catalytic methods or a combination of the two. The fully-impregnated specimens produced by these techniques generally possess excellent strength, stiffness and durability properties and have a final in-place estimated cost that is twice as high as that of ordinary concrete. The process, however, does not readily lend itself to treatment of in-place structures such as highway bridge decks.

Previous research has been conducted with the goal of developing partial impregnation of slabs. It was found that low viscosity monomers are more volatile and have low initial diffusion rates through the concrete. After the slab is removed from the monomer bath, the monomer continues to penetrate due to capillary action and also tends to evaporate from the surface, which makes it difficult to achieve a sufficient polymer loading to yield an adequate surface treatment.(21,22) Specimens treated by soaking ponded methyl methacrylate (MMA) into the concrete and polymerizing by irradiation showed little visual evidence of any polymer present. It was concluded that "lack of polymer in the specimens was probably caused by evaporation prior to the completion of the polymerization." Abrasion tests indicated little difference in wear on the treated slabs compared to that on the controls. Some improvements were noted in freeze-thaw behavior, however.(25)

The use of more viscous monomers, such as polyester-styrene, which have lower diffusion rates, are less volatile and are more easily controlled, has been accomplished with the aid of 100 psi overpressure. Up to 3/4-in. penetration of the polymer was reported. Abrasion resistance for the treated specimens was found to increase significantly while skid resistance was about the same for some specimens and lower for others.(25)

1.3 Scope of Investigation

This investigation had the general objective of developing practical and durable polymer-impregnated concrete surface treatments for highway bridge decks. More specifically the objectives were:

(1) Development and identification of monomer systems that were suitable for surface impregnation of in-place bridge decks;

(2) Development of practical methods of application and polymerization suitable for field use;

(3) Evaluation of the strength and durability properties of the surface treatments; and

(4) Investigation of other uses for highway applications, including repair of cracked slabs and polymer-impregnated wood and concrete piles.

CHAPTER 2.

Investigation of Monomer Systems

2.1 Introduction

Polymer-impregnated concrete has been produced with a variety of monomer systems;(20-23) however, the nature of this process largely restricts the choice of monomers to those which have double bonds and can be polymerized by a free radical mechanism. The impregnation of existing concrete with a monomer which is to be subsequently polymerized involves a series of chemical and physical processes. In principle almost any monomer can be employed; however, in practice the successful implementation of this concept requires a monomer system with a select balance of characteristics. This balance is more critical in highway applications (where surface penetration into an existing bridge deck is involved) than in other applications involving smaller pre-cast concrete elements where total penetration is usually sought. Specific monomer characteristics to be considered are:

1. viscosity
2. evaporation rate
3. polymerization rate characteristics

4. wetting angles and surface tension
5. resultant polymer properties
    a. mechanical
    b. thermal
    c. environmental stability
6. safety in handling
    a. toxicity
    b. flammability
7. cost

Since viscous flow controls the rate of penetration of the monomer into the concrete pores, it is imperative to have a low viscosity monomer so that adequate penetration can be developed in a reasonable time. Apparently the main driving force for flow into the pores is the capillary forces that result from the monomer wetting the concrete, and thus these forces are crucial to good penetration. Polymerization rate characteristics inherent in a given monomer are important since they will limit what can be done with the rate by altering process parameters. Successful impregnation requires that the monomer not begin to polymerize until adequate penetration has been realized since this would raise the viscosity and virtually halt further penetration. Once the desired penetration has been reached, it is then necessary for polymerization to proceed at a fairly rapid rate so that excessive time is not required for conversion of monomer into polymer.

If the monomer is very volatile, appreciable evaporation can occur during this time and result in a diminution in the loading of polymer in the concrete. Evaporation losses during monomer application also can be severe. Monomer evaporation can have a detrimental effect on the quality of the surface treatment, the economics of the process and the safety of personnel in the application area. To some extent, most organic monomers are toxic and flammable; however, the severity of these factors can be greatly reduced by use of monomers of low volatility. In general there is an inverse relationship between viscosity and volatility so some optimization is always indicated. To date there is no thorough understanding of the connection between the properties of the polymer and the polymer-impregnated concrete although it is clear that environmental and thermal stability of the polymer are necessary requirements.

There is a complex interplay between the various characteristics previously described, and the importance of each is strongly dependent on the exact method of application and cure that is used. Because of this it is not possible to identify with much reliability potentially successful monomer systems by merely examining a list of these properties, although this may be helpful. The most reliable screening approach is to employ laboratory surface impregnations using a variety of conditions in conjunction with exploratory test tube scale polymerizations. A number of monomers have been examined during the course of this work. Table 2.1 provides a list, along with selected characteristics, of monomers which have met with some success in surface treatments. The survey of monomers carried out to date, which has

TABLE 2.1 PROPERTIES OF MONOMERS

Monomer	Viscosity (Centistokes)	Boiling Point	Glass Transition of Polymer	Density (gm/cm^3)	Cost Per Pound[a]
Isobornyl Methacrylate	6.0	very high	170°C	0.95	unknown
Isobutyl Methacrylate	0.98	155°C	48°C	0.90	$.30
Isodecyl Methacrylate	3.3	very high	-41°C	0.87	$.55
Methyl Methacrylate	0.60	100°C	105°C	0.94	$.185
Stearyl Methacrylate	10.5	310°C	38°C	0.85	$.55
Styrene	0.81	145°C	100°C	0.90	$.09
Tert-Butyl Styrene[b]	1.6	219°C	134°C	0.88	30

[a] cost for bulk quantities

[b] no longer available commercially

culminated in Table 2.1, is by no means exhaustive, and it is possible that for some uses more nearly optimum monomers are available. These systems have been identified simultaneously with developing a process for surface-impregnation. Future monomer screening would be aided by the perfection of this process, and other monomer choices may be possible with different processes.

So far methyl methacrylate (MMA) is the monomer which has been used most extensively in this work. The reasons for this are that: (1) it has been the most widely used monomer in previous polymer-impregnated studies and therefore considerable information is available; (2) early attempts at surface treatment were most successful with this monomer compared to other monomers; and (3) it was convenient to gain experience with a single monomer while the application development was underway. Methyl methacrylate is a very good monomer for surface treatments; however, its use here does not imply that some other monomer would not be more optimum.

Polymerization of double-bonded monomers requires a source of free radicals to initiate the reaction. Early work in polymer-impregnated concrete used γ rays from Cobalt 60 as the means of generating these reactive radicals.(20) This was convenient because the monomer could be allowed to penetrate the concrete first and then be exposed to γ rays only after this was complete. In addition, the polymerization initiated by γ rays can be carried out at ambient temperatures. However, the use of radiation in highway surface treatments is not practical so some other approach had to be pursued.

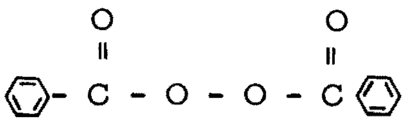
Polymerization of monomers on a commercial scale such as in plastics manufacturing is frequently initiated by free radicals generated by the decomposition of peroxides or other initiators. Polymerization is usually carried out at elevated temperatures since this speeds up the reactions to an acceptable level. A similar approach has been developed in this study for surface treatments which consists essentially of the following procedure. A peroxide initiator is dissolved into the monomer and by necessity this must precede penetration of the monomer into the concrete. A properly chosen system will not react at any noticeable rate at ambient temperature and so penetration is possible. Once the monomer-initiator mixture has penetrated the concrete, polymerization can be made to proceed at an acceptable rate by raising the temperature of the concrete. The details of implementing this approach are described in subsequent sections.

The heating required in this approach is a distinct disadvantage; however, it appears to be a necessary part of a system that does not employ radiation. A considerable effort was expended in trying to eliminate the need for this step by using accelerators to catalyze the peroxide decomposition as in the practice of many polymer casting operations where heat is not applied. However, adequate penetration was never attained because polymerization was occurring during the time the monomer was flowing into the pores. Subsequent efforts were directed at selecting systems which would minimize both the temperature and time required during the heating cycle.

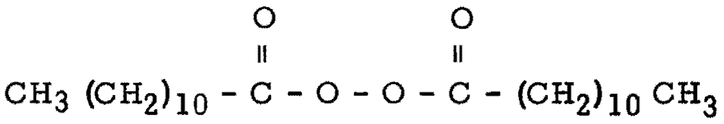
Polymerization rate characteristics are one of the major factors to be regulated in this process. For a given monomer, there are a number of factors that can be used to adjust this rate. Those which have been employed are:

1. type and amount of peroxide (catalyst)
2. temperature
3. addition of a cross-linking agent (type and amount)
4. addition of an accelerator (type and amount)

There are a large number of peroxide initiators available and a number have been explored in this work, but generally benzoyl peroxide (BP), i.e.,



has been most satisfactory. Some use has been made of lauroyl peroxide (LP), i.e.

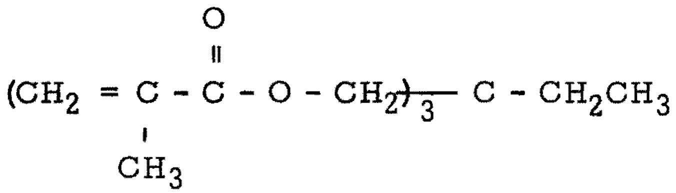


$$CH_3(CH_2)_{10}-\overset{O}{\overset{\|}{C}}-O-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{10}CH_3$$

and undoubtedly there are others which are suitable for certain systems. Specific amounts of peroxides recommended for various treatments will be discussed subsequently but these are generally within the range of 0.5 to 2 percent by weight.

The temperature for polymerization is set by several factors, including such considerations as available heat sources and monomer volatility.

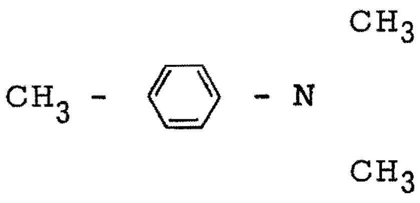
During the early stages of process development it was realized that the polymerization rate of methyl methacrylate was not as high as desired and so the use of an additional monomer which is multi-functional was adopted since its use had been shown to increase the polymerization rate by Brookhaven workers.(20) Such agents also produce cross-linking in the polymer and are, therefore, often referred to as cross-linking agents although their principal reason for being used here is for the increase in polymerization rate they produce. The specific agent used here to date is trimethylolpropane trimethacrylate (TMPTMA), i.e.,



$$(CH_2 = \underset{CH_3}{\underset{|}{C}} - \overset{O}{\overset{\|}{C}} - O - CH_2)_3\, C - CH_2CH_3$$

Other agents are available and some may be equally or more efficient than this one. Specific amounts recommended for various treatments will be described later but these amounts are generally 10 percent by weight or less.

Chemicals are available which accelerate the decomposition of the peroxide and can often be employed to allow polymerization at lower temperatures. These agents are called accelerators. One particular one N, N-dimethyl-p-toluidine (DMPT), i.e.,



has been found particularly successful for the MMA-BP system. However, research to date has been unsuccessful at using accelerators to reduce or eliminate the need for heating in surface treatments. However, accelerators have been useful in other ways, such as to provide an overlay treatment to heat up the concrete and in preparing monomer mixes for crack repair.

Laboratory test tube studies of polymerization rates have been found useful but the results do not translate directly to polymerization inside the concrete. A major reason for this is that polymerization is a highly exothermic reaction and so in bulk experiments the reaction mass heats up unless the heat can be removed. In the concrete the large mass and the small size of the pores insure that the monomer does not heat up. However, in the laboratory it is almost impossible to avoid this temperature build-up. This temperature rise then causes the rate of polymerization to increase. Thus in general it is easier and requires less time to achieve polymerization in the laboratory than in concrete. For this reason exact times for curing must be worked out by actual studies with concrete rather than in test tubes.

Some laboratory experiments, however, do serve to illustrate some of the important aspects of the current system and will be presented here. The exotherm was followed as a key to the polymerization rate. In such cases the sample size and thermal environment are very important factors which must be carefully controlled and designed if the results are to be reproducible. The system adopted is shown schematically in Fig. 2.1. It consists of an aluminum plate resting on a bed of sand. A disposable aluminum pan

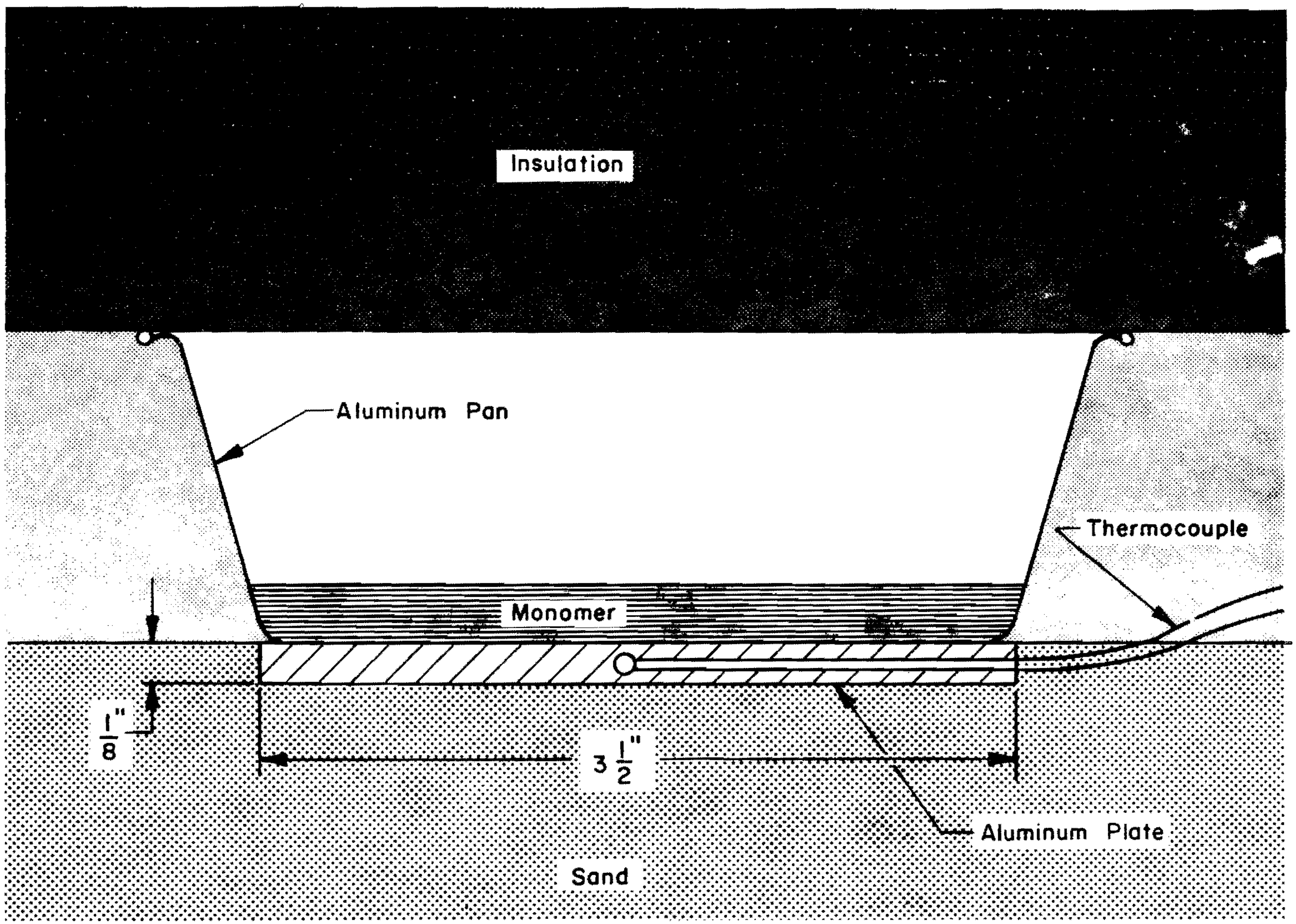


FIG. 2.1 THERMAL APPARATUS FOR MEASURING POLYMERIZATION EXOTHERM

is placed on this plate, and a thermocouple is embedded in the aluminum plate to measure the temperature rise. The insulation shown was installed to reduce evaporation and spurious air currents and to duplicate conditions where heat loss is not large.

The apparatus and monomer mixture were initially at room temperature (24 °C) in all experiments. The monomer and initiator system were introduced into the pan at time zero after which the temperature reading of the thermocouple was followed by a recording potentiometer to produce data such as shown in Fig. 2.2. The peroxide was dissolved in one-half of the monomer and the accelerator in the other half, and the two halves were mixed together in the pan.

Fig. 2.2 shows results for polymerizing MMA with various levels of BP and DMPT at a fixed sample size of 50 ml. Each curve shows a rapid rise in temperature which peaks out in about 12 minutes for curbe 5 but about in 30 minutes for curve 1. For curve 4 there is a very pronounced second peak which occurs after about one hour. There is a less exaggerated second peak for curves 1 and 2 appearing at longer times.

The slopes prior to the first peak depend on the concentration of BP and DMPT and are approximately related to their product. According to the fundamental studies the peroxide and amine react in equimolar proportions, and this would then be the most efficient proportion in which to combine them. This is born out here in that a weight ratio (BP/DMPT) of two corresponds very nearly to equimolar proportions.

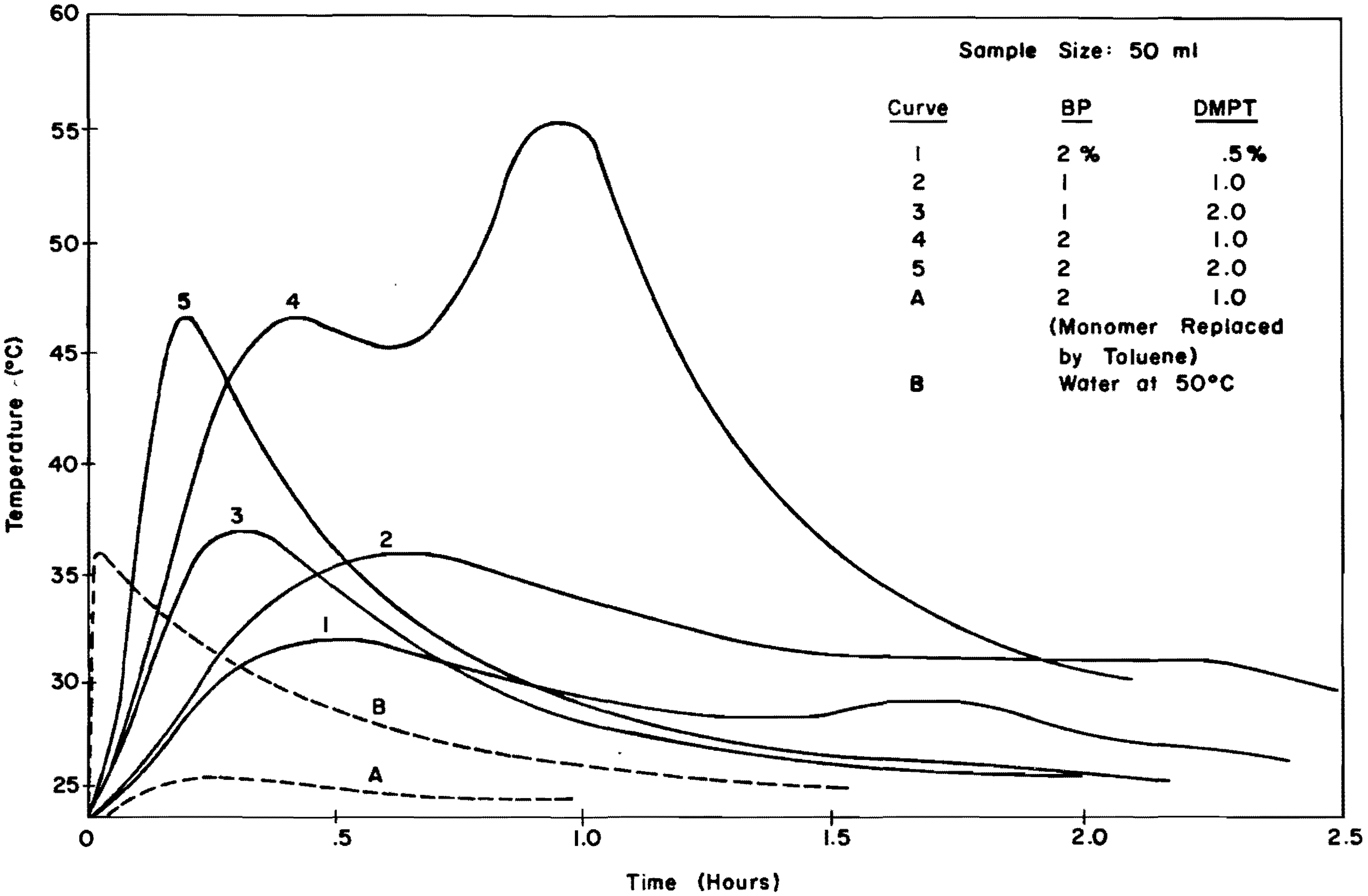


FIG. 2.2 TEMPERATURE VS. TIME FOR MONOMER SYSTEMS. Curves 1-5 show exotherm for MMA using indicated peroxide and accelerator levels in weight percent. Curve A shows heat generation by initiator system when there is no polymerization. Curve B illustrates cooling characteristics in the absence of heat generation.

In the apparatus shown in Fig. 2.1 the ability of the sample to lose heat, or its heat transfer coefficient, is effectively independent of the sample size. However, the ability to generate heat and the heat capacity are directly proportional to the sample size. Thus, by changing the sample size this balance is altered, and as a result the temperature rise will be changed. This will affect the polymerization rate and the quality of the cure. Fig. 2.3 shows results for adding different quantities of MMA (plus 2 percent BP and 1 percent DMPT) to the pan. The first peak appears at approximately the same time for each curve; however, it is diminished in magnitude for smaller samples, as may be expected from the reduced potential for heat generation. Of interest also is the effect on the second peak. At 60 ml and above it does not occur. It is most exaggerated for 40 and 50 ml but falls off in intensity and is shifted to longer times as the sample size is reduced. The 80 ml sample was a thick syrup at the end of two hours while the 70 ml sample had a hard core and the 60 ml was hard with a tacky surface. The 40 and 50 ml ones were thoroughly cured but the 30 ml sample had a syrupy layer on top and the 20 ml sample was syrupy throughout. It is thus evident that there is an optimum heat balance determined by sample size.

Multi-functional monomers or cross-linking agents are often added to cast systems to build up the molecular weight and to increase the polymerization rate. The former may be necessary to offset the tendency to form quite short chains at high polymerization rates. The effect goes beyond this usually to produce cross-linked networks. Some thermal results for a fixed

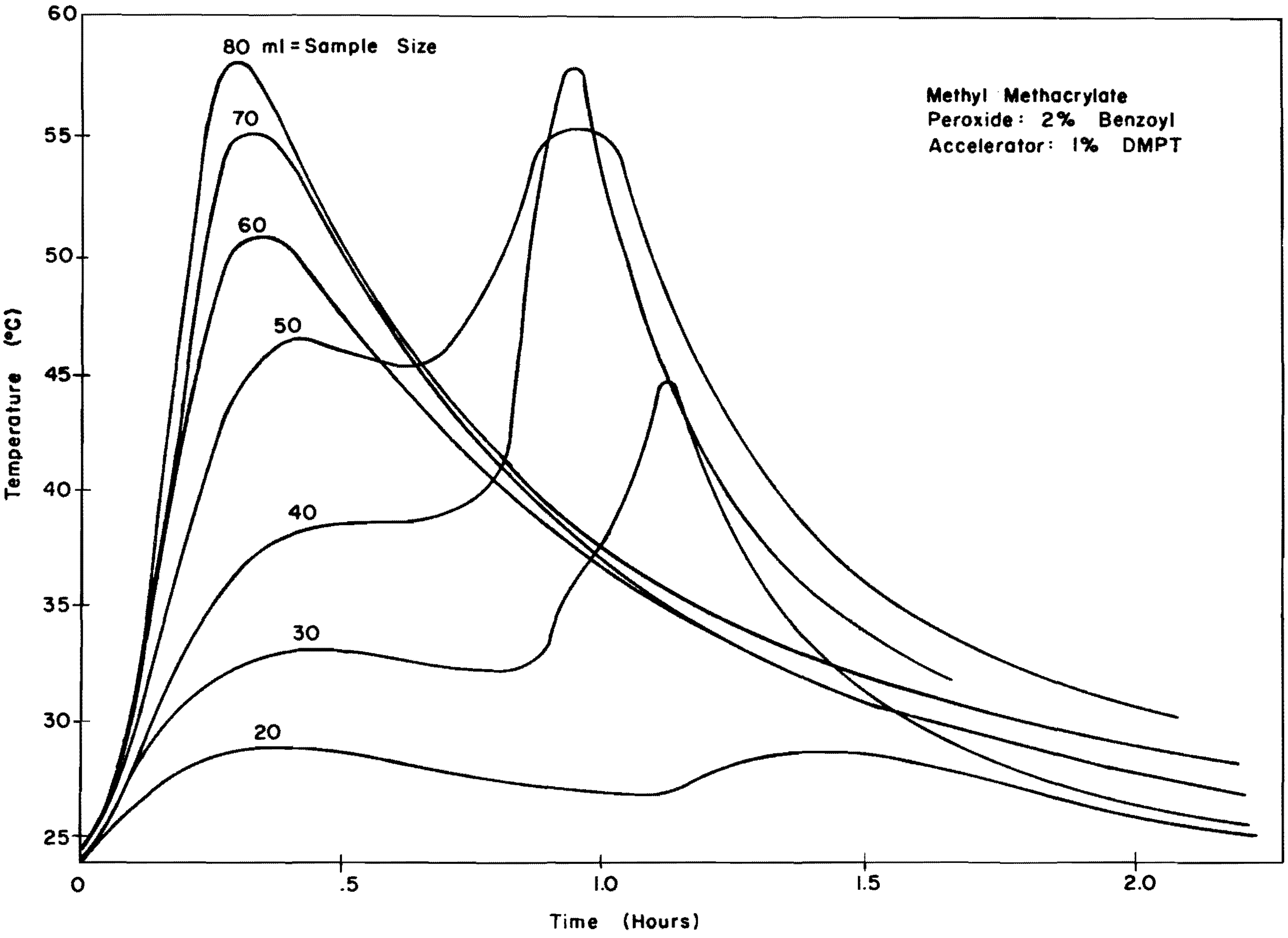


FIG. 2.3 EFFECT OF SAMPLE SIZE ON THE NATURE OF THE EXOTHERM

sample size and initiator system but varying levels of TMPTMA are shown in Fig. 2.4. As the proportion of this agent is increased, the second peak is increased in magnitude and shifted to shorter times to the point where it merges with or surpasses the first peak. Fig. 2.5 illustrates the uniform shift of this peak. TMPTMA has a very profound effect on the polymerization rate.

All of the products were very hard with no tacky surfaces. However, another effect is produced in the product by the cross-linking that occurs, viz, brittleness. The samples with the highest contents of TMPTMA were so brittle that they were cracked from thermal stresses. This problem diminished as the TMPTMA content was decreased.

2.2 Preliminary Monomer Penetration Studies

In the preliminary phase of the investigation, qualitative studies were made to determine the effect of several variables on monomer penetration into concrete. The variables were viscosity, temperature, soak time, surface preparation, and hydrostatic pressure. The tests were performed on 6 x 10 x 10-in. concrete slabs. Monomer was ponded in 4-in.-diameter steel rings bonded to the surface with silicone adhesive. Two rings were used per slab. Plastic film was placed over the rings to prevent evaporation during the soaking period. At the end of the soaking period, excess monomer was poured off, the rings were removed, and the specimen was immediately broken across both wetted areas. Initially, dye was used in the monomer to determine penetration depth, but this was discontinued when it was found that the dye filtered

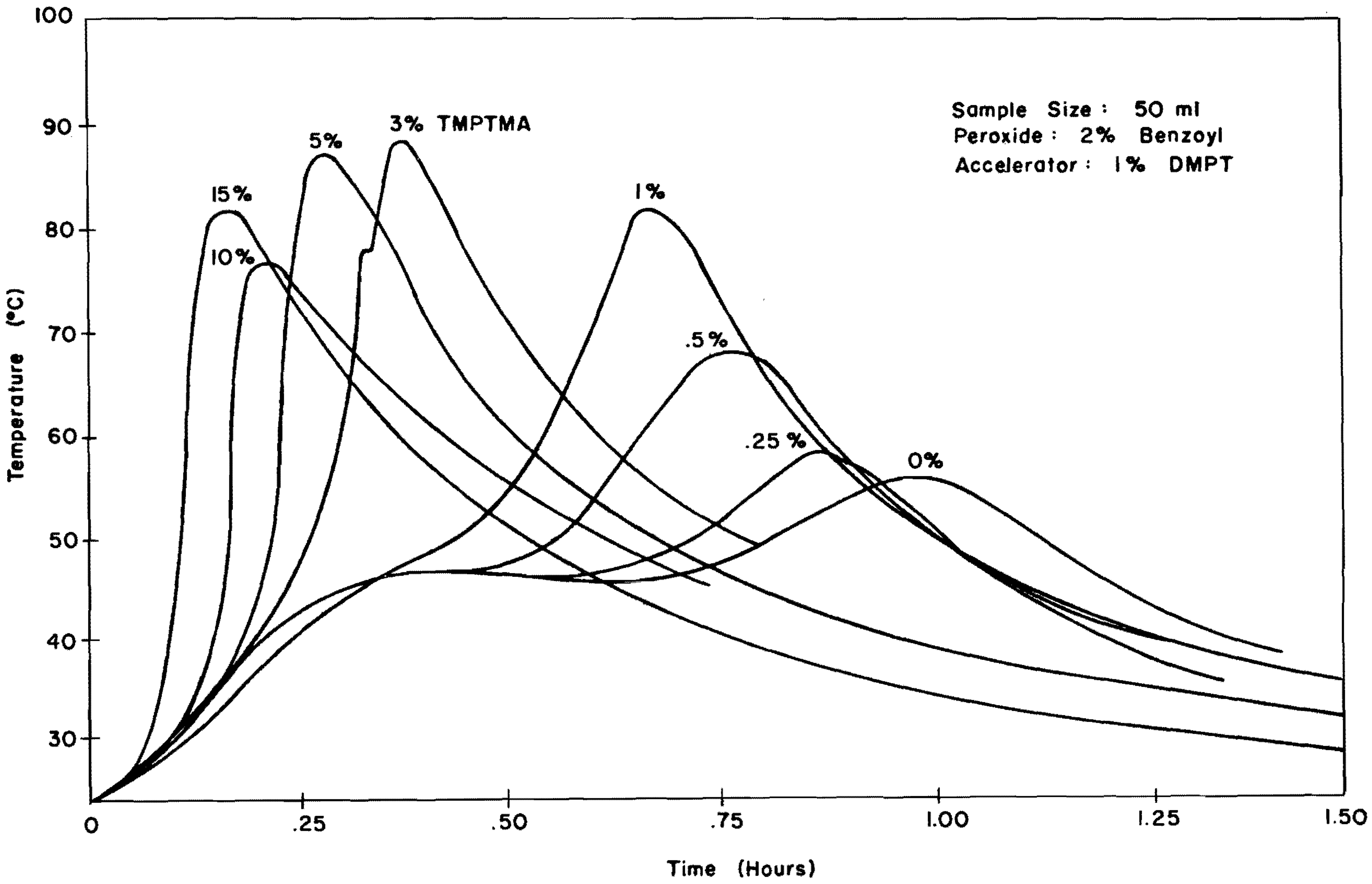


FIG. 2.4 COPOLYMERIZATION OF MMA WITH THE CROSSLINKING AGENT TMPTMA

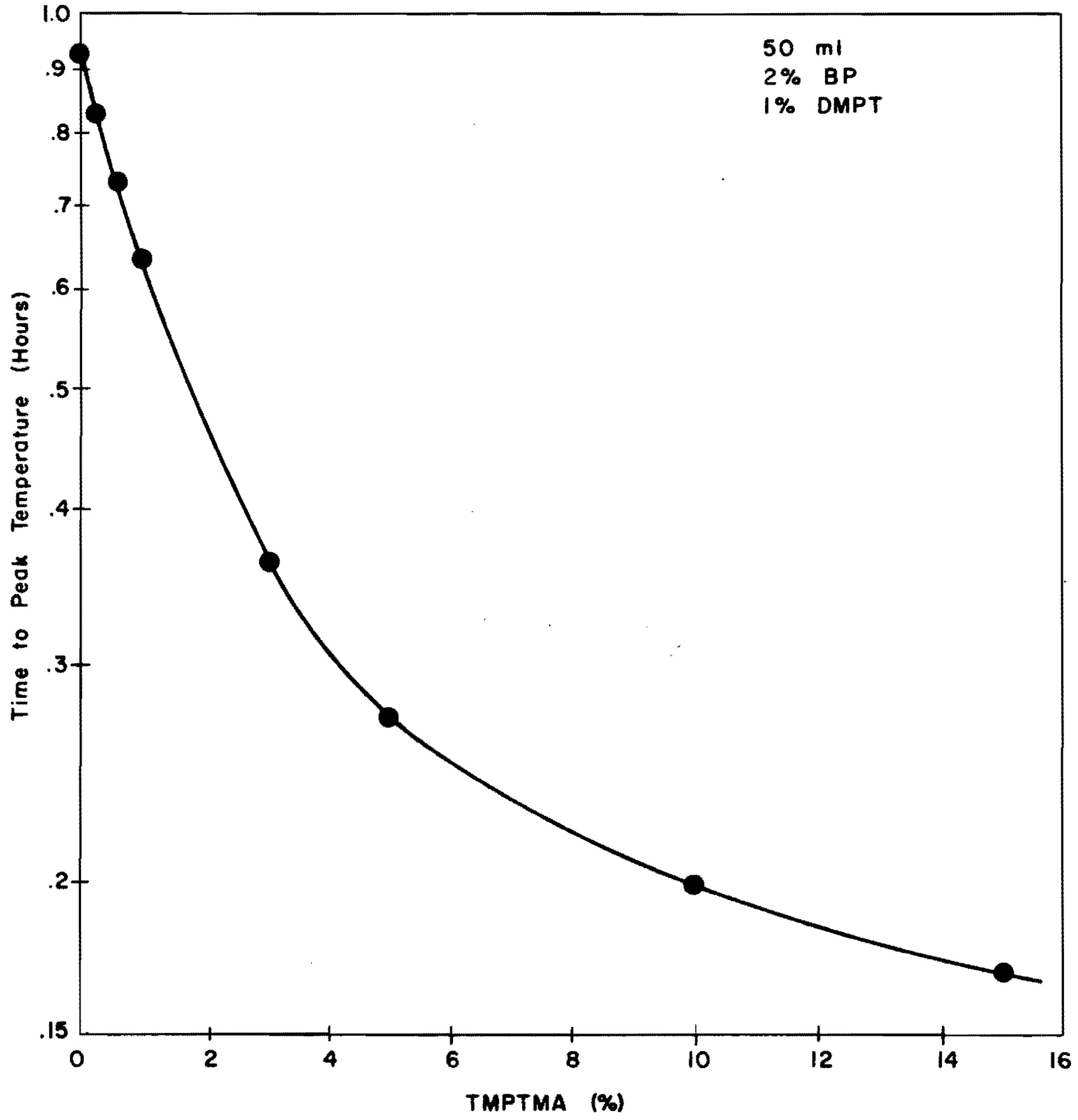


FIG. 2.5 EFFECT OF TMPTMA LEVEL ON THE TIME TO PEAK TEMPERATURE Data from Figure 2.4.

out near the slab surface. Thereafter, the depth of penetration was marked on the broken surface.

