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An Investigation Into the Use of Polymer-Concrete for Rapid Repair of Airfield Pavements

AIR FORCE INSTITUTE OF TECHNOLOGY
WRIGHT-PATTERSON AFB, OH 45433

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An investigation of a high-strength, fast setting mixture of methyl methacrylate and dry aggregate was conducted. The resulting polymer-concrete (PC) was very strong, durable, and bonded excellently to concrete. Tests were conducted to determine the variables affecting the polymerization time and strength of polymer-concrete. Field tests were conducted to interstate highways and a major airport taxiway which demonstrated the feasibility of making rapid polymer-concrete repairs at a reasonable cost. Laboratory tests of a 3-foot by 6-foot area repaired by PC and an individual PC slab under repeated

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loadings of simulated truck and aircraft traffic demonstrated the excellent strength and durability of the material. A cost analysis found the cost of monomer to be approximately $10/cubic foot for most repairs.

PREFACE

This report was prepared by the Air Force Institute of Technology (AFIT) for Detachment 1, Armament Development Test Center, Civil and Environmental Engineering Development Office, Tyndall Air Force Base, Florida, under job order 21042B27. This work was performed by Captain Michael T. McNerney as an AFIT student at the University of Texas at Austin for fulfillment of his master's thesis. This report summarizes work done between March and December 1977. Captain Raymond S. Rollings was the project officer.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS) where it will be available to the general public including foreign nations.

This technical report has been reviewed and is approved for publication.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

SECTION I
INTRODUCTION

1.1 BACKGROUND

Cracking, spalling, and pop-outs are common problems that are often seen in many airfield pavements. In the military, there is also a potential problem of bomb damage to pavements. The time that it takes to repair these pavements can be costly to the military during time of war. It is possible that some of the new materials in use today can satisfy the need for both routine repairs and emergency repairs in a few hours. This study is an investigation for the use of one such material, polymer-concrete, for the rapid repair of portland cement pavements.

The use of polymers in concrete in the United States began in 1965 at the Brookhaven National Laboratory (BNL) in Upton, New York, as a result of suggestions from the United States Bureau of Reclamation (USBR) in Denver, Colorado (References 1,2,3,4,5). This early work initially concentrated on bars of mortar and concrete cylinders soaked in monomer and then polymerized with radiation. The increased strength and durability of the impregnated specimens has suggested additional research to develop applications to utilize these properties.

1.2 PREVIOUS RESEARCH

In addition to the research performed by BNL and USBR, several federal and state agencies are currently performing research in concrete-polymer materials. The Federal Highway Administration (FHWA) has published some information and is currently working on the use of polymer-concrete as a highway patching material (Reference 6).

The Center for Highway Research (CFHR), at the University of Texas, funded by the Texas Department of Highways and Public Transportation, has performed considerable research into highway applications of concrete-polymer materials (References 7,8,9,10). Recent studies have shown that polymer-concrete materials can repair wide cracks in concrete (References 11,12). The CFHR has made several repairs of bridge decks in Texas using polymer-concrete.

1.3 SCOPE OF THESIS

The primary purpose of this thesis is to conduct a pilot study to develop monomer systems, investigate the behavior and evaluate the performance of polymer-concrete as a rapid repair material for highway and airfield pavements. The secondary purpose is to evaluate the performance of polymer-concrete to adequately fulfill the needs of the United States Air Force as a rapid repair material for bomb damaged runways.

The relationship of the variables that affect strength as well as repair time will be discussed. Several field tests will be discussed also. Criteria will be developed and evaluation of the materials performance presented.

Section II describes the material, typical repair processes, and basic laboratory tests for material testing.

Section III lists and describes the major variables that affect the setting time of the material.

Section IV describes the major variables that affect the strength of the material.

Section V describes a laboratory test of two polymer-concrete repaired slabs under dynamic loading conditions. It also discusses the results and analyses of the tests.

Section VI describes some of the field tests which were carried out during the course of this research.

Section VII is an analysis of both the laboratory and field tests which permits the evaluation of the material.

Section VIII discusses the costs, storage, and safety requirements of the material. It also discusses the advantages and applications of the material.

Section IX presents the conclusions and recommendations for future studies.

SECTION II

POLYMER-CONCRETE MATERIALS

This section explains the different types of concrete-polymer materials and the chemical composition of polymer-concrete. Also discussed are the methods for making and testing polymer-concrete.

2.1 TYPES OF MATERIALS

There are basically three distinct types of concrete-polymer materials that are under investigation today.

(1) Polymer-impregnated concrete (PIC)

(2) Polymer-concrete (PC)

(3) Polymer-portland cement concrete (PPCC)

Polymer-impregnated concrete (PIC) is produced by filling the voids in portland cement concrete with polymer. To accomplish this the concrete to be impregnated is thoroughly dried to remove all moisture, soaked with liquid monomer, and then polymerized using heat, radiation or promoter-catalytic reaction. PIC exhibits very significant improvements in strengths, durability, and water impermeability (References 1,2,3,4,5). This has brought PIC out of the laboratory and into commercial use, such as the treating of new bridge decks in Texas (Reference 13).

Polymer-concrete (PC) is made by mixing dry aggregate and a monomer system together. The monomer system is then polymerized by heat or promoter-catalytic reaction. The resulting composite is a strong, durable material which uses the polymer to bond the aggregate together without using water or portland cement.

Polymer-portland cement concrete (PPCC) is a formulation which uses a normal concrete mix of water, portland cement, and aggregate, but replaces some of the water with monomer or polymer during the mixing. The materials are subsequently cured and polymerized in place. This material is the most desirable due to its simplicity, but due to the incompatibility of water and most monomers, it has been the least successful.

2.2 CHEMICALS

The following is a partial list of the chemicals used in this study. For more detailed information see Appendix A.

2.2.1 Monomers

Methyl-methacrylate (MMA) is a clear liquid monomer used in the making of Plexiglas and Lucite^R. MMA is the primary ingredient in all formulations studied in this investigation.

Butyl acrylate (BA) is a liquid monomer sometimes added to increase ductility to polymer-concrete.

Trimethylolpropane trimethacrylate (TMPTMA) is a cross-linking agent which is sometimes added to the monomer system.

Silane coupling agent is a liquid monomer sometimes added to improve the strength of polymer-concrete.

2.2.2 Initiators

Benzoyl peroxide (BP) is a very active initiator used for promoter-catalytic initiation of the polymerization process. This agent is commercially available in three forms: powder, 50 percent powder, and 50 percent paste.

Lauroyl peroxide (LP) is a powdered initiator which is not as active as BP.

2.2.3 Promoters

Dimethyl-p-toluidine (DMPT) is a highly active chemical which is used as a promoter; it helps promote the promoter-catalytic process of polymerization.

Dimethyl aniline (DMA) is also a promoter used in the promoter-catalytic process of polymerization, but it is not as active as DMPT.

2.3 METHODS OF APPLICATION

The typical methods of applying polymer-concrete differ only in the mixing and placing process. However, the sequence and actual method used has a direct bearing on the strength of the material. In all methods, the monomer formulation must be mixed together. A typical formulation would be:

Chemicals	Percent by Weight	
MMA	95	100 percent monomers
TMPTMA	5	
LP	3	
DMPT	1-1/2	

In this report, the standard convention is to express the monomer as 100 percent and to express the initiator and promoter as a percentage of the monomer weight.

The method of mixing used most often in this study was to first dissolve the initiator in the measured amount of monomer, MMA. Then the additional monomers were added after the initiator was dissolved. The promoter was added last. The mold or repair was partially filled with dry aggregate, then the monomer system was poured into the aggregate The PC mixture was then rodded or vibrated. This process was repeated until the mold or repair was filled, and the monomer was added until the aggregate was saturated. The PC was troweled smooth and allowed to polymerize, at ambient temperature, due to the promoter-catalytic process.

Brookhaven National Laboratory has had excellent results by mixing the monomers and aggregate in concrete mixers before placing into the molds. Due to safety considerations the concrete mixer must have spark-proof blades and an explosion-proof motor.

2.4 METHODS OF MATERIAL TESTING

2.4.1 Compressive Strength and Modulus of Elasticity

The test for compressive strength was ASTM C39-72: "Compressive Strength of Cylindrical Concrete Specimens". For this test, the specimens used were 3 x 6 inches or 6 x 12 inches.

After casting, the ends were checked for squareness and trimmed with a diamond-bladed saw. Some specimens were also capped with molten sulfur to improve the smoothness and reduce the possibility of eccentric loading. The specimen was loaded along its longitudinal axis at a uniform rate to avoid any dynamic effects (Figure 1). The highest load reached by the specimen before it failed was divided by the cross sectional area of the specimen to determine the ultimate compressive stress.

The test for modulus of elasticity was ASTM C469-65: "Static Modulus of Elasticity of Concrete in Compression". This test was the same as the compressive strength test except that a

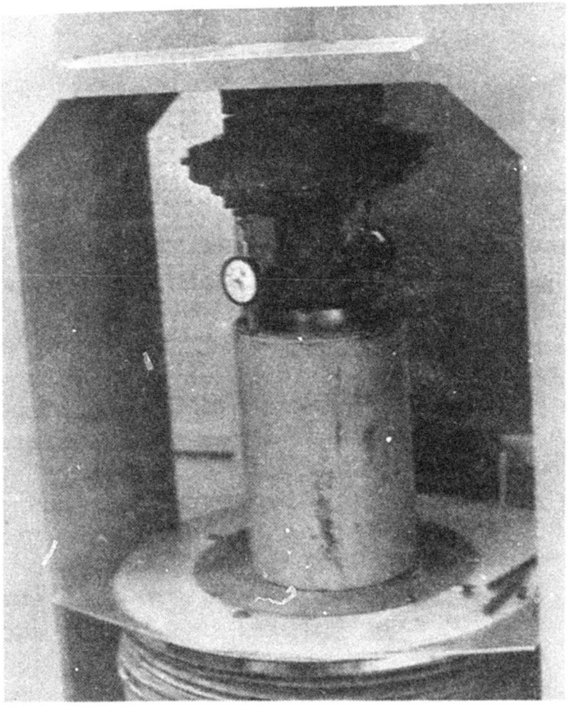


Figure 1. Compression Strength of Modulus of Elasticity Tests

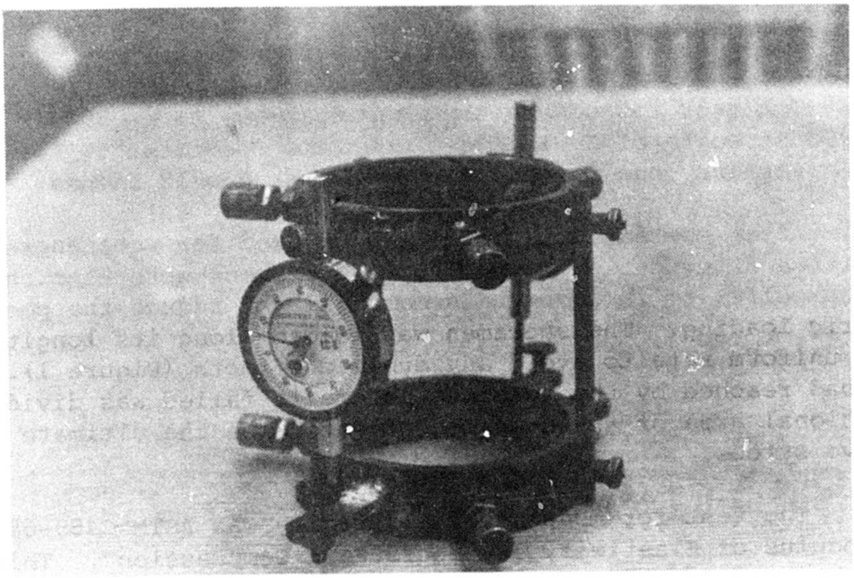


Figure 2. Compressometer

compressometer was fastened to the cylinder to read the compression of the specimen under load (Figure 2). The compressometer had two dial gages, on opposite sides of the cylinder, to read the vertical deformations of the specimen in gage lengths of 4 or 10 inches (Figure 3). The average gage reading was divided by the gage length to obtain the strain of the specimen in inches/inch. The compressive stress was plotted versus the strain to obtain the modulus of elasticity, using the secant modulus of the strain at 50 percent of the ultimate compressive strength.

2.4.2 Test for Splitting Tensile Stength

The test for splitting tensile strength was ASTM C496-71: "Splitting Tensile Strength of Cylindrical Concrete Specimens". The specimens were 3 x 6 inch cylinders. A strip of 1 inch wide by 1/8 inch thick plywood was placed longitudinally along the top and along the bottom of the cylindrical specimen. The specimen was carefully placed on its side such that the loading frame was centered directly above the center of the cylinder. The load was applied at a uniform rate until failure. The highest load was then used to compute the splitting tensile stress in the specimen according to the formula:

$$f_t = \frac{2P}{\Pi DL}$$

where P = maximum load

D = diameter of specimen

L = length of specimen

2.4.3 Test for Flexure Strength

The test used to determine flexural strength was adopted from ASTM C78-64: "Standard Method of Test for Flexural Strength of Concrete (Using Simple Beams with Third Point Loading)". The test specimens were prisms measuring 3 x 3 x 16 inches. The apparatus included a loading block, which provided two concentrated loads 4 inches apart and a bearing plate, which provided two knife-edge supports with a 12-inch clear span. The specimen was centered on the bearing platform providing 2-inch overhang on each side of the supports. The loading block was then centered on the top of the specimen so that equal loads were applied at the third points of the 12-inch span (Figure 4). Once the specimen and apparatus were properly aligned, load was applied at a uniform rate to avoid dynamic effects. The specimen was loaded to failure and the maximum load was recorded. The modulus of rupture was calculated by:

$$f_r = \frac{Mc}{I}$$

where M is the moment at maximum load.

c is the distance from the neutral axis to the extreme fiber.

I is the moment of inertia.

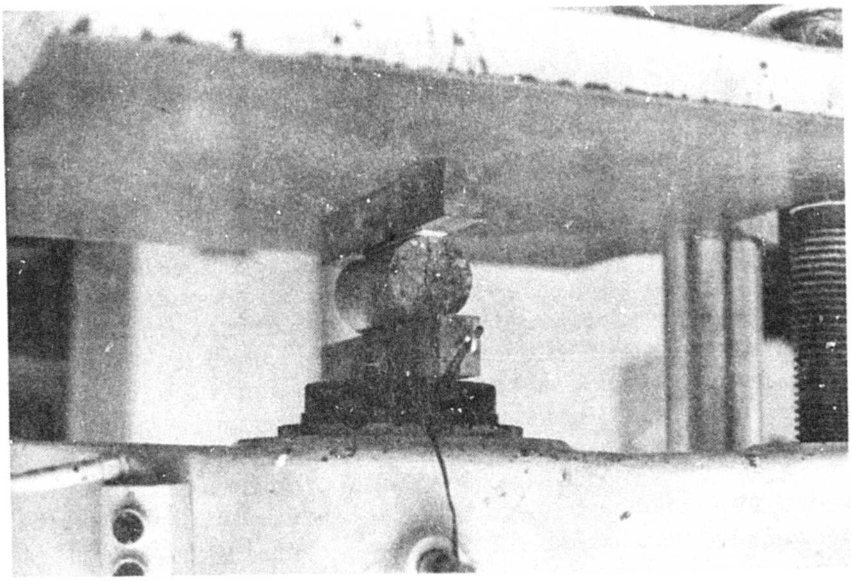


Figure 3. Splitting Tensile Strength Test

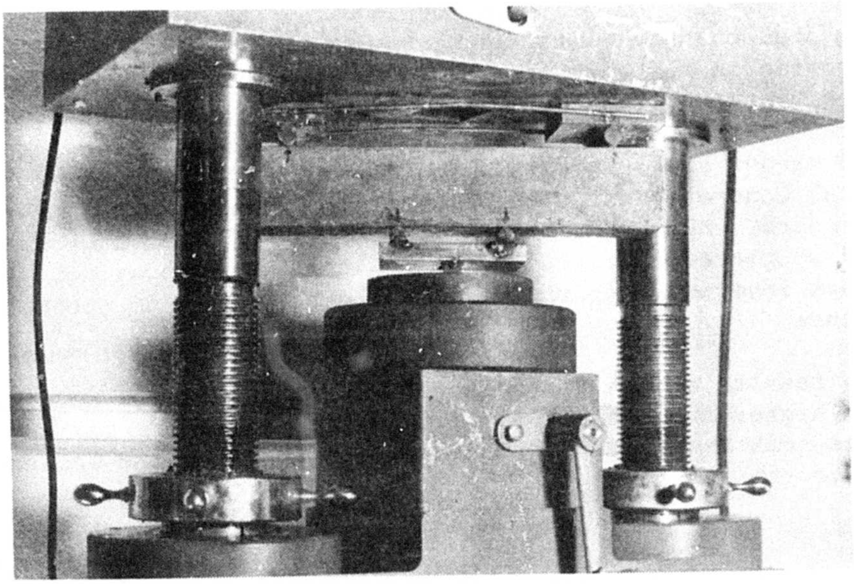


Figure 4. Modulus of Rupture Test

SECTION III
VARIABLES AFFECTING POLYMERIZATION TIME

Polymer-concrete is made from a chemical reaction that produces polymerization. In order to specify the rapidity of repair, all the variables that affect polymerization time must be identified. This chapter identifies the major variables that affect polymerization time and the relative effect of each.

3.1 AMBIENT TEMPERATURE EFFECTS

Ambient temperature has one of the most significant effects on the time that it takes polymer-concrete to harden. A typical batch of polymer-concrete that is promoter-catalytic polymerized generates heat. In most cases, it is possible to monitor the temperature of the promoter-catalytic reaction and determine when polymerization has occurred. A typical plot of temperature versus time is shown in Figure 5. There are several factors which affect the shape and time required to reach peak temperature. As a general rule, when polymer-concrete has reached peak temperature the reaction is essentially complete. As the polymer-concrete cools, it hardens and reaches it maximum strength. Because polymer-concrete does not significantly increase in strength with time, as in the hydration process of concrete, the time to reach maximum temperature is referred to as set time rather than cure time.