Only MMA alone and a solution of MMA and a low molecular weight acrylic copolymer (Rohm and Haas 6906-XP) were used in this preliminary investigation. The copolymer was used to reduce the vapor pressure since it was assumed early in the investigation that evaporation would be one of the most seriour problems to be overcome in developing surface treatments. No attempt was made in these preliminary tests to polymerize the monomer.

The effects of viscosity, temperature and soak time on monomer penetration into the concrete are shown in Fig. 2.6. Viscosities are shown only for the monomer applied to concrete at room temperature. The viscosity was varied by addition of the copolymer. The penetration was significantly affected by viscosity and by slab temperature. It was later found that the soak time should be longer than those shown in Fig. 2.6, but the qualitative results were useful in determining relative importance of the variables.

The condition of the surface was found to affect penetration. Textured surfaces were found to be more easily penetrated by the monomer than smooth troweled ones. Wire brushing parallel to the screeding lines on the surface also aided penetration; this seems to be the result of breaking the concrete surface film formed during the hydration of the concrete.

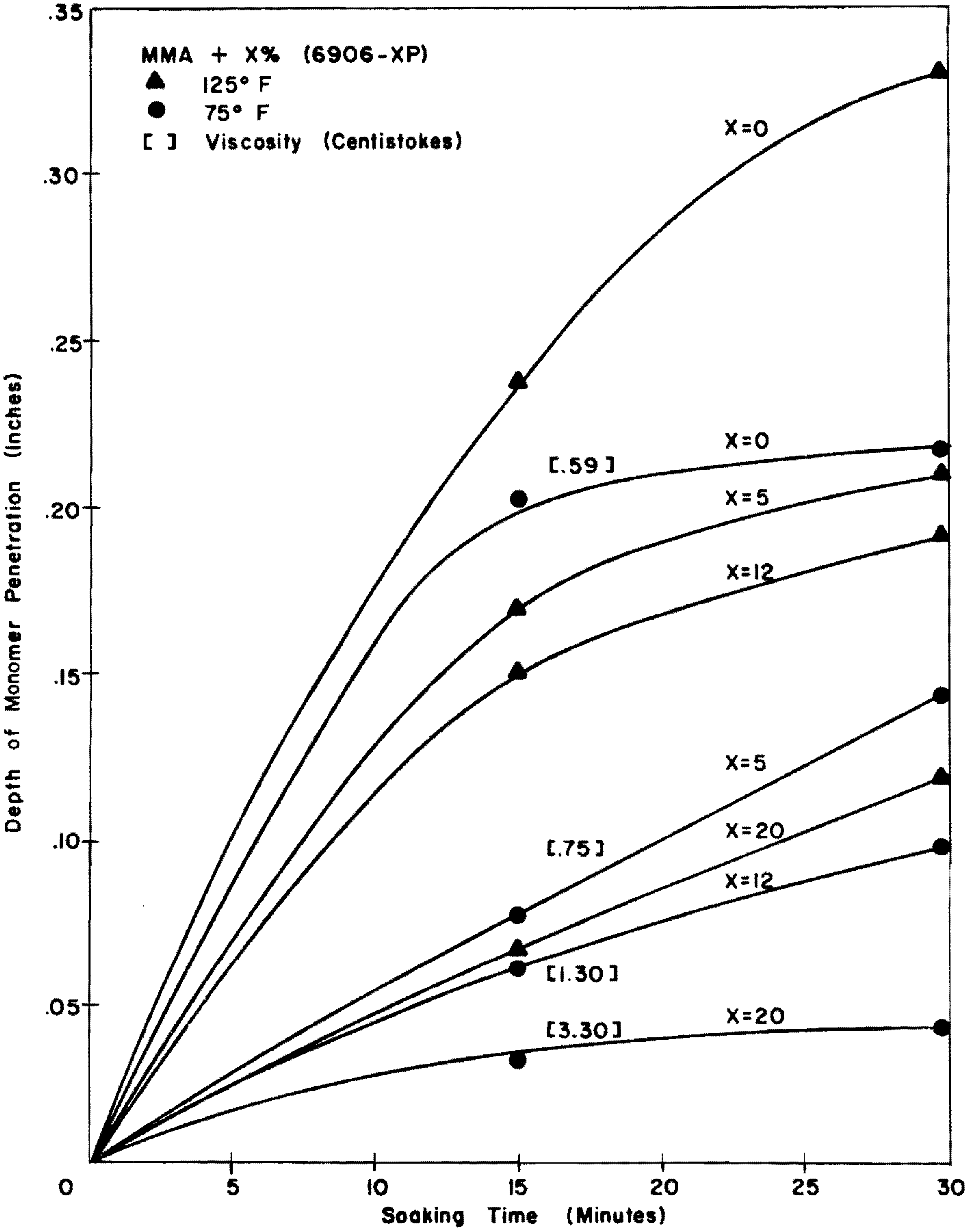


FIG. 2.6 EFFECT OF VISCOSITY, TEMPERATURE, AND SOAK TIME ON MONOMER PENETRATION IN CONCRETE

Increasing the depth of monomer from 1/8 in. to 1/4 in. had no perceptible effect on monomer penetration. As noted in section 2.1, capillary forces seem to predominate. Later tests verified that no ponding was necessary to achieve satisfactory penetration.

CHAPTER 3.

Surface Treatments

3.1 Statement of Problem

The studies reported in chapter 2 permitted a better understanding of the problems associated with obtaining surface treatments in concrete. However, these studies yielded primarily qualitative information, and these results could not be used to directly predict performance of surface treatments. It became obvious that the pasic investigations of monomer systems and penetration would have to be supplemented by actual tests on concrete using realistic conditions.

In the early phases of the investigation, three major problems in obtaining satisfactory surface treatments were identified. They were:

3.1.1 Development of Monomer Systems--As discussed in section 2.1, monomer systems that could successfully be polymerized at room temperature in test tubes were not found to polymerize in the concrete at room temperatures. It became obvious that the addition of either cross-linking agents, accelerators, heat, or some combination of these, to the monomer and catalyst would be necessary to obtain polymerization in concrete. The search for suitable monomer systems became essentially a trial and error solution, using concrete slabs and the trial monomer system.

3.1.2 Application Techniques--From the beginning of the studies it was known that evaporation posed a potential problem since most low viscosity monomers suitable for surface treatment have low vapor pressures. For surface treatments the problem was more pronounced because of the large surface-to-volume ratio and the time required for penetration. The use of evacuation (application of a vacuum) and overpressure to accelerate the saturation of the concrete was not considered to be feasible, even though some investigators have used them for small laboratory specimens.(25)

3.1.3 Curing Methods--After little success was achieved using room temperature polymerization, it became necessary to investigate methods of supplying external energy to assist polymerization. Use of nuclear irradiation, extensively used for laboratory specimens,(20) was not deemed feasible because of both the weight of the portable field apparatus required and the safety hazards involved. To be successful the curing method had to be economical, available outside urban areas, safe, and suitable for treating large areas of concrete.

3.2 Development of Monomer Systems

3.2.1 Procedures--The general procedure for investigating surface treatments was to dry the slabs, mix the monomer solution, soak the solution into the slab, cure the concrete, break the slabs, and record the results.

All of the laboratory tests were performed on 2 x 10 x 10-in. or 6 x 10 x 10-in. slabs to which 1 x 9-1/2 x 9-1/2 in. metal frames (Fig. 3.1) or 4-in.-diameter metal rings were attached. The rings were used initially because two could be used on each slab. However, the edge effects were large as evidenced by the presence of only a small amount of polymer in the center of the rings. For that reason the larger square frames have been used in nearly all of the later studies. Six-in.-thick slabs were used initially and are still used for slabs which are evaluated for durability. Two-inch slabs, which are more easily handled and require less concrete, are used in the qualitative tests to determine the results of a treatment.

3.2.2 Monomer System Investigated--Approximately 20 or 25 monomers, or combinations of monomers, have been investigated for feasibility. Most of these have been methacrylates. Several of these have produced satisfactory surface treatments of 1/2-in. depths or more. Combinations of styrene and polyester were used. However, because of the high viscosity of the polyester, adequate penetration could not be achieved even with a solution containing 90 percent styrene by volume.

The monomers selected for further study were:

1. methyl methacrylate (MMA)
2. isobutyl methacrylate (IBMA)
3. isodecyl methacrylate (IDMA)
4. butyl acrylate (BA)
5. isobutyl acrylate (IBA)
6. butyl methacrylate (BMA)

The last three have only recently been identified as being successful for surface treatments, and evaluation tests have just begun. In addition, tert-butyl styrene indicated considerable potential, but it has been discontinued by the manufacturer. All of the monomer systems utilize 1 percent (wt) benzoyl peroxide (BP) as the catalyst and 10 percent (wt) cross-linking agent, trimethylolpropane trimethacrylate (TMPTMA). All of these systems have been shown to polymerize in concrete at a temperature of 125°F.

Several methods of combining the catalyst and monomer were attempted. The most common method reported by others(20) and the most successful method in this project was to mix the catalyst in the monomer before application to the concrete. However, potential safety hazards would be involved if large quantities of monomer solution were mixed before application to the concrete.

Another method investigated was to deposit the catalyst, using 2 to 5 percent of the estimated polymer weight in the concrete, in the saturated pores in the cured concrete with acetone. The theory was that the acetone would evaporate, leaving the BP in the pores of the concrete to later react with the monomer solution. A solution of MMA and cross-linking agent was soaked into the concrete and after soaking, heat was applied to polymerize the monomer. However, only one specimen out of five showed any polymer, and it was shallow and faint.

Another means of introducing BP into the concrete was to mix it in the fresh concrete. This was attempted using BP paste instead of dry powder. Sufficient BP (o.22 lbs./cu.ft. of concrete) was added to provide 2.5 percent of BP for a 6 percent (wt) monomer loading. However, an adverse reaction took place in the concrete mix with the BP present. The compressive strength (2420 psi) was approximately one-half of the values found for similar mixes without BP present. Surface treatments were attempted using MMA and TMPTMA soaked into the concrete, but only slight traces of polymer were obtained.

3.3 Application Techniques

Application techniques were developed using 2 x 10 x 10-in. and 6 x 10 x 10-in. concrete slabs in the laboratory and 5-1/2 x 40 x 43-in. slabs in the field. Application consisted of drying the slabs, soaking the slabs with monomer solution (Fig. 3.1), preventing evaporation, and curing.

3.3.1 Drying--Drying of the concrete to remove free water has been found to be important.(20) The effect on surface treatments was evaluated qualitatively by treating air dried and oven dried (175°F) 2-in. and 6-in. slabs with a monomer system using MMA. After curing, the oven-dried slabs had approximately three times greater polymer depth, and, in addition, the polymer was darker, indicating a higher polymer loading.

Slabs used for qualitative surface treatment were dried at 125°F or 175°F for a minimum of three days. Treated slabs used for evaluation purposes were dried for a minimum of seven days. Field treated slabs were left exposed to the air for a minimum of two months before being covered with polyethylene film to prevent saturation with rain. Heating blankets were then applied and left in place a minimum of three days.

While heating blankets may not be feasible for large-scale treatments, the use of plastic covers to keep the surface dry and to absorb solar heat to assist the drying process does seem practical. For accelerated drying, heaters placed under a plastic sheet enclosure or a warm forced-air system could be used.

3.3.2 Evaporation Barriers--Initially monomer was ponded to a depth of 1/8 to 1/4 in. on level 10 x 10-in. slab specimens to provide a surplus of monomer to compensate for evaporation loss. Plastic-wrapped plywood was placed over the metal frames to minimize evaporation. The slabs were then placed in an oven at 125°F to polymerize the monomer. However, only a shallow depth (≃ 1/8 to 1/4 in.) of polymer was obtained, and there was usually a thin (≃ 0.05 in.) zone of unpolymerized concrete at the surface caused by evaporation.

It was found that a thin (≃ 1/4 in.) layer of fine aggregate placed on the top of the slab served as an evaporation barrier. The monomer could be applied in sufficient quantities to wet the sand, and the sand served as a wick for the slab. This permitted a much longer soak time without the monomer evaporating completely off the surface. Initially lightweight aggregate fines were used since, because of their skid resistant characteristics, it was theorized that if the aggregates were bonded to the surface during polymerization, a skid resistant surface would result. The sieve analysis for all of the lightweight aggregate used in the tests reported is given in Table A.3 in the appendix.

More recently it has been found that the use of regular fine aggregate seems to yield deeper surface treatments. This can probably be explained by the fact that the more porous lightweight aggregate is a better insulator and prevents the concrete from reaching as high a temperature as when normal aggregate is used during the curing process.

Since actual bridge decks are sloped to permit drainage of water, tests were performed on sloped slabs to determine if adequate penetration of the monomer could be achieved. Small laboratory slabs and the larger field treated slabs were sloped 1/4 in./ft. The field treated slabs were covered with 1/4-in. oven-dried lightweight aggregate fines (Fig. 3.2). Current tests are underway on slabs covered with natural sand.

3.3.3 Monomer Application--In the laboratory, the monomer solution was mixed in beakers and poured onto the slabs with the metal frames and, in later treatments, sand cover. The initial volume of monomer usually varied between 250 ml and 400 ml. The specimens were covered with the plastic wrapped plywood to help prevent evaporation. If during the soaking period, the sand became dry, additional monomer (100 ml) was added.

For the larger field-treated slabs, the monomer was mixed in and applied with galvanized water sprinkler cans (Fig. 3.2). The slabs were immediately covered with polyethylene film to minimize evaporation losses.

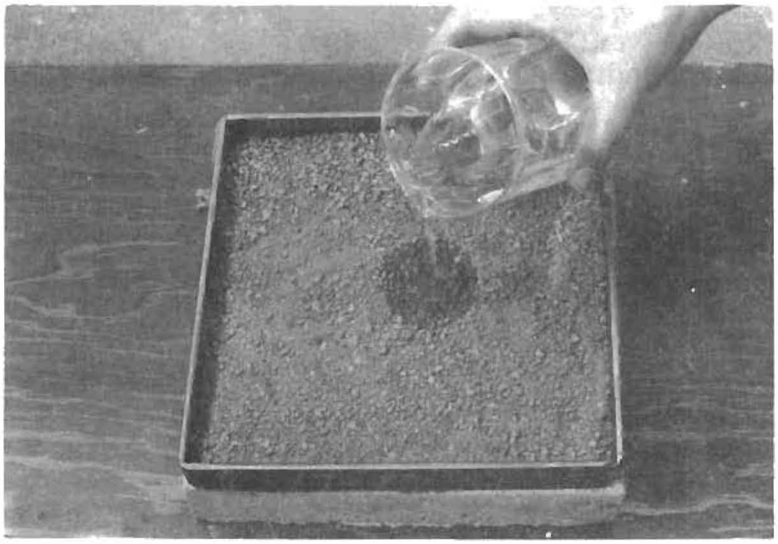


FIG. 3.1 APPLICATION OF MONOMER TO 2 IN. SLAB COVERED WITH FINE AGGREGATE

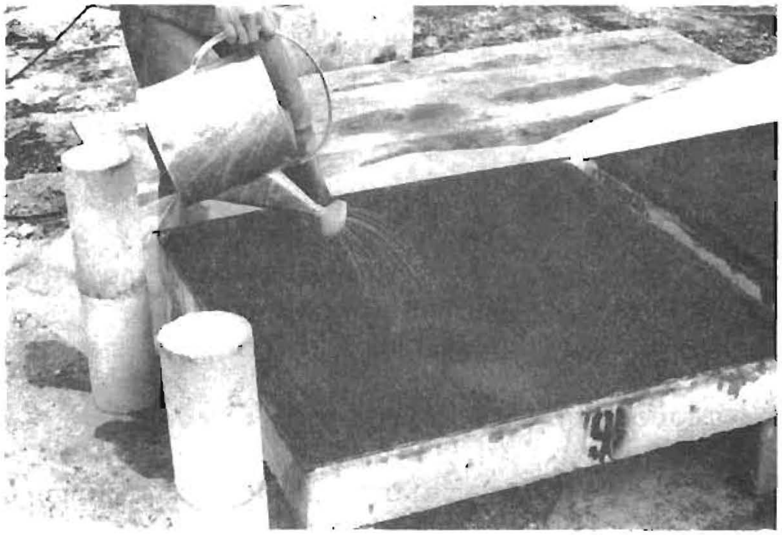


FIG. 3.2 APPLICATION OF MONOMER DURING FIELD TREATMENT OF SLOPED SLABS WITH FINE AGGREGATE COVER

On warm, sunny days when the exposed slab temperature would exceed 100° F, the slabs were shaded to prevent premature polymerization before adequate penetration had been achieved. Additional monomer solution was added if the lightweight fines became dry. It was usually observed that IBMA had less tendency to dry out on the surface than did MMA.

It should be emphasized that most treatments to date have had the primary purpose of either determining the feasibility of monomer systems or treating slabs to be evaluated for durability. In most cases, the monomer was applied rather liberally to insure a good treatment. However, this investigation is also concerned with optimizing the procedures to obtain the most economical treatments possible. Current studies are underway to determine the minimum amount of monomer solution consistent with acceptable treatments.

3.3.4 Soak Time--Most of the soak times used in the surface treatments for laboratory specimens ranged from 20 to 24 hours. A series of 2-in. slab specimens were treated using soak times of 5, 10, 15, 20, and 25 hours. The treatment consisted of approximately 400 grams of MMA with 1 percent BP and 10 percent TMPTMA, with the exception of the slabs soaked for 20 and 25 hours, which had an additional 100 grams added after 15 hours since the aggregate appeared dry. The results of this test (Fig. 3.3) indicate that there is little difference between the specimens soaked 10 hours or more. While other variables, such as concrete permeability and monomer viscosity will affect penetration into the concrete, an 8 to 10 hour minimum soak time seems adequate for MMA in most cases.

These results may not seem consistent with the data presented in chapter 2 from the penetration tests, which indicate monomer penetration of greater than 1/4 in. after 30 minutes of soak time. However, when a slab is placed in the oven to cure after a 30 minute soak time, the resulting depth of polymer impregnation is approximately 1/8 in. This seems to indicate that for short soak times the concrete pore walls are visibly wetted but the pores are not filled. The longer soak times are necessary to fill the pores. It should be emphasized that in order for the longer soak times to be effective, it is necessary to keep the sand moist.

3.3.5 Methods of Curing--Considerable effort has been expended on developing simple, practical methods for polymerizing the monomer system in slab surfaces. Initially in the investigation, specimens were placed in a 125°F oven for curing while more practical methods for curing large areas of bridge decks in the field were investigated. The value of 125°F was selected since it represented the lowest nominal temperature at which polymerization would occur in a reasonable time period. Unless a heat generating system could produce slab surface temperatures of at least 125°F, it was not considered a potential solution.

To determine the required curing time for surface treatments, five 2-in. slabs were soaked for 24 hours with the MMA system, cured in an oven at 125°F, and removed at times varying from 2-1/2 to 10 hours and permitted to cool. A good surface treatment was obtained for all five cure times (Fig. 3.4). These specimens indicate that 2-1/2 hours of cure in an oven provide adequate surface treatment. For other methods of heat application shorter cure times have been obtained.

Several of the curing methods investigated are briefly discussed here.

1. Solar energy--From the standpoint of economy, solar energy is a very appealing heat source. It is well known that solar energy produces temperatures in concrete significantly higher than the air temperature. Temperatures on a bridge deck in July in Austin were monitored to determine if they were sufficiently high to polymerize the monomer. It was found that on days when the maximum air temperature ranged from 96 to 103°F the temperature of the slabs was approximately 30°F higher than for the air, with maximum values approximately 135°F (Fig. 3.5). The slabs remained at 125°F or above for nearly six hours. It was noted that a rapid decrease in slab temperature occurred when the sun was obscured by clouds.

Limited tests on slab specimens indicated that solar energy does have potential use. Three slabs treated with an MMA solution containing 2 percent BP, one with 10 percent TMPTMA and two with 5 percent TMPTMA, developed shallow surface treatments approximately 1/8 in. deep when exposed to sunlight for an afternoon, with the slab reaching a temperature of ≈ 130°F. The monomer solution was applied for only 30 min. prior to exposure to the sun.

However, the use of sunlight is limited by variables which cannot be fully controlled. Air temperature, cloud cover, moisture, and perhaps

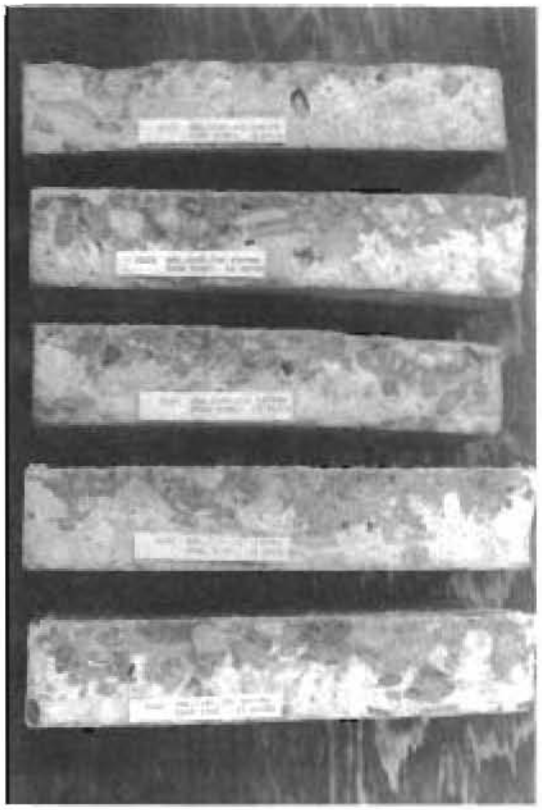


FIG. 3.3 EFFECT OF SOAK TIME ON POLYMER DEPTH (5, 10, 15, 20, and 25 hrs--top to bottom)

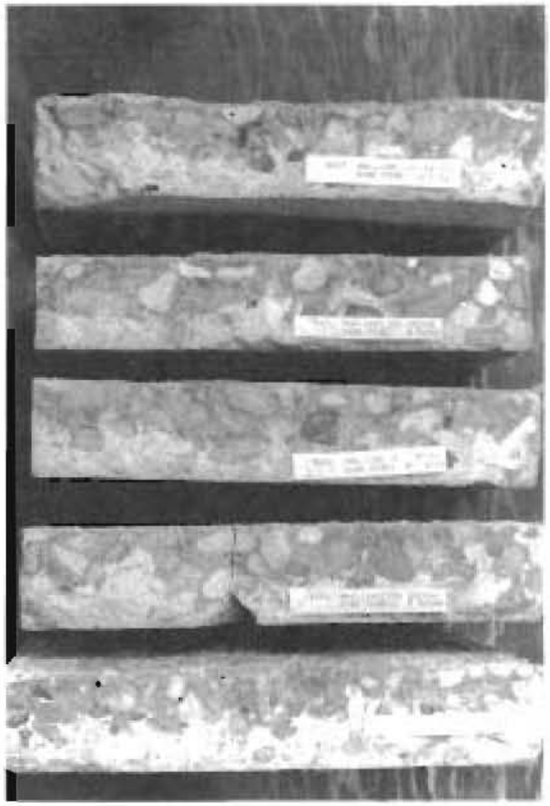


FIG. 3.4 EFFECT OF CURING TIME AT 125° F ($2\frac{1}{2}$, 4, $5\frac{1}{2}$, 7, and 10 hrs--top to bottom)

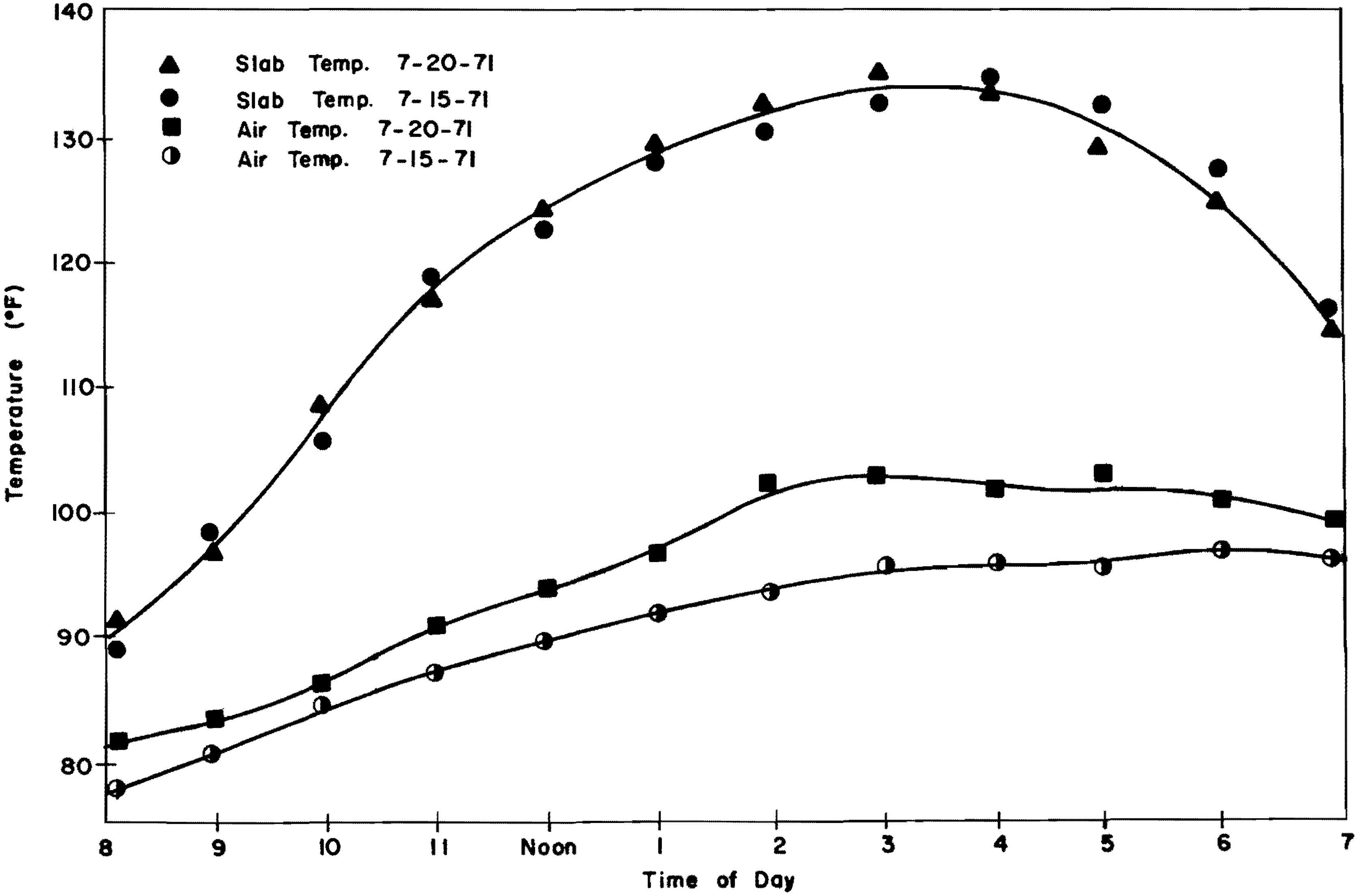


FIG. 3.5 SLAB SURFACE TEMPERATURES FOR SOLAR HEATING

relative humidity affect slab temperatures. Treatments would have to be on a day-to-day basis, which would make planning difficult. In many parts of the U.S. sufficient temperatures for polymerization would occur in only a few months each year. Also, surface evaporation would probably be more difficult to control. For these reasons solar energy has not been considered a prime method for polymerization.

2. Microwave heating--Some attempts were made to introduce heat into the slabs by the use of microwaves. A microwave oven, commonly used to heat pastries, was obtained to explore the potential of this technique. The concrete slabs were treated with monomer in the standard fashion. After the desired penetration was achieved, the excess monomer was removed and the 2-in. concrete slab was broken into approximately 5 x 5-in. pieces. The specimens were broken because they were too large to be accommodated by the oven. Each specimen was placed in the oven and heated for various time intervals. Temperatures of the specimens were taken upon removal from the oven. Fluctuation of these temperatures was very great, presumably because of the variations in the mass of the concrete placed in the oven. No quantitative studies were performed to verify this assumption. No data are shown, since only very limited success with the microwave oven resulted when twenty slabs were treated and cured. The feasibility of using microwave heating for field conditions seems improbable at this time.

3. Reactive Monomer System--The use of a second, more reactive

treatment that could be applied over the usual initial treatment was explored with the goal of developing sufficient heat to cause polymerization. One reactive monomer system that has shown some potential consisted of MMA, 4 percent lauroyl peroxide and 4 percent N, N-dimethyl-p-toluidine. This solution, when ponded on the surface of specimens already saturated with MMA, benzoyl peroxide and TMPTMA, achieved polymerization within two hours. Typically the heat generated will polymerize the initial monomer treatment to a depth of a quarter-inch or less, although in one specimen a polymer depth of 3/4 in. was obtained. The sand cover serves an additional purpose, providing a friction-resistant surface instead of the glossy polymer coating that could develop on the slab. The second treatment serves, initially, as an evaporation barrier and, after polymerization, as a wearing surface, which may be more important than its heat-generating capabilities. In most current investigations additional heat sources are applied for curing even when the second treatment is used.

4. Heating Blankets--Heating blankets, which have long been used in cold climates to cure concrete, were investigated for use. The blankets are capable of developing relatively high concrete temperatures. Several field-treated slab specimens used heating blankets with a capacity of 25 watts/sq. ft. as the energy source for polymerization (Fig. 3.6). The time-temperature relationship for a typical treatment is shown in Fig. 3.7. Slab temperatures were measured with thermocouples mounted on the surface. Top surface temperatures in the range of 140°F or more were reached;

FIG. 3.6 POLYMERIZATION CURE BY USE OF HEATING BLANKET

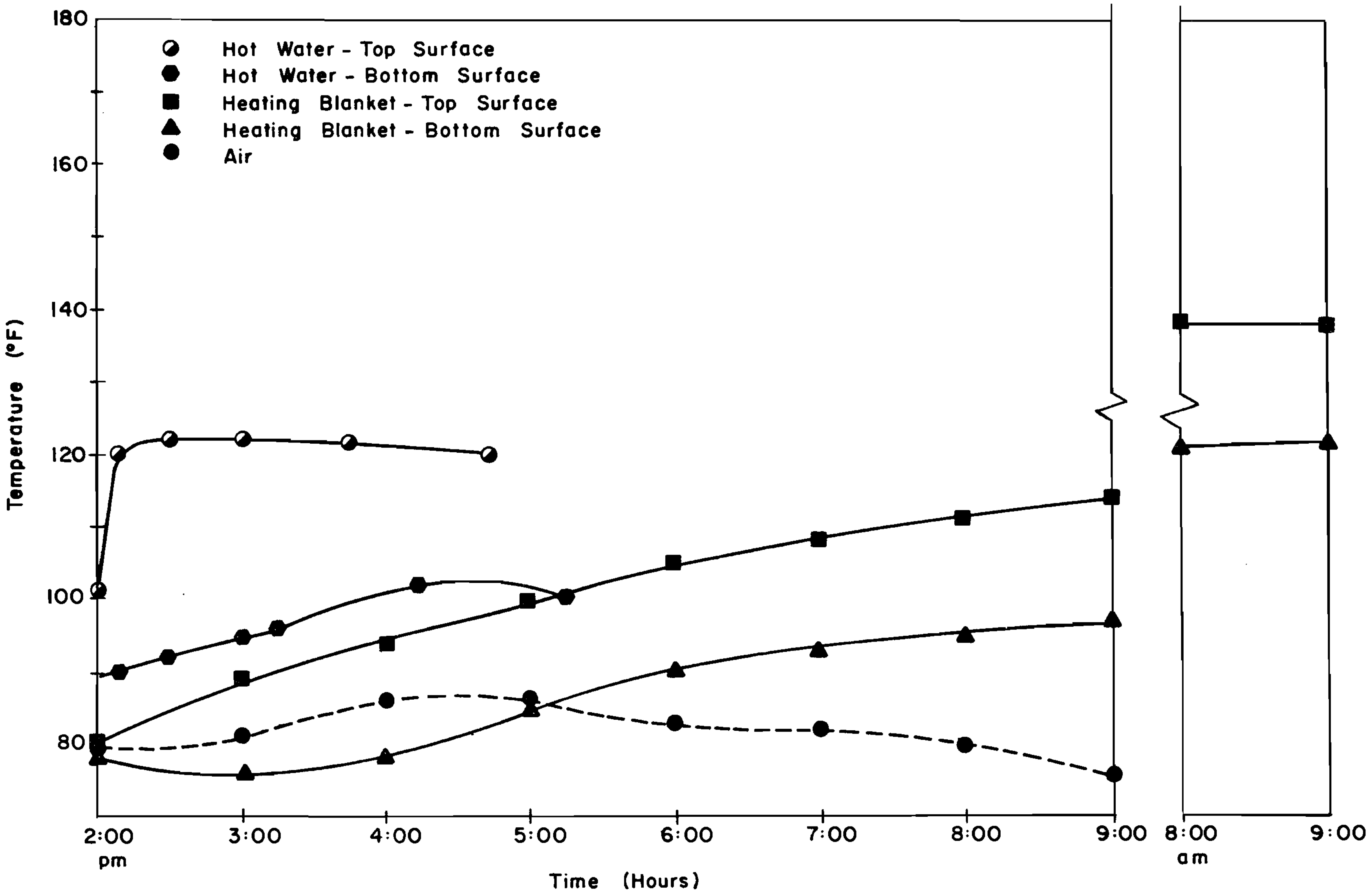


FIG. 3.7 TIME-TEMPERATURE CURVES FOR FIELD-TREATED SLABS

however, these temperatures were reached very slowly, which required the addition of considerable amounts of monomer to keep the fine aggregate moist. Polymerization was achieved, and heating blankets represent one method of heat generation.

5. Steam--Steam was used to cure several slab specimens. After soaking overnight with the monomer system, the slab surfaces were sprayed with steam. The three slabs shown in Fig. 3.8 were steam cured for 4, 8 and 11 minutes. The depth of polymer was approximately 3/4 in.; however, the evaporation due to the high surface temperature was excessive, ranging from 1/8 to 3/16 in. A number of evaporation barriers, including sand, wet burlap, sheet metal, and polyethylene, were tried with little success.

However, the use of a steam curtain, used for curing in concrete products plants, is being investigated. An enclosure made of canvas or plastic film is placed over the slab. Steam is supplied to the enclosed space to heat up the slab. Since steam is not applied directly to the surface of the slab, the evaporation losses are reduced. Current tests indicate that the steam curtain method is capable of generating slab temperatures in excess of 200°F in a short period of time. While these high temperatures are probably not desirable for bridge decks, they do indicate the potential of this method. Using 2-in. slabs, polymer treatments have reached a depth of 1-3/4 in. Further tests could indicate that this method is the simplest and most economical.

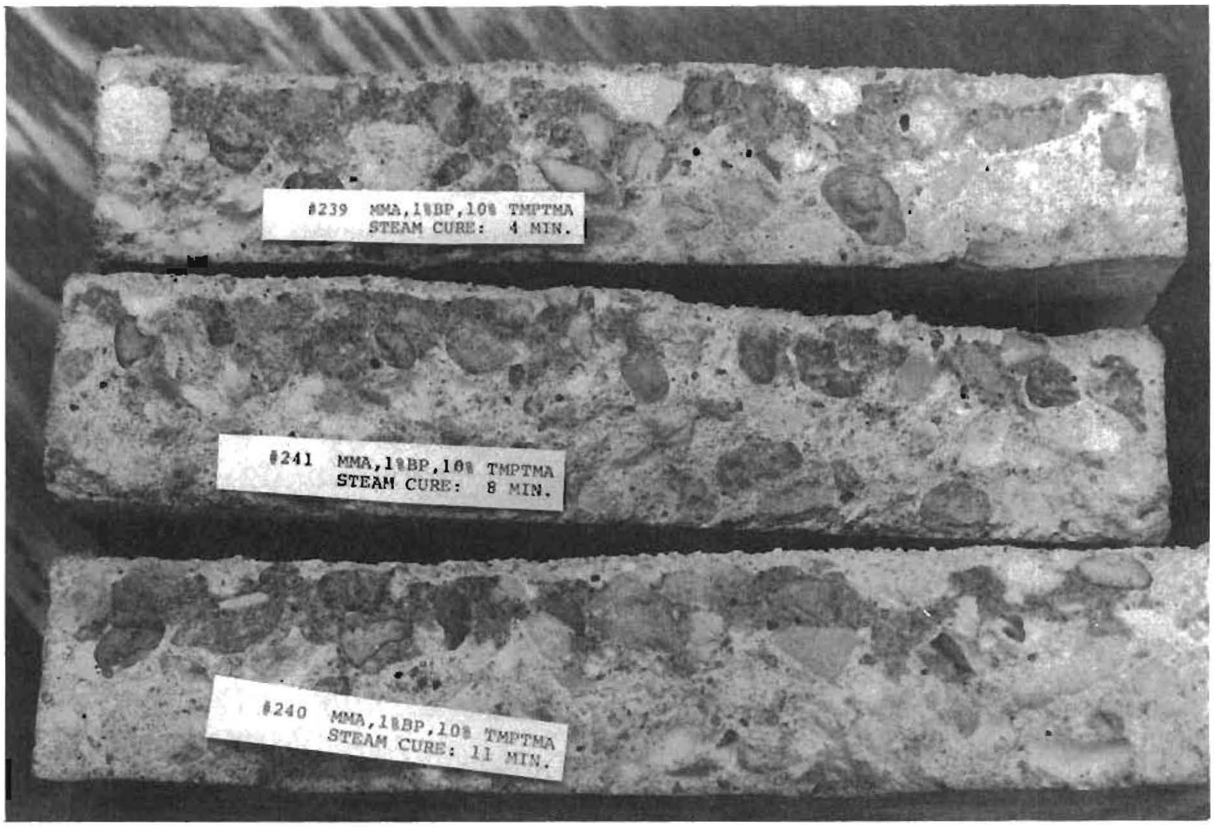


FIG. 3.8 2-IN. SLABS CURED WITH STEAM APPLIED TO SURFACE (4, 8, and 11 min.--top to bottom)

6. Hot Water--One very successful means of polymerization to date has been the use of hot (≈190°F) water. After the soak period, a polyethylene sheet is placed over the sand cover and turned up the side of a frame around the edges to form a pond for the water. Hot water is ponded to a depth of approximately 3-in. In the laboratory the temperature of 2 x 10 x 10-in. slabs was monitored by a thermocouple mounted on the slab surface beneath the regular fine aggregate for three different water application times (Fig. 3.9). The slabs were insulated around the edges to minimize the heat flow. As the hot water was removed, the slab temperature dropped significantly after reaching a maximum of 125 to 135°F. This compares to a maximum of about 120°F when lightweight aggregate fines were used (Fig. 3.7).

A comparison of the polymer depth versus hot water application time for slabs covered with the two types of aggregate is shown in Fig. 3.10. The insulating effect of the lightweight aggregate was found to be significant. The use of regular aggregate produces a 3/4-in. polymer depth in one hour while lightweight aggregate requires two hours.

Field treatments on larger slabs have yielded good temperatures even in cold weather. In a recent treatment during a day on which the air temperature failed to reach the predicted high of 70°F, a scheduled treatment was continued even though the air temperature reached only 50°F. Within minutes of the hot water application, the slab temperature reached 138°F. Regular fine aggregate was used in this treatment.

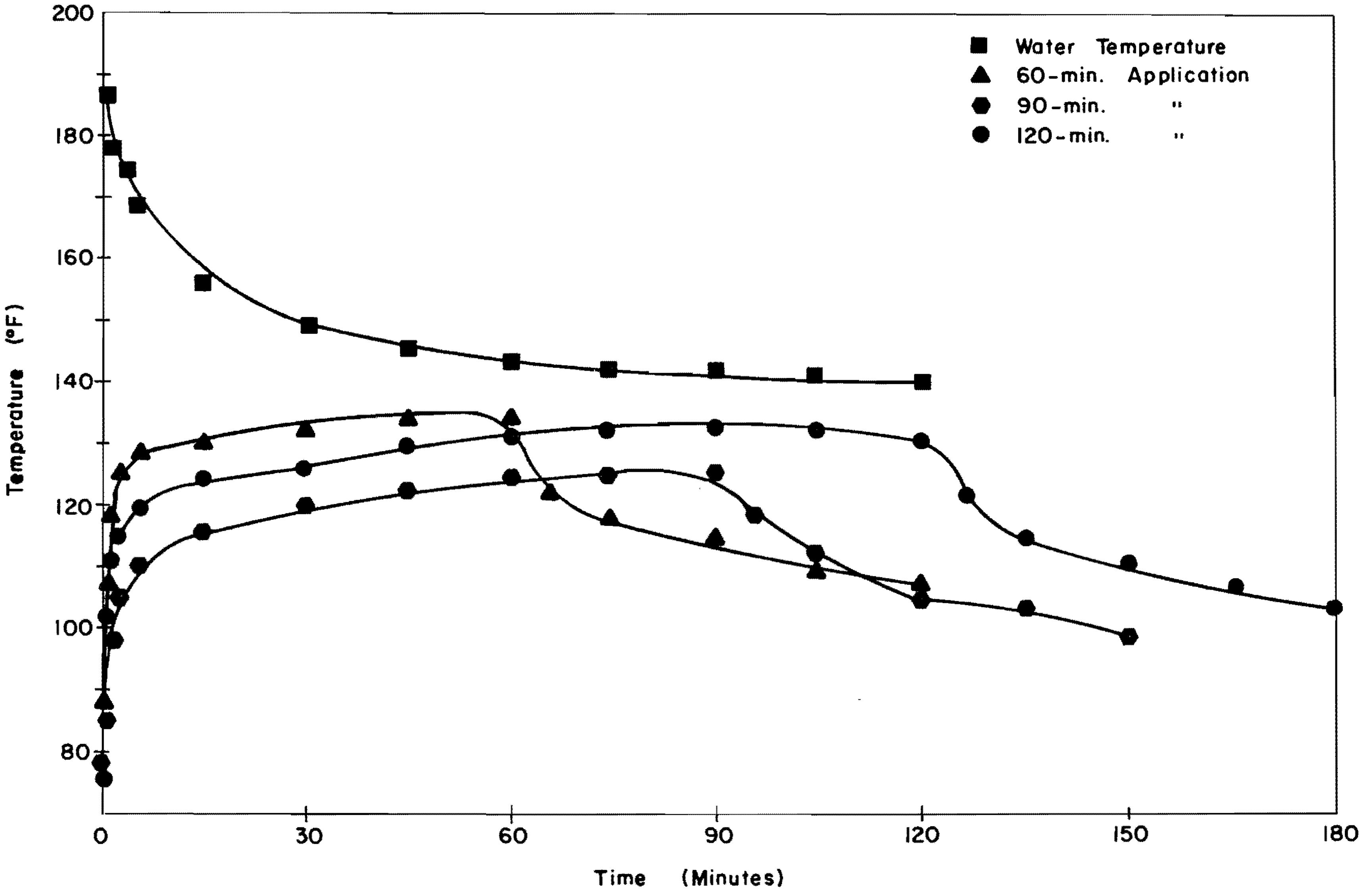


FIG. 3.9 SLAB TEMPERATURES FROM 3 IN. OF HOT WATER WITH A REGULAR FINE AGGREGATE TOPPING

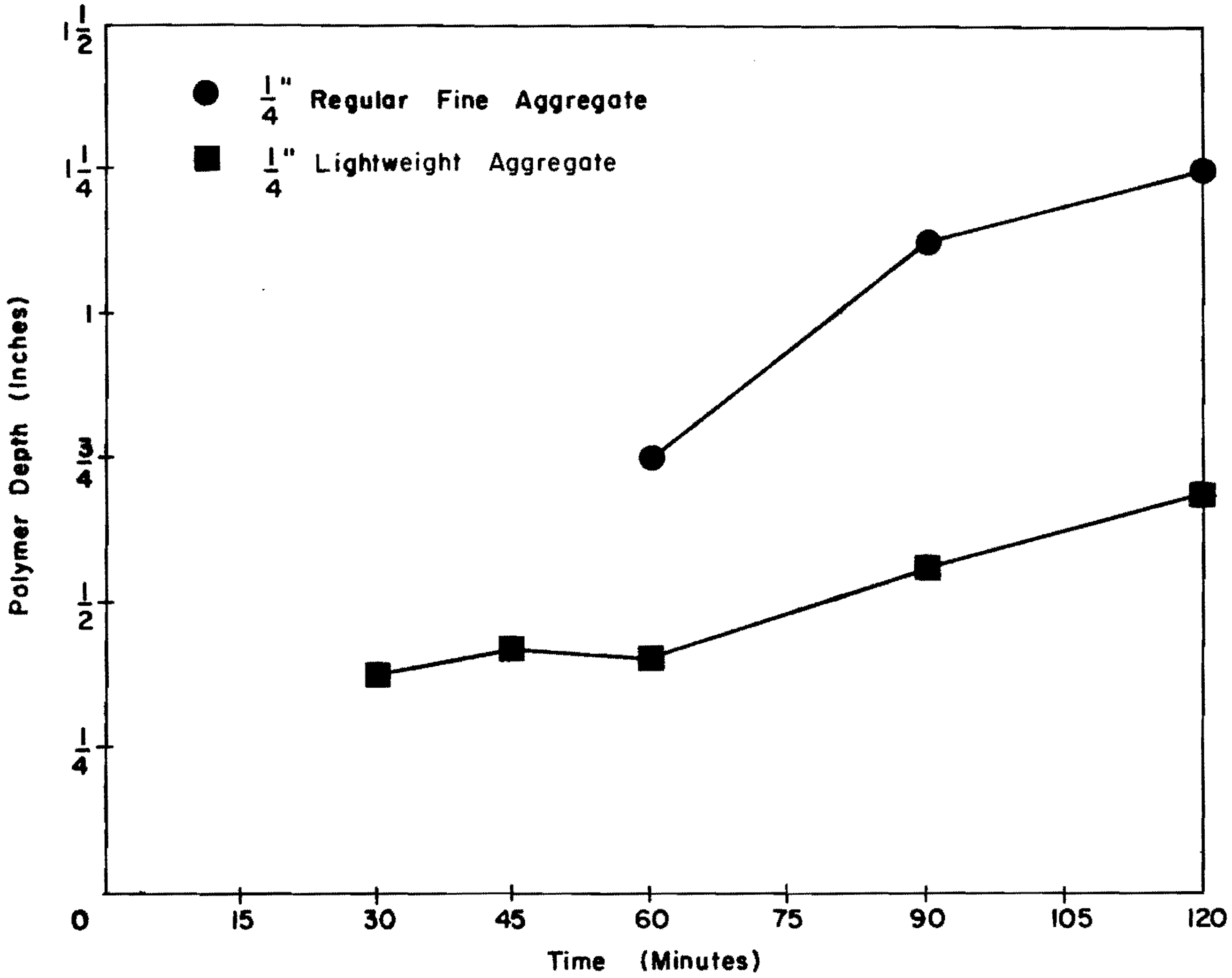


FIG. 3.10 EFFECT OF CURING TIME WITH 3 IN. OF HOT WATER ON POLYMER DEPTH USING MMA, 1% BP, AND 10% TMPTMA

7. Warm Air--Warm air ovens have been extensively used to cure the small slabs. Temperatures of 125°F have been adequate to produce good surface treatments. The sand cover prevents evaporation from the slab surface. While ovens per se would not be feasible for curing bridge decks, heaters placed in enclosures over the slab or forced-air heating systems with ducts into an enclosure would accomplish the same purpose. A simple frame one to two feet in height with a canvas or insulated panel covering would provide the enclosure.

3.4 Summary of Treated Slabs

Several hundred slabs have been treated to qualitatively evaluate monomer systems, application techniques, and curing methods. In addition, three types of slabs have been treated for the purpose of performing quantitative evaluation tests.* The treatments utilize the application and curing techniques described in section 3.3. The monomer solution was applied quite liberally to ensure an adequate treatment. The treatments and resulting depth of polymer impregnation are summarized here.

3.4.1 Laboratory-Treated Slabs--Seven series of five or more 5 x 10 x 10-in. slabs were treated with MMA monomer solutions. These treatments are summarized in Table 3.1. All specimens soaked or cured at 125°F were placed in an oven.

The first four series of slabs were treated before the advantages of using fine aggregate evaporation barriers were known. In addition, these

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*Mix designs are given in Table A.1 in the appendix.

TABLE 3.1 LABORATORY-TREATED SLABS

Series No.	Fine Lightweight Aggregate Cover, in.	Treatment(s)[b]	Quantity of Monomer, ml	Soak Time & Temp.	Cure Time & Temp.	Average Polymer Depth, in.
1PC-3	none	MMA,1%BP, 10%XL	139	48 hrs @ 125°F	--	1/8 in. light, irregular
1PC-4	none	MMA,1%BP, 10%XL[a]	139	48 hrs @ 125°F	--	1/8-1/4 in. irregular
2PC-4	none	MMA,2%BP, 10%XL	139	2 hrs @ 125°F	--	1/4 in.
		MMA,2%BP, 10%XL, 1% DMPT	46	1 hr @ 125°F		
1PC-6	none	MMA,2%BP, 5%XL	150	24 hrs @ 125°F	--	1/4 in. light, irregular
1PC-7	1/8	MMA,1%BP, 10%XL	140	24 hrs @ room	--	1/4 in. lightweight aggregate
		MMA,4%LP, 4%DMPT	100	room		
1PC-10[b]	1/4	MMA,1%BP, 10%XL	≈670	24 hrs @ room	48 hrs @ 125°F	1-1/8 in.
1PC-12	1/4	MMA,1%BP, 10%XL	300	18 hrs @ 73°F	24 hrs @ 125°F	1-1/2 in.
		MMA,1%BP, 10%XL	200	6 hrs @ 73°F		

[a] MMA = methyl methacrylate, BP = benzoyl peroxide, XL = cross-linking agemt (TMPTMA), LP = lauroyl peroxide

[b] All specimens treated on 1/4 in./ft slope

four series reflect the practice adopted early in the study of applying the monomer and immediately placing the slabs in the 125°F oven. This resulted in polymerization being initiated before appreciable monomer penetration occurred. The polymer depth varied from 1/8 in. to 1/4 in. The second reactive treatment applied to series 2PC-4 had little effect on the polymer depth.

Series 1PC-7 utilized a fine lightweight aggregate cover of 1/8 in. to act as a skid resistant surface for the second treatment, applied 24 hours after the first treatment. The heat of reaction, without additional external heat, resulted in a polymer depth of 1/4 in.

Series 1PC-10 and 1PC-12 utilized the current recommended procedures for evaporation barriers and a soaking interval before heat application. The results (1-1/8 in. and 1-1/2 in. polymer depths) are an indication of the effectiveness of these techniques. Series 1PC-10 was treated with each slab sloped 1/4 in./ft.

3.4.2 Laboratory Treated Wear Track Slabs--A total of 27 slabs were treated for use in determining wheel wear and skid resistance. These treatments are summarized in Table 3.2. All slabs, with the exception of specimen 2, were treated with a 1/4-in. fine lightweight aggregate cover on the surface. Three monomers--MMA, IBMA, and IDMA--were used for the treatments. Series 4 and 9 were given a second, reactive treatment to bond on the aggregate cover; external heat was used to polymerize the monomer. Four of the series used hot water at an initial

TABLE 3.2 WEAR TRACK SLABS (Concrete Mix PC-18)

Spec. No.	Treatment(s)[a]	Quantity of Monomer, ml	Soak Time & Temp.	Cure Time & Temp.	Average Polymer Depth, in.
1	MMA,1%BP, 10%XL	500	24 hrs @77°F	72 hrs @125°F	x[c]
2[b]	MMA,1%BP, 10%XL	500	24 hrs @77°F	72 hrs @125°F	x[c]
3A,B,C	MMA,1%BP, 10%XL	900	18 hrs @75°F	24 hrs @125°F	1
4A,B,C	MMA,1%BP, 10%XL	800	23 hrs @90°F	72 hrs	1-1/8
	MMA,4%LP, 4%DMPT	150	45 min @91°F		
5A,B,C	MMA,1%BP, 10%XL	800	23 hrs @90°F	hot water	1-1/4
6A,B,C	IBMA,1%BP, 10%XL	600	17 hrs @75°F	72 hrs @125°F	5/8-3/4
7A,B,C	IDMA,1%BP, 10%XL	600	18 hrs @75°F	48 hrs @125°F	1/2-3/4
8A,B,C	50%MMA, 50%IDMA, 1%BP,10%XL	600	17 hrs @75°F	72 hrs @125°F	1/2
9A,B,C	MMA,1%BP, 10%XL	900	24 hrs @75°F	hot water	1-1/4
	MMA,4%LP, 4%DMPT	100	20 min @75°F		

(Continued)

Table 3.2. continued

Spec. No.	Treatment(s)[a]	Quantity of Monomer, ml	Soak Time & Temp.	Cure Time & Temp.	Average Polymer Depth, in.
10A,B	IBMA, 1%BP, 10%XL	600	26 hrs @ 75°F	hot water	1-1/4
11A,B	IBMA, 1%BP, 10%XL	600	23 hrs @ 90°F	hot water	3/8-1/2
12A,B,C	CONTROL	--	--	--	--

[a] MMA = methyl methacrylate, IBMA = isobutyl methacrylate, IDMA = isodecyl methacrylate, BP = benzoyl peroxide, XL = cross-linking agent (TMPTMA), LP = lauroyl peroxide

[b] no aggregate cover on surface

[c] indicates no visible polymer impregnation

temperature of ≈212°F; all other slabs were cured in a 125°F oven. The trapezoidal-shaped slabs were 2 in. thick.

With the exception of specimens 1 and 2, all slabs had at least some polymer impregnation. Slab 2, which had no aggregate cover, apparently lost all of the monomer due to evaporation during the long soak period. There is no obvious explanation for the lack of polymer in slab 1.

Other than specimens 1 and 2, IDMA or IDMA and MMA had the shallowest depths of polymer impregnation, ranging from 3/8 in. to 3/4 in. The specimens treated with MMA developed polymer depths of 1 in. or more.

3.4.3 Field-Treated Slabs--To investigate the monomer application and curing techniques under field conditions, twelve pairs of 5-1/2 x 40 x 43-in. slabs were cast and field-treated (Table 3.3). One reinforced slab and one unreinforced slab comprised a pair. Reinforcement consisted of No. 8 bars at 7-in. o.c. with one inch clear cover.

After curing for several months during the winter, the slabs were predried with a heating blanket for a minimum of three days. In order to simulate actual bridge conditions, the surfaces of all slabs were sloped 1/4 in./ft. During the drying and polymerization periods (March through June) air temperatures ranged from 37°F to 95°F. The slabs were protected from rain by polyethylene membrane.

After the slabs had been dried and permitted to cool to air temperature, a 1/4-in. dry lightweight fine aggregate cover was placed on each

TABLE 3.3 FIELD-TREATED SLABS (Concrete Mix PC-19X)

Slab No.	Treatment(s)[a]	Quantity of Monomer, ml	Soak Time & Temp.	Cure & Temp.	Average Polymer Depth, in.
1	Control	--	--	--	--
2	MMA, 1%BP, 10%XL	4750	10 hrs @73-94°F	hot water (212°F)	1/2-3/4 faint, uniform
3	IBMA, 1%BP, 10%XL	4000	10 hrs @77-93°F	hot water (200°F)	3/4 faint, uniform
4	IBMA, 1%BP, 10%XL	5000	24 hrs @75-90°F	hot water (200°)	1/2-5/8 to 1-1/2 in places, faint, uniform
5	IDMA, 1%BP, 10%XL	3000	10 hrs @77-93°F	hot water (200°F)	1/4-1/2 very faint, uniform
6	Control	--	--	--	--
7	IDMA, 1%BP, 10%XL	4000	24 hrs @75-90°F	hot water (200°F)	1/4-1/2: dark to 1/4, faint to 1/2
8	MMA, 1%BP, 10%XL	7500	24 hrs @75-93°F	hot water (200°F)	1/2-3/4 faint, uniform
	MMA, 4%LP, 4%DMPT	1000	15 min		

(Continued)

Table 3.3. continued.

Slab No.	Treatment(s)[a]	Quantity of Monomer, ml	Soak Time & Temp.	Cure & Temp.	Average Polymer Depth, in.
9	MMA, 1%BP, 10%XL	5000	18 hrs @59-80°F	heating blanket	1/4-1/2 faint, not uniform
	MMA, 4%LP, 4%DMPT	1500	1 hr		
10	MMA, 1%BP, 10%XL	7500	24 hrs @75-90°F	hot water (200°F)	1/2-3/4 faint, uniform
11	MMA, 1%BP, 10%XL	11,000	18 hrs @59-80°F	heating blanket	1/4-1/2 faint, uniform
12	MMA, 1%BP, 10%XL	11,000	24 hrs @58-82°F	heating blanket	1/2 very faint, uniform

[a] MMA = methyl methacrylate, IBMA = isobutyl methacrylate, IDMA = isodecyl methacrylate, BP = benzoyl peroxide, XL = cross-linking agent (TMPTMA), LP = lauroyl peroxide

slab. The slab was then thoroughly wetted with the monomer system (Fig. 3.2). Periodic applications of monomer were made as required to keep the aggregate moist. The aggregate was very effective in preventing monomer run-off. The total monomer volume required for each slab ranged from 3000 ml to 11,000 ml (Table 3.3). The slabs using IDMA, which had the highest viscosity of the three monomers used, required only 3000 ml and 4000 ml, respectively. The slabs using IBMA required 4000 ml and 5000 ml, respectively. Slabs using MMA, which had the lowest viscosity and was the most volatile, required 4750 ml to 11,000 ml per slab. However, it should be emphasized that liberal amounts of monomer were used and, for some slabs, the soak time was as long as 18 or 24 hours, which resulted in significant evaporation losses.

The first slabs treated were cured with heating blankets (Fig. 3.6). However, the heating blankets required a relatively long period of time to reach a slab temperature of 125°F. For example, when the blanket was applied at 9:00 a.m., the slab temperature had only reached 105°F by late afternoon (Fig. 3.7).

All of the later treatments were cured by hot water. Water was heated to 200°F or higher in steel drums using gas heaters. The water was placed on the slabs in shallow vats which consisted of polyethylene membrane draped over the slab and a perimeter wood form (Fig. 3.11). A minimum water depth of ≈3 in. was maintained. Polyethylene membrane and plywood were placed over the water vat to minimize the heat loss from

FIG. 3.11 POLYMERIZATION CURE BY USE OF HOT WATER

the water. Concrete surface temperatures of ≈130°F were reached with air temperatures of approximately 90°F.

Due primarily to the high quality concrete used in the construction of the slabs, the monomer penetration was not as deep as usual. The resulting polymer depths varied considerably and the impregnated zone was generally faint in color.

CHAPTER 4.

Properties of Polymer-Impregnated Concrete

4.1 Full-Impregnation Techniques

Ideally, it would be desirable to evaluate the properties in the surface treated specimens, but there are no reliable tests to determine the mechanical properties for a thin layer of treated concrete which is monolithic with plain concrete. To evaluate the mechanical properties of the polymer-impregnated surface, tests were performed on fully-impregnated concrete specimens.

Tests on 3 x 7 in. cylinders and 3 x 3 x 14 in. beams were performed to determine: (1) modulus of elasticity; (2) utlimate compressive stress; (3) ultimate tensile stress; and (4) modulus of rupture. In all cases three specimens were treated and tested to obtain an average value.

All specimens were moist-cured for seven days after which they were air-dried until an age of 28 days had been attained.

4.1.1 Drying--Before the specimens were impregnated, they were subjected to an additional drying period of seven days in an oven to eliminate the free water in the pores. The drying temperature ranged from 125°F to 220°F. After drying, and just prior to application of the vacuum the specimens were removed from the oven and wrapped in polyethylene to minimize absorption of moisture from the air until the concrete had cooled to room temperature.

4.1.2 Evacuation--After cooling, the specimens were unwrapped and immediately placed in the vacuum chamber. A negative gauge pressure of ≃27 in. Hg was maintained for a minimum of three hours. Previous studies had shown that longer evacuation times failed to produce higher polymer loadings.(24)

4.1.3 Monomer Soaking--After completion of the evacuation, the monomer solution was injected into the container holding the specimens inside the vacuum chamber. After the specimens were completely immersed in the monomer, the vacuum was released, yielding an effective overpressure of ≃27 in. Hg on the monomer to assist the impregnation.

A soak time of five hours for MMA had been found to be adequate(24) to obtain full impregnation in conjunction with the three hour evacuation time. For monomers having viscosities in excess of five centistokes, the soak time was increased to 15 hours.

4.1.4 Curing--Upon completion of the soak period, the specimens were removed from the monomer and immersed in a water bath to minimize evaporation of the monomer. In the initial phase of the study the specimens were first wrapped in polyethylene before being placed in the water. In later treatments, the polyethylene was omitted since the monomers used are essentially insoluable in water, and there was no discernible difference in the polymer loading or strength. The water was maintained at a temperature of ≃130°F for a minimum of 24 hours for MMA; all other monomers were cured for 120 hours.

Later investigations indicated that much shorter cure times are adequate. Figure 4.1 indicates compressive strength versus cure time for MMA at a water cure temperature of ≃130°F using three different concrete batches. All specimens were 3 x 6 in. cylinders. It is apparent that six hours is sufficient to cure the MMA. Styrene, the most difficult to cure of the monomers used in this study, required approximately 65 hours.

After curing, the specimens were placed in a 175°F oven for drying. After drying, the specimens were cooled to room temperature before testing.

4.2 Compression Strength

All cylinders were tested in accordance with American Society for Testing Materials (ASTM) specification C39. Control specimens consisting of untreated specimens were tested with each series of PIC specimens.

Table 4.1 summarizes the compression strength of a large number of specimens impregnated with MMA. Some of the monomer solutions contained no TMPTMA while some used 10 percent and .5 percent. The specimens without TMPTMA averaged 14,770 psi while specimens with 10 percent TMPTMA averaged 13,790 psi. The strength ratio, defined as the ratio of treated specimen strength to control strength, ranged from 2.41 to 3.28.