A laboratory test was made to verify the effects of ambient temperature on set time. The experiment consisted of placing the monomer and aggregate in an environmental chamber where the ambient temperature could be regulated. After the monomer and aggregate had reached the temperature of the chamber, the monomer components were mixed in the environmental chamber. Standard concrete test cylinders, 3 x 6 inches, were prepared in the chamber. In each case, special care was taken to insure that the gradation and moisture content of the aggregate was kept constant. Care was also taken to prepare the cylinders in a standard manner and in general conformance with ASTM C192-69: "Making and Curing Concrete Test Specimens in the Laboratory." In preparing the cylinders, the mixed monomer was used to wet the aggregate so that it could be placed into the cylinders without segregating. A thermocouple was inserted into the polymer-concrete cylinder to monitor the temperature.

The results of the tests showed conclusively, for all formulations, that the higher the ambient temperature the less time was required to reach the peak temperature. Conversely, the lower the ambient temperature, the longer the set time.

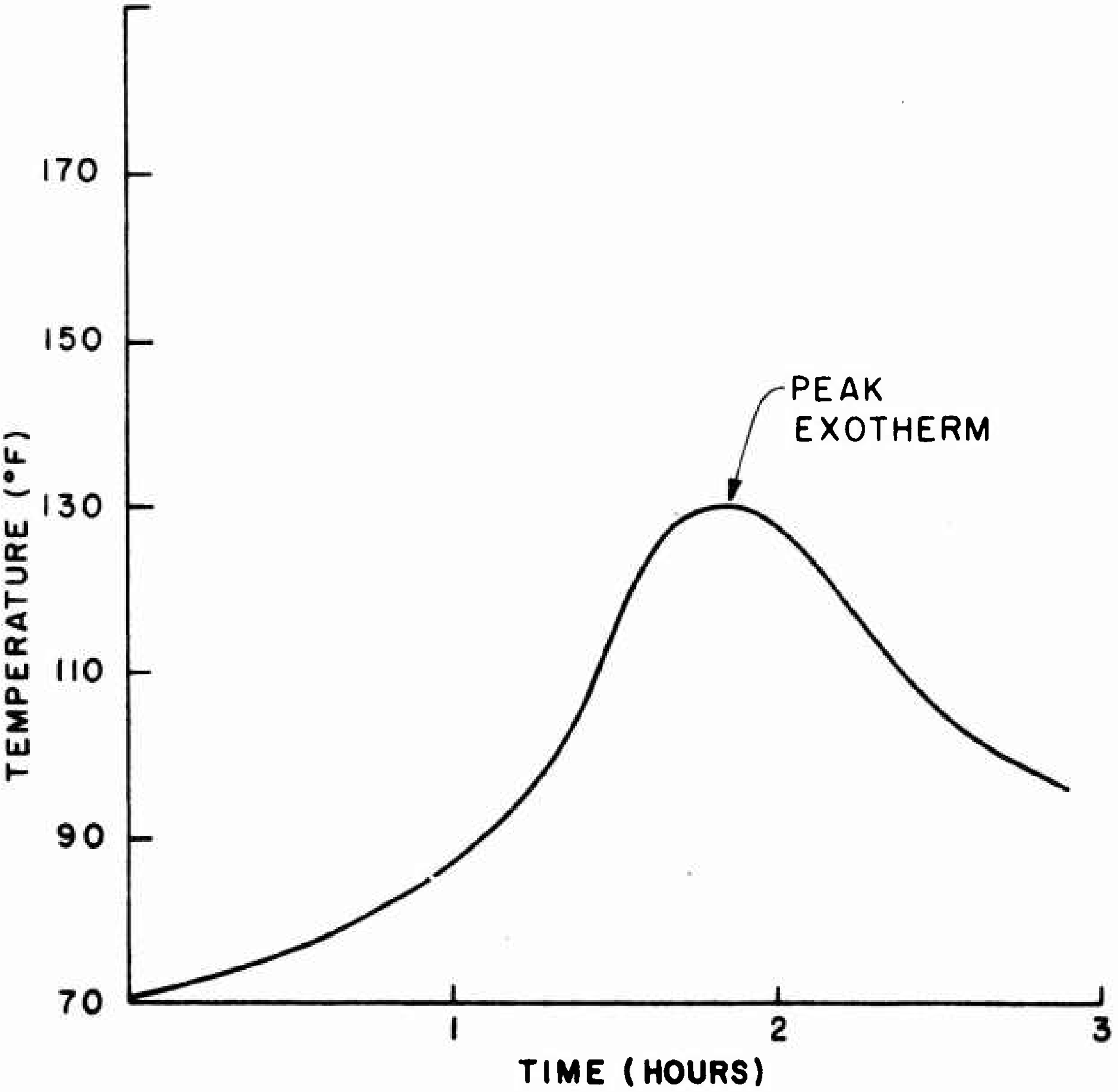


Figure 5. Typical Time Temperature Curve for PC

The tests also showed that the effect of ambient temperature on set time is exponential. Figure 6 shows that a formulation takes only 14 minutes to set at 75°F. If the ambient temperature is reduced to 50°F the set time is doubled to 28 minutes. If the ambient temperature is reduced to 25°F, the set time is more than doubled again to 65 minutes. This formulation was successfully polymerized at -30°F but the set time was approximately 10 hours.

In another example of ambient temperature effects, the same formula was mixed in two different ways. In both cases the aggregate and monomer were placed into the environmental chamber at -30°F to cool. In one case, with the MMA temperature of 25°F, the cylinders were prepared outside the environmental chamber at 70°F and approximately 9 minutes later placed into the -30°F chamber. In the second case, with the MMA temperature of -18°F, the cylinders were prepared inside the chamber. The set time for the first case was only 90 minutes, while the set time for the second case was approximately 10 hours.

The effect of aggregate and monomer temperature is a factor on set time. However, for most pavement applications, the temperatures of the aggregate and monomer are expected to be near ambient temperature. For this reason, no tests were performed to determine the effects of aggregate and monomer temperatures independent of ambient temperature.

3.2 CHEMICAL COMPOSITION

There are several ways that the mixture of monomers or aggregate can affect the set time for polymer-concrete. The most obvious and the most useful is by varying the amounts of initiator and promoter concentrations.

3.2.1 Initiator and Promoter Concentrations

Initiators and promoters are used in promoter-catalytic polymerization to produce heat. Therefore, it is logical that the more initiator and promoter used, the hotter the peak temperature as well as a faster polymerization rate. Generally this is true; however, there are limits to these effects. If the proportion of promoter and initiator are out of balance, the resulting polymerization may be incomplete with zones of unpolymerized material (Reference 11).

Tests were made by Tiffany at the University of Texas on small samples of sand and methyl-methacrylate in test tubes in which the percentage by weight of the initiator and promoter was measured and the time required to reach maximum temperature was recorded as set time (Table 1).

By selectively using initiator and promoter concentrations, the effects of ambient temperature on set time can be counteracted.

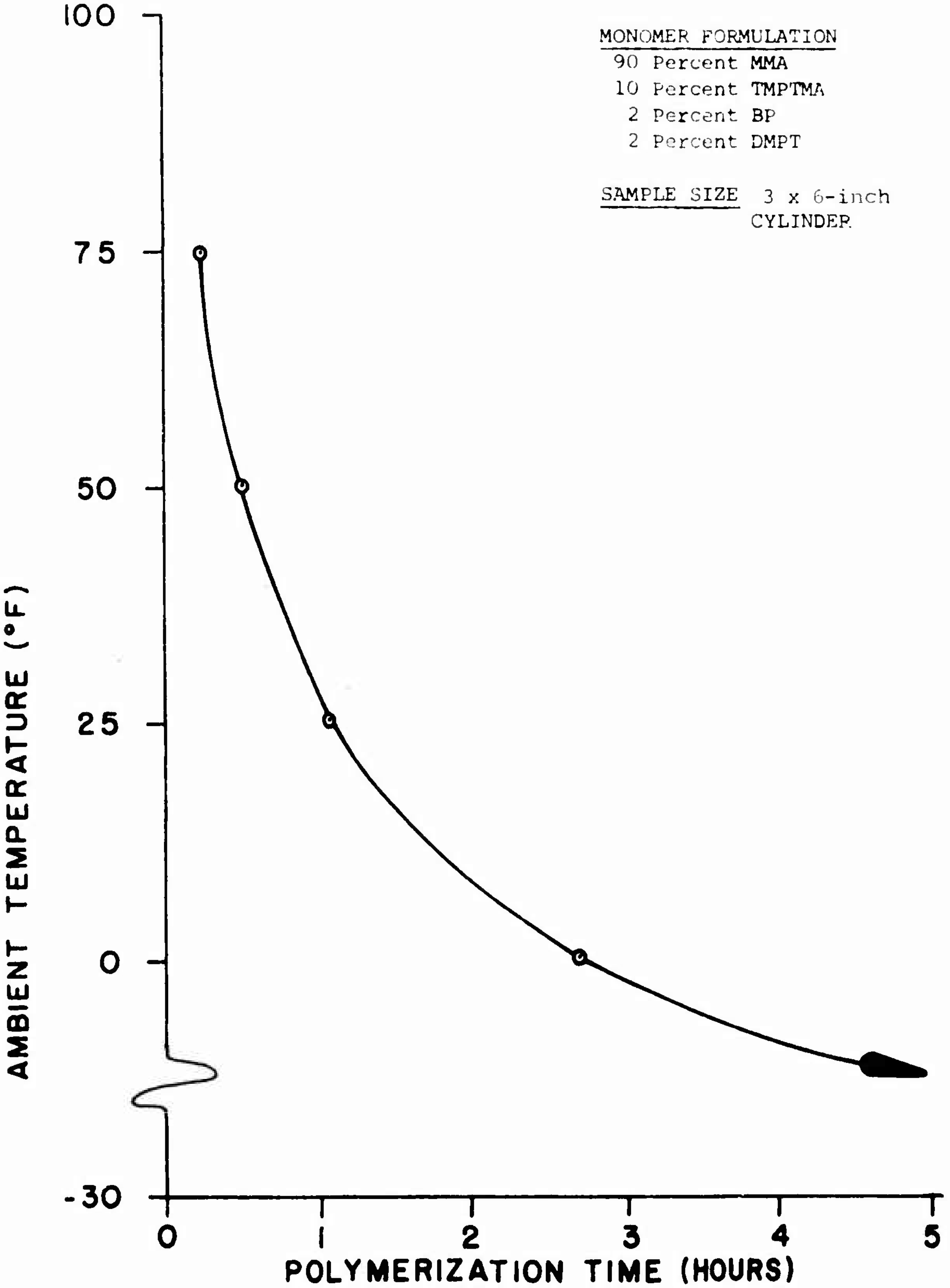


Figure 6. Effects of Ambient Temperature on Polymerization Time

TABLE 1. POLYMERIZATION TIME OF MMA WITH LP INITIATOR AND DMPT PROMOTER

SAMPLE SIZE 10 grams

AMBIENT TEMP 80°F

TIME: HOURS + MINUTES

PERCENT LP BY WEIGHT

6%	1+22	0+58	0+48	0+41
5%	1+30	1+03	1+10	0+53
4%	1+57	1+16	1+00	0+54
	2%	3%	4%	5%

PERCENT DMPT BY WEIGHT

For example, a typical formulation consisting of 95 percent MMA, 5 percent TMPTMA, 4 percent LP, and 2 percent DMPT takes approximately 1 hour and 30 minutes to set at 75°F. The same formulation only takes 23 minutes at 100°F ambient temperature. If the LP and DMPT are reduced to 3 and 1-1/2 percent, respectively, the set time is delayed an additional 15 minutes at 75°F and an additional 10 minutes at 100°F. It is possible to arrive at the desired set times for various ambient temperatures by varying the initiator and promoter concentrations (Table 2).

3.2.2 Cross-Linking Agent

The addition of trimethylolpropane trimethacrylate (TMPTMA) as a cross-linking agent will increase the polymerization rate. When polymers react, they chemically form long chains. When a cross-linking agent is added this permits free molecules to attach at points in the chain other than the end, and increase the rate of polymerization. Previous work at the University of Texas has confirmed the increase in polymerization rate with an increase in TMPTMA (Figure 7) (Reference 7).

3.2.3 Silane Coupling Agent

The purpose of adding silane coupling agent to the formulation is primarily to add strength by increasing the bond between the polymer and siliceous aggregate. Tests of polymer-concrete, with silane coupling agent, showed that 1 percent silane added to the formulation of 95 percent MMA, 5 percent TMPTMA, 3 percent LP and 1-1/2 percent DMPT, increased the set time from 1 hour 15 minutes to 1 hour 32 minutes at ambient temperature of 75°F.

3.2.4 Aggregate Gradation

The aggregate gradation not only affects the strength of polymer-concrete but also affects the set time. Aggregate acts like a heat sink during polymerization, and the higher the aggregate-to-monomer ratio, the slower the polymerization rate. If there were no aggregate, just monomer, the mixture would set much faster; this time is called the "pot life" of the mixture. Generally, the pot life of a formulation of polymer-concrete that would set in 90 minutes, would be about 60 minutes for the monomer alone. The pot life varies with ambient conditions and the presence of oxygen. A well-graded aggregate with a smaller percentage of voids requiring a smaller amount of monomer sets more slowly, and develops a lower exotherm temperature.

3.3 INHIBITOR CONCENTRATIONS

Methyl methacrylate is chemically inhibited with either methyl ether of hydroquinone (MEHQ) or hydroquinone (HQ) which require the presence of dissolved oxygen to be effective, MMA can be purchased from the supplier at inhibitor concentrations ranging from 10 to 100 ppm. The more

TABLE 2. POLYMERIZATION TIMES OF POLYMER-CONCRETE

Formulations (Percent)	Ambient Temperature -30°F	0°F	25°F	50°F	75°F	100°F
97.5 MMA 2.5 TMPTMA 2 LP 1 DMPT						0+55*
95 MMA 5 TMPTMA 3 LP 1½ DMPT					1+45	0+33*
95 MMA 5 TMPTMA 4 LP 2 DMPT					1+30	0+23*
90 MMA 10 TMPTMA 4 LP 2 DMPT				2+00	0+55	
95 MMA 5 TMPTMA 1½ BP 1 DMA ½ DMPT				1+25	1+05	
90 MMA 10 TMPTMA 1½ BP 1 DMA ½ DMPT				0+50	0+20	
90 MMA 10 TMPTMA 2 BP 2 DMPT	Approx 10 hrs	2+45	1+05	0+28	0+14	
90 MMA 10 TMPTMA 3 BP 2 DMPT		1+47				
90 MMA 10 TMPTMA 3 BP 3 DMPT	1+30					
3 x 6-inch cylinders *6 x 12-inch cylinders	TIME: HOURS + MINUTES					

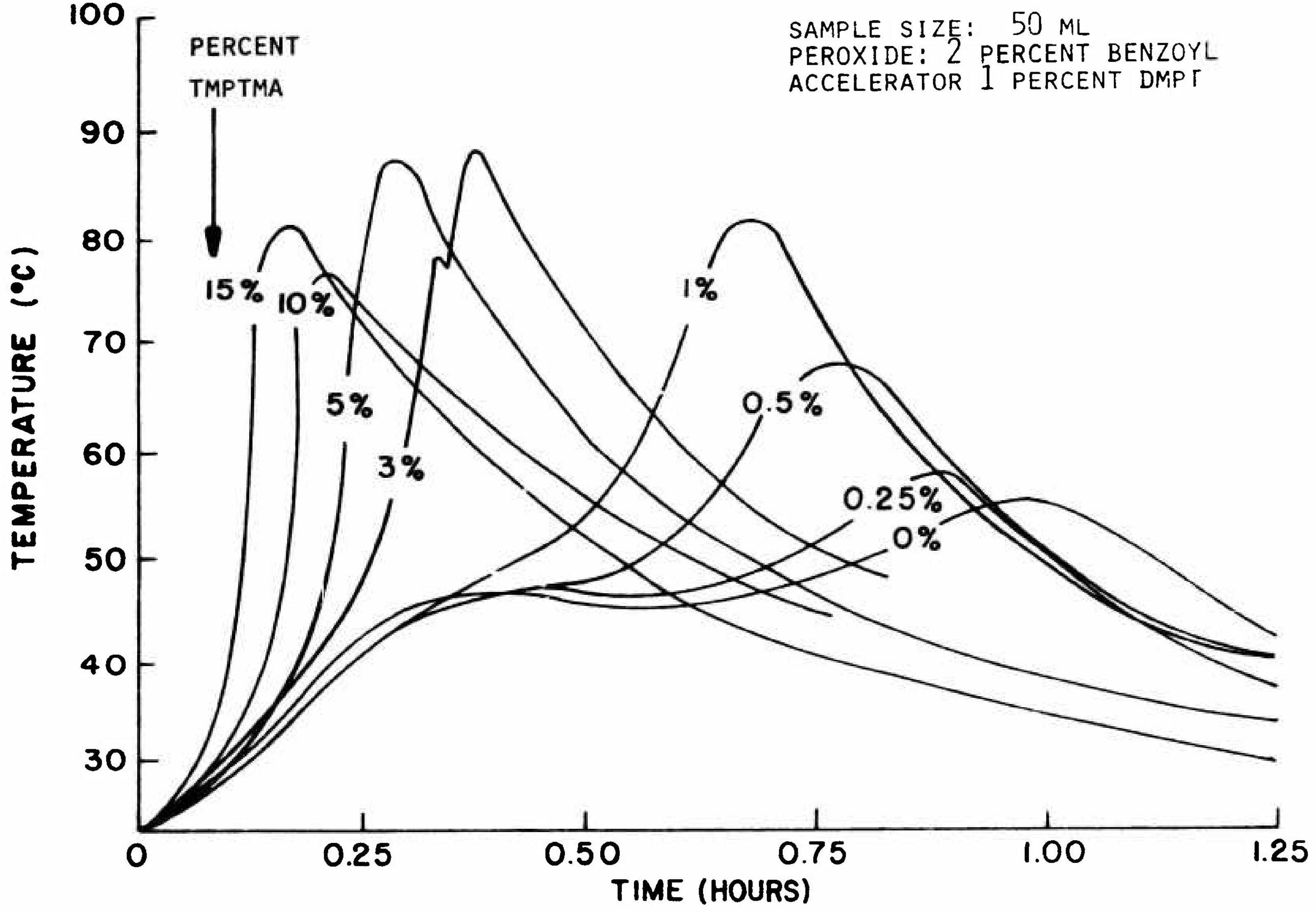


Figure 7. Effect of TMPTMA on Polymerization Time (Reference 15)

inhibitor the longer the shelf life. Inhibitor can also be added periodically to increase the shelf life. Figure 8 is a calibration curve used to determine the amount of inhibitor present in a sample of MMA (Reference 2). It also shows the effect of inhibitor concentration on polymerization time, measured by the peak exotherm method.