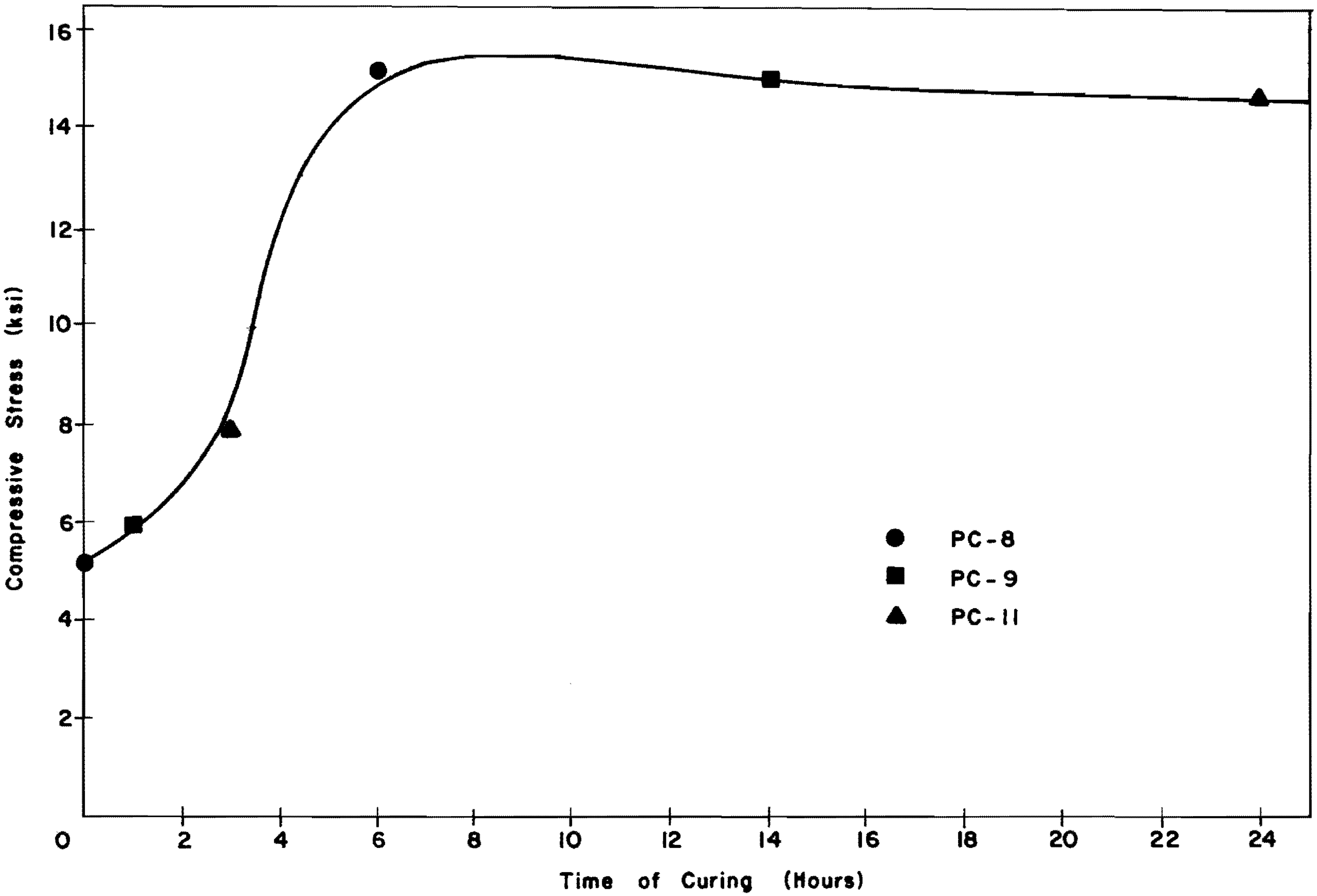

FIG. 4.1 EFFECT OF CURING TIME ON ULTIMATE COMPRESSIVE STRESS OF SPECIMENS IMPREGNATED WITH MMA

TABLE 4.1

MMA-IMPREGNATED COMPRESSION TESTS

Specimen No.	Concrete Mix	TMPTMA, %	Polymer Loading, %	Ultimate Stress, psi	Strength Ratio
1,2,3	PC-1	0	5.70	16083	3.06
4,5,6	PC-1	10	6.42	13800	2.63
Control	PC-1	-	0	5250	1.00
1,2,3	PC-2	0	5.98	16000	2.79
4,5,6	PC-2	10	6.21	13800	2.41
Control	PC-2	-	0	5730	1.00
1,2,3	PC-3	5	-	13923	3.28
Control	PC-3	-	0	4240	1.00
1,2,3	PC-4	10	-	13760	3.05
Control	PC-4	-	0	4510	1.00
1,2,3	PC-5	0	6.17	14440	2.98
4,5,6	PC-5	0	-	13783	2.84
Control	PC-5	-	0	4850	1.00
1,2	PC-7	0	5.96	13555	2.92
Control	PC-7	-	0	4650	1.00

Using similar monomer solutions, other investigators have found higher strengths. This is due in all probability to lower polymer loading in many of the specimens, perhaps as a result of lower drying temperatures.

Compressive strengths for several monomers are compared in Table 4.2. The specimens with stearyl methacrylate, isobornyl methacrylate, and high percentages of isodecyl methacrylate developed the lowest compressive strengths. The relatively low polymer loadings are due to the higher viscosities of some of the monomers and due to the higher impermeability of the concrete, which had a control strength of 6600 psi. The polymer loading can be observed to be dependent upon the monomer viscosity from Fig. 4.2.

4.3 Moduli of Elasticity

The moduli of elasticity have been found for many of the monomers evaluated in this investigation. The strains used to calculate the moduli were obtained during the compression tests. The first of the three specimens was loaded to its ultimate load without the strain apparatus attached. The strains were measured on the other two specimens by means of a dial gauge extensometer with a 4 in. gauge length. The apparatus was removed at 60 percent of the anticipated ultimate load to prevent damage to the dial gauges.

Table 4.2 summarizes the moduli for different monomers. While the modulus is increased for most monomers, the increase is not as great as for compression strength.

TABLE 4.2 COMPRESSION AND MODULUS OF ELASTICITY TESTS WITH VARIOUS MONOMERS

Monomer	Polymer Loading, %	Ultimate Stress, psi	Modulus of Elasticity, psi	Strength Ratio
Isobutyl Methacrylate	4.99	16293*	$5.42\text{x}10^6$	2.47+
Tert Butyl Styrene	4.90	15527	$6.35\text{x}10^6$	2.35
Stearly Methacrylate	2.52	6920	$3.48\text{x}10^6$	1.05
Isobornyl Methacrylate	2.80	9060	$4.70\text{x}10^6$	1.37
Methyl Methacrylate	5.27	16350*	$6.12\text{x}10^6$	2.47+
80% MMA + 20% Isodecyl MA	5.19	16593*	$5.90\text{x}10^6$	2.51+
60% MMA + 40% Isodecyl MA	5.23	15767*	$5.72\text{x}10^6$	2.39+
40% MMA + 60% Isodecyl MA	4.97	14060	$4.85\text{x}10^6$	2.13
20% MMA + 80% Isodecyl MA	3.63	8507	$3.78\text{x}10^6$	1.29
Isodecyl Methacrylate	3.51	7000	$3.38\text{x}10^6$	1.06
Control	0	6607	$3.5\text{-}4.5\text{x}10^6$	1.00

*Cylinder strength exceeded machine capacity

Note: Tests were performed on concrete designated PC-22

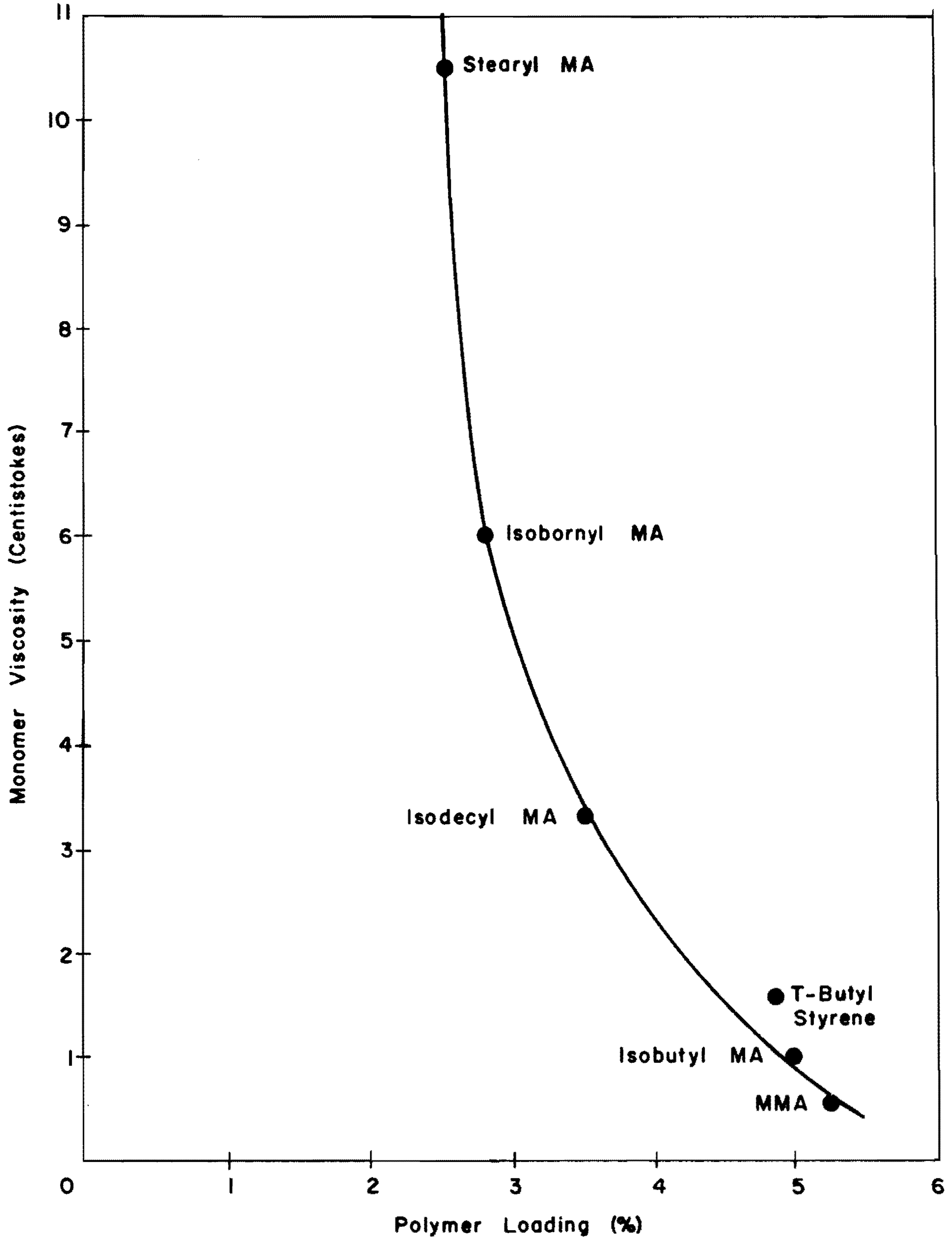

FIG. 4.2 EFFECTS OF MONOMER VISCOSITY ON POLYMER LOADING

4.4 Moduli of Rupture

The moduli of rupture were obtained from flexural tests of 3 x 3 x 14-in. beams. The simply supported beams had a span of 12 in. and were loaded at the third points. The tests were performed in general accordance with ASTM C78-64.

The impregnation procedure was similar to that used for cylinders. All of the specimens contained 1 percent BP; the amount of TMPTMA was varied from 0 to 10 percent. Some of the specimens had air entraining agents added to the mix which yielded 5 percent air entrainment.

The results for specimens impregnated with MMA are shown in Table 4.3. It is interesting to note that the polymer loading increased slightly with increasing cross-linking agent while the modulus of rupture decreased, apparently because of the more brittle polymer produced with TMPTMA.

4.5 Tensile Strength

A limited number of 3 x 6-in. cylinders were tested in accordance with ASTM C 466 to determine tensile strength. Table 4.4 summarizes these tests. MMA-impregnated concrete developed a strength ratio of 2.06 compared to 2.71 for styrene-impregnated cylinders. All monomer solutions used 1% benzoyl peroxide catalyst.

TABLE 4.3

MMA-IMPREGNATED MODULUS OF RUPTURE TESTS

Specimen No.	Concrete Mix	TMPTMA, %	Air Entrainment, %	Polymer Loading, %	Ultimate Stress, psi	Strength Ratio
1,2,3	PC-7	0	5	6.24	1361	2.39
4,5,6	PC-7	3	5	6.28	1068	1.88
7,8,9	PC-7	10	5	6.68	903	1.59
Control	PC-7	-	5	0	569	1.00
1,2,3	PC-9	0	1	6.59	1510	2.23
4,5,6	PC-9	3	1	6.61	1364	2.01
7,8,9	PC-9	10	1	6.87	1097	1.62
Control	PC-9	-	1	0	677	1.00

TABLE 4.4 TENSILE STRENGTH

Concrete Mix	Monomer	TMPTMA, %	Ultimate Stress, psi	Strength Ratio
PC-4	MMA	10	961	2.06
PC-4	Control	--	467	1.00
PC-6	Styrene	10	1340	2.71
PC-4	Control		494	1.0

CHAPTER 5.

Evaluation of Surface-Treated Slabs

In the evaluation of the performance of concretes subjected to the various polymer treatments, as previously discussed, several types of test methods were used. Those which have produced sufficient data for discussion at this time include freeze-thaw tests, surface wear and abrasion studies, resistance to water penetration studies and skid resistance tests. Long term tests to evaluate the degree of protection afforded embedded reinforcement by surrounding concrete are still in progress and limited data are available for discussion. In that study treated and control specimens have been exposed to the influence of the weather combined with the effects of a salt water spray and partial immersion in sea water.

5.1 Freeze-Thaw Tests

Polymer treatments which showed promising results in preliminary studies with 2-in.-thick slabs were subjected to freeze-thaw exposure. There are two possible failure mechanisms which merited study by this test. First, if the impregnated polymer is unable to maintain its resistance to penetration of water into the concrete during freezing and thawing, the typical ice expansion failure mechanism will likely produce scaling and, or, splitting of the concrete under test.(26) Second, since the thermal coefficients of expansion of polymers like polymethyl methacrylate are typically ten times that of concrete, there is the possibility of thermal volume change incompatibility. In that case the polymerized layer of concrete of a slab might spall-off at the interface with the untreated concrete, and, or the internal stressing which results may produce cracks which gradually enlarge as the number of test cycles increases.

Tests were conducted on the 6-in. x 10-in. x 10-in. slabs treated in the laboratory and on 12-in. x 12-in. sections sawed from the field treated slabs (PC-19X). A summary of the polymer treatments employed is given in Tables 3.1 and 3.2 and a summary of concrete mix designs and strengths is found in Table A.1 of the appendix. Three specimens were used for the evaluation of each treatment, including control specimens. The procedures used in exposing the specimens to freezing and thawing, and in evaluating their relative durability, are discussed in detail in section A.1 of the appendix.

To date, freeze-thaw tests have been completed on 20 series with 4 additional series under test. Completed tests include 12 treated series and 8 untreated control series. Visual evaluation of all freeze-thaw specimens, including those under test, shows that the treated surfaces are generally much more resistant to scaling and cracking than the untreated control specimens. Several photographs are shown in Figs. 5.1, 5.2, 5.3 and 5.4 to illustrate the range of effects of freezing and thawing on selected

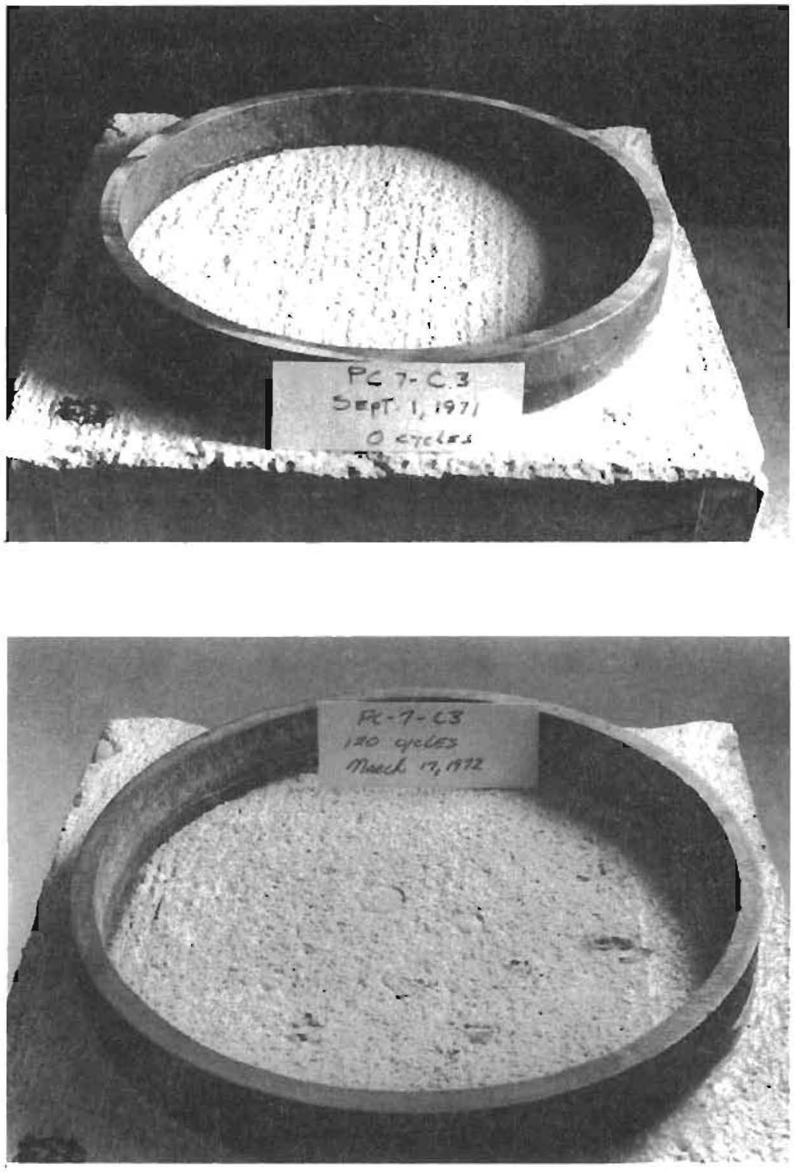

FIG. 5.1 AIR ENTRAINED CONTROL SLAB AT ZERO AND 120 CYCLES OF FREEZE-THAW TESTING (PC-7-CONTROL)

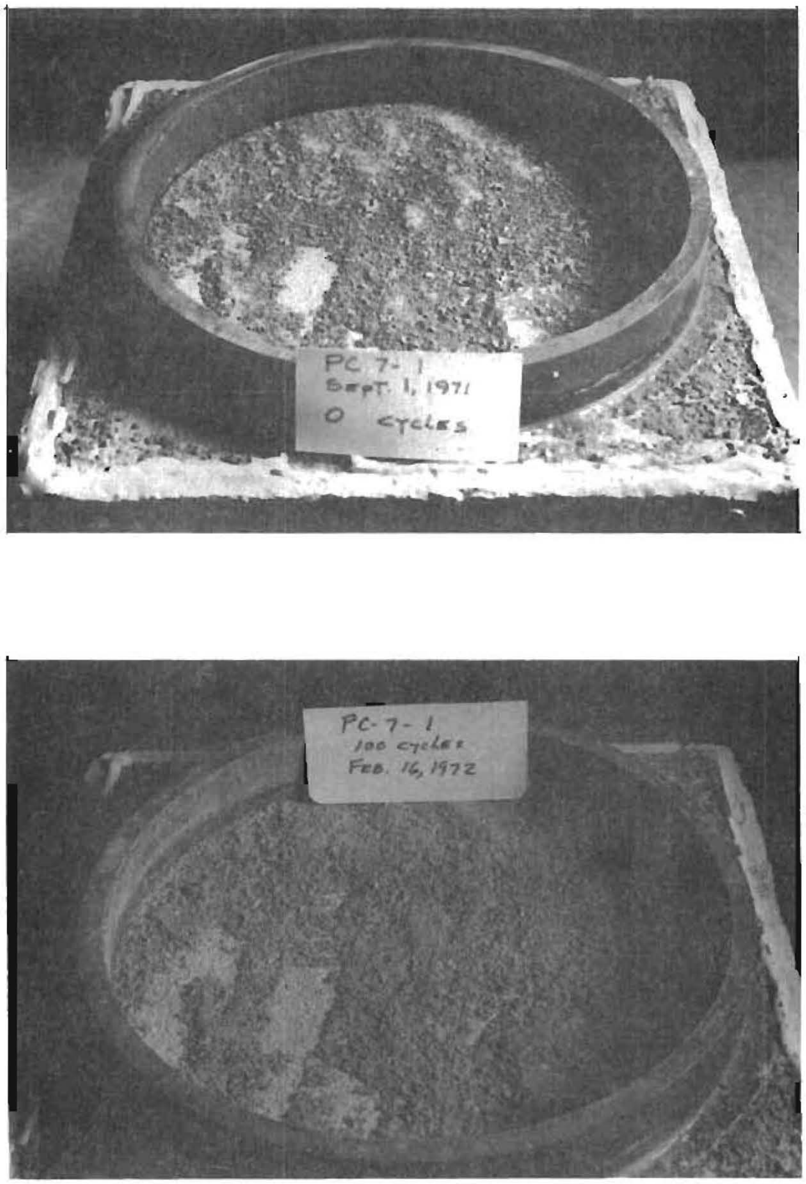

FIG. 5.2 MMA LAB TREATED SLAB AT ZERO AND 100 CYCLES OF FREEZE-THAW TESTING (PC-7)

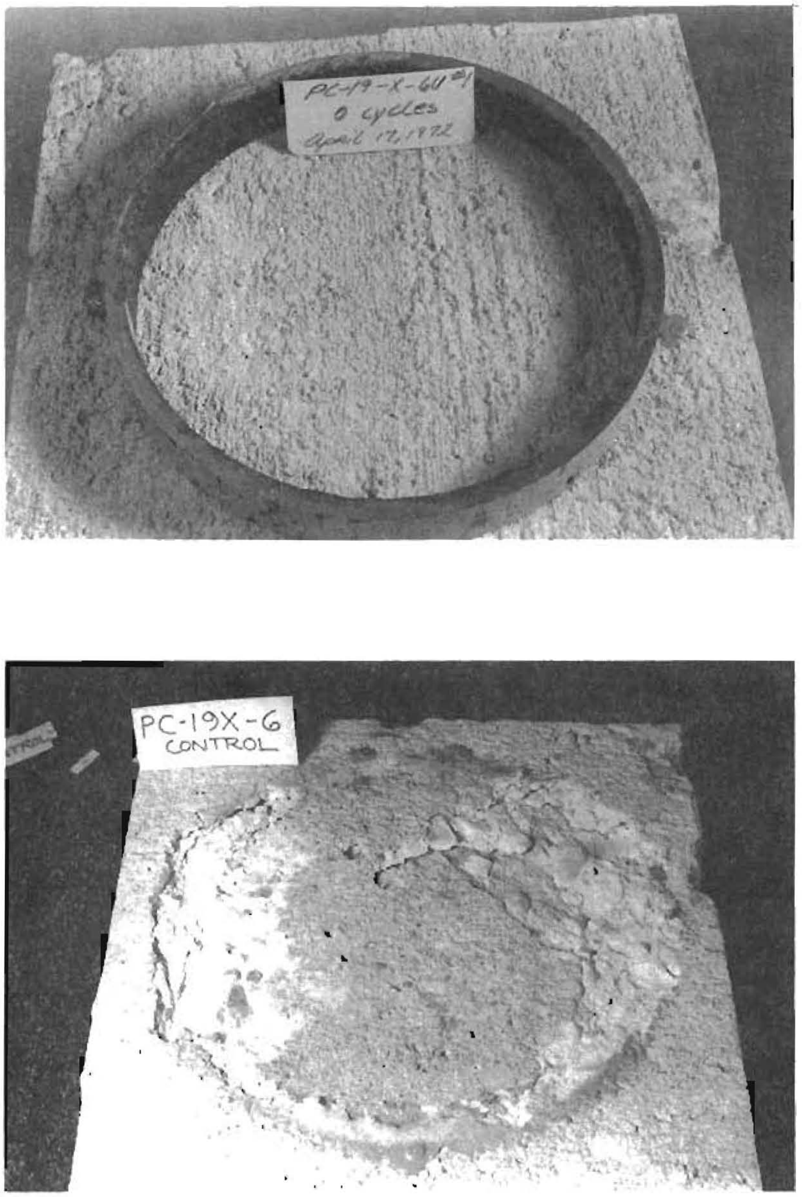

FIG. 5.3 NON-AIR ENTRAINED CONTROL SLAB AT ZERO AND 40 CYCLES OF FREEZE-THAW TESTING (PC19X-6)

FIG. 5.4 MMA FIELD TREATED SLAB AT ZERO AND 120 CYCLES OF FREEZE-THAW TESTING (PC-19X-12)

specimens treated in the laboratory and field. The moderate scale of the specimen in Fig. 5.1 after 120 test cycles is typical for the air-entrained control concrete specimens. Also, no severe cracking was observed in the air-entrained concretes through 120 test cycles although localized pitting of the surfaces from 1/4 to 3/8 in. depths was typical.

Although the scaling seen in Fig. 5.1 might not be classed as severe, it can be seen in Fig. 5.2 that the polymer treatment of the same concrete mix has almost totally protected the exposed surface from freeze-thaw damage through 100 cycles. The light areas seen within the metal ring in both photos of Fig. 5.2 are the bare concrete surface exposed when a portion of the lightweight aggregate topping did not initially bond to the top of the specimen. Close examination of these areas revealed that no change in the exposed concrete could be detected through 120 cycles of freezing and thawing. Furthermore, very few of the aggregate particles of the lightweight topping were broken free as a result of 120 cycles of freeze-thaw exposure.

A similar comparison for the non-air-entrained concrete of the field treatment series is given in Figs. 5.3 and 5.4. Note in Fig. 5.3 that the non-air-entrained control specimens had badly deteriorated by severe cracking after only 40 cycles of test. On the other hand, the field application of MMA with subsequent cure by heating blanket (treatment of PC-19X-12) furnished complete protection of the specimen through 120 cycles of test as shown in Fig. 5.4. Note in Fig. 5.4 that the thin layer of unintentionally bonded, lightweight fine aggregate has remained essentially unaffected by the freeze-thaw exposure.

By use of the mechanical strain gauge readings, as described in Appendix A.1, the specimens were compared with regard to the contraction occurring at the top and bottom of the slabs during the first freeze cycle. If the polymer treated slabs are compared as a group to the control specimens, the data show that polymer impregnation has resulted in greater contraction in the upper half of the specimen. For example, calculations of the contraction upon first freeze show that in 40 of 42 treated specimens, the top strain exceeded the bottom strain by an average of 65 μ in./in., i.e., tops of specimens exhibited the greater contraction. By comparison, for the control series only in 8 of 17 specimens did the top strain exceed that of the bottom. Furthermore, if a general trend for the control specimens is considered, the net effect is that the average control specimen exhibited approximately 5 μ in./in. greater contraction in the bottom half of the slab. If the field treated specimens (PC-19X) are considered as a separate group, the same trends are noted, with control specimens averaging zero strain differential while eight of the treated series averaged 45 μ in./in. greater top contraction. It is of interest to note that the remaining two treated series of PC-19X (numbers 8 and 9) exhibited 120 μ in./in. greater top contraction. The reason for the greater strain differential shown by the latter two series was most probably the presence of the polymer in the 1/4-in.-thick layer of intentionally bonded, lightweight fine aggregate.

Although a photographic record was made of each specimen throughout the freeze-thaw test period, it was determined that a more useful measure of the specimen's volume stability during test could be provided by use of continued strain measurements. For this purpose the mechanical strain gauge was used to obtain readings at approximately every twenty cycles of freezing and thawing. The results of these measurements are presented in Figs. 5.5, 5.6 and 5.7 where, for clarity, only the top strain values were plotted throughout the freeze-thaw exposure period. Strain computations are based on a comparison of the initial, unfrozen state and subsequent frozen states of the specimens.

The results of the volume stability measurements for the laboratory treated slabs are given in Fig. 5.5. Note that all specimens initially exhibited thermal contraction strains of approximately 100 to 400 μ in./in. with the treated slabs experiencing the greater strains, as previously indicated. As freeze-thaw cycling progressed, one non-air-entrained control series (PC-12 control) was found to quickly deteriorate, as indicated by the formation of cracks and loss of ponded water during thaw cycles. The appearance of cracks was observed between 20 and 30 test cycles, and a photograph showing a typical specimen after 55 test cycles is given in Fig. 5.8. From Fig. 5.5 it is seen that the deterioration of the PC-12 control series is also indicated by the rapid increase in strain as freeze-thaw cycling continued. The increase in strain accompanying the deterioration of the concrete is expected as the internal structure of the concrete matrix is ruptured by the expanding ice in saturated capillary pores.

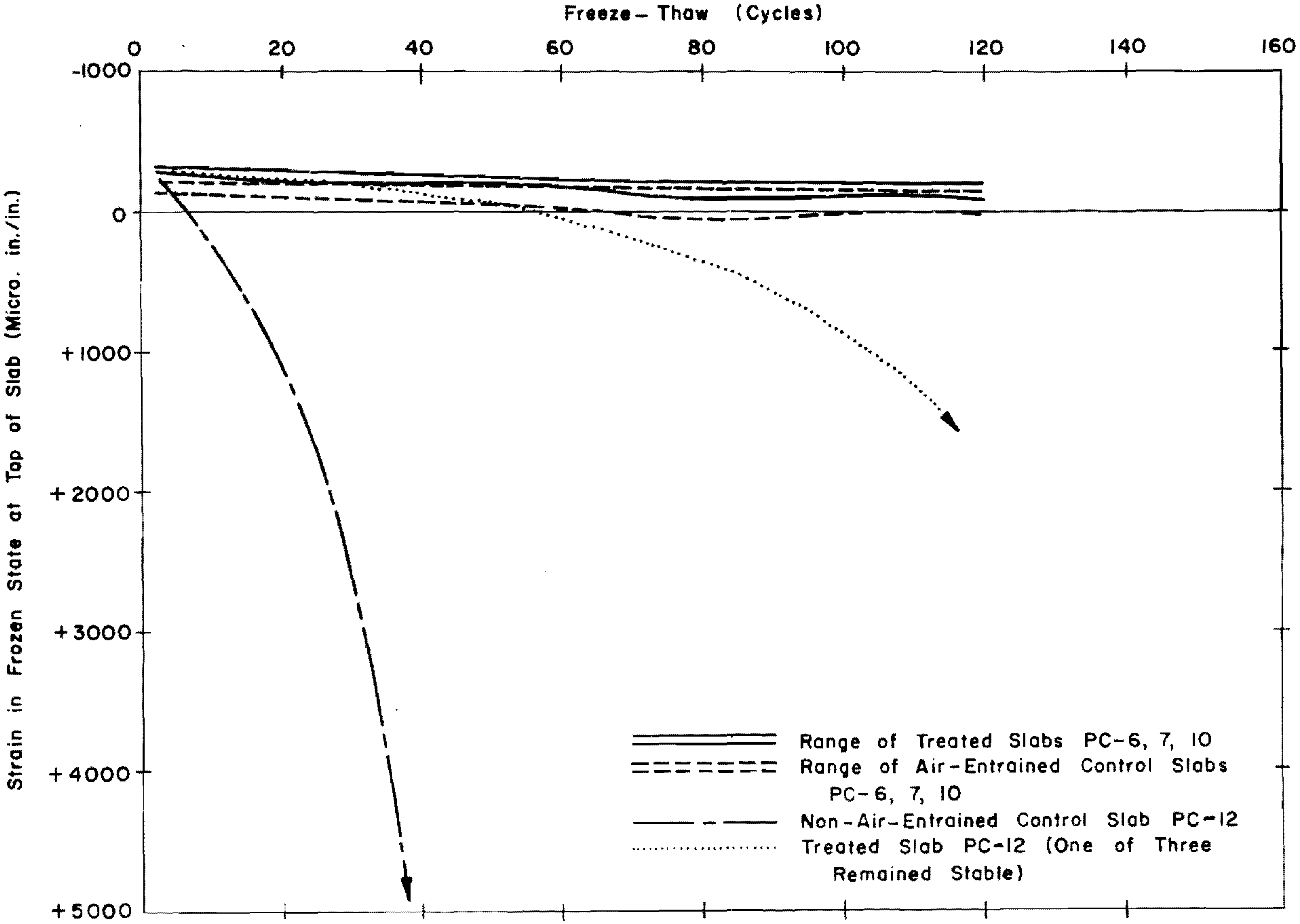

FIG. 5.5 EFFECT OF FREEZE-THAW EXPOSURE ON VOLUME STABILITY OF LABORATORY TREATED AND CONTROL SLABS

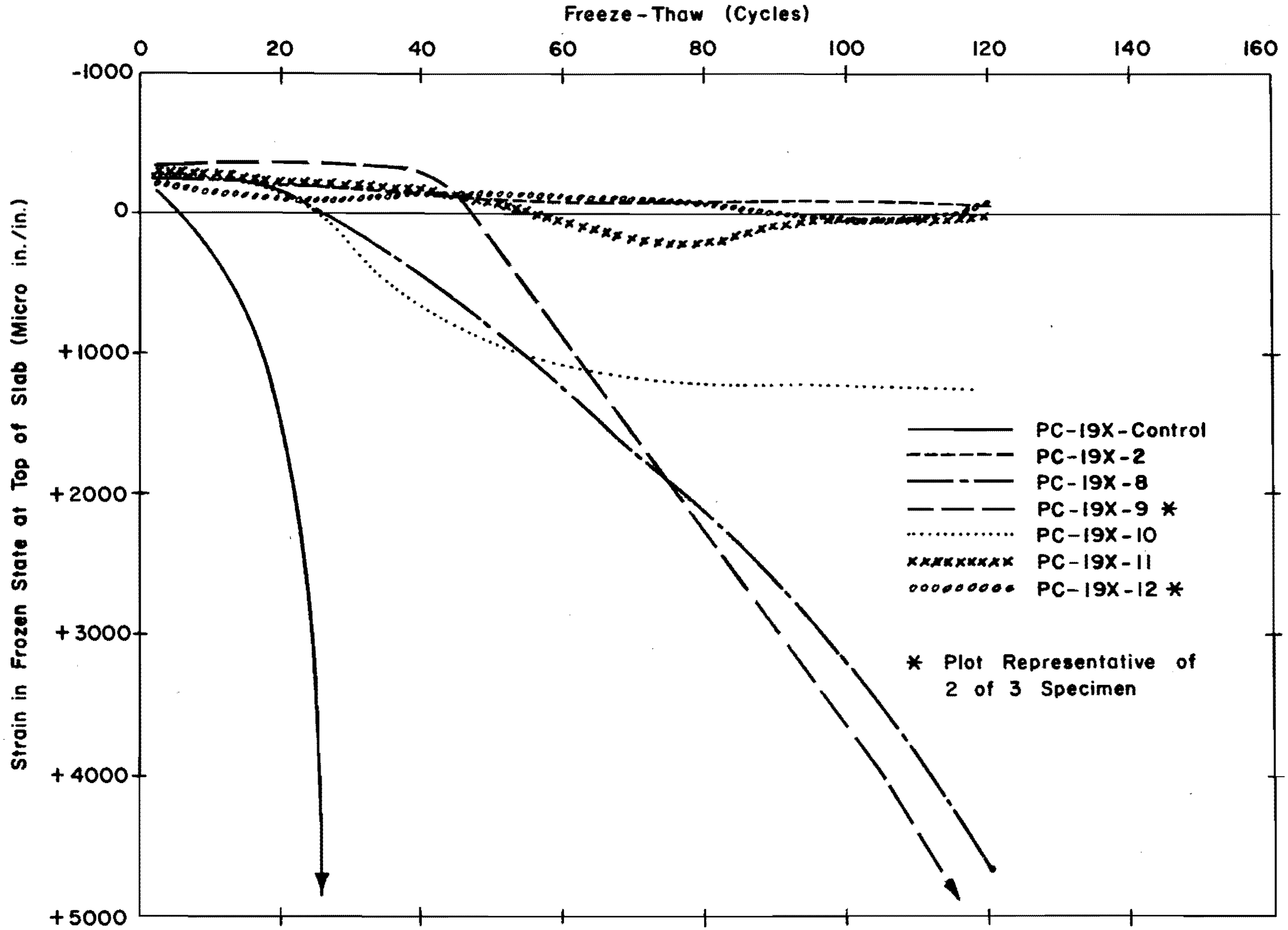

FIG. 5.6 EFFECT OF FREEZE-THAW EXPOSURE ON VOLUME STABILITY OF MMA FIELD SURFACE TREATMENTS (PC-19X)