3.4 SAMPLE SIZE

The size of the polymer-concrete sample that is being polymerized affects the polymerization rate. A test was developed to determine the effects of varying depth on polymerization rate. Wooden box forms were constructed, 10-1/2 by 10-1/2 inches and 5-1/2 inches high. A monomer formulation that has been used in the field to repair highways was selected (90 percent MMA, 10 percent BA, 4 percent LP and 2 percent DMPT). The only variable was the depth of the polymer-concrete repair which was varied from 1-1/4 inches to 5-1/4 inches. Other variables such as ambient temperature, aggregate, and monomer formulation were all kept constant. The polymer-concrete was mixed and placed in the forms, and a thermocouple was inserted to record the temperatue with respect to time. The results in Figure 9 show polymerization rate increased with the increasing depth.

One additional discovery was that a 3-3/4 inch depth specimen in which the monomer partially leaked from the forms was slower to polymerize than the others. Excessive leaking of the monomer in some of the field tests which required additional monomer also tended to slow the polymerization rate. From field tests of polymer-concrete repairs as large as 2 cubic yards its seems that very large PC repairs can be made successfully.

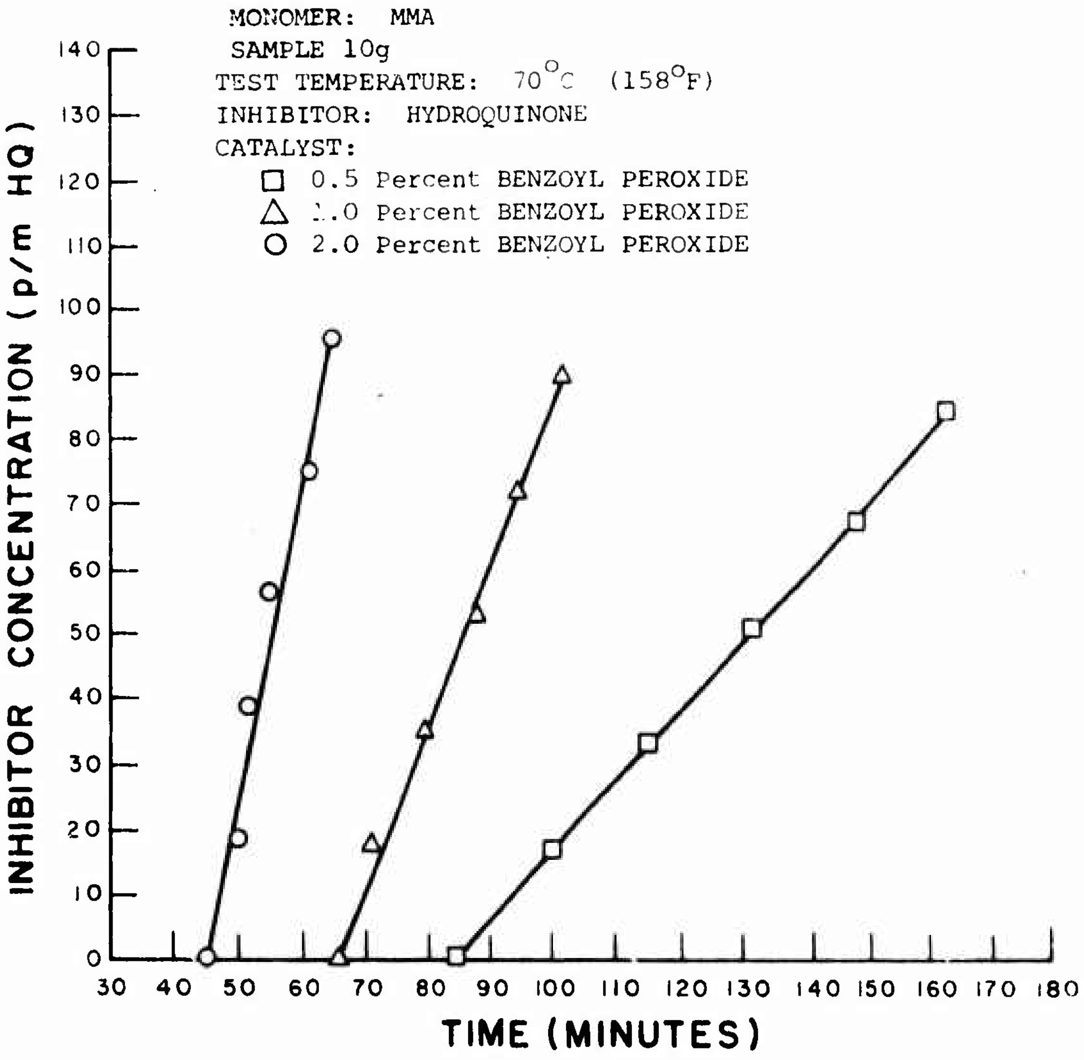


Figure 8. Effect of Inhibitor Concentration on Polymerization Time

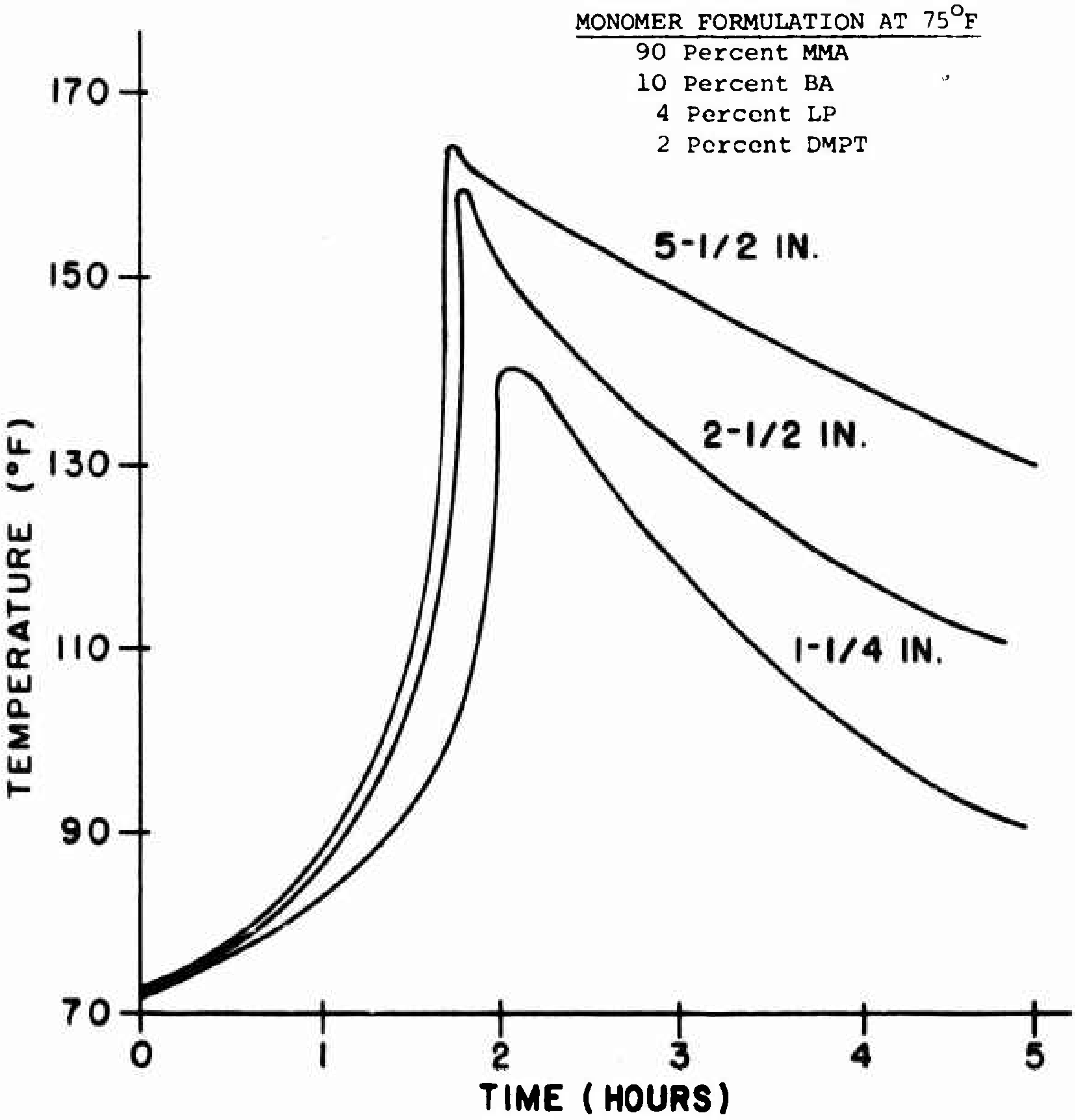


Figure 9. Effects of Repair Depth on Polymerization Time

SECTION IV
VARIABLES AFFECTING STRENGTH

This section discusses the major variables that can be controlled or must be considered by the user of polymer-concrete. Specifically, this section will discuss the polymerization rate, chemical composition, the temperature at testing, and effects of aggregate in mix design.

4.1 POLYMERIZATION RATE

The polymerization rate affects the strength of PC. Generally, the faster the polymerization rate, the lower the strength. The PC cylinders from the test described in Section III were tested in compression at room temperature to define the relationship between strength and set time. The results of the compressive tests are plotted in Figure 10.

It is theorized that strength decreases with decreased set time because the monomer has less time to fill all the pores between the aggregate effectively and to penetrate into the aggregate. It is known that the monomer penetrates into existing concrete at an initial rate of 1/2 to 1 inch per hour depending on the density of the concrete (Reference 12). The penetration of the monomer into concrete is the reason for the excellent bond of PC to concrete, in constrast to relying on purely surface adhesion as in higher viscosity epoxy concretes. If the set time is reduced, the PC should have a reduction in bond and compressive strengths.

4.2 CHEMICAL COMPOSITION

4.2.1 Initiators

Two initiators, or catalysts, were used during this study: lauroyl peroxide (LP) and benzoyl peroxide (BP). BP is the more active initiator, meaning that it takes less time to polymerize monomers for a given amount of initiator. Because formulations with BP took less time to polymerize than with LP, the BP specimen seemed to develop lower compressive strength. When comparing BP-initiated specimens with respect to LP-initiated specimens with the same polymerization time, the data are insufficient to be conclusive.

4.2.2 Butyl Acrylate

Butyl acrylate (BA) is sometimes added to the monomer system to increase the ductility of polymer-concrete (Reference 14). The resulting ductility is achieved by a lower modulus of elasticity and lower compressive strength (Figure 11).

4.2.3 Trimethylolpropane Trimethacrylate

Trimethylolpropane trimethacrylate (TMPTMA) is a cross-linking agent which is used in the monomer formulation for several

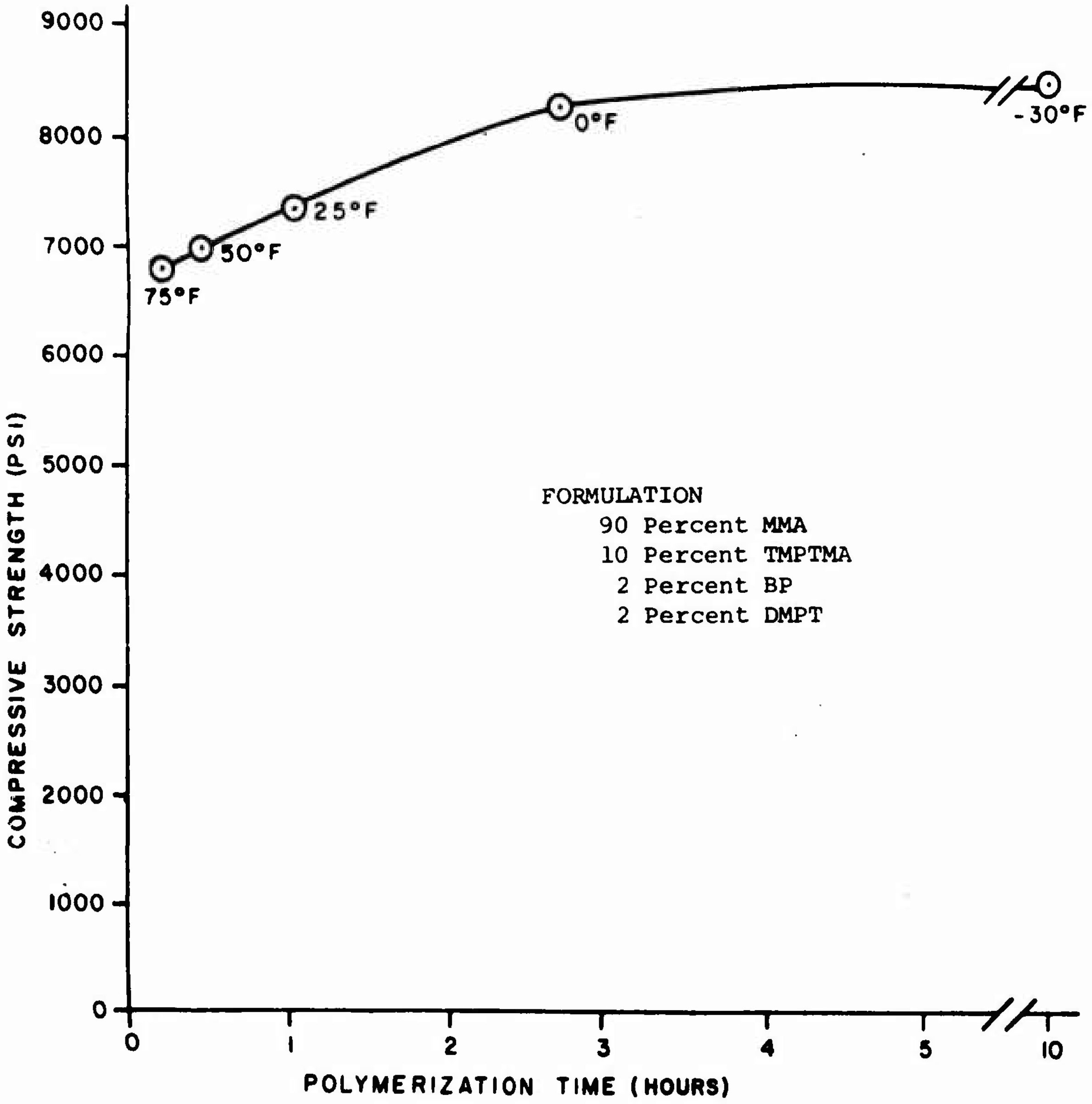


Figure 10. Effect of Polymerization Time on Compressive Strength

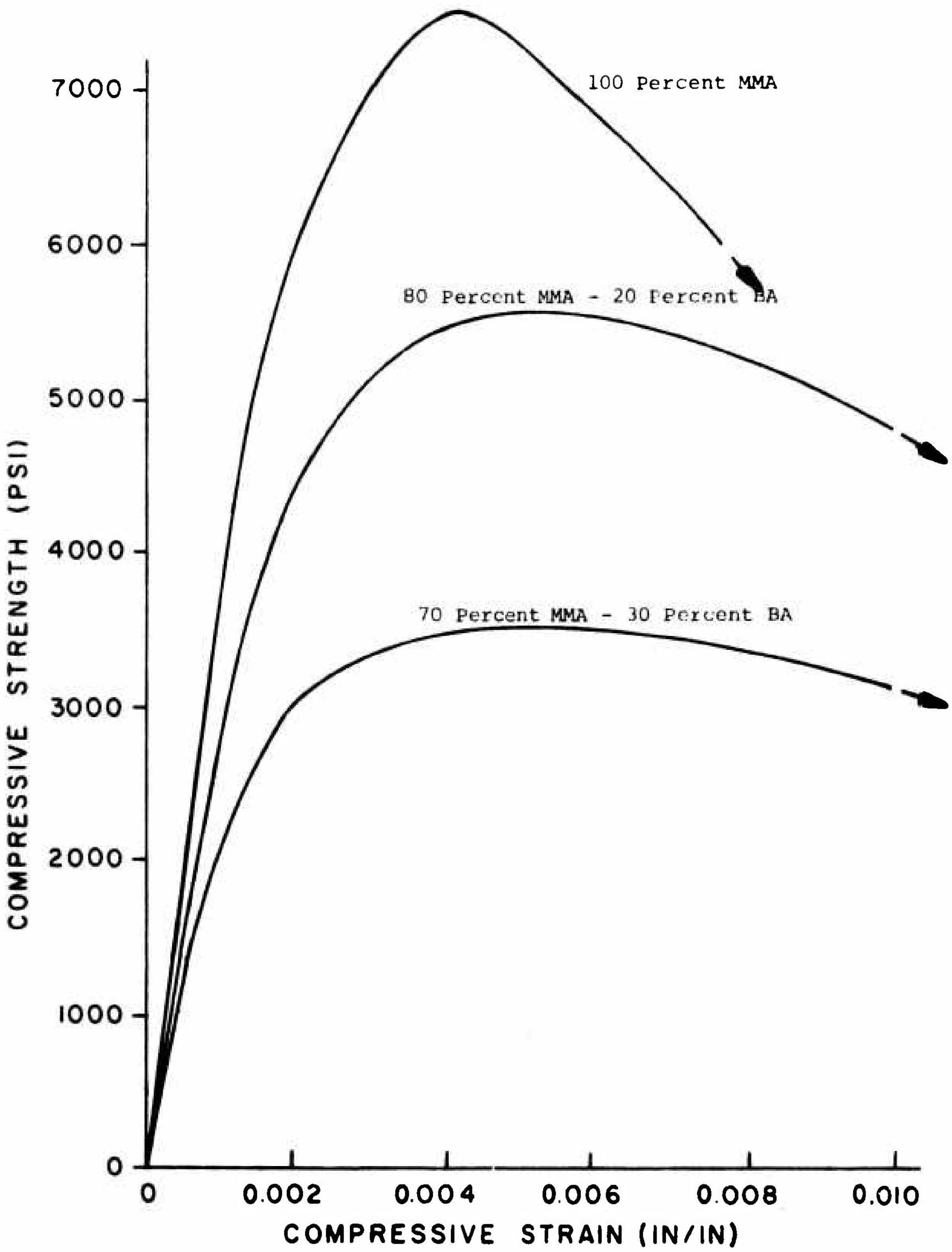


Figure 11. Effects of BA on Compressive Strength

different reasons. Section III discussed the effect of increasing the percentage of TMPTMA to decrease the set time, which in turn decreases strength. However, there are data which suggest that adding TMPTMA increases strength.