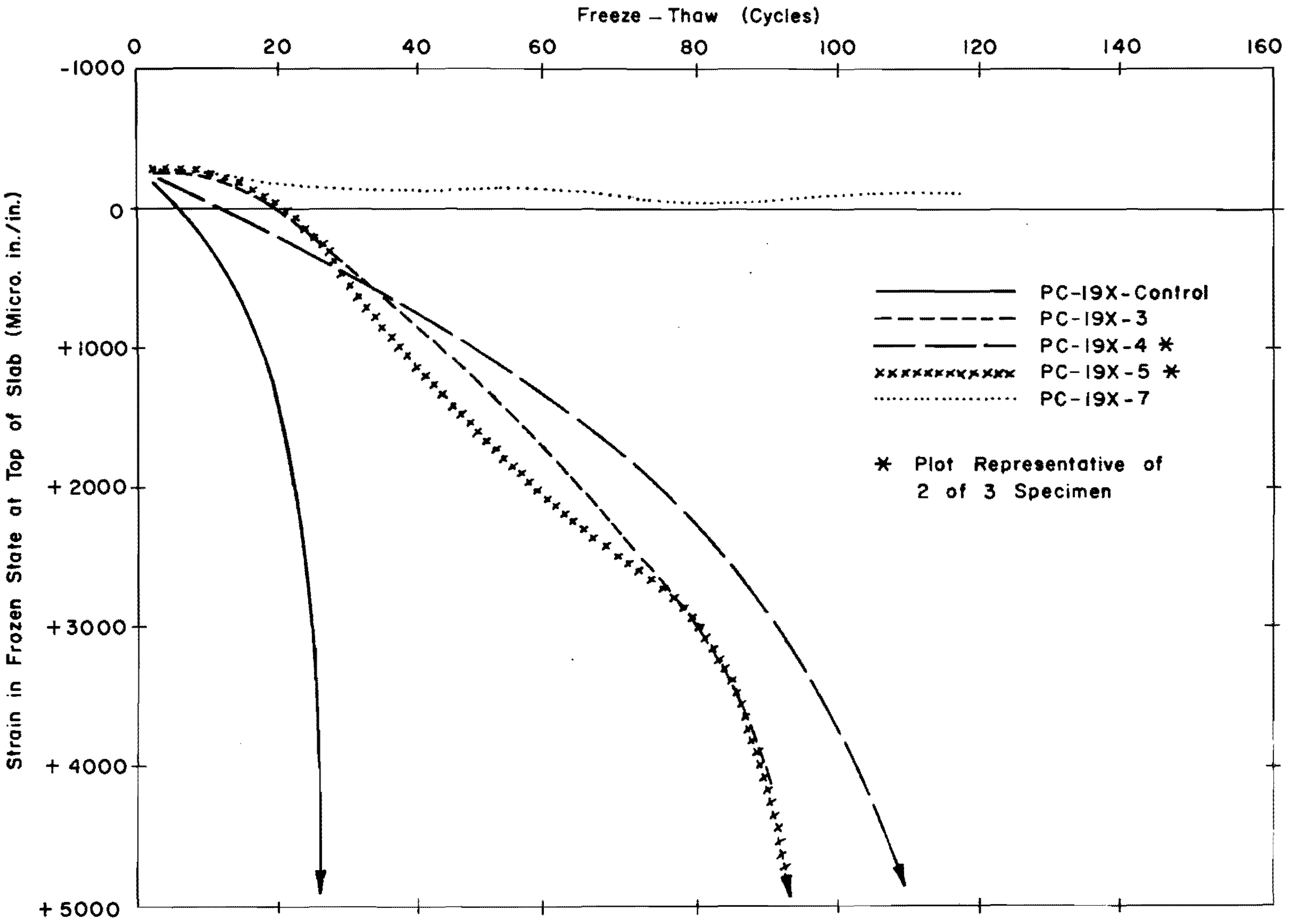

FIG. 5.7 EFFECT OF FREEZE-THAW EXPOSURE ON VOLUME STABILITY OF IBMA AND IDMA FIELD SURFACE TREATMENTS (PC-19X)

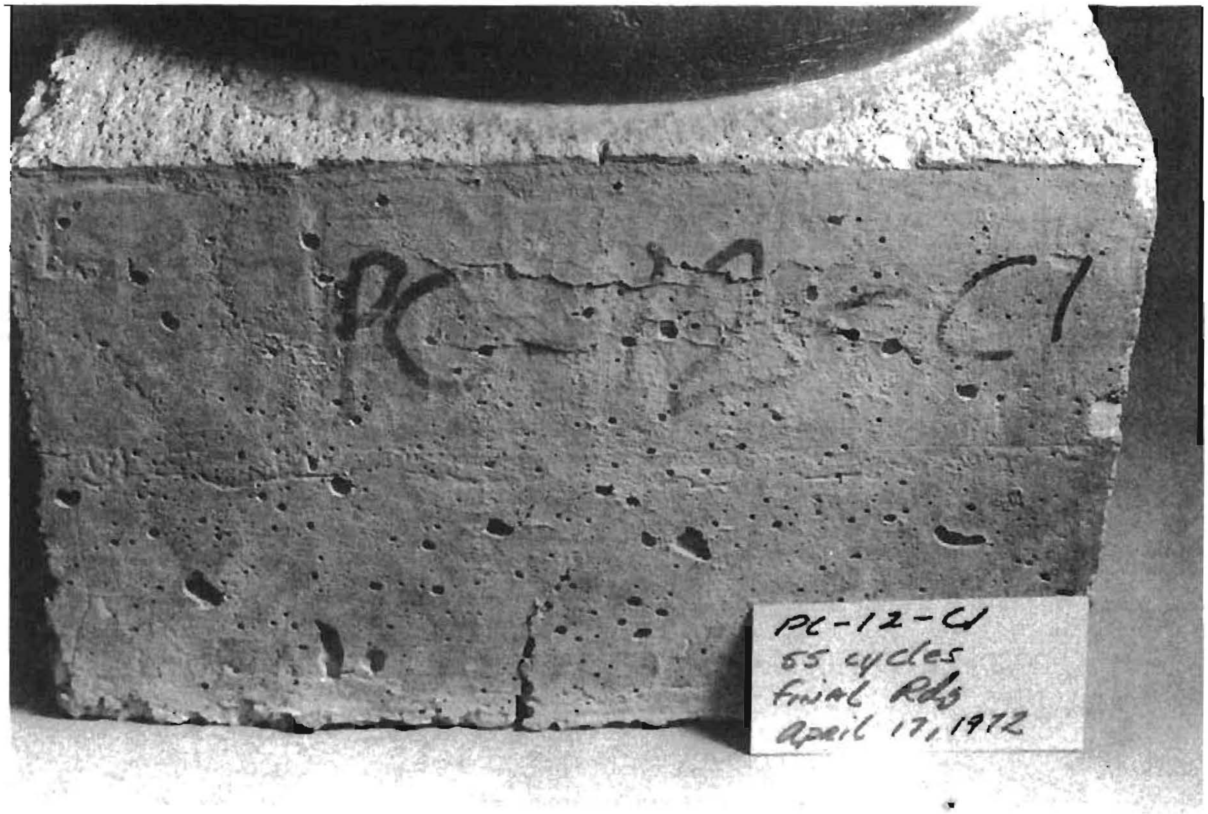

FIG. 5.8 TYPICAL CRACK PATTERN PRODUCED BY FREEZE-THAW EXPOSURE OF NON-AIR ENTRAINED CONTROL SPECIMEN

The next concrete to show signs of distress in Fig. 5.5 is the MMA-treated series PC-12. Within that group two specimens exhibited moderate cracking and water loss at 60 and 100 cycles respectively and a third specimen completed 120 test cycles in good condition. The curve shown in Fig. 5.5 corresponds to the average strain of the two failing specimens and again correlates well with the observed deterioration of the specimens.

All other test series given in Fig. 5.5 are seen to have maintained relatively stable volume throughout the test period. Visual observation detected no cracking in these specimens although moderate surface scaling was noted in all control concretes (see Fig. 5.1).

From the data of Fig. 5.5 it is apparent that for the non-air-entrained concrete, polymer impregnation of the slab surfaces did extend the life of the specimens under these relatively severe test conditions. Also, somewhat unexpectedly, air-entrained control concretes are shown to compare favorably with surface impregnated specimens in regard to volume stability. However, some beneficial effects from surface impregnation were noted in somewhat greater resistance to surface scaling.

The volume stability curves for the field treated test series (PC-19X) are given in Figs. 5.6 and 5.7. The average of six control specimens is repeated in both figures and all MMA treated specimens are given in Fig. 5.6 while those of IBMA and IDMA are shown in Fig. 5.7 for reasons of convenience only.

In the analysis of the data of Fig. 5.6, it is helpful to review the treatment methods used, as given in Table 3.3. From Table 3.3 note that the MMA treatments can be grouped in pairs as follows: 2 and 10, 8 and 9, and 11 and 12. Although this grouping does not represent duplication of treatments, the treatments are sufficiently similar for such consideration here.

As was the case in Fig. 5.5, the non-air-entrained control specimens of Fig. 5.6 displayed more rapid deterioration than any treated series. Considerable cracking and water loss were noted in the control specimen at 20 to 25 cycles of test. As observed previously, failure of the control specimens was accompanied by rapidly increasing top strain as shown in Fig. 5.6.

The least durable treated slabs of Fig. 5.6 as indicated by volume instability are those of series 8 and 9, which were characterized by the intentionally bonded layer of lightweight fine aggregate. Visual observation revealed that cracks first appeared at 60 to 70 cycles in both series and moderate water leakage occurred at approximately 80 cycles of test. A factor which may have contributed to the early failure of these specimens is the thermal volume change incompatibility of the bonded layer and surface concrete. This mechanism is suspect in view of the particularly high differential strains exhibited by the specimens of these two series, as previously mentioned.

A comparison of series 2 and 10 in Fig. 5.6 indicates that, in spite of a greater quantity of monomer and longer soak time during treatment, series 10 exhibited somewhat less durable concrete compared to that of series 2. In all respects the series 2 specimens are in very good condition through 95 test cycles and these specimens were still in test at the time this report was being written. Although the series 10 concrete displayed an expansive strain slightly in excess of 1000 μ in./in. at 55 test cycles, the top strain stabilized for the remainder of the test period, with moderate cracking and moderate water loss being noted during that period. Again, an important indication in the comparison of these two series is that the freeze-thaw durability of the concrete was not a simple function of the quantity of monomer and length of soak time used.

Finally, series 11 and 12 specimens of Fig. 5.6 displayed relatively stable volume through 120 cycles of test, with no cracking and little water loss observed. An exception to this behavior was noted for one specimen of series 12 which failed very rapidly at 95 cycles and was not included when the average trend was drawn, as shown in Fig. 5.6.

The freeze-thaw stability characteristics of the field treated IBMA and IDMA slabs are shown in Fig. 5.7. From the standpoint of similarity in treatment the series may be grouped in pairs, 3 and 4 (IBMA) and 5 and 7 (IDMA).

In Fig. 5.7 both IBMA treatments (3 and 4) are shown to lose volume stability progressibely during testing. Visual observations revealed that specimen cracking developed at 40 to 45 cycles in series 3 and at 60 to 65 cycles in series 4. Some loss of ponded water was noted shortly after the development of cracks. In addition, a white powdery material gradually developed in the cracks of the specimens of series 4. No attempt has been made to analyze this material to date although the possibility exists that it may be the result of calcium dioxide leaching. It is of interest to note that these white deposits were not observed in the specimens of series 3 which were treated with the same monomer system.

The two IDMA treatment series of Fig. 5.7 show contrasting stability, with series 7 being very stable throughout the exposure period while series 5 gradually lost stability with cracks and some water loss noted at approximately 80 test cycles. In this case, it is tempting to explain the more durable character of the series 7 specimens by noting that more monomer and a longer soak time were used in the treatment. However, as previously discussed, the assurance of durable concrete involves a more complex interaction of the treatment variables than that of total monomer volume and soak time used.

In view of all the data presented in Figs. 5.5, 5.6 and 5.7 it may be concluded that the top strain measurements provided a more sensitive measure of volume stability and freeze-thaw durability than visual observation alone. This is especially true since surface scaling was not the primary mode of deterioration of the overall group of specimens studied here. Furthermore, it is apparent that visual cracks usually were observed whenever the top strain values exceeded about 1000 μ in./in. From a conservation standpoint a lack of durability could perhaps be characterized by a top strain in excess of 500 μ in./in. when specimens are tested by the procedures used in this study. If this failure criteria is valid, then the following polymer impregnated treatment series produced durable concretes: PC-6, 7, and 10 and 19X-2, 7, 11, and 12.

5.2 Water Tightness Study

Two or three specimens of each slab treatment series as well as control specimens were subjected to a water penetration study. This method of test is described in some detail in a previous research study(27) and only a brief description will be given here. After the polymer cure was completed, selected specimens were oven dried at 190°F (±10°F) for a minimum of seven days and then coated with epoxy on all vertical surfaces leaving uncoated the polymer impregnated and bottom surfaces of the slab. The specimens were next cooled to room temperature and immersed, polymer treated side down, in a vat of water to a depth of 5 inches above the treated surface. The 5-inch water head was maintained for a period of 24 hours, after which the specimens were immediately split open and the depth of penetration was marked. The line of water penetration was generally found to be uniform across the broken surface of the specimen, and the average depth was taken as the test value. A photograph of specimens immersed in the soaking vat is given in Fig. 5.9(a) and a view of a split specimen with depth of penetration marked is given in Fig. 5.9(b).

In addition to performing water penetration tests on specimens as treated, an effort was made to determine the effects of weathering on the

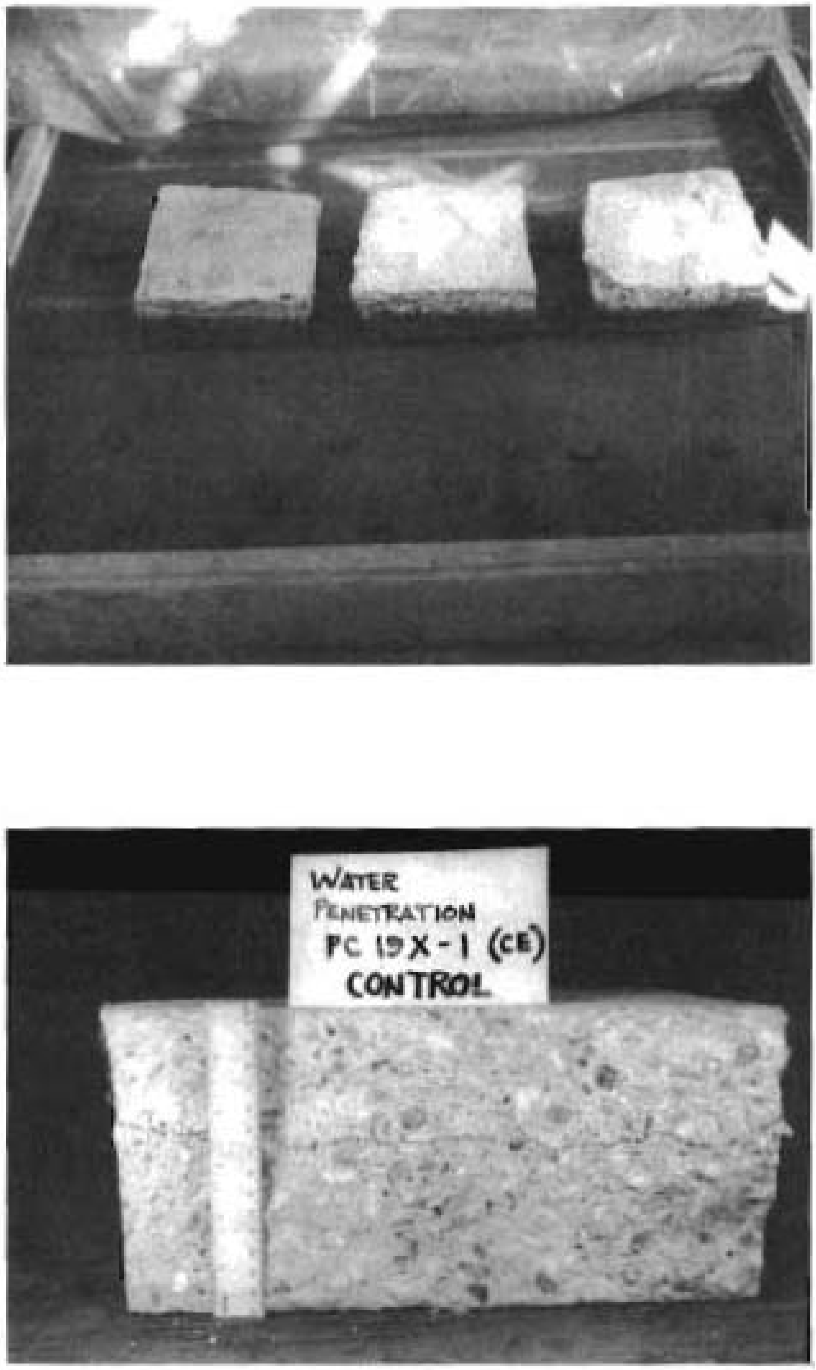

FIG. 5.9 WATER PENETRATION TEST

water tightness of the various polymer impregnated concretes. This was accomplished by subjecting to the water penetration test those specimens which had previously been used in the freeze-thaw study. Only the very severely deteriorated freeze-thaw specimens were not used in the penetration study.

The results of the water penetration study are shown in Figs. 5.10 and 5.11 where a comparison of penetration before and after freeze-thaw of both treated and untreated control concretes is given. It is of interest first to consider the general behavior of all the control concretes. For example, the non-air-entrained control concretes,* PC-12 and PC-19X, are found to have greater penetration values both before and after freeze-thaw exposure than those of the air-entrained mixes, PC-3, 4, 6, 7 and 10. These comparisons are in agreement with generally accepted trends relating such mix properties as water-cement ratio and air content to concrete permeability. It should also be noted that the increase in penetration after freeze-thaw is much greater for the non-air-entrained control concretes than for the air-entrained specimens. This is indicative of the beneficial effects of air-entrainment on the freeze-thaw durability of concrete.

In Fig. 5.10 all polymer impregnated concretes are seen to exhibit less penetration than their companion control specimens, and those of

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*Mix properties of all concretes are given in Table A.1 of the appendix.

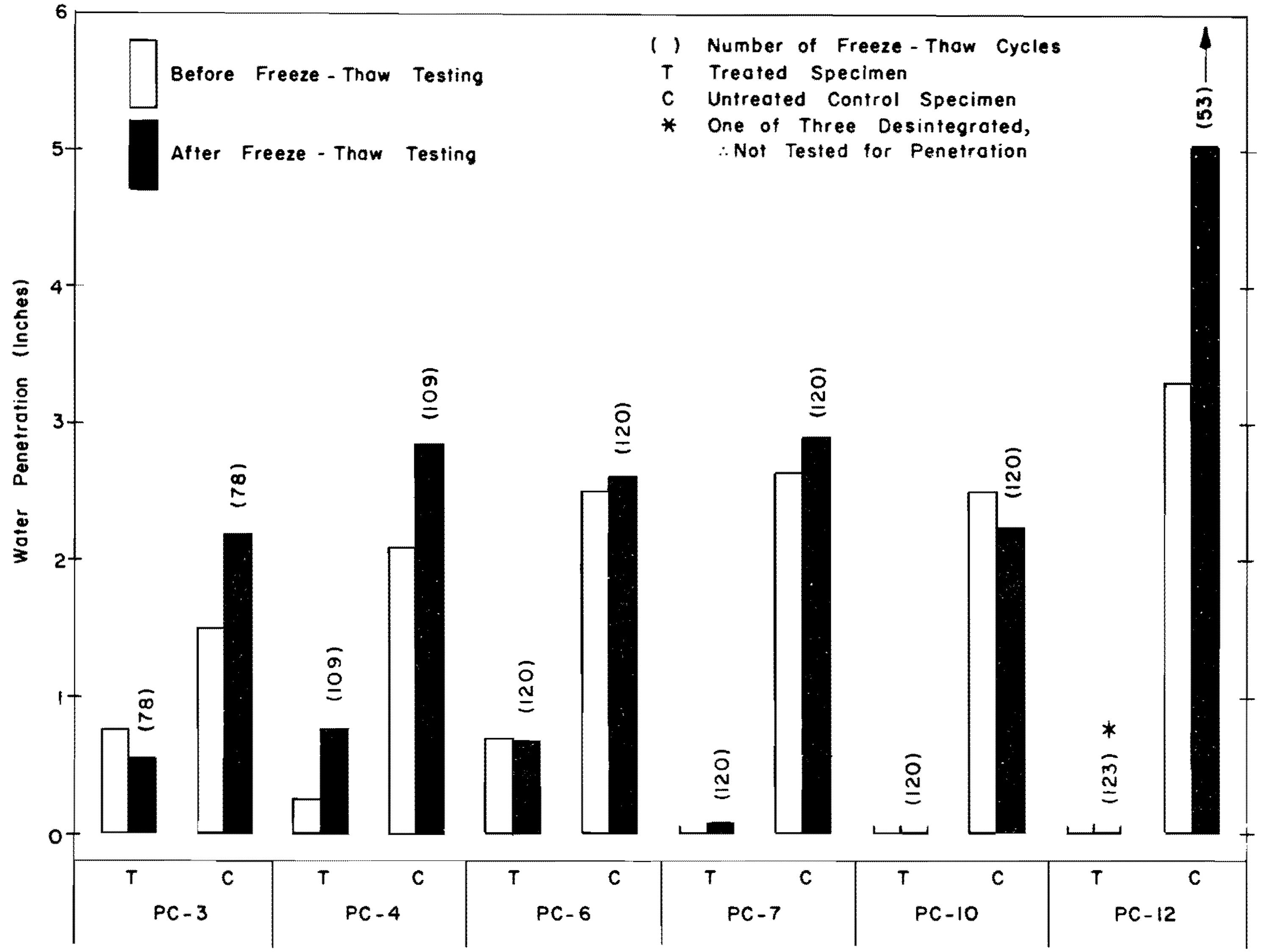

FIG. 5.10 WATER PENETRATION OF MMA LAB TREATED SLABS BEFORE AND AFTER FREEZE-THAW TESTING

series PC-7, 10 and 12 are shown to initially be completely watertight by this test. Further, these specimens remained essentially watertight after freeze-thaw exposure, with the exception of one specimen of the PC-12 series which greatly deteriorated during freeze-thaw testing and was not tested for penetration. Although the treatments of series PC-3, 4, and 6 did initially allow water penetration to depths of 1/4 to 3/4 in., these concretes remained relatively watertight after freeze-thaw testing.

An evaluation of the physical appearance of all specimens of Fig. 5.10 at the completion of freeze-thaw testing indicated that only the non-air-entrained control series, PC-12, uniformly deteriorated under test and that one specimen of the treated series PC-12 failed in a similar fashion. All other test specimens, treated and control, survived the freeze-thaw exposure with moderate surface scaling observed on most control surfaces and slight scaling on treated surfaces.

In considering the penetration data of Fig. 5.11, one finds that all polymer treatments except that of series 5 produced watertight concretes initially. However, in spite of the initial sealing achieved, freeze-thaw failures* resulted in all but series 2, 7, 11 and 12, as discussed in section 5.1. Among these four durable concretes, water penetration is shown to have been increased slightly by freeze-thaw exposure. Except for series 9, freeze-thaw exposure increased the penetration of the non-durable concretes to a greater extent, as might normally be expected.

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*Failure here infers volume instability as discussed in section 5.1.

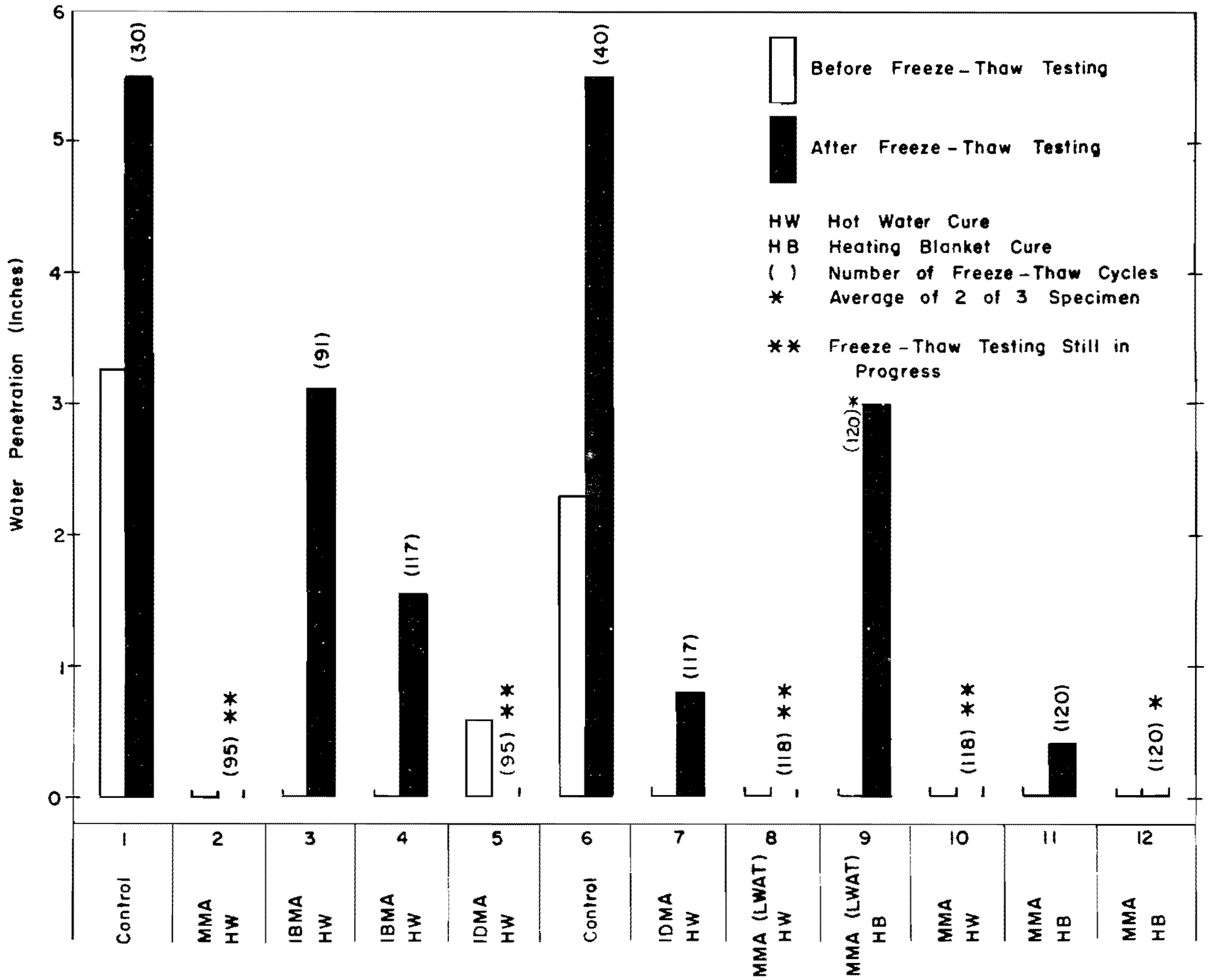


FIG. 5.11 WATER PENETRATION OF FIELD TREATED SLABS (PC-19X) BEFORE AND AFTER FREEZE-THAW TESTING

The behavior of the concrete of series 9 as well as that of the treated specimens of series PC-12 in Fig. 5.10 may be of some importance here. These specimens were found to be initially watertight and, in fact, remained essentially watertight after freeze-thaw exposure. Yet, in spite of the rather effective sealing of the specimens, freeze-thaw exposure produced volumetric instability, as was seen in Figs. 5.5 and 5.6. This suggests that a more complex failure mechanism than that of capillary ice expansion may have contributed to the failure of these concretes. For example, note in Fig. 5.12 that the treated specimens of series 12 were very effectively impregnated to a depth in excess of one inch, and thus watertightness was achieved. Effective sealing was also provided by the bonded lightweight aggregate layer on the specimens of series PC-19X-8 and 9. At this point it should be recalled from previous discussion that these concretes displayed relatively high values of strain differential from top to bottom of slab. This same behavior would also seem to apply to the specimens of PC-12 although the strain data were inconclusive in this respect. In summary, the implications are that strain incompatibility may produce volume instability during freeze-thaw exposure even in specimens which are effectively sealed to water penetration. However, no definite conclusion can be reached at this time and additional study should be directed at fully evaluating this possible failure mechanism in polymer concrete.