Table 3 gives the results of tests of four different formulations at 100°F. In formulas one and two the formula with 5 percent TMPTMA had a higher strength than the exact same formulas three and four, the formula with 5 percent TMPTMA again had a higher compressive strength than the one with only 2-1/2 percent TMPTMA which had a longer set time. The modulus of elasticity, however, decreased slightly with increasing amounts of TMPTMA.

Table 4 shows that the change from 5 to 10 percent TMPTMA by weight in three different tests resulted in decreased compressive strength as the set time decreased.

The only conclusion that can be drawn from these data is that amounts of 5 percent of cross-linking agent may improve strength, but amounts of 10 percent may decrease strength.

4.2.4 Silane Coupling Agent

Silane coupling agent is a liquid that is sometimes added to the monomer formulation for the sole purpose of increasing strength. Silane coupling agent improves the bond between the polymer and siliceous aggregates. Tests at BNL have shown that silane coupling agent can be added in three different ways with different results (Reference 14). The easiest method is to add a small percentage of silane directly to the monomer formulation; unfortunately it has the least effect. The second method is to wash the aggregate in diluted solutions of silane coupling agent which produces better results. The best method is to pass the aggregate over the vapors of silane coupling agent (Table 5).

In this study, silane was added directly to the monomer to make cylinders for testing in compression and tension and beams in flexure. The cylinders and beams were then prepared the same with identical formulations except one had 1 percent silane coupling agent added. The results showed an increase in compressive strength, splitting tensile strength, modulus of elasticity, and no change in flexural strength (Table 6). The flexural strength was based on only one test specimen each, and therefore is not conclusive.

4.3 TEMPERATURE EFFECTS

Studies at BNL have shown that as the PC temperature at testing increases, the strength of PC decreases and vice-versa. Table 7 shows the results of tests conducted by BNL at temperatures of -15°F, 70°F, 120°F, and 190°F (Reference 2). Figure 12 is a graph of the compressive strength versus ambient temperature which shows that the change in strength is almost linear.

TABLE 3. EFFECT OF TMPTMA ON STRENGTH AND MODULUS OF ELASTICITY

No	Formulation (Percent)	Set Time (min)	Compressive Strength (psi)	Modulus of Elasticity (10^6 psi)
1	95 MMA 5 BA 4 LP 2 DMPT	40	3750	2.60
2	95 MMA 5 BA 4 LP 2 DMPT --5 TMPTMA--	22	4070	1.45
3	95 MMA --5 TMPTMA-- 3 LP 1½ DMPT	33	5850	1.92
4	97.5 MMA --2.5 TMPTMA-- 2 LP 1 DMPT	55	5390	2.07

Test of one 6 by 12-inch cylinder cast outdoors at approximately 100°F.

TABLE 4. EFFECT OF TMPTMA ON COMPRESSIVE STRENGTH

Promoter-Initiators (Percent)	Ambient Temp (°F)	95 MMA 5 TMPTMA (psi)	90 MMA 10 TMPTMA (psi)	Reduction (percent)
4 LP 2 DMPT	72	7230	5870	19
1½ BP 1 DMA ½ DMPT	72	6300	5390	14
1½ BP 1 DMA ½ DMPT	50	6190	5610	9

TABLE 5. EFFECT OF SILANE COUPLING AGENT TREATMENT ON COMPRESSIVE STRENGTH (REFERENCE 14)

Silane Treatment	Compressive Strength (psi)
1 percent wt. silane blended with MMA	13,800
Aggregate treated with 1 percent wt. silane hydrolyzed in water, dried, and then mixed with MMA	15,800
Aggregate exposed to silane vapor, then mixed with MMA	16,000
No Silane Coupling Agent	11,000

TABLE 6. EFFECT OF 1 PERCENT SILANE ON STRENGTH

	Compressive Strength (psi)	Modulus of Elasticity (10^6 psi)	Splitting Tensile Strength (psi)	Modulus of Rupture (psi)
Without Silane	8,840	3.12	1140	1867
With 1 Percent Silane	12,650	5.41	1355	1786
Percent Increase	43	73	19	-4

Formulation:
(Percent)

95	MMA
5	TMPTMA
3	LP
1½	DMPT

Aggregate:
(Percent)

50 3/8 inch pea gravel
37.5 sand
12.5 portland cement
See Table 9

TABLE 7. EFFECT OF PC TEMERATURE ON PROPERTIES (REFERENCE 2)

MMA - TMPTMA

Property	Temperature (°F)	Result
Tensile splitting strength*	-15	1,510 psi
	70	1,430 psi
	190	1,370 psi
Compressive strength stress*	-15	24,800 psi
	70	19,600 psi
	120	15,800 psi**
	190	14,100 psi
Modulus of elasticity*	-15	6.11 x 10^6 psi
	70	5.28 x 10^6 psi
	190	4.44 x 10^6 psi
Poisson's ratio*	-15	0.24
	70	0.23
	190	0.22
Elastic limit stess*	-15	14,000 psi
	70	7,500 psi
	190	4,800 psi
Ultimate compressive strain	-15	5,360 x 10^{-6} in/in
	70	7,080 x 10^{-6} in/in***
	190	8,000 x 10^{-6} in/in
Unit weight*	-	149.1 pcf
Specific gravity*	-	2.40
Water absorption	-	0.6 percent

* Average values for three 6 x 12 inch cylinders
** Values of single cylinder
***Average values for two cylinders

Formulation:
(Percent)

97.5 MMA
2.5 TMPTMA
1 BP
½ DMA
½ Silane Coupling Agent

Aggregate:

See Table 9

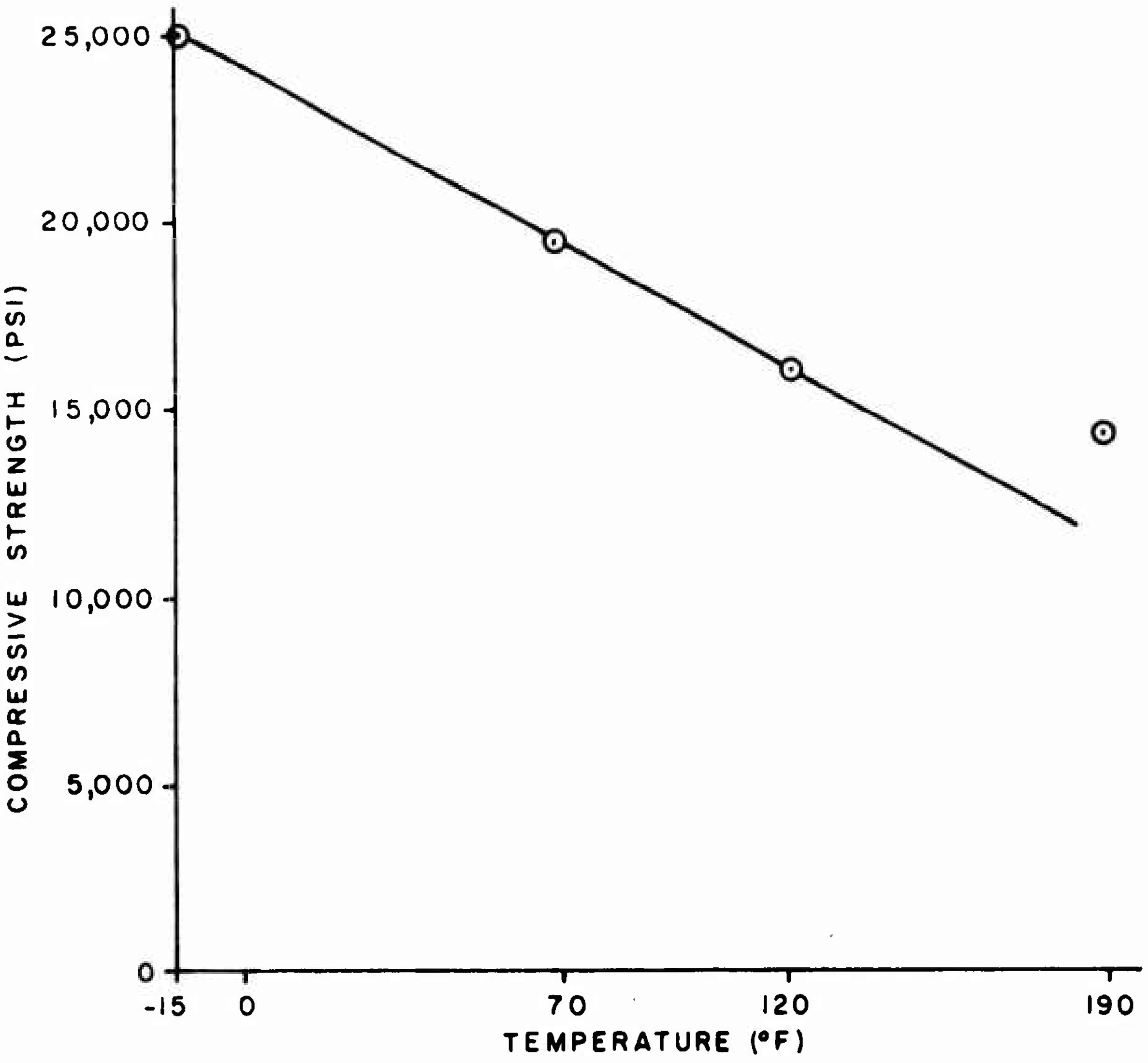


Figure 12. Effect of Ambient Temperature on Compressive Strength (Reference 2)

A test was developed to test the hypothesis that PC gains its maximum strength at peak exotherm. The temperature at peak exotherm affects the strength at that time, just as the temperature of PC affects the strength at any time that it is tested. To perform the experiment, PC specimens had to be tested within a very short time after peak exotherm temperature had been reached. Compressive strength cylinder specimens were ruled out because it took too much time to cut the top surface. Modulus of rupture beams were chosen because of the short time needed for their preparation. The aggregate was 100 percent sand to reduce the variation in aggregate and thereby minimizing the coefficient of variation of the test results.

Because only three beam forms were available the test was conducted as follows: First, two separate batches of three beams each were cast and tested at room temperature to establish a mean and standard deviation for each batch at 75°F. Next, three additional beams were cast to determine the strength as a function of temperature of the PC after the exotherm occurred. The peak exotherm temperature was approximately 175°F, and when the temperature of the beams had cooled to 130°F (approximately 25 minutes later), one of the beams was tested for modulus of rupture as described in Section II. The next day one of the two remaining beams was heated in an oven, removed, and tested when the temperature cooled to 130°F. The mean and standard deviation of the oven-heated beam and the reaction-heated beam were calculated and compared to strength of the first two batches tested at 75°F. The remaining beam of the batch was tested at room temperature and the strength was compared to the beams tested at 75°F.

A fourth group of three beams was cast, and the procedure was the same as the third batch except a temperature of 100°F was used. One beam was tested at 100°F approximately one hour after peak exotherm, and the second beam was placed in a heated oven 3 days later and tested when it cooled to 100°F. The results of the test summarized in Table 8 show that the coefficients of variation of the oven-heated beams to the reaction-heated beams were less than the coefficients of variation of the 75°F tested batches.

Although the number of samples was limited, the data indicate that PC develops almost all its strength by the time the exothermic reaction occurs, and further changes in strength are a function of temperature rather than chemical reaction.

Therefore, PC has no real curing time as in concrete. It is possible to permit traffic on polymer-concrete pavements as soon after peak exotherm as the temperature allows design strength. Further research is needed to determine if the cooling time might be reduced by spraying the PC with water immediately after peak exotherm without any ill effects.

TABLE 8. RESULTS OF CURE TIME AND PC TEMPERATURE ON MODULUS OF RUPTURE

Batch	Age at Testing	Test Temp (°F)	Modulus of Rupture (psi)	Mean Stress (psi)	Coefficient of Variation (percent)
1	5 days	73	2189	2114	3.20
			2087		
			2057		
2	2 days	73	2084		7.96
			2071	1986	
			1804		
3	25 min	130	1394	1447	5.03
	1 day	130	1498		
	1 day	75	1880		
4	60 min	100	1648	1656	0.21
	3 days	100	1653		
	3 days	75	2189		

4.4 AGGREGATE EFFECTS

The aggregate can affect the strength of PC in three ways: the aggregate strength, the aggregate gradation, and the moisture content of the aggregate.

4.4.1 Aggregate Strength

Just as portland cement concrete depends largely on the strength of the aggregate for the strength and modulus of elasticity so does polymer-concrete. Polymer-concrete can be made from dense, lightweight, and normal aggregates just like portland cement concrete. The stronger the aggregate the stronger the PC. In most cases, the failure plane in PC tends to pass through the large aggregate (Figure 13). In tensile tests, it is common to see the failure plane pass through more than half of the large aggregate (Figures 14 and 15).

4.4.2 Aggregate Gradation

MMA that is polymerized without aggregate is a brittle, glass-like material. If the aggregate is not well-graded and has large voids filled with polymer, the result is pockets of relatively weak polymer. However, a well-graded aggregate that has a low void ratio will have higher strength. It has been demonstrated by BNL that portland cement can be added to the aggregate as a ready-available source of fines (Reference 11). Comparative tests were made of two batches of PC, one with a mixture of 50:50 pea gravel and sand, the other with 50 percent pea gravel, 37.5 percent sand, and 12.5 percent portland cement (Table 9). The results of the compressive tests showed a 17 percent increase in strength (Table 10).

4.4.3 Moisture Content of Aggregate

Because MMA is only 1.5 percent soluble in water, it has been suspected that moisture in the aggregate would decrease strength. During one of the field tests, some of the aggregate had not been fully dried. The PC repair was made and has been in service over a year, but the effect of moisture in the aggregate had not been studied.

A test was developed to measure the effect of moisture content of sand on compressive strength and tensile strength. Aggregate consisting of 50 percent pea gravel (3/8-inch) and 50 percent oven-dried concrete sand was selected (Table 9). Water was added to the sand in three different amounts and stirred by hand until uniform color was achieved. Two samples of each sand were taken and weighed, oven-dried and reweighed to determine moisture content. Six PC cylinders, 3 x 6-inch, were prepared using each variation of moisture content. Three PC cylinders each were tested in compression and splitting tension. The specimens with the highest moisture content (5.65 percent) were too weak to removed from the molds undamaged. Only three specimens could be removed from the molds at a mositure content of 1.64 percent (Figure 16). It

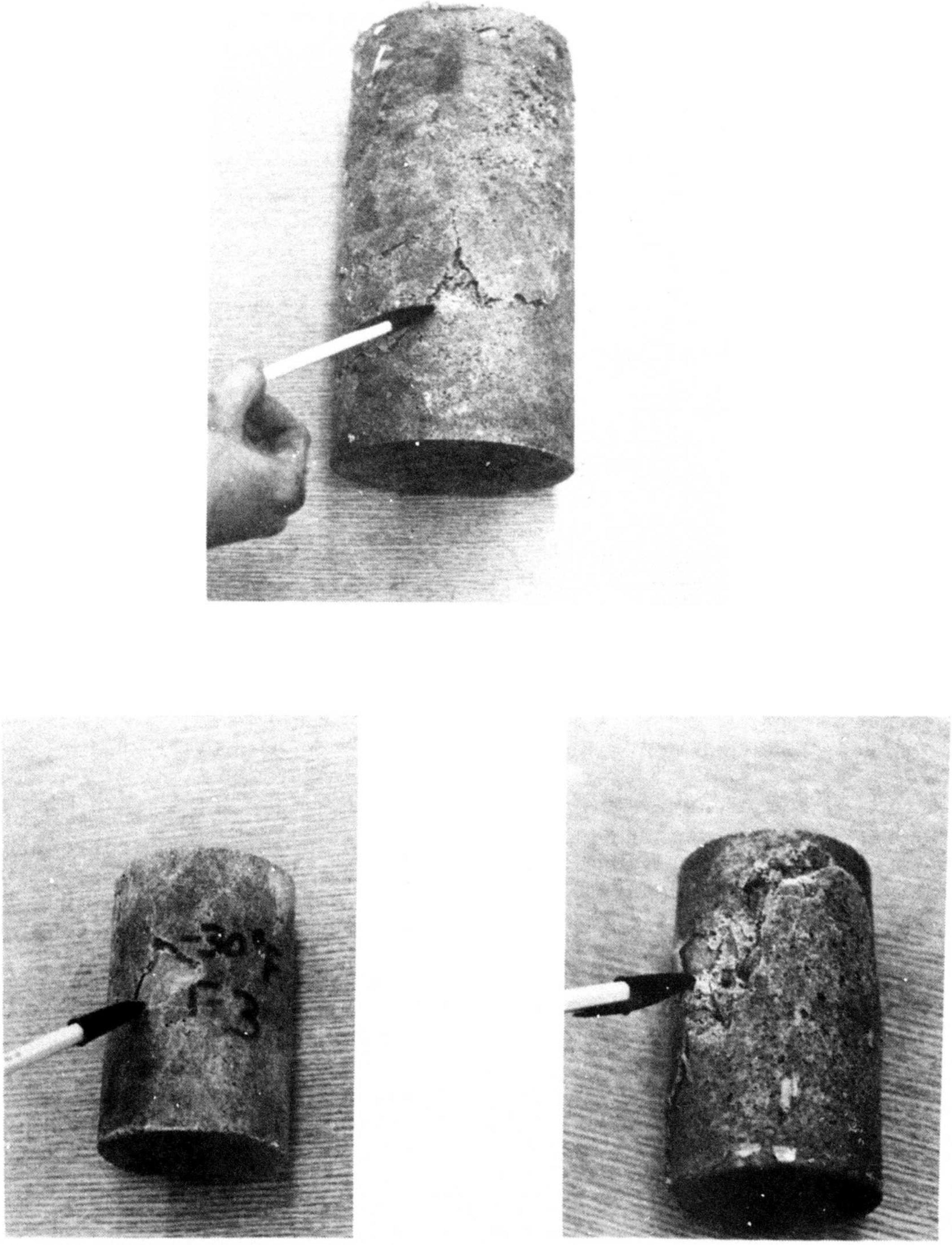


Figure 13. Failure Plane Through Large Aggregate

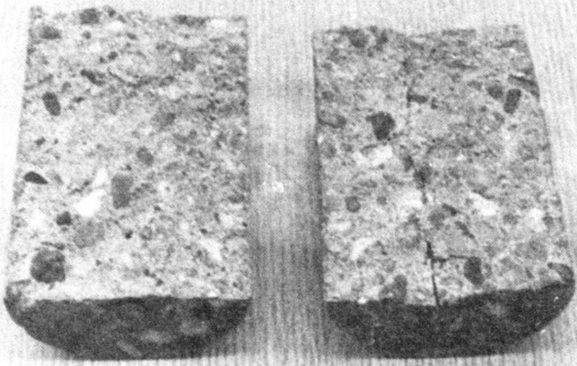


Figure 14. Failure Plane of PC Cylinder

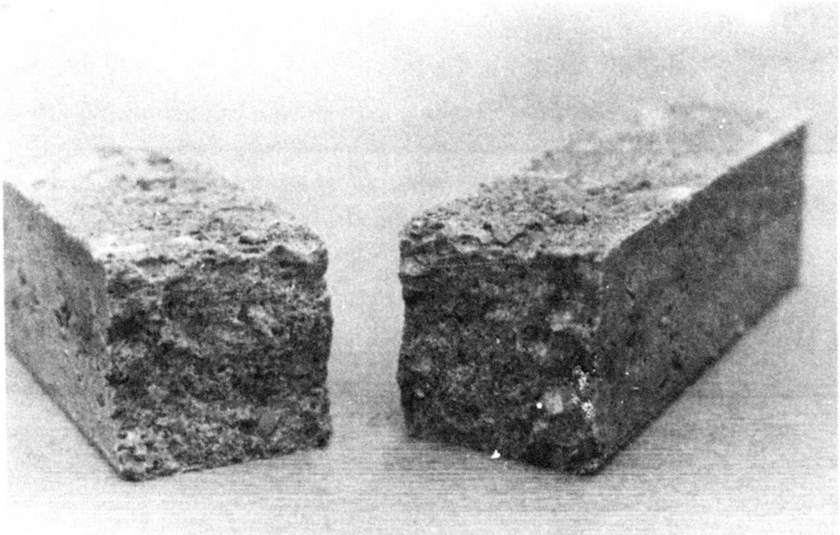


Figure 15. Failure Plane of PC Beam

TABLE 9. COMPARISON OF AGGREGATE GRADATIONS

Sieve Size	50 Percent Pea Gravel 50 Percent Sand Percent by Weight	50 Percent Pea Gravel 37.5 Percent Sand 12.5 Portland Cement Percent by Weight	BNL Tests Percent by Weight
3/8 to 3/4	9.1	14.0	30.0
No 4 to 3/8	36.3	38.4	19.9
No 8 to No 4	4.0	3.0	5.5
No 16 to No 8	6.4	4.1	5.5
No 30 to No 16	12.1	7.4	9.1
No 50 to No 30	23.2	10.9	8.8
No 100 to No 50	8.1	8.5	5.8
Pan	7.8	13.8	15.4

TABLE 10. EFFECT OF AGGREGATE GRADATION ON COMPRESSIVE STRENGTH

Gradation (Percent)	Average Compressive Strength (psi)	Standard Deviation (psi)
50 Sand 50 Pea Gravel	7540	106
50 Sand 37.5 Pea Gravel 12.5 Portland Cement	8840	450
	(Avg of three cylinders)	
Formulation: (Percent) 95 MMA 5 TMPTMA 3 LP 1½ DMPT		

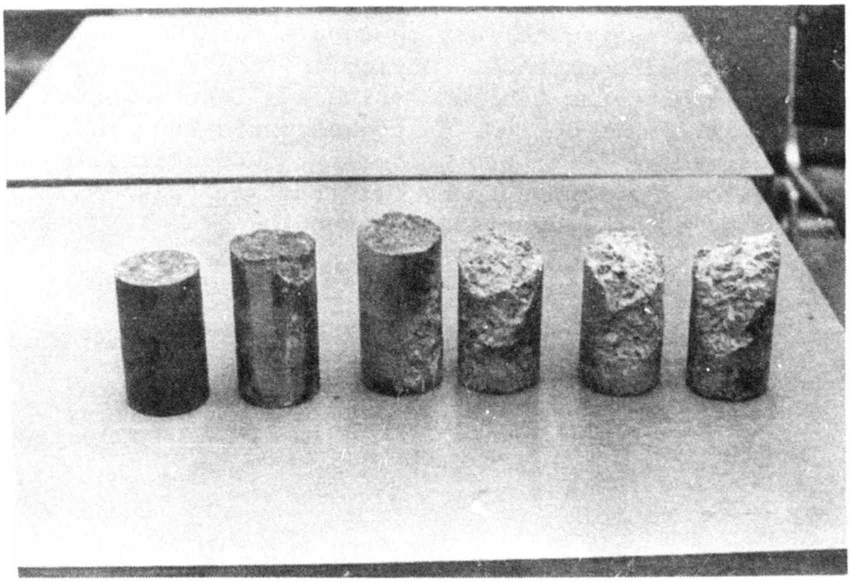


Figure 16. Specimens at 1.64 Percent Moisture Content

seemed as moisture content increased the specimens bonded to the steel molds even though the molds were well coated with the most effective mold release agent tested.

Results of the test show that relatively small amounts of moisture reduce the compressive and tensile strengths by as much as 40 percent (Figure 17 and 18). At a moisture content of 0.78 percent the sand was noticeably wet yet good strengths were obtained. This indicates that if the sand can be dried until it has the appearance of dry sand, the moisture content will be low enough to produce good results. The driest sand used (0.185 percent moisture content) had been oven-dried approximately one month earlier and stored in an air conditioned laboratory.

How dry the aggregate must be to use for PC repairs depends on each individual circumstance. Obviously, the economical balance between oven-drying the sand and using a slightly wetter sand with a decreased PC strength depends on the strength required. In most cases, it would be preferable to use the driest sand available. However, in actual practice the sand used by construction crews may not be completely dry and could result in decreased strength.

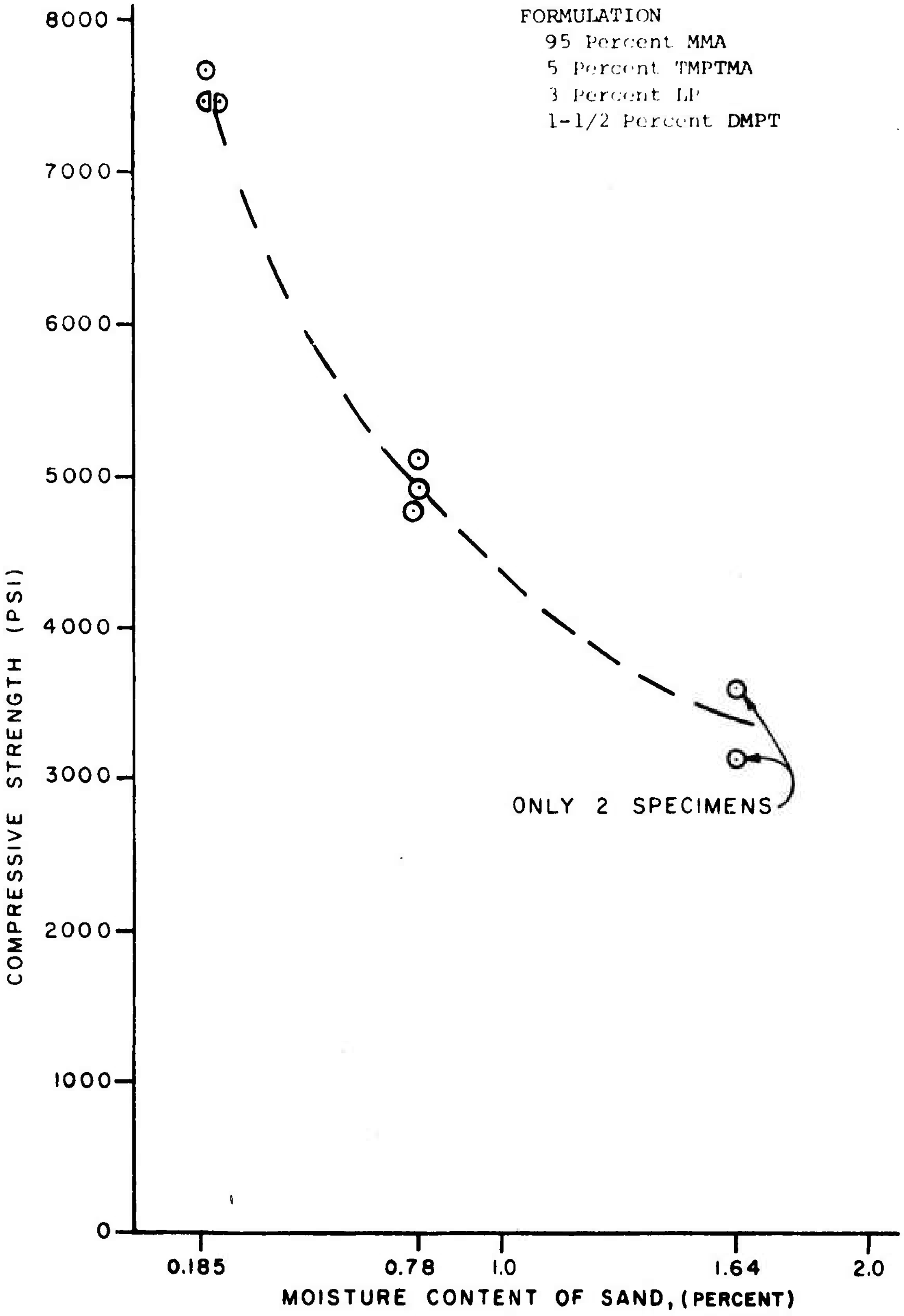


Figure 17. Effect of Moisture Content of Sand on Compressive Strength

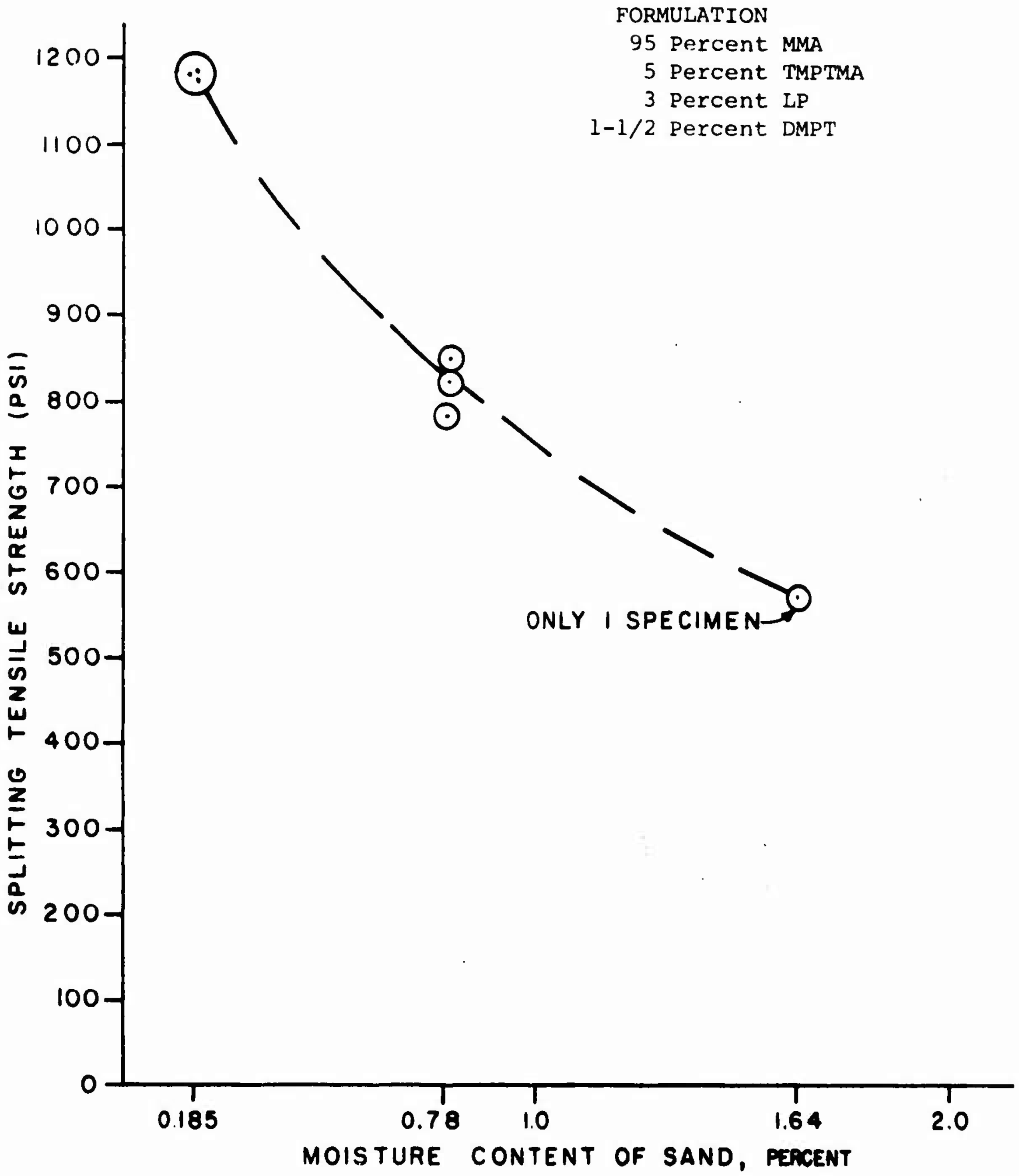


Figure 18. Effect of Moisture Content of Sand on Splitting Tensile Strength

SECTION V
LABORATORY SLAB EXPERIMENTS

5.1 BACKGROUND AND PREVIOUS RESEARCH

The durability of polymer-concrete repairs has been well established, e.g., no PC failures have been recorded in any of the field tests performed for the SDHPT. Included in those field tests were three repairs on pavements. However, an experiment was desired which showed conclusively that polymer-concrete could withstand the high loads of fighter aircraft and satisfy all the requirements of the US Air Force Bomb Damage Repair Project.

The desired requirements of the Bomb Damage Repair Projects are to repair a bomb crater in 4 hours. The repair must support F-4 aircraft for 50 passes at a temperature range of 32°F to 100°F over a subgrade with modulus of subgrade reaction (k) equal to 120 pci. The design F-4 has a single wheel load of 27,000 pounds over a contact area of 102 square inches with a tire pressure of 265 psi.

Because of the great difficulty in building a homogeneous subgrade of such a low modulus in the laboratory, it was decided the slab test would have to be modeled. Previous research at the University of Texas has successfully incorporated dynamically loaded modeled slabs over a rubber mat subgrade (References 15, 16). It was decided to duplicate the testing of CFHR Study 177 test slabs to give a good comparison between the performance of PC and concrete under heavy truck traffic. Also it was decided that the near-equivalent load of F-4 aircraft could be applied to the slab to evaluate the performance of PC under dynamic F-4 loads.