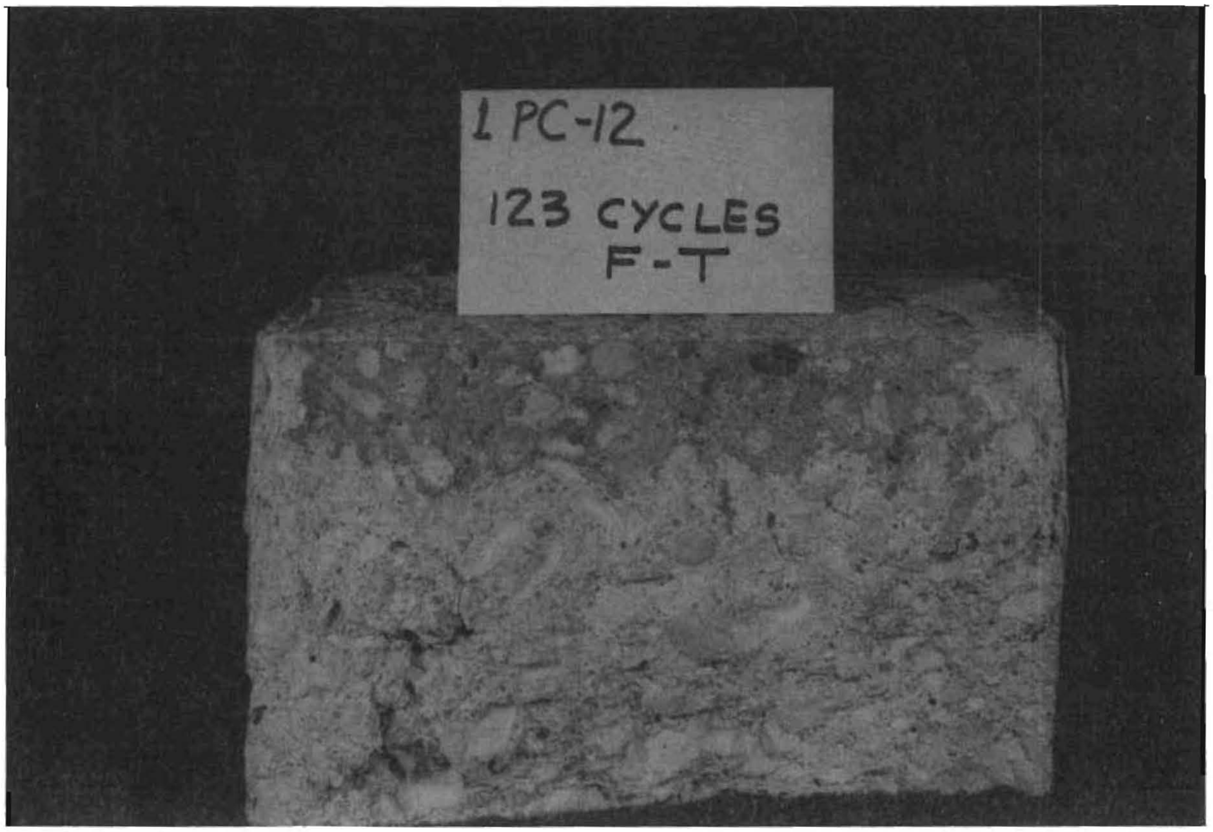


FIG. 5.12 EXTENT OF POLYMER IMPREGNATION IN PC-12 SERIES

5.3 Wear Track Friction Study

Before giving a discussion of the friction data of this study, some preliminary comments are necessary. The subject of skid testing of concrete pavement surfaces has generated a great deal of research literature in the past five to ten years.(28) It was not the purpose of this research program to conduct a detailed analysis into the complexities of friction measurement techniques or those of pavement-tire interaction. Of major concern here was whether or not polymer impregnation of concrete pavements is detrimental to the skid resistance properties of these surfaces. For that reason an effort was made to provide data which, from a relative standpoint, would allow a reliable comparison of polymer-impregnated and control concretes. To that end, all concrete specimens were given the same type of initial surface finish by use of a bristle broom. As a secondary study, two test series (4 and 9) were treated to provide a 1/4-in. surface topping of bonded lightweight fine aggregate (LWAT). Photographs of the surfaces of representative specimens are shown in Fig. 5.13A, B and C. Note that the goal of providing equivalent initial surface textures was not achieved for series 3, 5, 6, 7, 8 and 10 due to unintentional bonding of some lightweight fine aggregate routinely used in the treatment procedure. However, as these specimens were worn down, comparable surface conditions were produced, as will be discussed.

A total of thirty trapezoid-shaped, 2-in.-thick slabs from concrete mix PC-18 were surface treated at atmospheric pressure in the laboratory

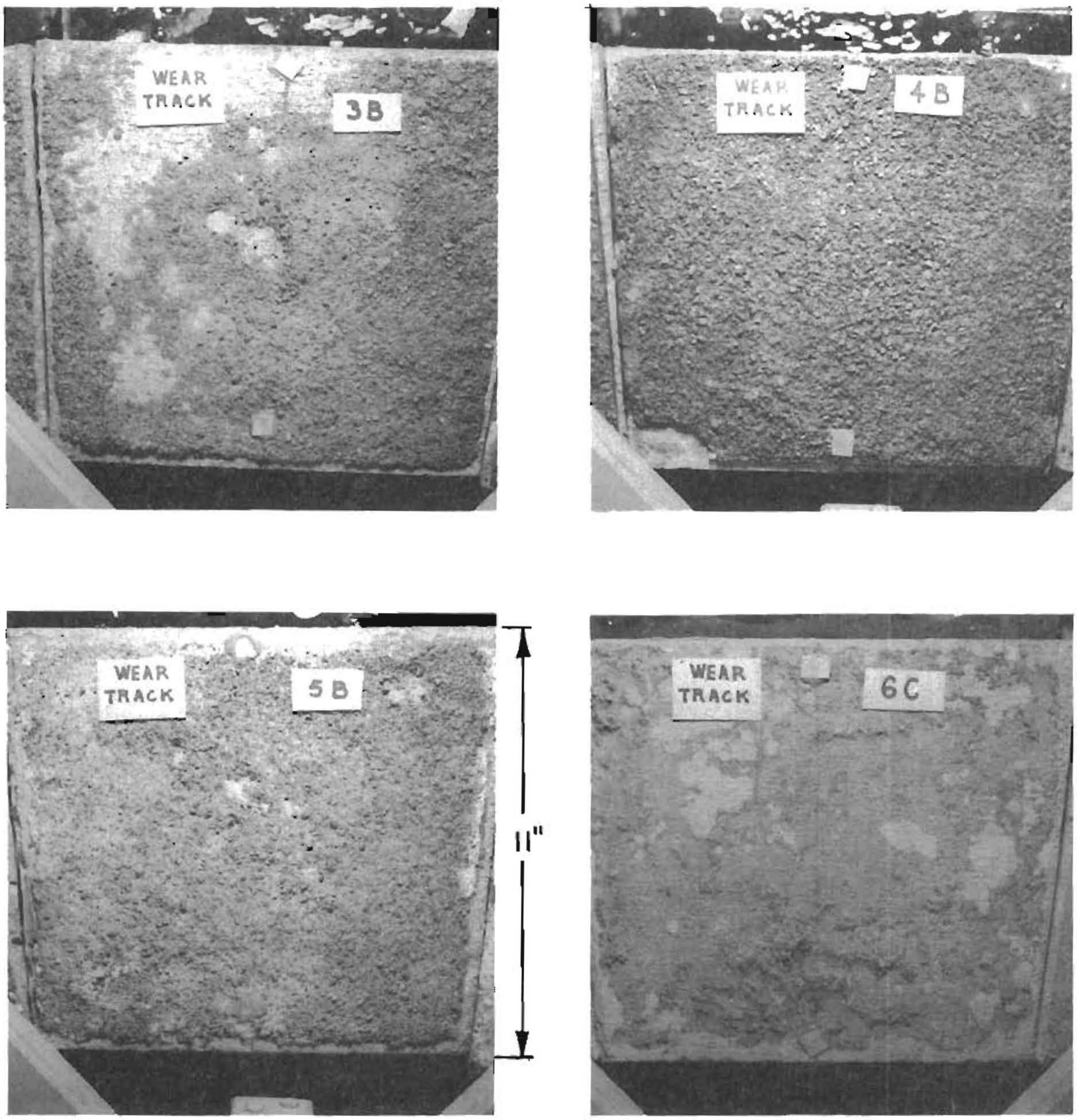


FIG. 13A PHOTOGRAPHS OF INITIAL CONDITION OF WEAR TRACK SPECIMENS

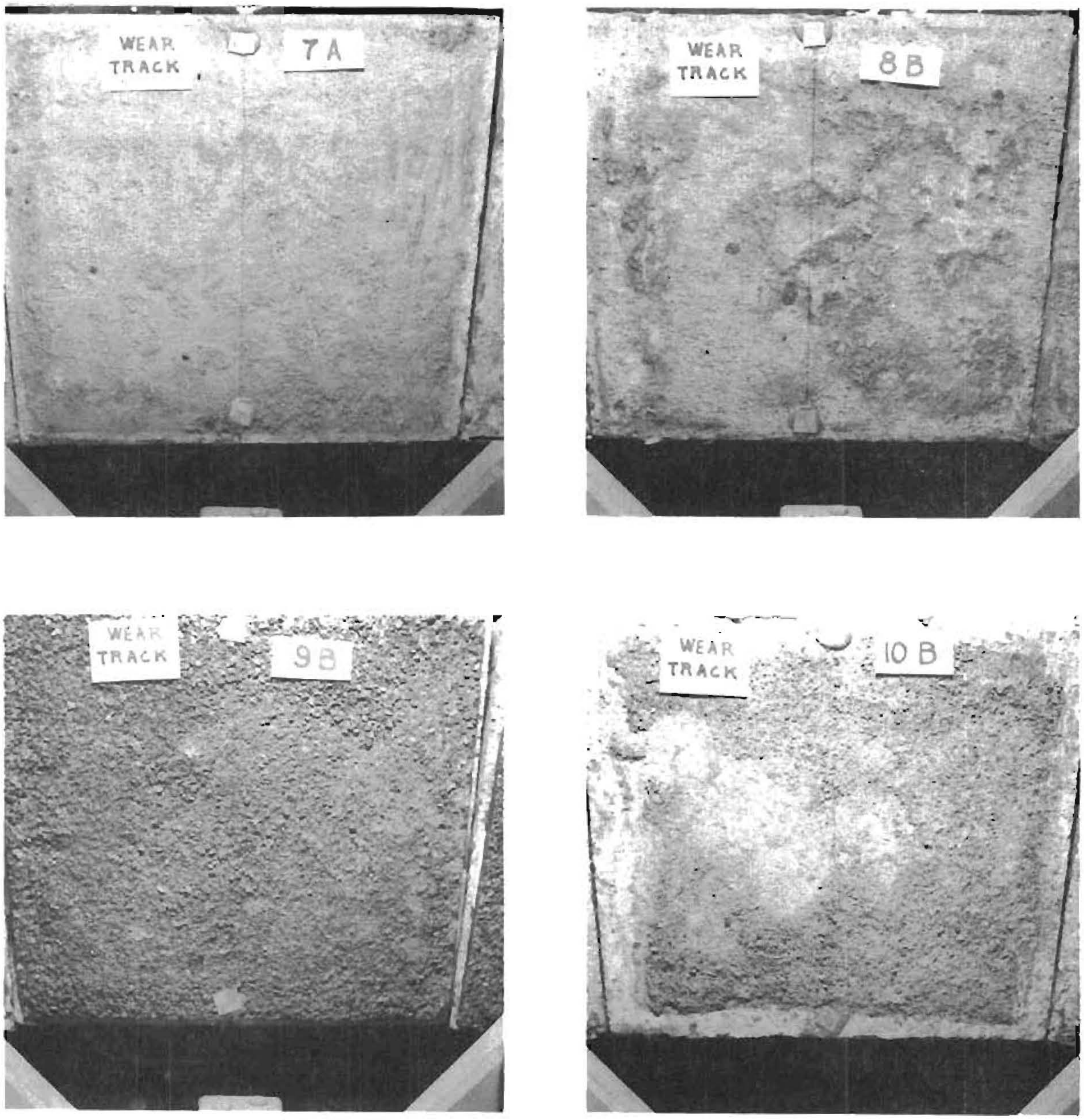


FIG. 13B PHOTOGRAPHS OF INITIAL CONDITION OF WEAR TRACK SPECIMENS

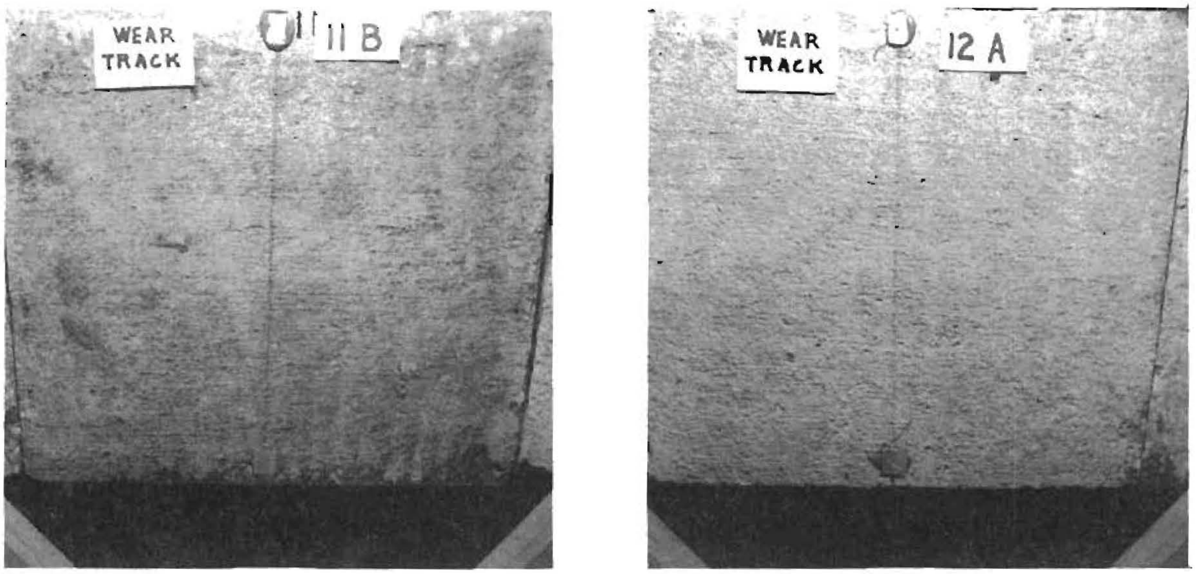


FIG. 13C PHOTOGRAPHS OF INITIAL CONDITION OF WEAR TRACK SPECIMENS for evaluation of frictional and wear resistance properties. Three untreated control specimens were also included in the test group. The impregnation treatments selected for presentation here are given in Table 3.2. A description of the test facility and procedures used to apply a simulated vehicular loading to the treated surfaces is found in section A.2 of the appendix. The vehicular loading consisted of 70,000 dry run revolutions (140,000 wheel passes) of two non-grooved tires, otherwise meeting ASTM E 274-70, followed by 140,000 revolutions (280,000 wheel passes) under wet conditions with no. 46 silicone carbide grit as a wearing agent.

Periodically, tire loading was stopped while measurements of surface friction were made. Surface friction values for each specimen were determined by use of the British Portable Testor (BPT) in accordance with ASTM E 303-69. The results of the friction study are presented in Figs. 5.14 and 5.15 where the average friction numbers of selected specimen were used to obtain friction curves through a total of 210,000 test revolutions. For ease of comparison the average friction curve of the untreated control specimens is shown in both figures.

The friction properties for the oven cured treatments are shown in Fig. 5.14. The initial skid numbers of all test series, including control specimens, are relatively high with only two of five polymer treated series falling slightly below the control values. As the dry wear loading progressed to 70,000 revolutions, the control concrete surfaces were polished by the tire wear, and the skid number decreased from 75 to 63. At the same time,

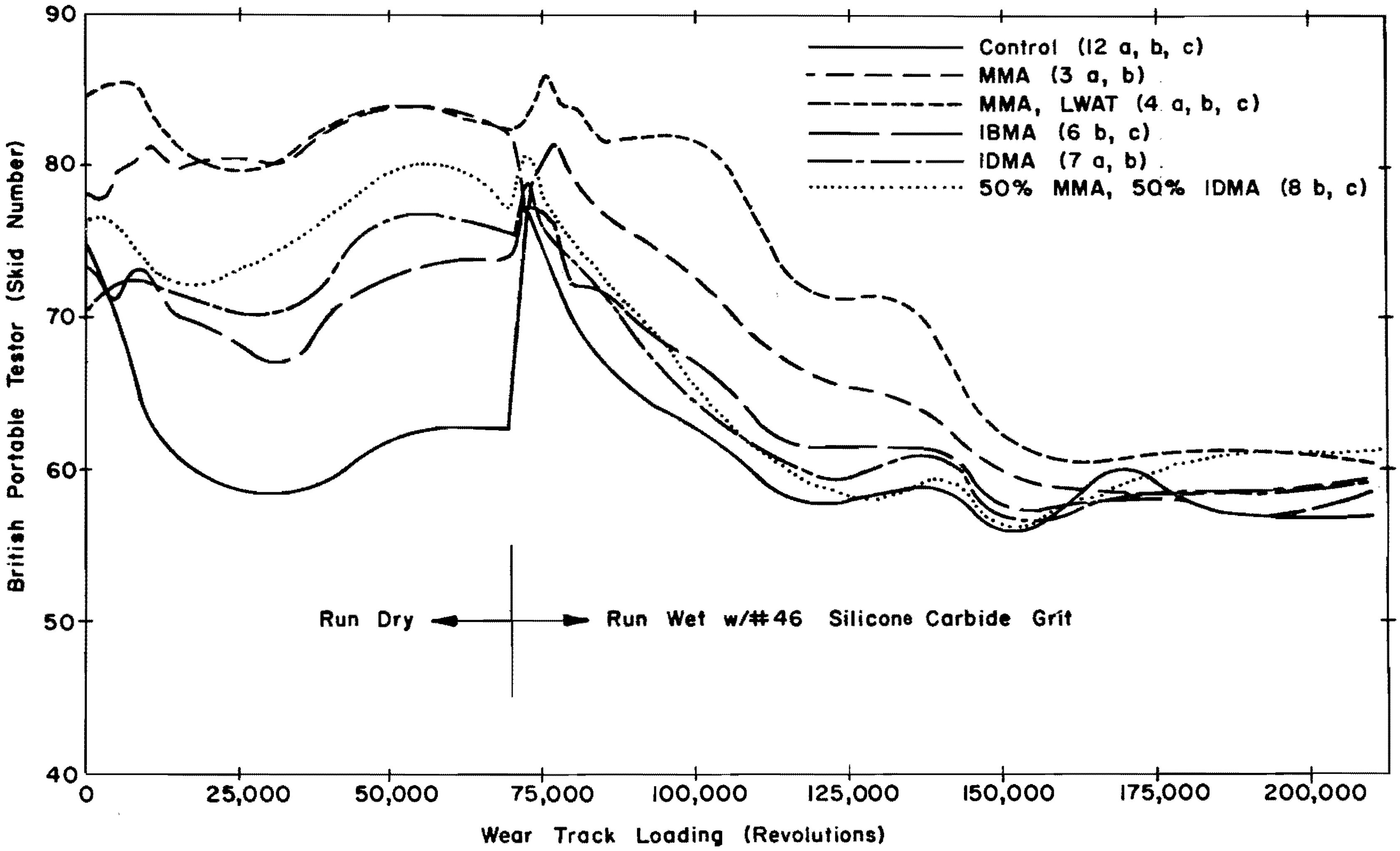


FIG. 5.14 WEAR TRACK FRICTION STUDY OF OVEN CURED SURFACE TREATMENTS

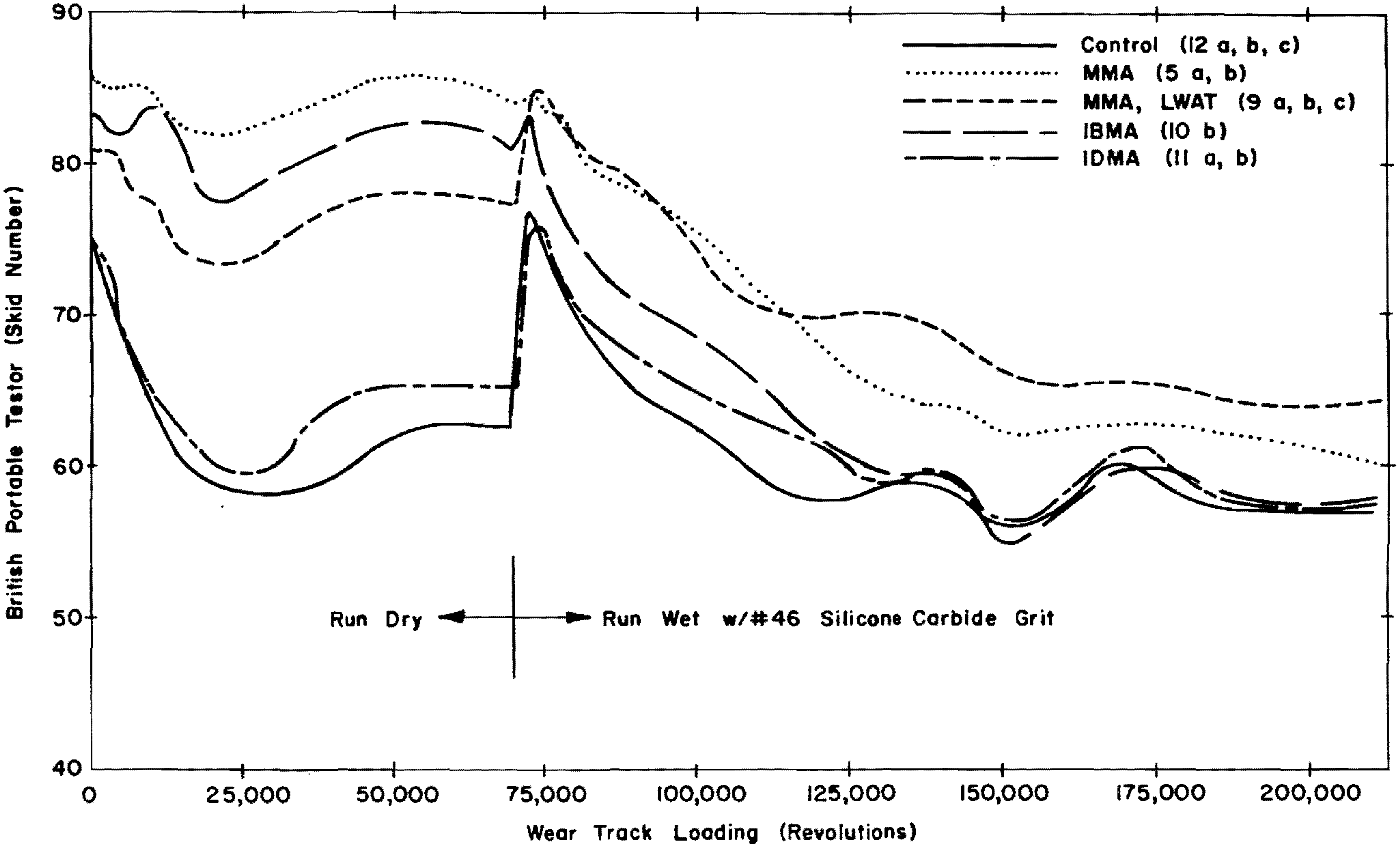


FIG. 5.15 WEAR TRACK FRICTION STUDY OF HOT WATER CURED SURFACE TREATMENTS

all treated surfaces displayed approximately the same or slightly increased skid numbers over their starting values. For the same loading period the hot water cured specimens of Fig. 5.15 also maintained their relatively high initial skid numbers except for series 11, which is seen to have polished in a manner quite similar to that of the control specimen.

After the completion of the first 70,000 test revolutions visual observation of the specimen surfaces revealed that very little physical wear had occurred. In fact, wear was so minor that, except for the rubber marking on the specimen surfaces, the location of the wheel path was barely discernible. As a result, it is apparent that the differences in initial surface texture as seen in Figs. 5.13A, B and C were substantially maintained to this point and thus resulted in the different skid properties as noted in Figs. 5.14 and 5.15.

After 70,000 test revolutions, the silicone carbide grit was applied with water in order to wear more deeply into the specimen surfaces. As a result, there was an immediate increase in the skid numbers of all specimens except those of series 3, which noticeably decreased. The greatest increase in skid number occurred for the control series although it remained, at best, approximately equal to the lower values of the treated specimens.

The influence of the grit in increasing the skid numbers of most of the surfaces was short lived as polishing effects were noted in all specimens after 5000 to 10,000 additional test revolutions. At the same time, all surfaces had begun to show visible signs of wear. From this point on, the silicone carbide grit gradually wore down all the test surfaces so that definite tire contact was made with the polymer-impregnated matrix of the various series treatments. Evidence of this contact is seen in the surface photographs of several specimens at the completion of testing as given in Fig. 5.16.

As the grit wore into the specimens, a significant polishing effect was seen. The skid numbers of all specimens of Figs. 5.14 and 5.15 gradually decreased to relatively constant levels beyond about 150,000 revolutions. This would seem to indicate that the base skid number for all specimens had been reached for these conditions of wear. At the same time, any inconsistency in the initial surface condition of specimens had been substantially negated by the action of the grit in wearing into all surfaces. This then provided a fairly stable condition in which one can compare the skid resistance properties of the impregnated and control surfaces.

From Figs. 5.14 and 5.15 a comparison of the skid numbers for the polished condition shows that the skid resistance of all polymer treated surfaces equaled or exceeded that of the control specimens at test termination. The differences in skid resistance of the treated specimens are seen to be relatively insignificant as all except series 9 fall within a range of 58 to 61. The layer of bonded lightweight aggregate of series 9 provided a final skid number of 64. Of most interest here, however, is that the polymer impregnation of the concrete surfaces did not result in adverse skid

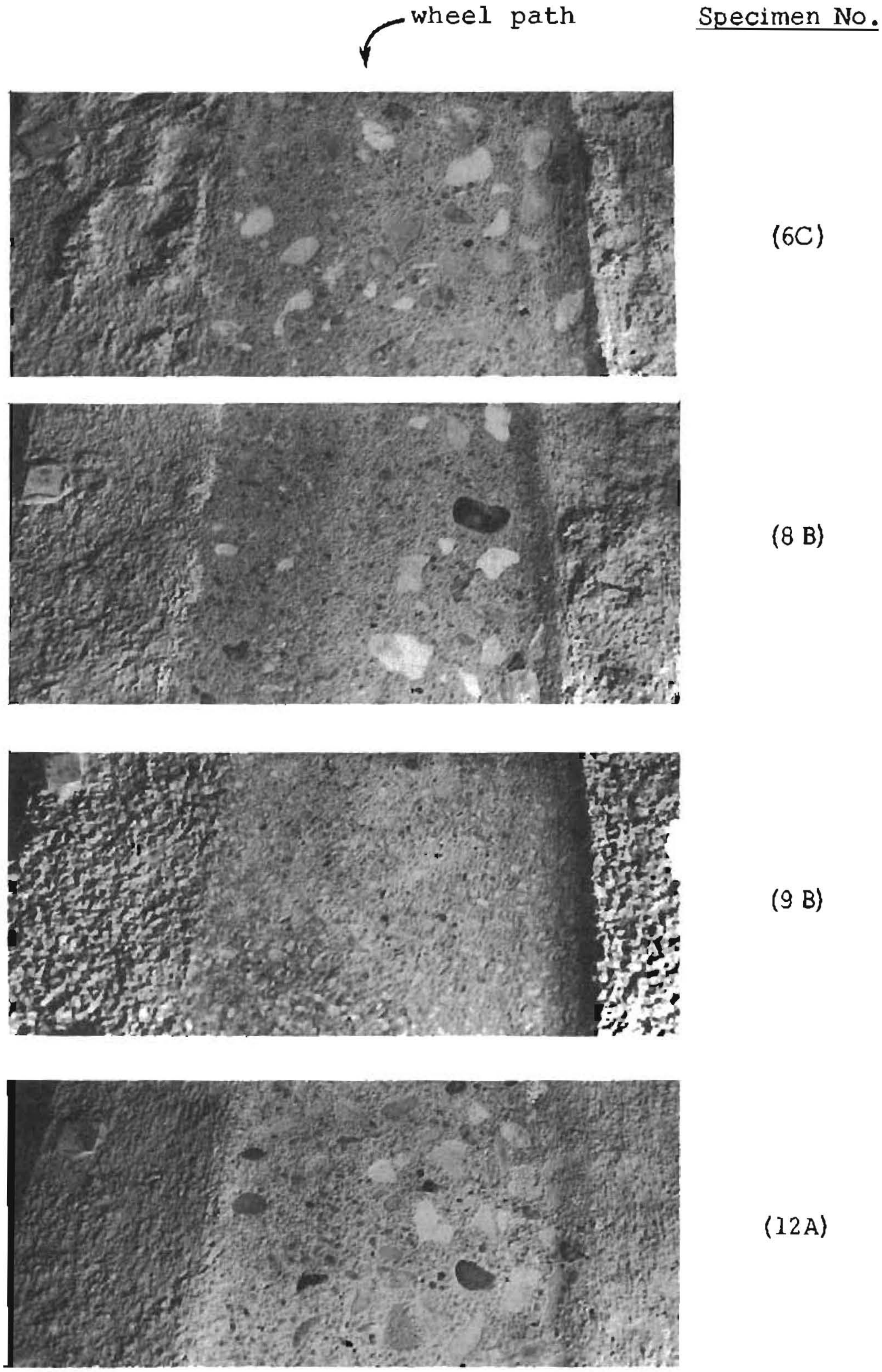


FIG. 5.16 WORN SURFACES OF WEAR TRACK SPECIMENS AFTER 210,000 REVOLUTIONS (420,000 WHEEL PASSES)

resistance properties as compared to control concretes. This conclusion is based upon the procedures of test used here and, of course, may not be completely relatable to field treatment methods, conditions of wear or skid measurement techniques.

5.4 Wear Resistance

An evaluation of the wear resistance of many of the polymer-impregnated and control concretes was made by two different techniques. The standard sandblast abrasion test (ASTM C 418-67T) and a measurement of depth of wear during wear track loading were used to provide data for two relatively different mechanisms of wear. A description of the test equipment and procedures used is found in sections A.2 and A.3 of the appendix.

5.4.1 Wear Track Abrasion--Periodically during wear track loading, depth of wear measurements were made at 0.03-ft. increments across the wheel path on each of the trapezoidal shaped specimens. These data were then computer processed to provide a measure of the x-section area worn away at various times during the loading history. The results of these measurements through 210,000 wear track test revolutions were averaged within each treatment series, and the resulting curves were plotted as shown in Figs. 5.17 and 5.18.

From both Figs. 5.17 and 5.18 it can be seen that with the exception of series 3 and 4, the wear characteristics of all specimens were similar through the first 70,000 revolutions of test. At 70,000 test cycles the wear area of series 3 and 4 was approximately double that of all other specimens.