5.2 SLAB TESTING EQUIPMENT

As much of the original equipment as possible was used to eliminate additional variables. The subgrade consisted of 6 inches of neoprene rubber bridge mats stacked in 1-inch layers to provide a uniform elastic support. The top inch of rubber mat was cut out to form a void 27 inches by 14 inches under the slab (Figure 19). The void size under the applied load was selected by previous research to create the highest deflections and stresses and to simulate as nearly as possible the naturally occurring voids in the field (Reference 16). The rubber subgrade was previously subjected to plate loading tests to determine the modulus of subgrade reaction. The results of the test (Figure 20) produced an experimental value of modulus of subgrade reaction of 255 pci.

The loading frame and loading device were the same as those used in the previous experiments (Figure 21). The load was applied by a hydraulically-driven piston connected to a load cell. The load cell was wired to the MTS loading machine which permitted the precise application of the desired load at 5 cycles per second in the form of a sine wave.

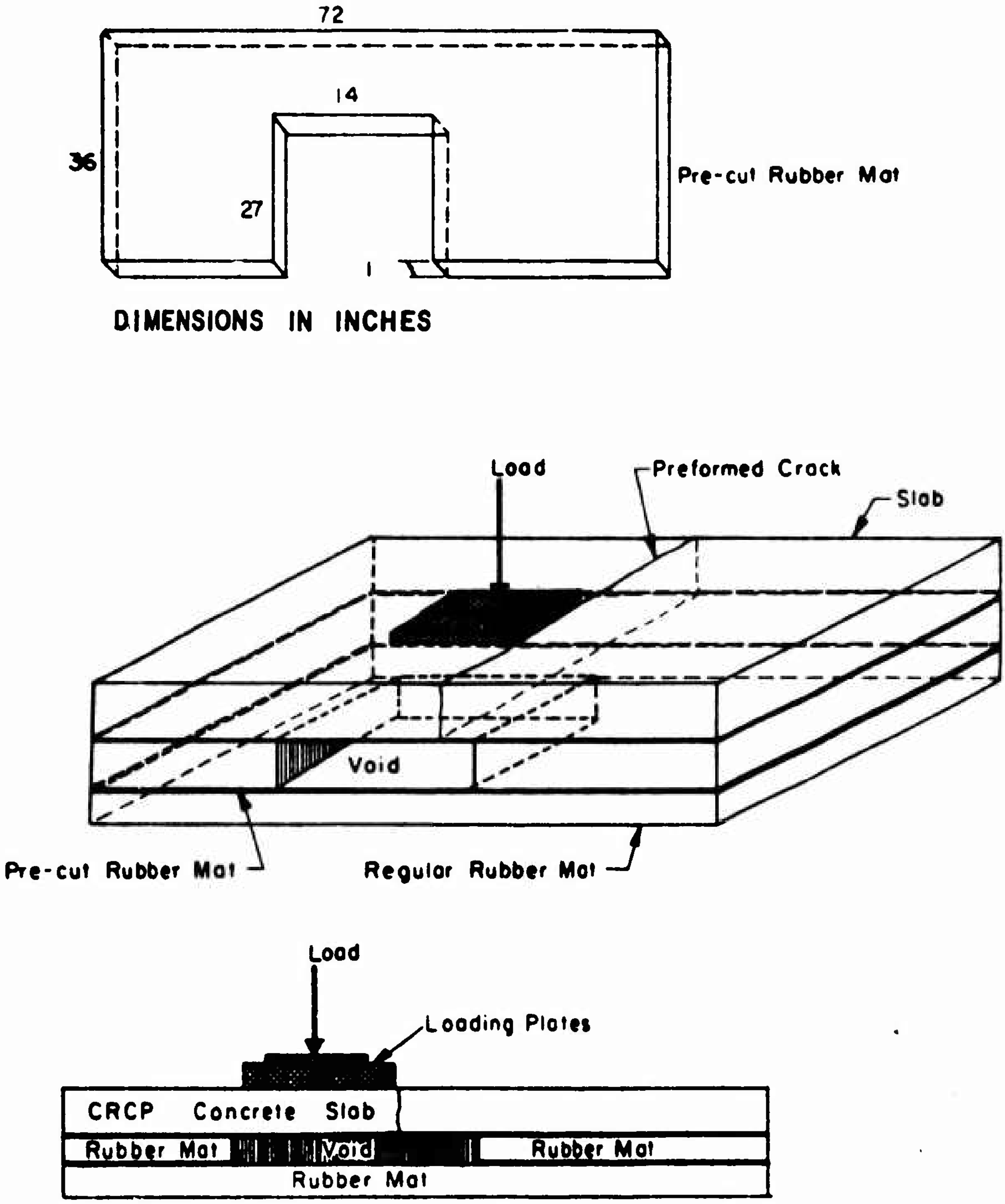


Figure 19. Rubber Subgrade

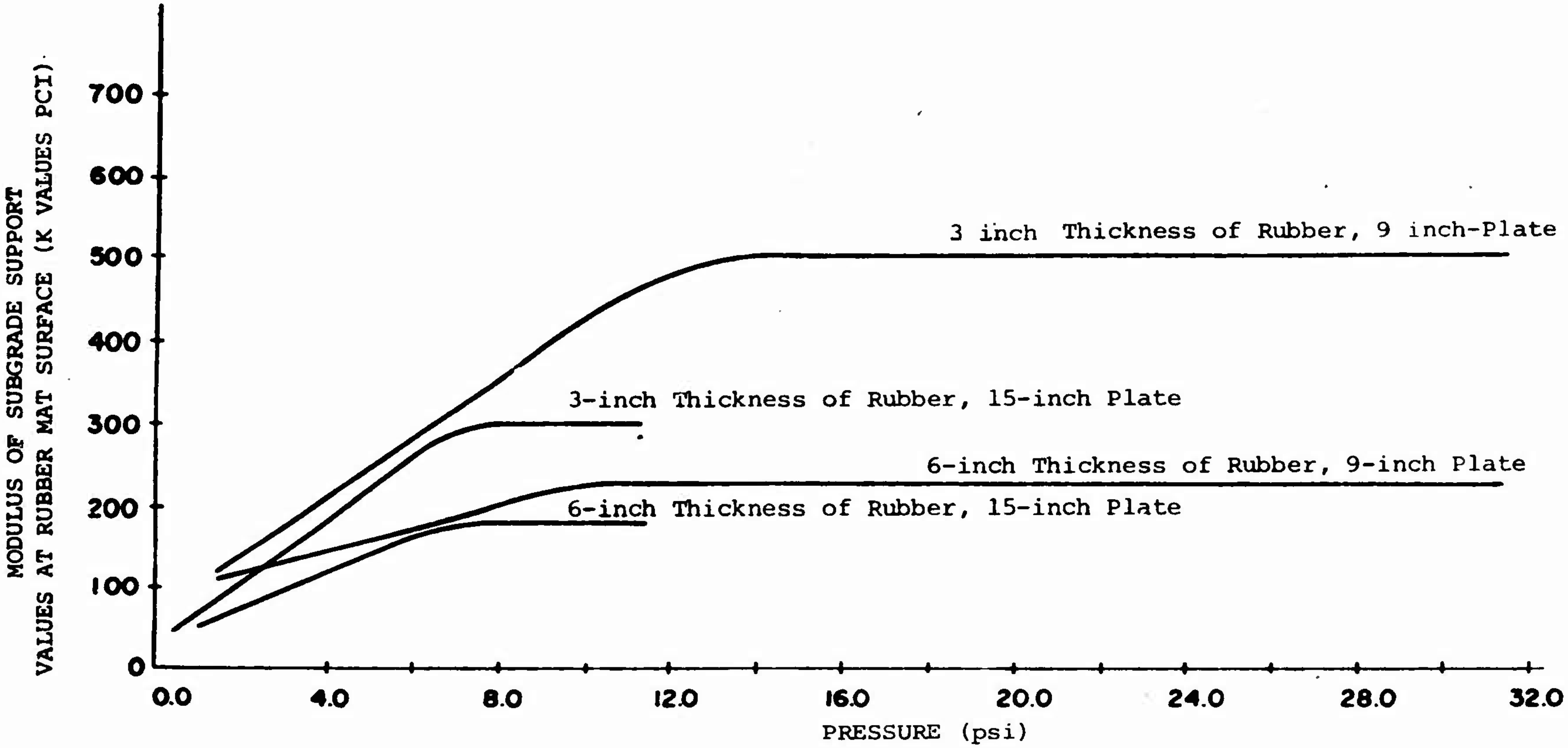
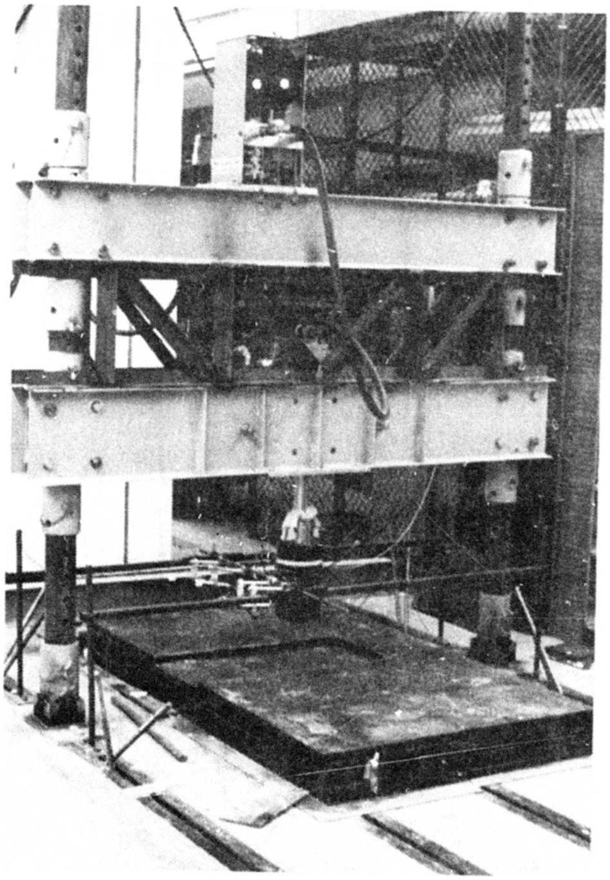


Figure 20. Test Results of Rubber Subgrade (Reference 20)



(Note void in rubber subgrade)

Figure 21. Loading Frame After Reinforcing

Deflections were recorded by the same LVDT's as used in slabs numbered 177-2 and 177-3 in the previous study (Figure 22). The LVDT output was wired to a galvanometer amplifier and then recorded on an oscillograph (Figure 23). The oscillograph was not the same as used in previous tests and could not be triggered automatically.

5.3 CONSTRUCTION OF TEST SLABS

5.3.1 Slab 1

Three concrete slabs from Study 177 were available for use: 177-1, 177-2, and 177-3. All three slabs had been previously tested for 4 million cycles at a 5000-pound load. The cracks in Slab 177-1 had been repaired with polymers resulting in a 5 percent increase in flexural strength. Slab 177-3 was a 2-inch slab which had sustained considerable damage.

Slab 177-2 was a 4-inch thick concrete slab with apparent cracking. To test the bond strength of PC and the bearing capacity of small PC patches. a hole 24 x 16 inches was jackhammered into Slab 177-2 (Figure 24). The repaired slab is hereafter designated Slab 1. The slab was 36 x 72 inches with a 20 gauge, 1-inch strip of sheet metal placed vertically along the bottom surface dividing the slab into two equal halves. The metal strip was used in the concrete slab to preform a crack in the original test program. The metal strip was left in the PC repair and coated with mold-release agent to create a weakened section. A double thickness of polyethylene was placed over the rubber subgrade as a bond breaker and a commercial sealant was applied around the perimeter of the repair.

At 2:20 PM the polymer-concrete repair was started. The ambient temperature was approximately 73°F and the temperature of the aggregate was 85°F, still cooling after being removed from the oven eariler in the day. The repair area was filled to mid-depth with dry aggregate: a 50:50 mixture of 3/8-inch pea gravel and normal concrete sand. The monomer formulation was poured over the aggregate and the mixture was rodded to fill all the voids (Figure 25).

This process was repeated twice more until the aggregate was filled to grade. A sizable leak developed and was stopped by applying pressure to the leak which was originating from the voided area. At 2:45 PM all the aggregate had been placed and saturated, after which the surface was troweled to a smooth sand texture. Due to the monomer leakage a second batch of monomer was mixed at 3:05 PM and sprinkled over the repair area to keep the PC saturated. At the same time, cylinder and beam specimens were cast to provide quality control. By means of a thermocouple inserted in the PC repair, the temperature was monitored. A peak exotherm temperature of 104°F occurred at 4:00 PM. At 4:30 PM the slab was lifted up several inches to remove the rubber mat used to form the void area. At 3:20 PM the next day, after careful calibration of all equipment, testing commenced on the slab.

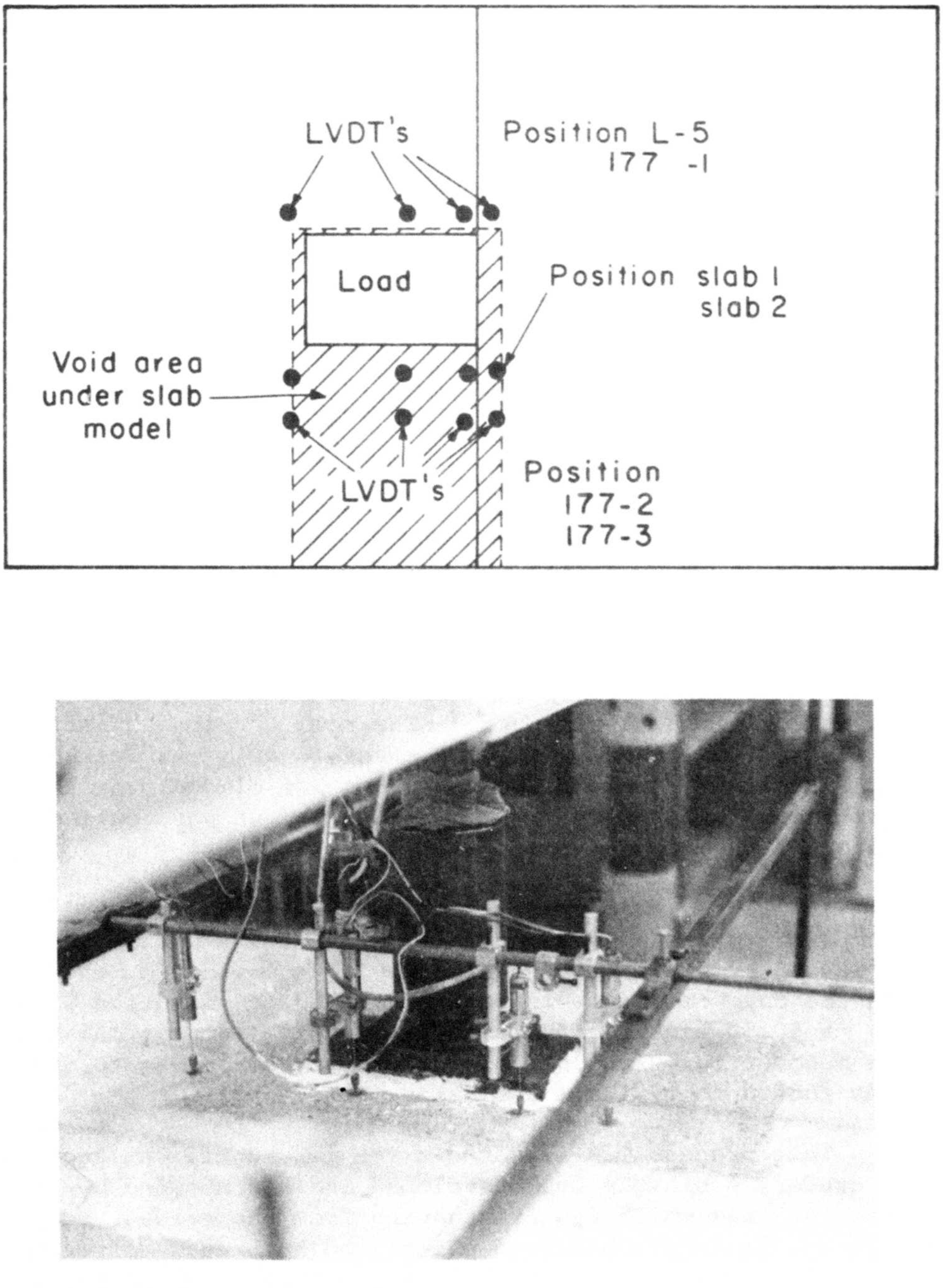


Figure 22. Modified Position of LVDT's for Slabs 1 and 2

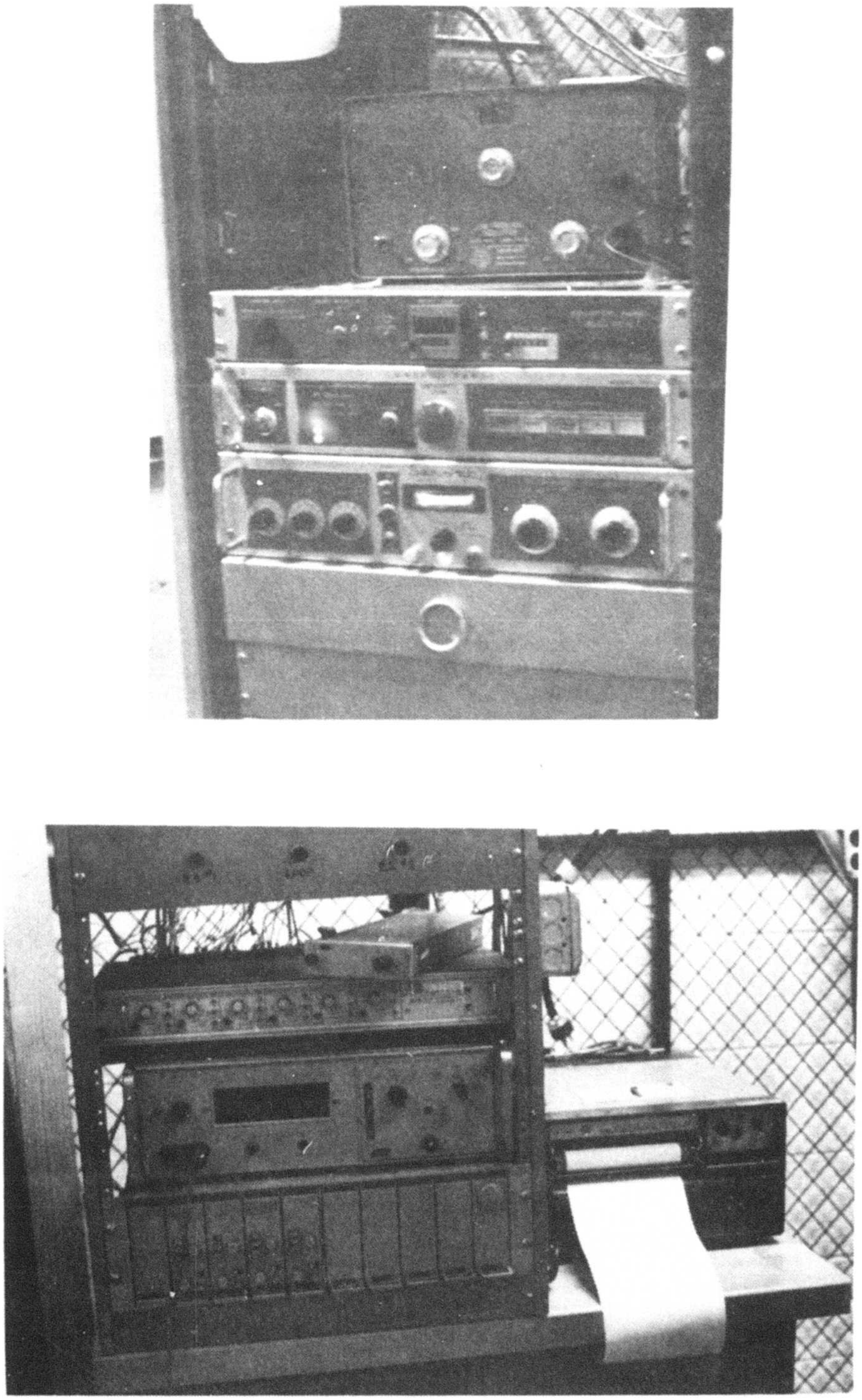


Figure 23. LVDT Recording Equipment and MTS Load Machine

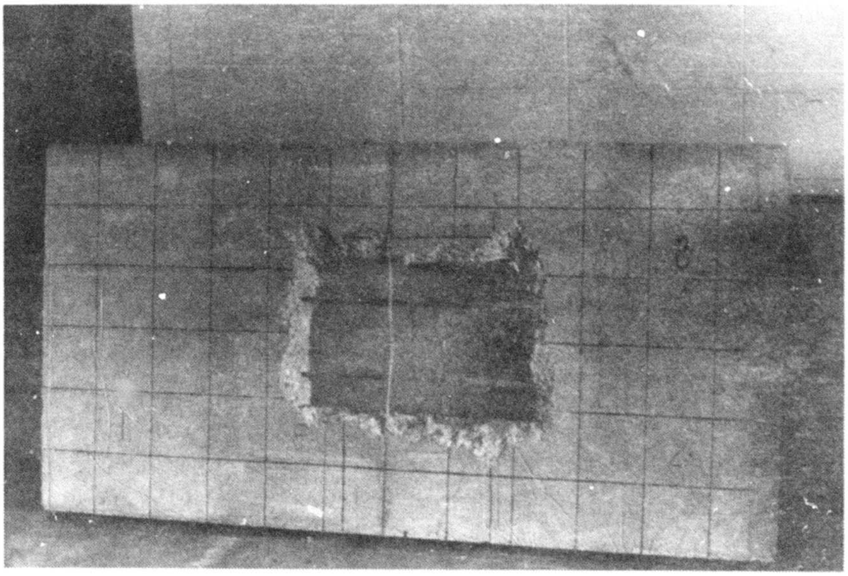


Figure 24. Slab 1 With Concrete Removed

Figure 25. Slab 1 Being Rodded

5.3.2 Slab 2

Slab 2 was a 2-inch thick, all polymer-concrete slab, 36 x 72 inches, reinforced with 6 x 6 inches 6 gauge welded-wire fabric placed at mid-depth. It was decided, after the repair of Slab 1, that Slab 2 would have to be cast outdoors to prevent the infiltration of the monomer vapors into the building air conditioning system. Four-inch metal forms were assembled on a plywood base with a 2-inch high plywood false bottom (Figure 26). The forms were lined with two layers of polyethylene stapled to the plywood bottom to reduce wrinkling. The first trial at casting the slab had No. 4 reinforcing bars extending through the form at each end for lifting hooks. The second casting used stirrups tied to the welded-wire fabric extending from the top of the slab for lifting hooks.

After testing Slab 1 it was noticed that it was very difficult to identify microcracking in the PC patch due to the slight roughness of the surface. It was decided that the second slab would be finished on the surface with a mixtue of oven-dried masonry sand and portland cement to improve the smoothness of the surface. The first attempt of pouring Slab 2 proceeded normally except for leakage at the ends which was due to the holes in the form around the lifting bars being inadequately sealed. After saturation of the aggregate, the sand and cement mixture was sprinkled over the surface and troweled to a smooth finish. However, 10 minutes later, the sand surface polymerized, preventing the application of additional monomer that had been lost due to leakage and evaporation. The combination of high ambient temperature without shading, leakage of monomer, and segregation of aggregate resulted in honeycombed polymer-concrete in the upper half of the slab. This slab was discarded and another was prepared.

At 1:45 PM, 30,000 cc's of monomer were mixed and the second attempt of the casting of Slab 2 began. Four hundred pounds of oven-dried aggregate (60 percent sand and 40 percent pea gravel) were mixed in a concrete mixer and placed in a shallow pan beside the slab form. To prevent segregation, monomer was poured over the aggregate to wet it. The wet aggregate was then shoveled into the slab form to a depth of about 1 inch (Figure 27). Additional monomer was applied and the mixture was added to fill the form and was saturated with monomer and rodded again. A layer of oven-dried masonry sand was sprinkled over the mixture and troweled smooth. An additional batch of monomer was mixed and applied to the slab to keep it saturated. However, very little monomer was needed as leakage was held to a minimum. The PC reached the peak exotherm temperature of 203°F in 60 minutes. At some point during the promoter-catalytic reaction, the plywood form deflected in the middle due to the weight. Consequently, the PC slab hardened in a slightly curved position in the longitudinal direction. At 4:00 PM the forms were removed and the PC slab was lifted and carried into the building with a small portable crane. The slab was carefully positioned into place on the rubber subgrade. The 6 x 11-inch contact plate was attached to the PC slab with hydrostone. At 7:00 PM a few cycles of load were placed on the slab, but due to equipment problems the normal uninterrupted loading was not started until 10:30 PM.

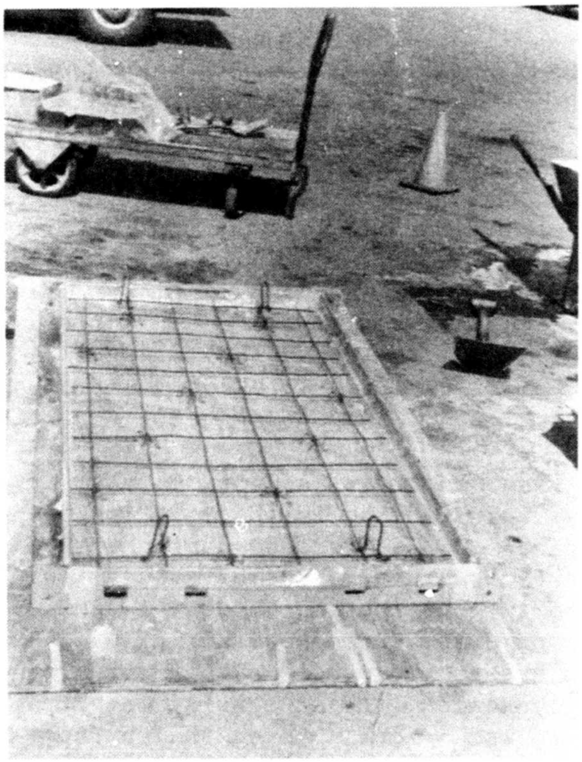


Figure 26. Slab 2 Form

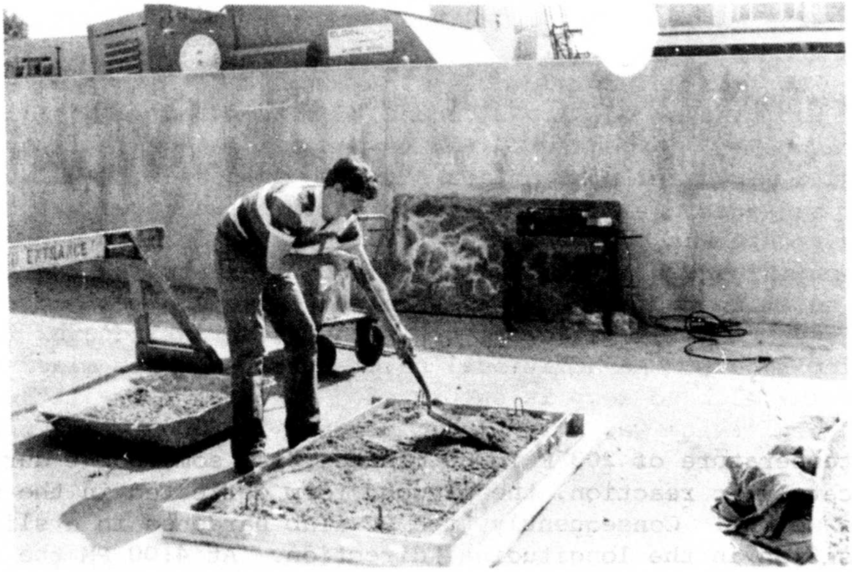


Figure 27. Slab 2 Being Poured

5.4 CYCLIC LOAD TESTS OF SLABS

5.4.1 Slab 1

In previous research, Slab 177-2 was pulled in tension until the intentional crack width, at mid-length, reach 0.01 inch. This simulated a tensile force in a continuously reinforce concrete pavement (CRCP) which occurs due to temperature effects. At the 0.01-inch crack width, Slab 177-2 was subjected to a 5 kip load over a contact area of 6 x 11 inches to simulate a 10 kip truck axle load at 76 psi tire pressure. After 2 million sinusoidal load applications the tension force was increased to maintain a crack width of 0.04 inch and a second 2 million load application were applied (Reference 16). Unfortunately, the force required to maintain the individual crack widths were not recorded in the previous research.

Duplication of the previous experiment of cracking the polymer-concrete repair in tension was not feasible with the available equipment nor would it have simulated actual field repair conditions. It was decided that repairing the slab with the steel in an unstressed state and then adding tension after the repair would simulate the worst condition of repairing the CRCP during warm weather and loading during cooler weather. Slab 1 was therefore tested with tensile forces that would approximate the forces used for Slab 177-2 and be representative of actual field conditions. An axial tensile force of 10 kips and a second 2 million applications of 5-kip load were applied uninterrupted. At this time, the slab was lifted to photograph and record the cracking on the bottom side of the slab.

Next, the slab was subjected to simulated aircraft loads. The desired load would have been 27 kips on a contact area of 102 square inches giving a tire pressure of 265 psi. Because it was decided that the practical capacity of the frame and loading device was only 21 kips, the load was modeled. A 17.5-kip load on the same 66-square inch plate used previously provided the equivalent stress. Because a 500-pound load was maintained on the slab at all times to protect the loading device, an 18-kip load was selected giving a tire pressure of 272 psi which would conservatively represent the desired loading stress. Slab 1 was subjected to an 18-kip repeated load with no axial tensile force. Slab 1 withstood 89,000 applications of the 18-kip load before testing was terminated due to equipment failure.

5.4.2 Slab 2

Because of the durability of Slab 1, it was decided that the thickness of Slab 2 should be reduced to 2 inches. Because most airfield pavements are jointed reinforced concrete pavements (JRCP) rather than CRCP, no axial tensile forces were applied. The percentage of reinforcement was originally planned as 0.1 percent but with the decreased thickness it was changed to 0.2 percent, which was still representative of JRCP.

A 5-kip load was applied to the 6 x 11-inch contact area and after 2 million uninterrupted load applications at 5 cycles/sec the test was stopped with no indications of any damage.

After the slab was inspected for damage, the slab was loaded to 18 kips statically three times to calibrate the instruments. The fourth time at 18 kips the slab was inadvertently loaded to 21 kips, producing major cracking. The slab was then loaded to 18 kips dynamically at 0.5 cycle/sec for 17 cycles, at which point it was determined that the steel reinforcement had failed and a crack of 1/4-inch width was visible.

5.5 RESULTS OF TESTING THE SLABS

5.5.1 Slab 1

The deflections of Slab 1 are shown in Table 11. An increase in deflection with time was recorded by the oscillograph. The amplitude of the sinusoidal deflection with respect to a reference line on the oscillograph increased with respect to time. Most of this increased deflection is thought to be a result of creep as it was nonrecoverable. Although no new major cracks developed in the slab or the PC repair, microcracking was observed in both (Figure 28 and 29).

Slab 1 was generally in excellent condition and the PC repair showed no signs of failing (Figure 30). It is felt that the slab could have taken many more applications of 18-kip loading without cracking the effectively 3-inch section across the middle.

5.5.2 Slab 2

After 2 million cycles of testing at a 5-kip maximum loading, Slab 2 showed no signs of distress on the top surface. There was no evidence of microcracking.

After 3 cycles of 18-kip loading, there was still no sign of microcracking although the deflections were excessive and partly non-recoverable. When the load was increased to 21 kips a loud noise was heard and within seconds two cracks were observed across the top of the slab (Figure 31). After cracking had occurred, an 18-kip cyclic load was applied for 17 cycles. At this point cracking was severe and the steel failed (Figures 32 and 33).

5.6 STRESS ANALYSES OF SLABS

Previous slabs of Study 177 were analyzed using a computer program developed at the University of Texas called Slab 49 (Reference 16 and 17). The analyses of Slabs 1 and 2 were also performed with Slab 49. Figures 34 and 35 show the stress concentrations in the top and bottom of Slab 2 predicted by Slab 49 using elastic theory.

TABLE 11. SUMMARY OF DEFLECTIONS OF TEST SLABS

					Deflections		
					Computed	Measured	
Slab	Support	Void Size (inches)	Thickness (inches)	Load (kips)	Max (inches)	Initial (inches)	Final (inches)
L-5[a]	Full	-	4	5	0.040	0.057	0.091
177-2[b]	Void	27x14	4	5	0.022	-	0.051
177-3[b]	Void	27x14	2	5	0.170	-	0.180
Slab 1[c]	Void	27x14	4	5	0.018	0.022	0.044
				18	0.065	0.108	0.095
Slab 2[d]	Void	27x14	2	5	0.064	0.060	0.088
				18	0.229	0.246	-

a. reference 15
b. reference 16
c. Slab 1 is the PC repaired Slab 177-2
d. Slab 2 is a 2-inch PC slab