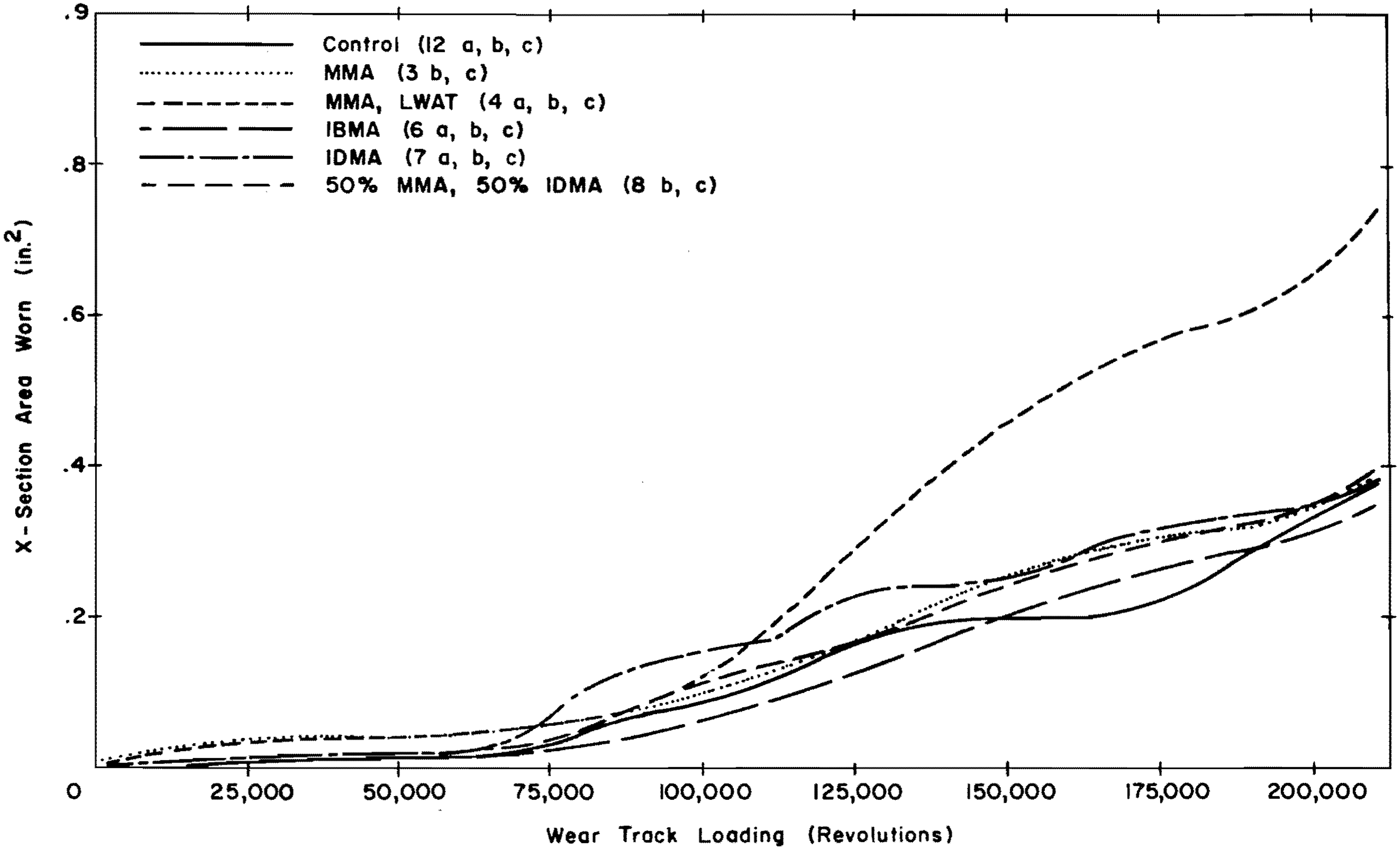


FIG. 5.17 WEAR TRACK ABRASION OF OVEN CURED SURFACE TREATMENTS

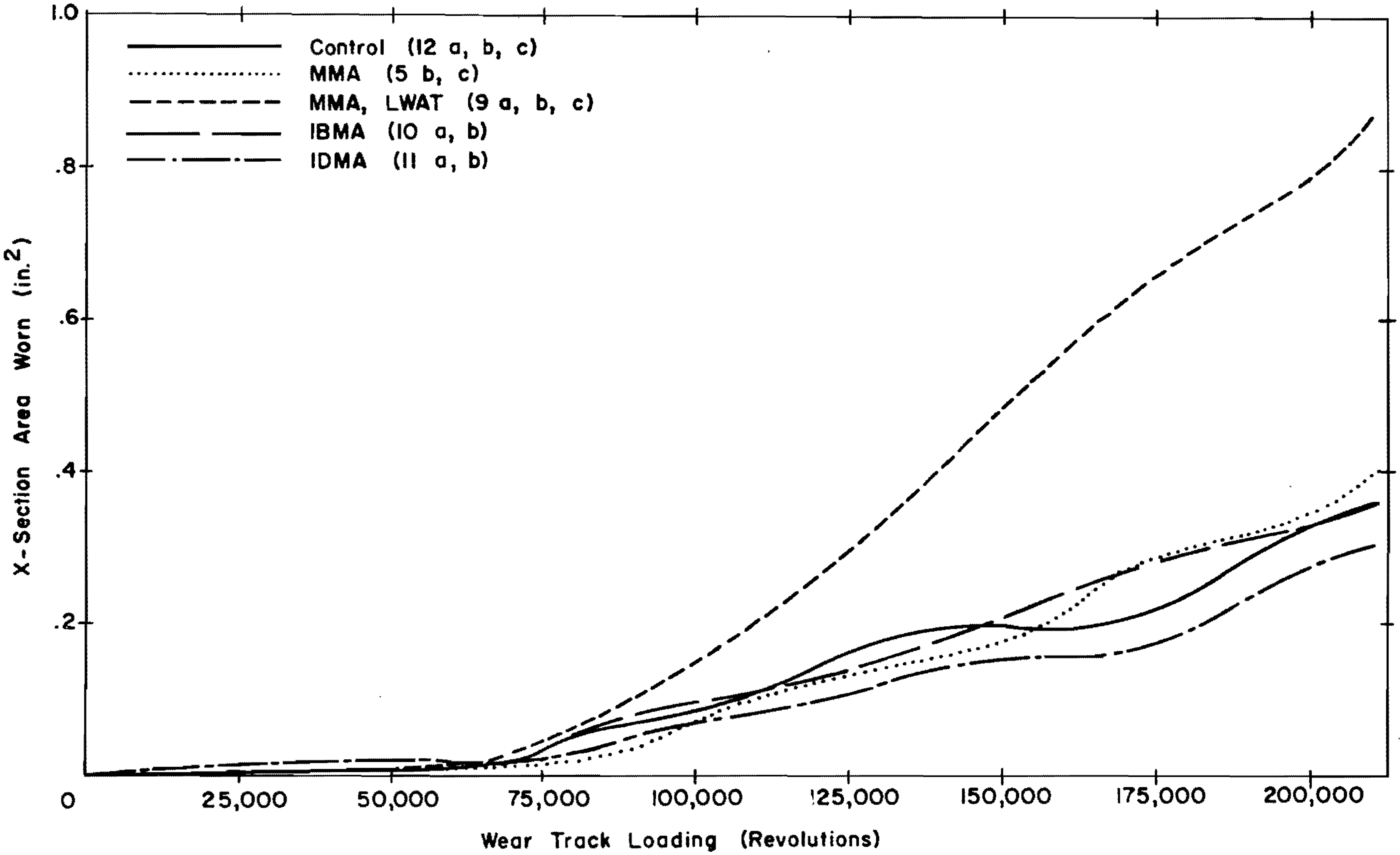


FIG. 5.18 WEAR TRACK ABRASION OF HOT WATER CURED SURFACE TREATMENTS

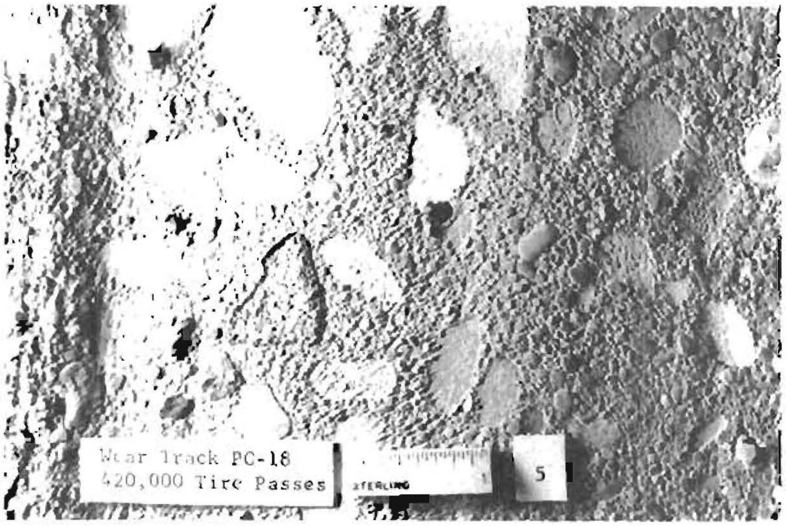
Specimen 9A

(LWAT)

Specimen 10B

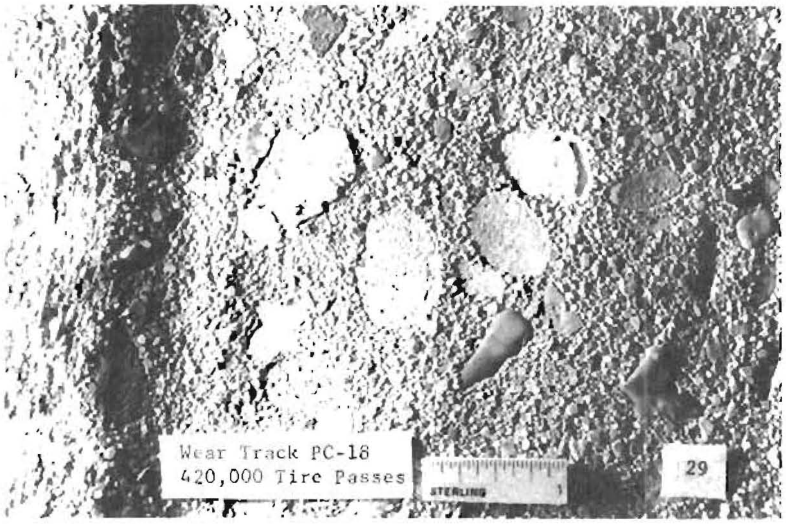
FIG. 5.19 X-SECTION WEAR RESULTING FROM WEAR TRACK LOADING

Specimen 3C



Specimen 12B

(control)



Specimen 9B

(LWAT)

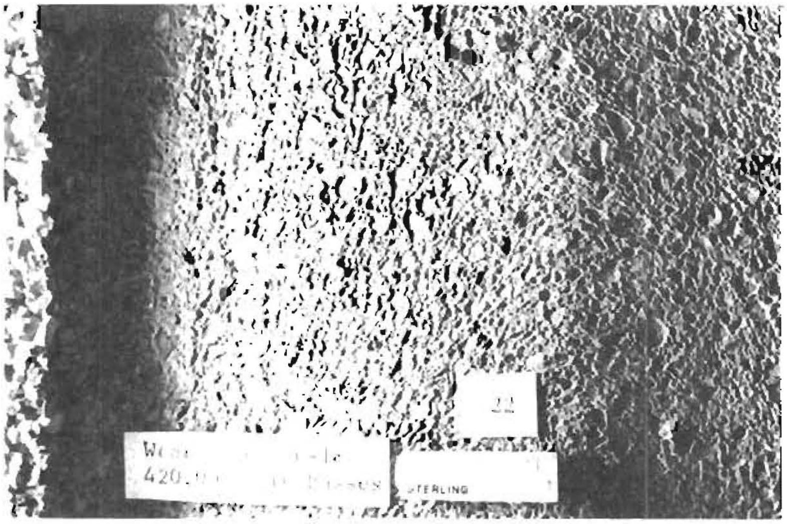


FIG. 5.20 ABRADED SURFACE TEXTURE AT THE TERMINATION OF WEAR TRACK TESTING

Beyond 70,000 test revolutions the application of silicone carbide grit and water is seen to have greatly accelerated the wear. However, except for the specimens with the bonded layer of lightweight aggregate (series 4 and 9), the rate of increased wear was relatively similar among the various test series. These similarities prevailed through 210,000 revolutions, at which time the test was terminated.

Photographs showing the extent of wear into the x-sections of typical specimens are given in Fig. 5.19. Close-up views of three specimens showing the nature of the abraded surface texture are given in Fig. 5.20. The photographs in both figures were made at the completion of the wear track study. A close visual examination of the abraded surfaces such as shown in Fig. 5.20 revealed that the mechanism of concrete wear was essentially the same for both control and treated specimens. For example, in Fig. 5.20, specimen 3c and 12b experiences the same type of wear, with a considerable portion of the larger aggregates being worn down below the level of the surrounding mortar. This indicates that the polymer reinforced mortar had about the same abrasion resistance as that of the untreated specimens. The wear data of both Fig. 5.17 and 5.18 provide the same conclusion.

The mechanism of wear into the bonded layers of lightweight aggregate of series 4 and 9 provided a different texture, as shown in the bottom photograph of Fig. 5.20. Close observation of these surfaces revealed that the silicone carbide grit wore into the porous cores of the individual lightweight aggregate particles. The outer skins of these particles and the cementing matrix of the polymer were more abrasive resistant and formed raised outlines on the worn surfaces. This texture was probably responsible for the relatively high skid resistance of these specimens, as reported in the previous section. However, from a wear standpoint these surfaces were less durable than those of all other series, with approximately 100 percent greater area worn.

From an overall evaluation of the wear depth data, it is concluded that the wear resistance of the polymer impregnated concretes was similar to that of the control concrete. However, there is some indication that in the absence of unintentionally bonded lightweight aggregate, the treated surfaces may be slightly more abrasive resistant than the control concrete.

5.4.2 Sandblast Abrasion Resistance--All concretes subjected to the water penetration test were also evaluated by sandblast abrasion tests. Two or three specimens were cut from the surfaces of the broken halves after water penetration testing. The standard ASTM C 418-67T procedure was followed except for a required modification in the method of determining abraded volume. A complete discussion of the procedure used is found in section A.3 of the appendix.

The results of the sandblast abrasion study are given in Fig. 5.21 where control specimens are shown as solid bars for easy comparison with companion treatments. A detailed summary of the treatment method used for these specimens is given in Tables 3.1 and 3.3. The mix properties of

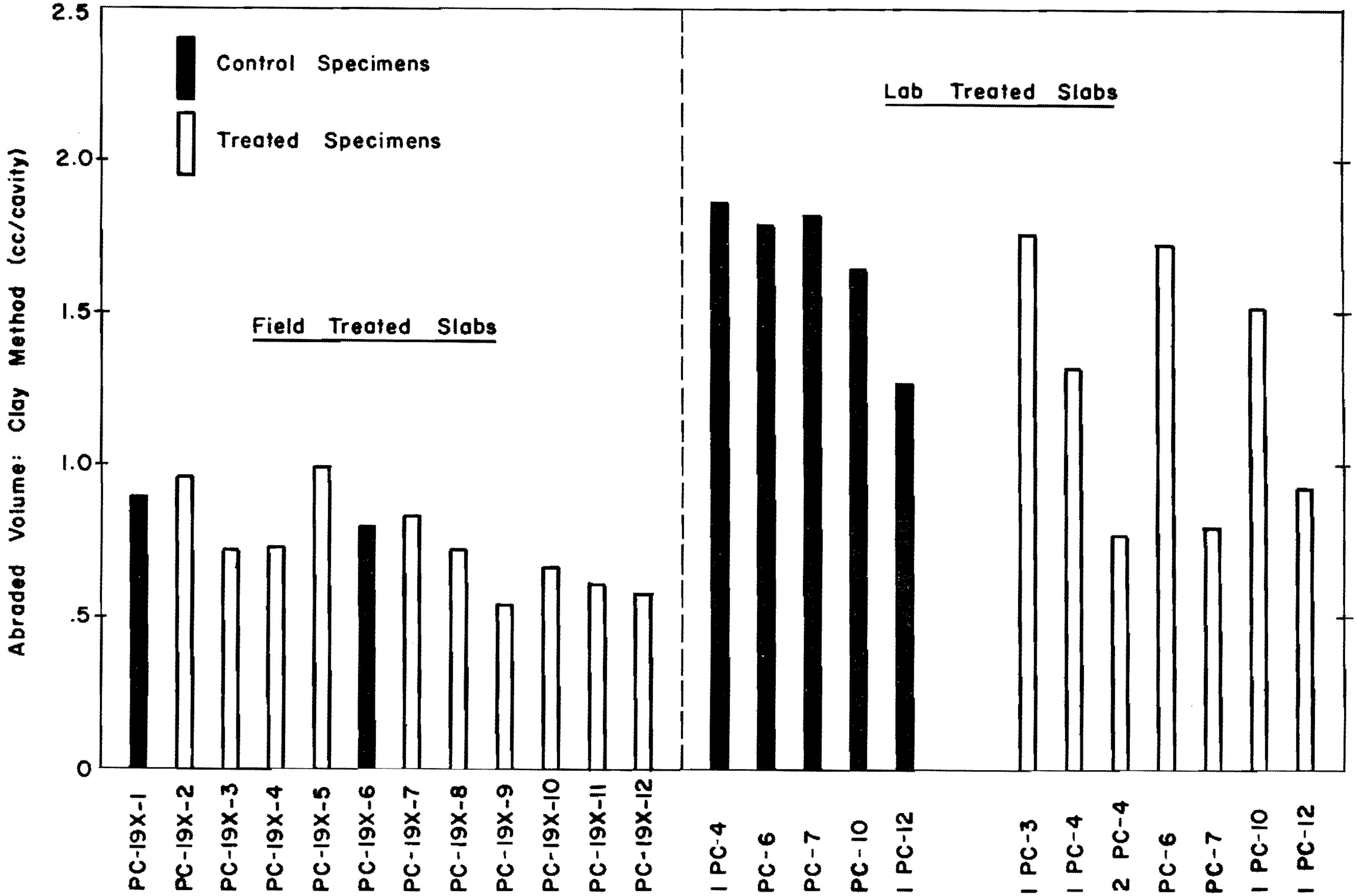


FIG. 5.21 SANDBLAST ABRASION OF SURFACE TREATED SLABS BY ASTM C 418 (MODIFIED)

the control concretes are found in Table A-1 of the appendix.

For the field treated specimens of Fig. 5.21, the control concretes gave an average abrasion loss of 0.85 cc per test cavity. Only the treatments of PC 19X-2 and 5 slightly exceeded the control values, with abrasion volumes of 0.96 and 0.99 respectively. The most abrasive resistant treatments of the field treated specimens were those of series 9, 10, 11 and 12. Within this group the abraded volumes were 64 to 78 percent of that of the control concrete. From a comparison of all field treatment specimens, it appears that impregnation did slightly improve sandblast abrasion resistance of most of the test series. Of those showing the most improvement, series 11 and 12 were also found to be stable by freeze-thaw evaluation.

In the analysis of the laboratory treated test series, one first notes the much larger abrasion losses of the control concrete and several impregnated specimens. These increased abrasion volumes are primarily due to the lower compressive strength of the laboratory treated concretes (see Table A-1). Since the same types of aggregates were used in all mixes, the relationship between strength and abrasion resistance indicated in Fig. 5.21 is to be expected.

Among the polymer treatments of the laboratory series, two show a significant improvement in abrasion loss over that of control specimens. The treatments of series 2PC-4 and PC-7 provided abrasion losses respectively amounting to 43 and 45 percent of that of the average control concrete

(1PC-4, PC-6, PC-7 and PC-10).* It should be noted here that treated series PC-7 incorporated a bonded layer of lightweight fine aggregate which was subjected to sandblast testing. In addition, the abrasion loss of series 1PC-12 was 70 percent of its companion control concrete while that of treatment 1PC-4 was 74 percent of the average control value. Thus, it can be concluded that for concrete of the quality used here, selected polymer treatments do provide increased abrasion resistance to the sandblast method.

A general comparison of the results of the wear track and sandblast abrasion studies is helpful at this point. First, since there are no direct test comparisons, a rating of the two test methods is difficult. The results of both tests on bonded lightweight fine aggregate seem to be contradictory with poor resistance to wear track abrasion and high resistance to sandblast abrasion. This comparison serves to clearly illustrate that the mechanisms of abrasion are very different in the two methods. As a result, future efforts will be made to determine what relationship, if any, exists between the two methods of wear evaluation. This is appropriate since each method has meaningful advantages. For example, the sandblast test has been standardized for concrete studies. On the other hand, abrasion loss during wear track loading is at least visibly related to traffic abrasion of pavement surfaces.

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*These concretes were of identical mix design, and strengths were similar, ranging from 4160 to 4500 psi.

5.5 Effects of Static and Cyclic Loading

To investigate the behavior of polymer-impregnated concrete under flexural loadings, a series of cyclic loadings on reinforced concrete beams with surface treatments is in progress. Each beam is 4 in. wide, 5-1/2 in. deep and 60 in. long, reinforced with a no. 5 grade 40 reinforcing bar with 1-1/2 in. clear cover. Control and treated beams are being tested under static and cyclic loadings. Equal concentrated loads are applied at a distance of 0.4 times the span length from each end. A span length of 56 in. is being used. The tests are still in progress.

The specimens were cast in the field at the same time slabs for field treatments were cast. The windy conditions caused the concrete to dry rapidly, and as a result the specimens were slightly honeycombed in spite of prolonged efforts to vibrate the concrete. Only the best specimens were selected for use in this study.

Table 5.1 summarizes the tests completed to date. The surface-treated specimens were treated the same as the laboratory test slabs described in Chapter 3. Curing was with hot water. The depth of surface treatment in the three treated slabs tested under static load ranged from 1/2 in. to 3/4 in. The concrete was probably more impermeable at the surface due to the longer period of vibration during casting.

The control specimens developed considerable flexural cracking on the tension side prior to failures. The failure was typical for under-reinforced beams, with a final compression failure occurring after consid-

TABLE 5.1 SUMMARY OF STATIC AND CYCLIC LOADING TESTS ON REINFORCED BEAMS

Specimen	Monomer[a]	Average Polymer Depth, in.	Ultimate Static Load, lbs	Cyclic load range, lbs, & frequency	Remarks
1RC-1	--		4350		compressive failure at top center of beam
1RC-2	MMA	1/2	6580		diagonal-tension failure
1RC-3	MMA	1/2	6400		diagonal-tension failure
1RC-4	--		5630		compressive failure at top center of beam
1RC-9	MMA	3/4	6170		diagonal-tension failure
1RC-10	--		5720		compressive failure at top center of beam
1RC-13	MMA			200-1360 @3cps	small flexural cracks in bottom quarter of beam
1RC-14	--			80-800 @5cps	no visible cracking

[a] Monomer system included 1%BP and 10%TMPTMA.

erable yielding of the steel had occurred. The average failure load was 5230 lbs.

The surface treated beams gave little evidence of cracking before a sudden diagonal tension failure occurred at an average load of 6380 lbs. Apparently, the higher strength and stiffness of the relatively shallow zone of polymer-impregnated concrete was large enough to result in the neutral axis lying significantly nearer the compression face. The accompanying increase in the lever arm between the resultant compressive and tensile forces was large enough to prevent significant yielding of the reinforcing from occurring before the failure occurred in shear. Further tests will be performed on beams with shear reinforcing.

Cyclic tests have just begun. Initially a control beam underwent 2,000,000 cycles of load which varied from 80 to 800 lbs. at 3 cps. No visible signs of distress were observed.

A surface-treated beam has undergone 2,000,000 cycles of load ranging from 200 to 1360 lbs. at 3 cps. A calculated stress in the reinforcing of 20,000 psi occurs at a load of 1360 lbs. Some small flexural cracks were observed during the test in the bottom quarter of the beams; however, there was no evidence of spalling or separation of the polymer-impregnated concrete from the rest of the beam. The beams tested under cyclic loads will be statically tested to determine if the fatigue conditions have any effect on the ultimate strength of the beams.

CHAPTER 6.

Other Applications

6.1 Polymer-Impregnated Piles

The use of fully-impregnated piles in an ocean environment has been considered to be a potential application of polymer-impregnated materials. Both wood and concrete are subject to attack in a marine environment.

In many coastal areas, wood is attacked by marine borers which rapidly bore through the wood until it is destroyed. There are some preservatives which offer protection against attack by some species, but apparently no single treatment offers protection against all species. There has been speculation that polymer-impregnated wood would be resistant to attack.

Concrete piles are subject to corrosion of the reinforcement which is accelerated by the presence of salt. Polymer-impregnated concrete is essentially impermeable, which reduces the probability of sale water reaching the reinforcing steel.

Concrete and wood pile specimens (3 x 3 x 46 in.) were impregnated with both MMA and styrene systems. The treatment summary is given in Table 6.1. The concrete mix design is given in the appendix. Each

TABLE 6.1 SUMMARY OF PILE TREATMENTS

Material	Specimen	Monomer	Catalyst	Evacuation Time, hrs.	Soak Time, hrs.	Polymer Cure (Hot Water)		Polymer Loading, %[b]
						Temp., °F[a]	Time, hrs.	
Concrete	1, 2, 3	--	--	--	--	--	--	--
	4, 5, 6	MMA	1%BP	16	5	~135	21	4.5
	7, 8, 9	Styrene	1%BP	13	5	~135	72	4.7
	10, 11, 12	MMA	½%BP	17	5	~135	72	4.7
Wood	1, 2, 3	--	--	--	--	--	--	--
	4, 5, 6	MMA	1%BP	62	6	~135	96	49.0
	7, 8, 9	Styrene	1%BP	15	5	~135	120	42.0
	10, 11, 12	MMA	½%BP	0	5	~135	48	1.4

[a] Specimens submerged in water tank placed in oven at 175°F. Water temperatures ranged from 130° to 140°F.

[b] $\frac{\text{Final weight}}{\text{Oven dry weight}} \times 100$

concrete specimen had one No. 6 reinforcing bar in the center. The specimens were treated in the same manner as the fully-impregnated specimens discussed in chapter 4. No cross-linking agent was used since it was not required for the water bath curing. One group of concrete piles (10, 11, and 12) had only 1/2 percent BP added to the solution to determine if the durability would be affected by slight changes in the catalyst. One group of wood piles (10, 11 and 12) was treated with no initial evacuation with the assumption that only the outer surface of the specimen would be impregnated with polymer. If this treatment proved adequate, surface treatments would require less monomer and be more economical.

The polymer loadings of the concrete piles were nearly uniform, ranging from 4.5 to 4.7 percent. For the two groups of evacuated wood piles the polymer loadings were 42 and 49 percent. The higher polymer loadings for wood reflect both the lower density of the wood compared to concrete and the larger pore volume of wood. The non-evacuated specimens showed very poor impregnation.

The specimens were placed in the ocean at Aransas Pass, Texas, in January 1972. Approximately 6 to 12 inches of each specimen was exposed above the water line. After seven months exposure, they were removed from the water for visual examination.

The wood specimens had been subjected to severe attack by the marine borers, and all of them were removed and brought to Austin for examination. No apparent damage could be detected in the concrete specimens, so only one pile from each of the four groups was removed for further examination; the other specimens were left in the water for further exposure.

In the laboratory, the concrete specimens were broken open to expose the steel (Fig. 6.1). No corrosion could be observed on any of the reinforcing bars in the treated specimens; the dark concrete indicates a good polymer loading which apparently prevented the salt water from penetrating to the steel. The control specimen, however, was found to exhibit a small corroded area on the surface of the reinforcing bar (arrow in Fig. 6.1). The corrosion was evident on a relatively small area, but it is likely that the affected area would have increased rapidly had the specimen remained in the water. The other concrete specimens will be left in the water for at least 18 months.

The wood specimens were cut into thin strips to observe the damage within the specimens. The specimens were severely honey-combed throughout. (Fig. 6.2). In fact, a large number of marine borers were still present in the water-soaked wood at the time of examination. Generally, little difference could be detected between the treated and untreated specimens. Only specimen 8, treated with styrene, showed significantly less damage than the control, but it is likely that in only a short time the damage would have been just as severe as the specimens treated with other monomers.

In summary, the polymer-impregnated concrete piles appear to provide greater corrosion resistance. The number of specimens available for preliminary inspection was limited, however, and no conclusions can be made

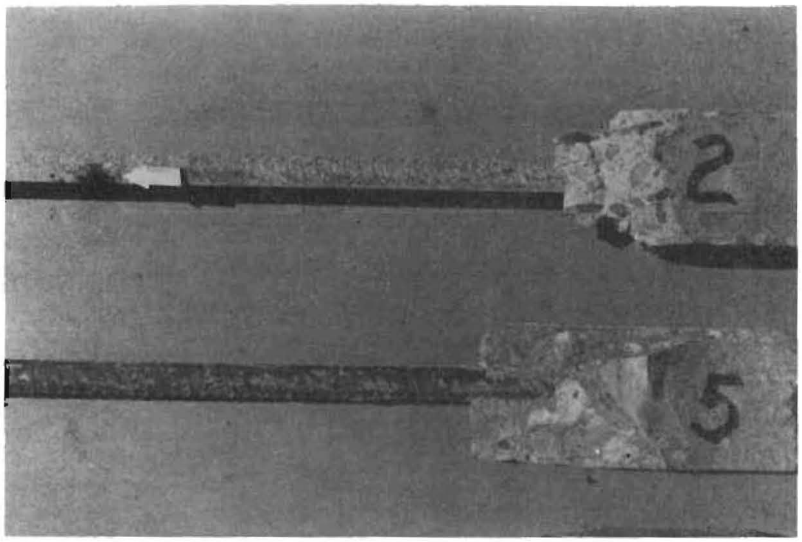

FIG. 6.1 COMPARISON OF UNTREATED AND TREATED CONCRETE PILES AFTER 7 MONTHS EXPOSURE

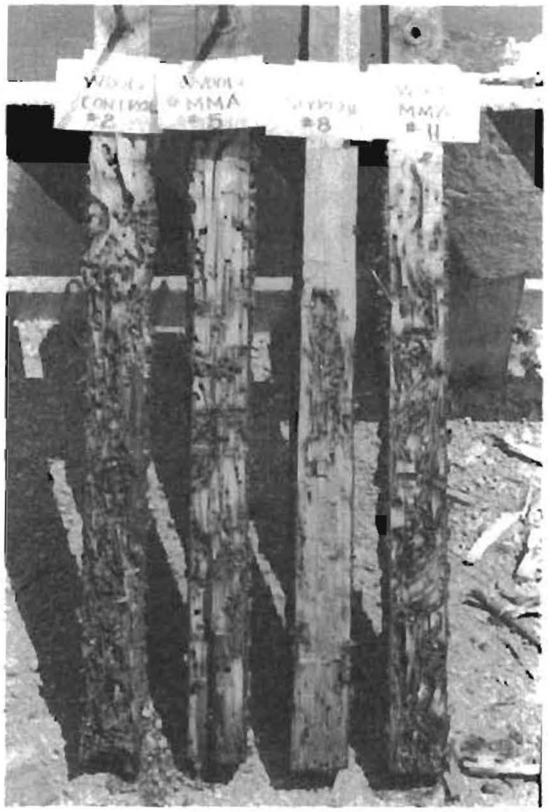

FIG. 6.2 COMPARISON OF TREATED AND UNTREATED WOOD PILES AFTER 7 MONTHS EXPOSURE

until the remainder of the specimens are observed. The polymer-impregnated wood specimens indicated no appreciable increase in resistance to marine borers. A further investigation to identify monomer systems, or additives to monomer systems, to provide effective resistance to the borers has thus far been unsuccessful.

6.2 Crack-Repaired Beams

One possible application of polymer-impregnation techniques is the repair of cracked bridge slabs. The penetration and bonding characteristics of the monomer systems give promise that cracks can be sealed and that some structural integrity can be restored to the concrete.

The evaluation of crack-repair techniques utilized 3 x 3 x 14 in. beams. The impregnated control specimens were subjected to the modulus of rupture test to determine the strength and to provide specimens to be "repaired." The two halves of each beam were placed together with a closed crack at the bottom (the original compression face) and a crack at the top ranging in width from 0.1 mm to 1 mm. Silicone adhesive was used to seal the crack on the bottom and sides and to form a shallow ($\simeq 1/4$ in.) dike around the crack on the top surface. The finite width of the crack permitted the monomer, ponded on the surface, to rapidly penetrade through the depth of the beam. After curing at room temperature or in a 125° F oven, the beam was again subjected to the modulus of rupture test with the beam placed with the same face in compression as in the initial test.

Two monomers (MMA and IBMA) were used with either lauroyl or benzoyl peroxide as the catalyst, the accelerator N, N-dimethyl-p-toluidine (DMPT) and the cross-linking agent (TMPTMA). The summary of the treatments and the test results are shown in Table 6.2. Generally the "repaired" specimen modulus of rupture was less than the control value. However, it was noted that in most cases the second failure crack did not coincide with the initial fracture. This seemed to indicate that the second failure occurred at the location of microcracks, resulting from the first test, that were not in the repaired zone. In some cases a portion of the second failure crack coincided with the first.

The most promising treatment from the standpoint of highest strength and highest strength ratio utilized MMA with 2 percent BP and 1 percent DMPT. Achieving nearly the same results was a system utilizing MMA, 2 percent DMPT and 4 percent lauroyl peroxide. The treatments utilizing IBMA did not fare as well, with a strength ratio of 0.74 being the highest observed. The coefficient of variation for the IBMA specimens was also much larger.

TABLE 6.2 SUMMARY OF CRACK-REPAIRED BEAM TESTS

	TREATMENT		TEST RESULTS				
			Control Beams		Repaired Beams		
Spec. No.	Monomer System Monomer-BP-DMPT-XL-LP, %	Cure Temp.	Modulus of Rupture, psi	Coefficient of Variation	Modulus of Rupture, psi	Coefficient of Variation	Strength Ratio[a]
PC-4-1,2,3	MMA-0-4-0-4	room	552	11.5	351	12.0	0.64
PC-5-1,2,3	MMA-1-0-10-0	125°F	723	5.0	484	19.0	0.67
PC-6-1,2	MMA-1-0-10-0	125°F	713	2.0	612	7.5	0.86
PC-7 PC-8-1 PC-15	MMA-2-1-0-0	room	637	3.5	538	11.0	0.84
PC-7 PC-8-2 PC-15	MMA-2-1-5-0	room	674	17.0	551	7.5	0.82
PC-7 PC-8-3 PC-15	MMA-2-1-10-0	room	634	10.0	544	9.0	0.86
PC-9-1,2,3	MMA-0-2-0-4	room	677	6.5	613	6.0	0.91
PC-11-2,3	MMA-0-2-0-4	room	661	2.0	664	1.0	1.00
PC-11-4,5,6	MMA-2-1-0-0	room	703	3.5	717	9.0	1.02
PC-12-1,2,3	IBMA-0-2-0-4	room	799	1.5	592	15.0	0.74
PC-12-4,5,6	IBMA-2-1-0-0	room	668	19.5	134	33.0	0.20
PC-12-7,8,9	IBMA-2-1-5-0	room	792	7.0	108	55.0	0.14
PC-12-10,11,12	IBMA-2-1-10-0	room	772	1.0	357	14.0	0.46
PC-14-7,8,9	MMA-1-0-10-0	125°F	784	2.5	492	28.0	0.63

[a] repaired beam strength/control beam strength

CHAPTER 7.

Implementation

7.1 Field Application

The investigation of polymer-impregnated concrete surface treatments has given the goal of developing practical and economical techniques the top priority. As a result, the procedures that have been developed appear to be suitable for highway application. It should be emphasized that the application techniques have been regularly improved since the beginning of the study, and the probability is quite good that further improvements will be made in the future. The following discussion summarizes recommendations for applying surface treatments based on the present state-of-the-art.

7.1.1 Drying the Slab--The slab should have an age of at least two months or more before application of the monomer, to permit as much air drying of the slab as possible. The slab should be protected from rain and dew by a plastic cover prior to monomer application. The clear plastic should be supported several inches above the slab surface to serve as a solar heater to assist the drying. However, there should be provision for air circulation to prevent moisture condensation. (If additional drying is necessary, warm air heaters in shallow enclosures over the slabs appear to be the most feasible solution.) Studies are currently underway to identify a method for determining when the slab is sufficiently dry to obtain an adequate surface treatment.

7.1.2 Application of Monomer--The slab should be covered with approximately 1/4 in. dry natural sand to prevent evaporation. For large-scale treatments of bridge decks, the monomer would be applied with a spray gun that would utilize a mixing nozzle to eliminate the hazard of premixing and storing large quantities of the monomer system. The estimated application rate would be in the range of 50 to 100 sq ft per minute which would permit the equivalent of 250 to 500 ft of a single lane to be wetted per hour. The wetted slab should be immediately covered with plastic film to prevent evaporation. A soak time of 10 hours is preferable to permit adequate penetration into the concrete. In cool weather, the soaking period could be during the day. When the slab temperature exceeds 100°F during the day, the slab should be covered to prevent premature polymerization of the monomer, or the soak period could be overnight to minimize the temperature and evaporation effects. One intermediate application of monomer after 4 to 6 hours may be necessary if the sand becomes dry.

7.1.3 Curing--After the soak time, curing could be accomplished by one of several methods:

1. Hot Water--Adjustable wood or metal frames with plastic sheets draped inside to hold the water would be applied over the slabs. For relatively flat decks the frames could be approximately 12 x 20 ft; for slabs

with steep slopes the frames would be further divided through the center to "terrace" the slab to prevent the necessity of excessive ponding of the water on one side to cover the entire area. Water heated by portable units would be pumped into the shallow ponds and could perhaps be recirculated through the heaters to maintain a water temperature of 160°F to 200°F. A minimum depth of 2 to 3 in. of water would be preferable. This would require about 1.5 to 2.5 gal/sq ft. Each 20 ft of a single lane width of bridge deck would require about 400 to 500 gals of water.

As an alternative to the use of water ponded in the open vats, the possibility of using a closed system is being investigated. This system would involve a large bag similar to a hot water bottle that could cover an area of perhaps 12 x 20 ft. The bag could be relatively thin since it would be connected to a water heater and circulating pump. The closed system would be easier to move, would have less heat loss, would minimize evaporation, and would probably require less water.

The water would be left on the slab for one or more hours, depending upon the temperature, after which the apparatus could be moved onto the next section to be cured.

2. Steam Heat--This method, which is in the process of being evaluated, perhaps offers more potential than hot water. This proposed method would require an enclosure to be placed over the soaked slab. Steam from portable generators would be used to heat the interior of the enclosure. The enclosures could consist of light metal frames approximately

6 x 12 ft supported by short (≈1 ft) legs. The frames would be placed side by side to provide as large an enclosure as required. Canvas could be used to cover the top and sides; there would be no need to make the enclosure air tight. The steam would be regulated to maintain an air temperature inside the enclosure of 125 to 175°F for the required cure time, which should not exceed 1 to 2 hours.

The tentative advantages of this method over the hot water are: (1) much less water required; (2) minimizes the problem of sloping decks; (3) simpler apparatus; (4) the potential of curing larger areas at one time; and (5) the ability to achieve higher temperatures.

3. Warm Air Heat--Warm air heat could be the most feasible solution for curing in some areas, especially if warm air drying is necessary prior to application of monomer. Enclosures similar to those proposed for steam curing would probably be adequate. The advantages of this method are: (1) ability to cure sloping decks and large areas; (2) no water required; (3) equipment is simple and readily available; and (4) the same apparatus can be used for preliminary slab drying.

7.2 Cost of Treatments

The cost of the treatments applied to actual bridges in the field can only be estimated at this time since no experience has been obtained with the application and curing methods on a large scale. The cost will involve many variables: (1) amount of initial drying required for the slab; (2) types of monomer systems; (3) evaporation losses; (4) type of curing system;

(5) availability of required apparatus; and (6) labor rates.

A range of estimated costs is as follows:

Drying slab	$0.05 to 0.15/sq ft
Monomer system, applications and evaporation barriers	$0.30 to 0.45/sq ft
Curing	$0.10 to 0.30/sq ft
Total estimated cost	$0.45 to 0.90/sq ft

These estimates assume that the apparatus costs would be amortized by large-scale usage.

The cost of polymer-impregnated surface treatments, for the benefits desired, seems economically feasible in comparison to the high cost of maintenance, repair and replacement using alternate methods. It is difficult to place a value on the benefits derived from not having to close a bridge for repair or maintenance for a much longer period of time.

CHAPTER 8.

Conclusions

The investigation reported herein has had the objective of developing uses of polymer-impregnated concrete for highway applications. Primarily the emphasis has been on development of surface treatments for bridge decks, but other applications such as piles and repair of cracked slabs have been studied. The following conclusions summarize the investigation.

Monomer Systems:

The most effective monomers identified for surface treatments are, in order: methyl methacrylate, isobutyl methacrylate, and isodecyl methacrylate. With the addition of 1 percent (wt) catalyst (benzoyl peroxide) and 10 percent (wt) cross-linking agent (trimethylolpropane trimethacrylate) the monomer solution will polymerize within concrete at 125°F.

Application Techniques:

Best results for surface treatments are obtained by soaking the concrete, covered with 1/4 in. of sand, with monomer solution for a minimum of 10 hours. During the soak period the concrete temperature should not exceed 90° to 95°F to prevent premature polymerization.

Curing Methods:

The most promising methods for applying the necessary heat to polymerize the monomer systems are: (1) ≃ 3 in. of ponded hot water (≃ 190°F to 200°F); (2) steam heating inside a curtain enclosure; and (3) warm air inside an enclosure, provided by heaters or a forced air system.

Stength and Stiffness Increases:

The increase in compressive strength for fully-impregnated concrete ranged up to 3.28 times the untreated specimen strengths. Modulus of rupture values up to 2.39 times those for control specimens were obtained, while tension strengths 2.06 times higher were obtained. The modulus of elasticity for treated concrete ranged up to 6.35×10^6 psi, which was slightly less than twice the value for control specimens.

Freeze-thaw Study:

Freeze-thaw durability was effectively measured in terms of strain at the tops of slabs during test. The parameter was considered a measure of volume stability.

High quality, air entrained control concretes compared favorably in volume stability with laboratory impregnated slabs.

Laboratory impregnated slabs were generally more resistant to scaling than air-entrained control slabs.

Non-air-entrained control slabs rapidly deteriorated as indicated by volume instability while all surface treated slabs were relatively more durable. Four of the field treatments apparently provided complete freeze-thaw protection throughout the test.

Failure of freeze-thaw specimens was normally observed whenever top strains exceeded +500μ in./in.

Water Tightness Study:

Polymer impregnation resulted in improved water tightness in all tests. In many cases impregnation entirely prevented water penetration as measured by the test used.

Several concretes found to be water-tight initially failed in freeze-thaw tests. In most cases the water penetration resistance of these specimens was decreased by the freeze-thaw exposure.

Several freeze-thaw specimens which failed by loss of volume stability were found to have remained essentially water-tight during freeze-thaw exposure. For these specimens, strain incompatibility is suspected as a possible failure mechanism.

Wear Track Friction Study:

For the first 140,000 wheel passes under dry conditions, all but one polymer-impregnated surface had significantly higher skid resistance than that of control concrete. The control and one treated series each experienced a decreasing skid number as they were polished by the simulated vehicular loading.

Beyond 140,000 wheel passes all specimens were significantly worn by the use of silicone carbide grit and water applied during wear loading. At the termination of tests, all treated specimens had reached a stable skid number which equalled or slightly exceeded that of the control specimen.

Wear Track Abrasion Study:

Surface wear induced by simulated traffic loading was found to be approximately equal for treated and control specimens with the exception of those with 1/4 in. thick bonded lightweight fine aggregate which experienced significantly more wear.

Sandblast Abrasion Study:

Eight of ten field-treated slabs were slightly more abrasion resistant than companion control specimens. The most effective treatment resulted in an abraded volume of 64 percent of that of the control concrete.

When a lower quality concrete was used for laboratory treatment studies, significant improvements in abrasion resistance were provided by impregnation. The most effective treatment resulted in an abraded volume of 43 percent of that of companion control concrete.

Static and Cyclic Tests of Surface-Treated Reinforced Beams:

The static strength of surface-treated reinforced beams was found to be 22 percent greater with a diagonal tension failure resulting, than that of untreated beams, which failed in flexure. No spalling has occurred in the cyclic tests of surface treated beams.

Repair of Cracked Slabs:

Small unreinforced concrete beams, broken in flexure, were repaired using several methyl methacrylate systems cured at room temperature. The original moduli of rupture were obtained.

Polymer-Impregnated Concrete and Wood Piles:

Fully-impregnated wood piles placed in sea water on the Texas coast were severely attacked by marine borers after seven months exposure. Fully-impregnated reinforced concrete piles showed no evidence of corrosion after the same exposure while the control specimen did show signs of corrosion.

Implementation Feasibility:

The polymer-impregnated surface treatments can be obtained for an estimated cost of $0.45 to $0.90 which is competitive with current methods of repair and maintenance, especially when the improvements in properties are considered. The methods of application and curing appear to be feasible and practical.

APPENDIX

APPENDIX A.

A.1 Freeze-Thaw Test Procedure

All slab specimens to be subjected to freeze-thaw testing were oven dried at 190 ± 10°F for a minimum of seven days. After the drying period, an 8 in. inside diameter metal ring was bonded to the treated surface of each test slab with a silicone adhesive. At this time four stainless steel reference tabs were epoxy bonded 8 in. apart on one vertical face of each slab at approximately 1/2 in. below the top surface and 1/2 in. above the bottom surface. A photograph showing a typical specimen with reference tabs is given in Fig. A.1. Next, the specimens were aged for 24 hours at 76 ± 3°F after which initial horizontal length measurements were taken by use of an 8-in. Berri gauge as shown in Fig. A.2.

The freezing and thawing procedure used early in the research program consisted of overnight freezing at -15 ± 5°F followed by a 2-1/2 hour thaw, a 4 hour freeze, a 2-1/2 hour thaw and finally an overnight freeze to complete the daily test routine. Prior to each freeze cycle, a solution of 5% sodium chloride in water was added as needed to maintain a depth of 1/4 in. within the metal rings throughout the test period. Although this procedure provided two test cycles per day, it was determined by use of

FIG. A.1 FREEZE-THAW SPECIMEN WITH REFERENCE TABS FOR STRAIN MEASUREMENT

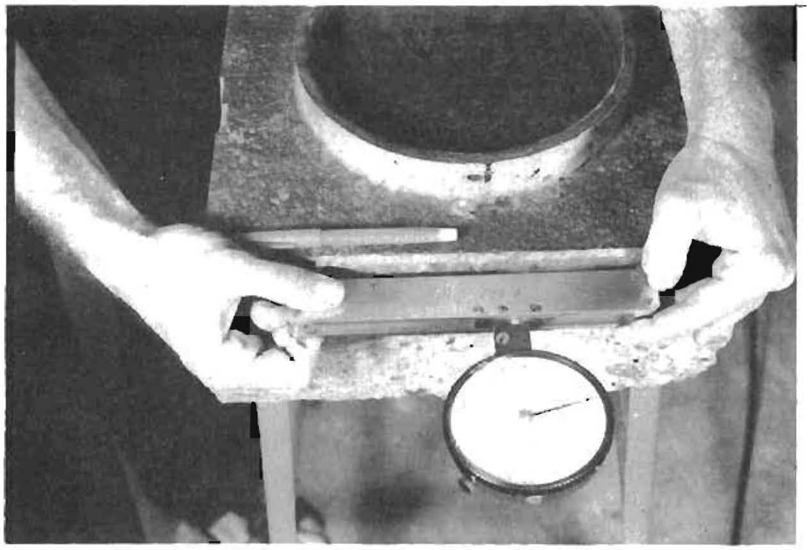

FIG. A.2 MEASUREMENT OF HORIZONTAL STRAIN OF FREEZE-THAW SPECIMENS BY USE OF BERRI GAUGE thermocouple readings that those specimens which absorbed large amounts of the ponded water were not adequately frozen or thawed during the day test cycle. The test procedure was therefore modified to provide overnight freezing followed by an 8 hour thaw during the day. Also, the use of salt water was discontinued and tap water was used as the freezing solution in all subsequent tests. One other modification of the test procedure provided for the first freeze-thaw cycle to be conducted with each specimen in the dry condition after which the testing was continued with water ponded to a 1/4-in. depth within the metal rings.

In order to provide numerical as well as visual data concerning the condition of the test specimens during freeze-thaw exposure, each specimen was evaluated periodically up to a maximum of 120 freeze-thaw cycles at which time the test was terminated. Length measurements were made on specimens immediately after removal from the freezing chamber after one cycle of freezing dry, after one cycle of freezing wet and, subsequently, at approximately twenty freeze-thaw cycle intervals. A final reading was taken after the specimen had completed the last thaw cycle and then aged approximately 24 hours at room temperature. Specimens which exhibited severe deterioration as shown by extensive cracking and inability to hold the ponded water during a thaw cycle were terminated prior to completion of 120 cycles of test. Photographs taken of each specimen at the time length measurements were made provided a visual record of the condition of the concrete throughout the test period.

A.2 Wear and Skid Resistance Test Procedure

A simulated vehicular loading was applied to thirty trapezoidal shaped specimens at the Texas Highway Department wear track facility in Austin, Texas. Photographs showing an over-all view of the test facility and specimen orientation are given in Fig. A.3(a) and (b). The specimens were epoxy bonded to steel plates which were bolted to a concrete foundation, thus forming a circular test surface approximately 10 ft. in diameter. Two non-grooved tires otherwise meeting ASTM E 274-70 specifications for skid resistance tests were mounted at each end of a weighted beam which was driven by a variable speed motor. The vertical load applied by each tire was 765 lbs. and the tires were driven at 10 miles per hour. Tires were aligned so as to have no cant and no toe. The test facility was designed to provide either dry or wet pavement conditions during simulated vehicular loading of the specimens. When the specimens were subjected to wet testing, #46 silicone carbide grit (-#30, +#50 mesh) at a rate of 1100 to 1200 grams per hour and water at a rate of 3.5 to 4.0 gallons per hour were simulatneously applied to the test surface through rotating dispensers.

At appropriate times during the wear track testing, measurements of test surface skid resistance and wear were made. The skid numbers for the test specimens were determined by use of the British Portable Testor in accordance with the procedures given in ASTM E 303-69. A 3-in. wide rubber pad with a 5-in. contact path as specified was used. A photograph of a skid test in progress is given in Fig. A.3(b).

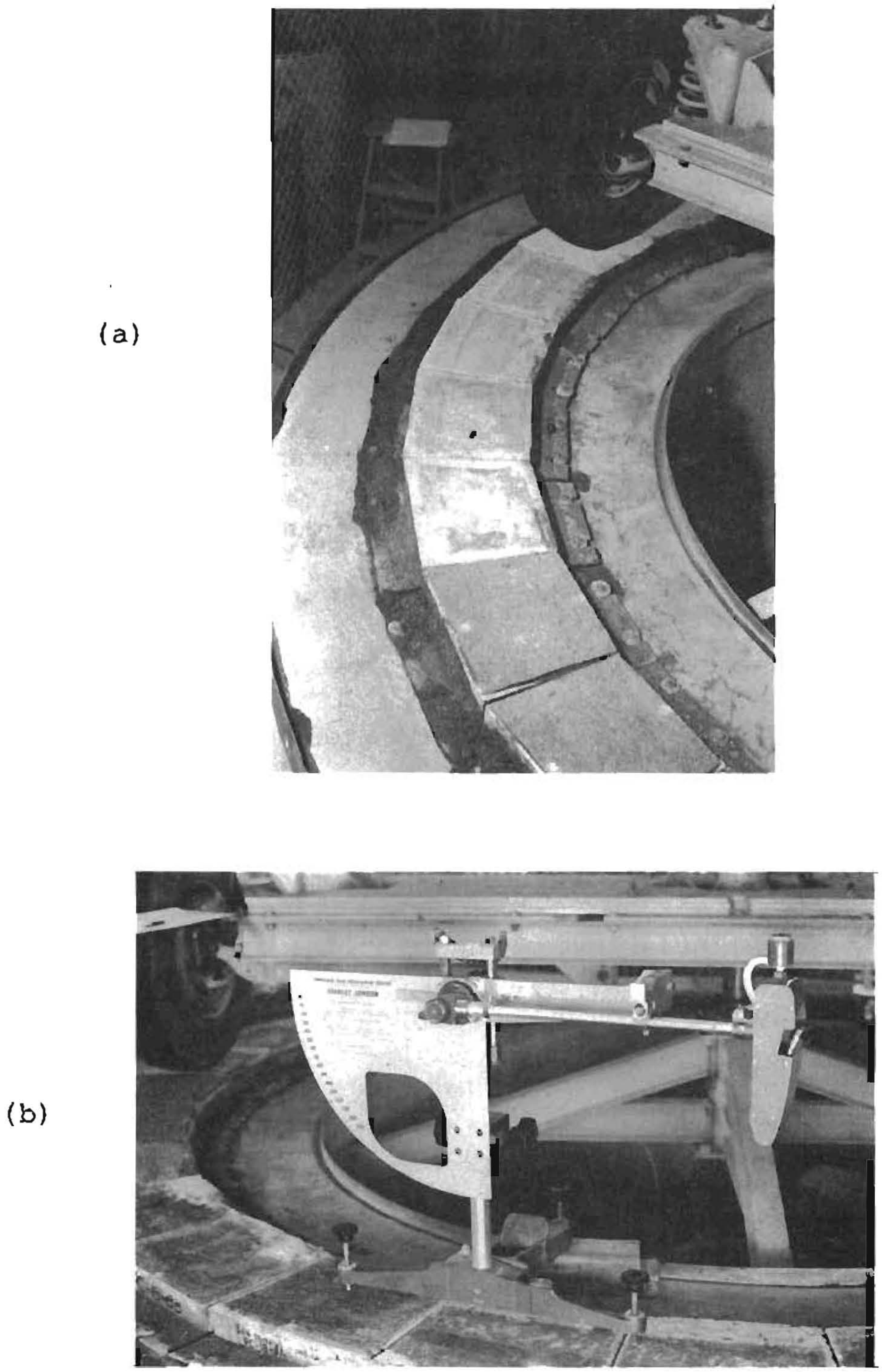

FIG. A.3 SIMULATED VEHICULAR LOADING WEAR TRACK FACILITY

In order to determine the relative wear resistance of the specimens subjected to simulated vehicular wear, a linear potentiometer mounted on a portable track was used. This device is pictured during a test in Fig. A.4. The potentiometer track was supported on three pointed rods which in turn rested on three metal positioning tabs bonded to the concrete foundation at the sides of each test specimen. These three tabs were indented with a punch so that the potentiometer track could be accurately repositioned on them for depth of wear measurements at any time during the test period. Two reference tabs were also bonded to each test specimen near the edges and in the line of travel of the potentiometer probe as shown in Fig. A.4. These two tabs were used to provide a positive reference elevation throughout the entire test period in order to minimize any error which might result from vertical movement of test specimens.

During a typical initial test measurement, the track mounted potentiometer was carefully located on the positioning tabs, and the potentiometer probe was then aligned over one of the two reference tabs. The elevation of the tab was recorded to the nearest 0.001 in. by means of a digital volt meter, and the transverse position of the probe was recorded by use of the scale bonded to the side of the potentiometer mount as seen in Fig. A.4. The probe was then brought to a position just outside the wheel path, and the elevation of the specimen surface and the transverse location of the probe were determined as previously described. Surface elevations were taken in this manner at 0.03 ft intervals across the wheel path with the

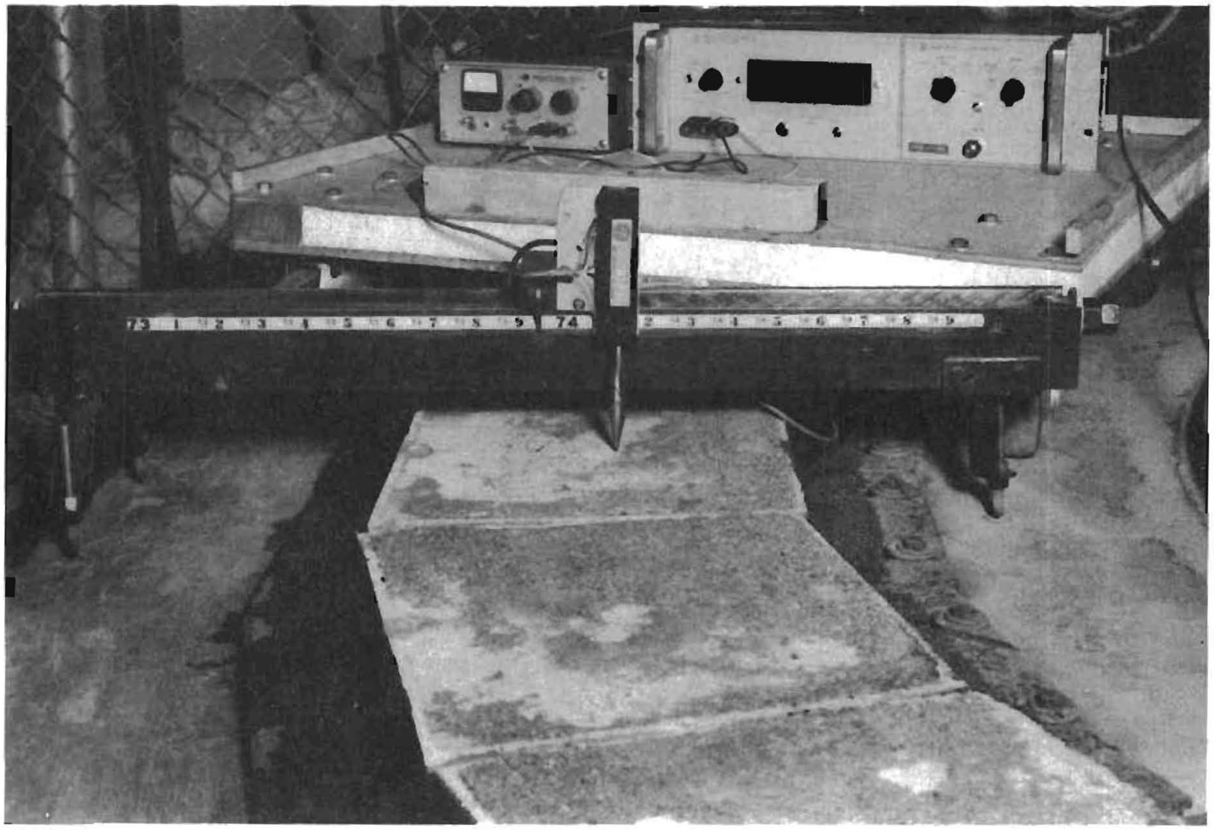

FIG. A.4 TRACK MOUNTED POTENTIOMETER FOR DETERMINING DEPTH OF WEAR last reading being just outside the wheel path. A final elevation was taken on the second reference tab to complete the measurements on a given specimen.

After a designated number of wheel loadings had been applied to the specimens, the test loading was interrupted while the potentiometer mount was repositioned, and probe readings were taken on the reference tabs and across the wheel path as previously described. In each case, the transverse position of the probe was adjusted to agree with that used in the initial test measurement. The data thus collected provided the maximum depth of wear, average depth of wear, and a means of calculating the wear profile area (X-section area of specimen worn away) at any time during the test period.

Calibration tests on the linear potentiometer showed the device to be accurate over the test range used. Ten repetitions across a typical transverse test span using a glass plate for the specimen surface indicated good reproducibility with a standard deviation of 0.0019 in. and a coefficient of variation of 0.42%. On numerous occasions, a second set of readings was taken on actual test specimens. These comparisons, which included any error resulting from remounting the potentiometer track on the positioning tabs, showed that the average difference in the readings was ±0.009 in. It was therefore concluded that the technique was sufficiently accurate for use in determining the relative wear resistance of the specimens in the wear track study.

A.3 Sandblast Abrasion Test

The abrasion resistance of surface treated and control concretes was determined by abrading cut sections of the specimens in accordance with the procedures given in ASTM C 418-67T. The apparatus used for sandblasting the specimens is shown in Fig. A.5(a).

Initially the entire standard test method including procedure for calculating abraded volume was followed. However, it was later determined that the standard method for calculating abraded volume was not valid for the polymer treated concretes of this study. This problem resulted from the non-uniform nature of the impregnated concrete in the abrasion zone. For example, a typical sandblast specimen may consist of a non-impregnated lower zone, a shallow zone of impregnated concrete and a shallow evaporation zone of non-impregnated concrete at the surface. As a result, the specific gravity of the specimen is variable in the test zone, and the abraded volume cannot be correctly calculated by the equations given in ASTM C 418.

A practical solution to this problem was found in what is termed the "modified clay filler method." The method was patterned after an ASTM Standard Method of Test presently being developed by a committee of ASTM C15 for use in evaluating floor and patio brick.

The method finally selected for use in evaluating the specimens of this study consisted of sandblasting the surfaces in accordance with ASTM C 418 and then determining the abraded volume by filling the abrasion cavities with modeling clay. By determining the specific gravity of the clay

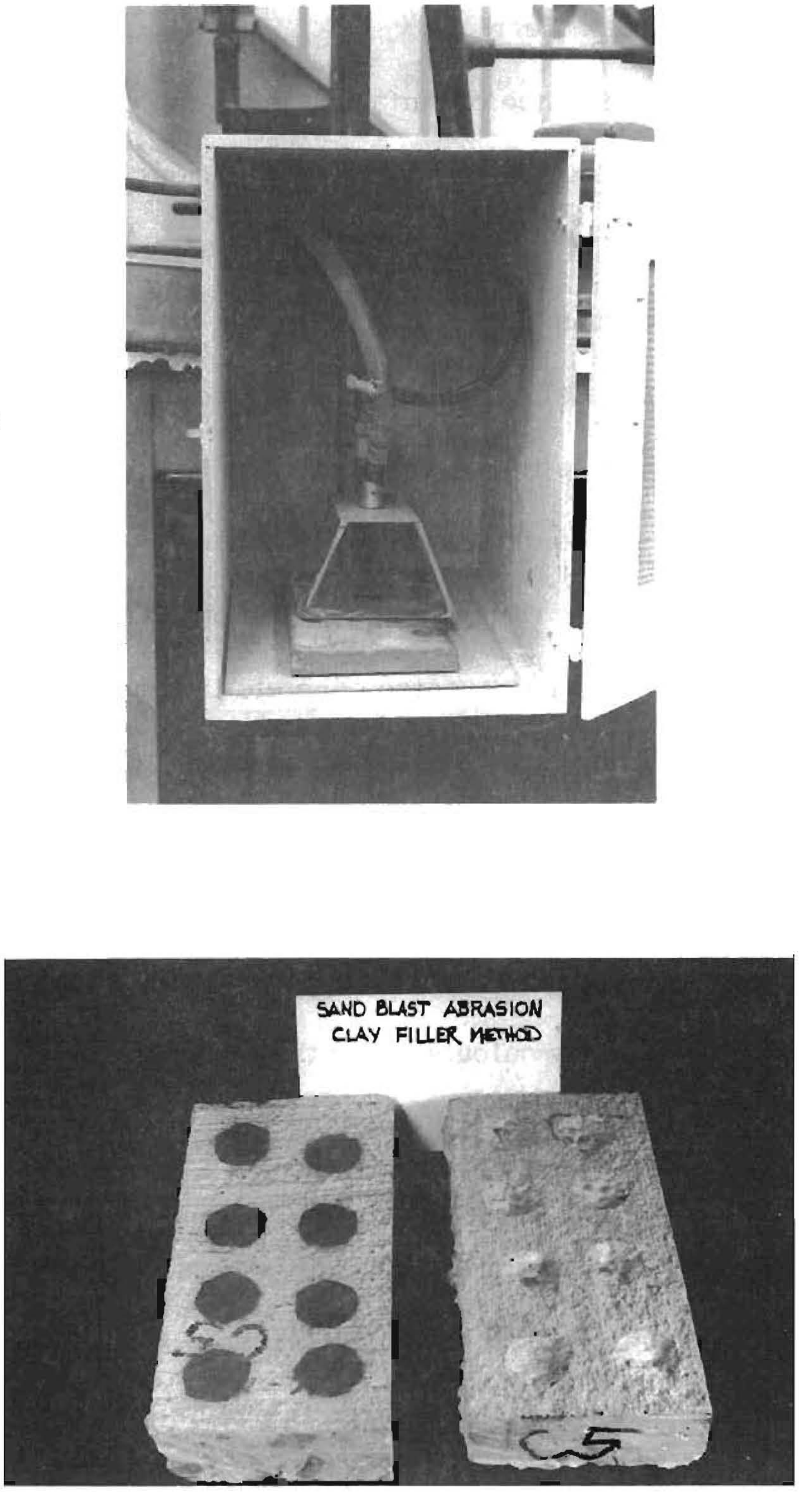

FIG. A.5 SANDBLAST ABRASION TEST BY MODIFIED CLAY FILLER METHOD as well as the weight of clay used in filling the cavities, the volume of the cavities was easily computed. A photograph showing a comparison of clay filled and unfilled cavities on two specimens is given in Fig. A.5(b). To reduce experimental error in the determination of abraded volume, only one technician performed the task of pressing the clay into the test cavities of all specimens. Also, the weight of clay used during a given test was determined by weighing the clay supply before and after the cavities were filled instead of trying to remove the clay from the filled cavities for weight determination.

A.4 Concrete Ingredients and Mix Properties

Batch properties of all concretes mentioned in this report are given in Table A.1 and aggregate data is given in Table A.2. Except for mix PC-19X, all concretes were laboratory batched in 6 and 12-ft^3-capacity, revolving drum mixers. Mix PC-19X was furnished by a local transit mix company using the same source of aggregates that was utilized in preparing laboratory mixes. Every effort was made to prepare mixes with accurate water-cement ratio and cement factor, and corrections for moisture content of stock-pile aggregates were determined for each batch. For mix PC-19X the aggregate moisture content was determined by electronic meter and supplied by the transit mix company. Type I portland cement was used in all mixes.

All tests on fresh concrete as well as preparation of test specimens followed ASTM recommendations. Specific methods used were: ASTM C 143 (slump test), ASTM C 192 (preparation of control test specimens), and

TABLE A.1 CONCRETE BATCH PROPERTIES

Batch No.	Treated Specimen Type	Specimen Dimensions, in.	Water-Cement Ratio, gal/sk	Cement Factor, sk/yd^3	Slump, in.	Air Content, %	Control Compressive Strength, psi[a]
PC-19X	field treatment slabs	5½ x 40 x 43	5.5	5.9	3	1.2	6,400
PC-18	wear track slabs	2 thick[b]	6.5	5.9	6½	0.7	4,740
PC-3, 4, 6, 7, 10[c]	freeze-thaw slab	6 x 10 x 10	6.0	5.7	4 to 6	4 to 5.5	4,160 to 4,500
PC-12	freeze-thaw slab	6 x 10 x 10	6.5	6.0	5	1.0	5,170
PC-16	corrosion piles	3 x 3 x 46	6.5	6.0	6	1.5[d]	5,190
PC-30	fatigue beams	4 x 5½ x 60	8.2	4.5	1-3/4	1.5[d]	4,180

[a] 28 day moist cure, 6 in. x 12 in. cylinders

[b] trapezoidal plan dimensions of base = 13.5 and 11.5 in. and altitude = 11 in.

[c] these 5 air entrained concrete mixes were of the same mix proportioning

[d] non-air entrained concrete, estimated air content based on measurements from previous mixes

TABLE A.2 AGGREGATE PROPERTIES

(a total of four different shipments were used)

Source: Colorado River, Austin, Texas

Type: Primarily rounded, siliceous river aggregate

SSD Bulk Specific Gravity:

Coarse Aggregate: 2.54 to 2.59
Fine Aggregate: 2.58 to 2.61

Absorption:

Coarse Aggregate: 1.8 to 2.3
Fine Aggregate: 0.9 to 1.3

Sieve Analysis (by ASTM C 136):

Coarse Aggregate: all shipments met ASTM C 33, grade 67
Fine Aggregate: all shipments met ASTM C 33, with fineness moduli of 2.51 to 2.79

TABLE A.3

SIEVE ANALYSIS OF LIGHTWEIGHT FINE AGGREGATE[a]

Sieve Number	Cumulative Percent Retained
4	0.1
8	19.7
16	44.0
30	62.5
50	76.2
100	85.3
Pan	100.0

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[a] Produced by Featherlite Corp., Ranger, Texas, plant.

ASTM C 173 (air content by use of rollameter). Compression and split tensile tests were conducted in accordance with the provisions of ASTM C 39 and C 496.

A.5 Finishing and Curing Specimens

All slab specimens were consolidated by use of vibration and then brought to proper elevation with wood screeds. A final coarse texture was applied with a bristle broom one to two hours after screeding.

All slabs were cured by a standard procedure. Two to four hours after screeding the specimens were covered with one to two layers of wet burlap and one layer of polyethylene sheet. The covering was kept in place seven days, after which it was removed and specimens allowed to dry. No effort was made to maintain a specific temperature during curing. However, within the laboratory cast specimens and within the field cast specimens, curing temperatures were reasonably consistent.

All cylinder specimens used for subsequent polymer impregnation as well as those used for companion control were steel trowled and cured with the slab specimens overnight. They were then placed in a moist room at 73 ± 3°F for the remainder of a seven day period. All mix control cylinder specimens were kept in the moist room for a period of 28 days before testing. Three specimens were used to determine each test value for treated as well as control properties.

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