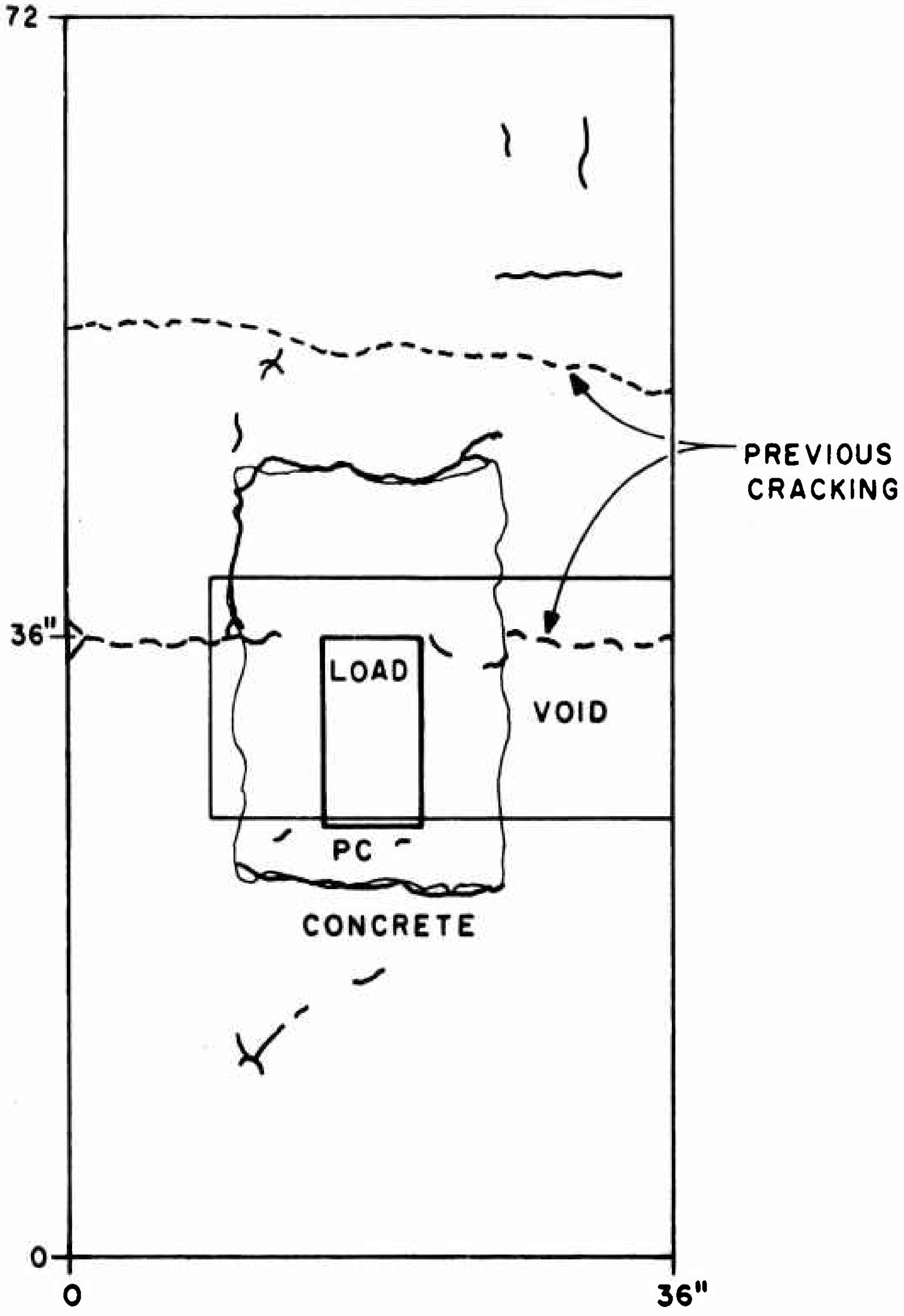


Figure 28. Crack Development on the Top of Slab 1

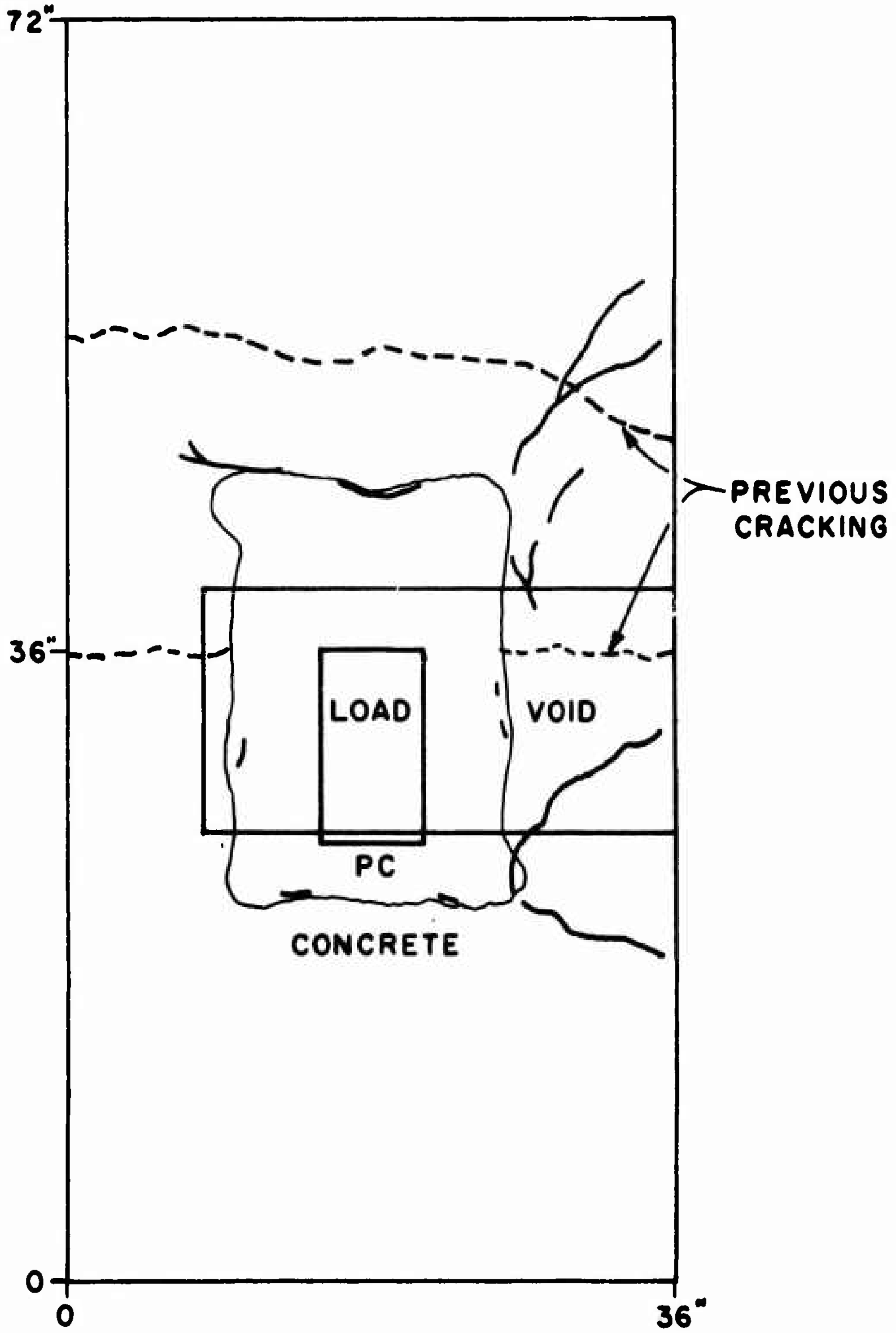


Figure 29. Crack Development on the Bottom of Slab 1

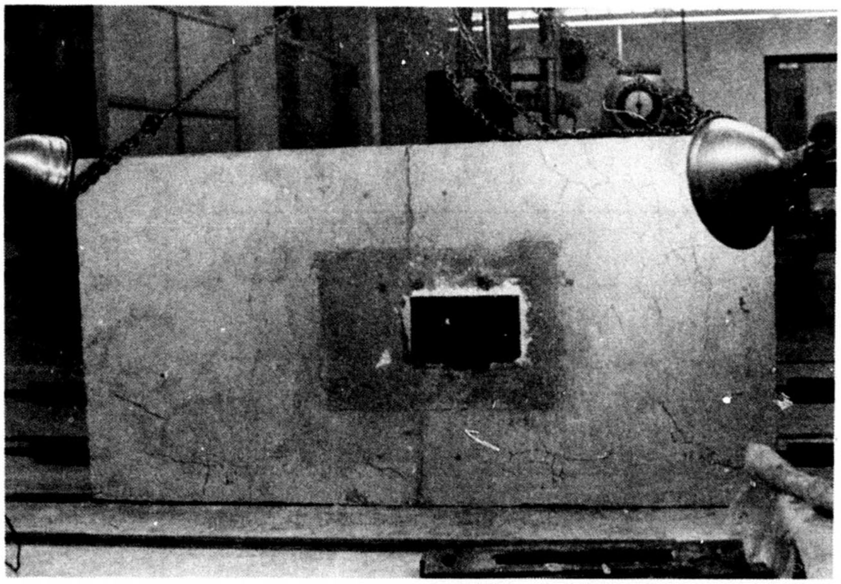


Figure 30. Top of Slab 1

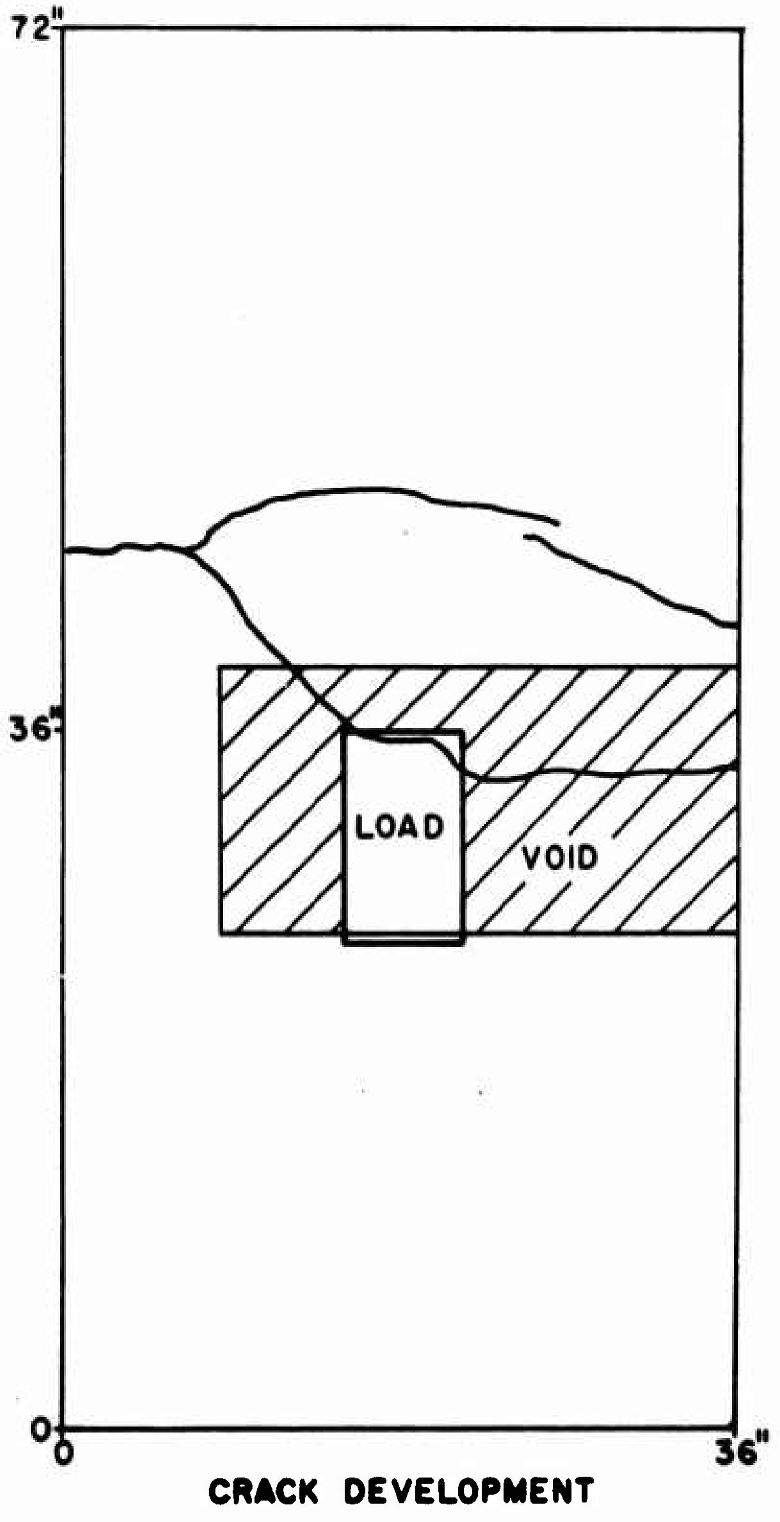


Figure 31. Crack Development on the top of Slab 2
After Application of 21 Kip Load

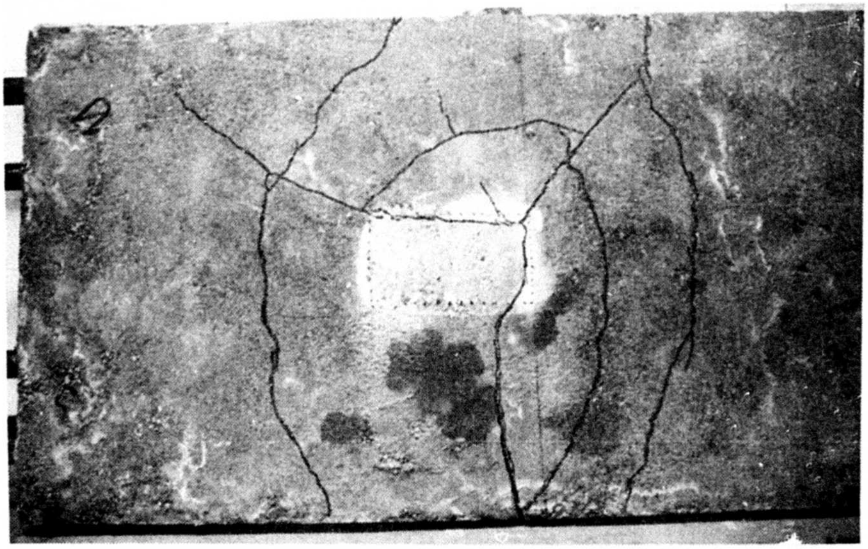


Figure 32. Top of Slab 2

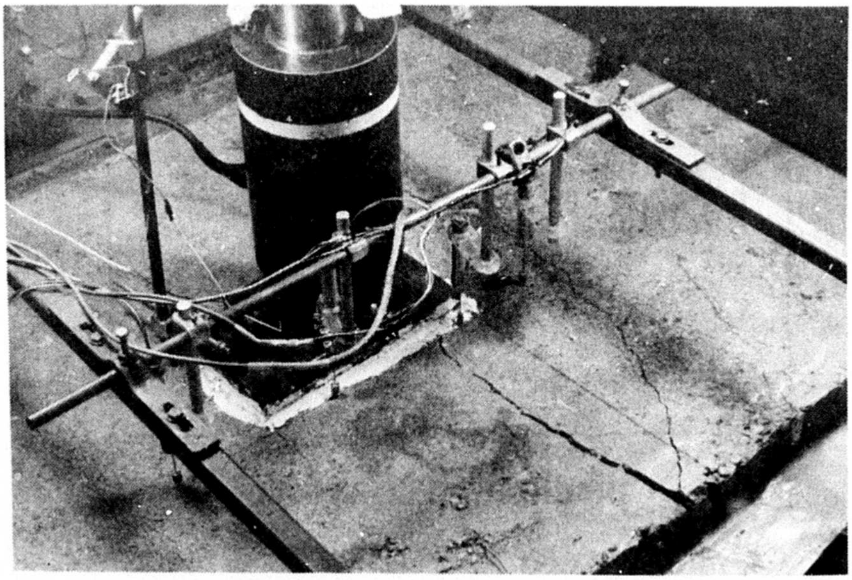


Figure 33. Cracking on Top of Slab 2

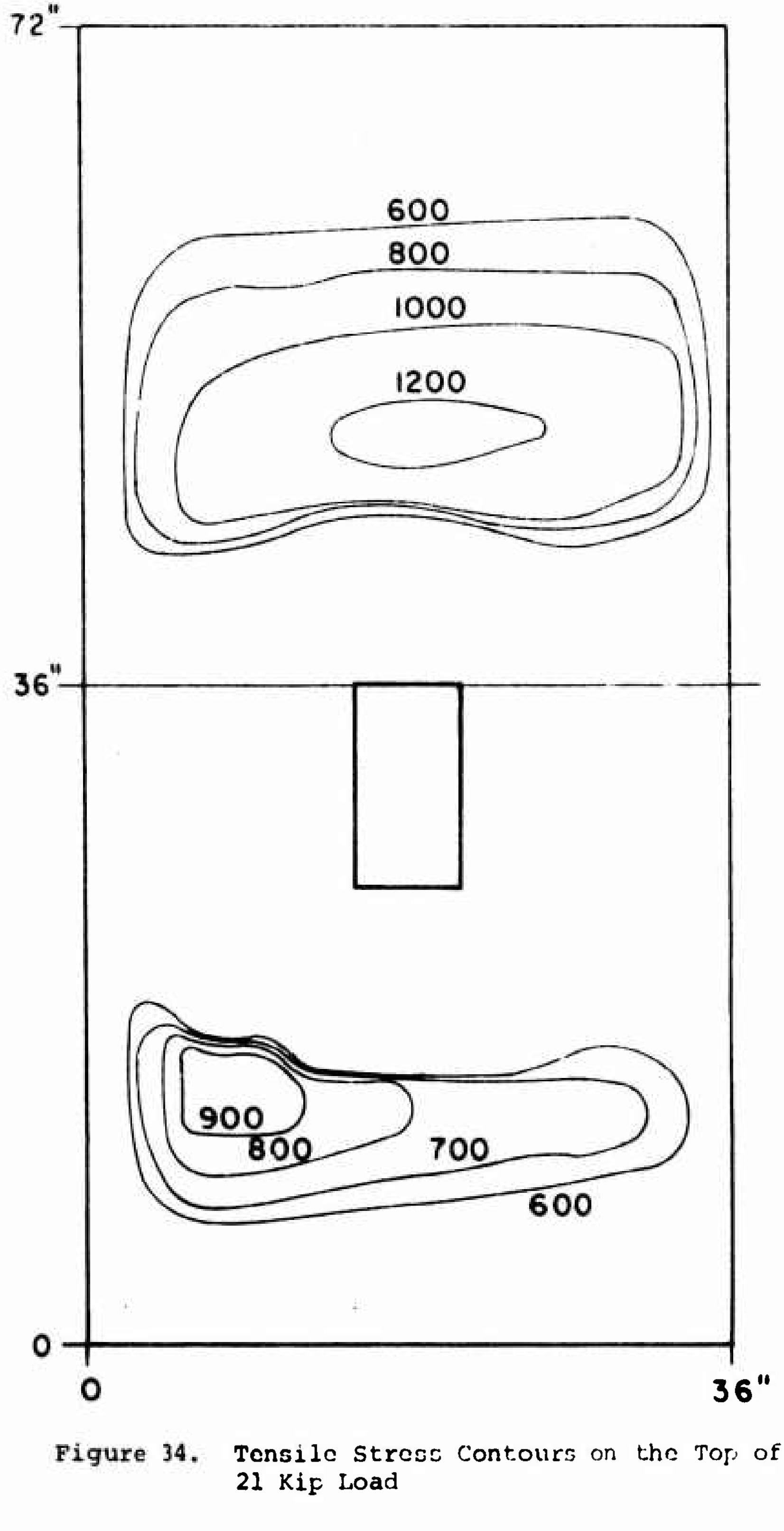


Figure 34. Tensile Stress Contours on the Top of Slab 2: 21 Kip Load

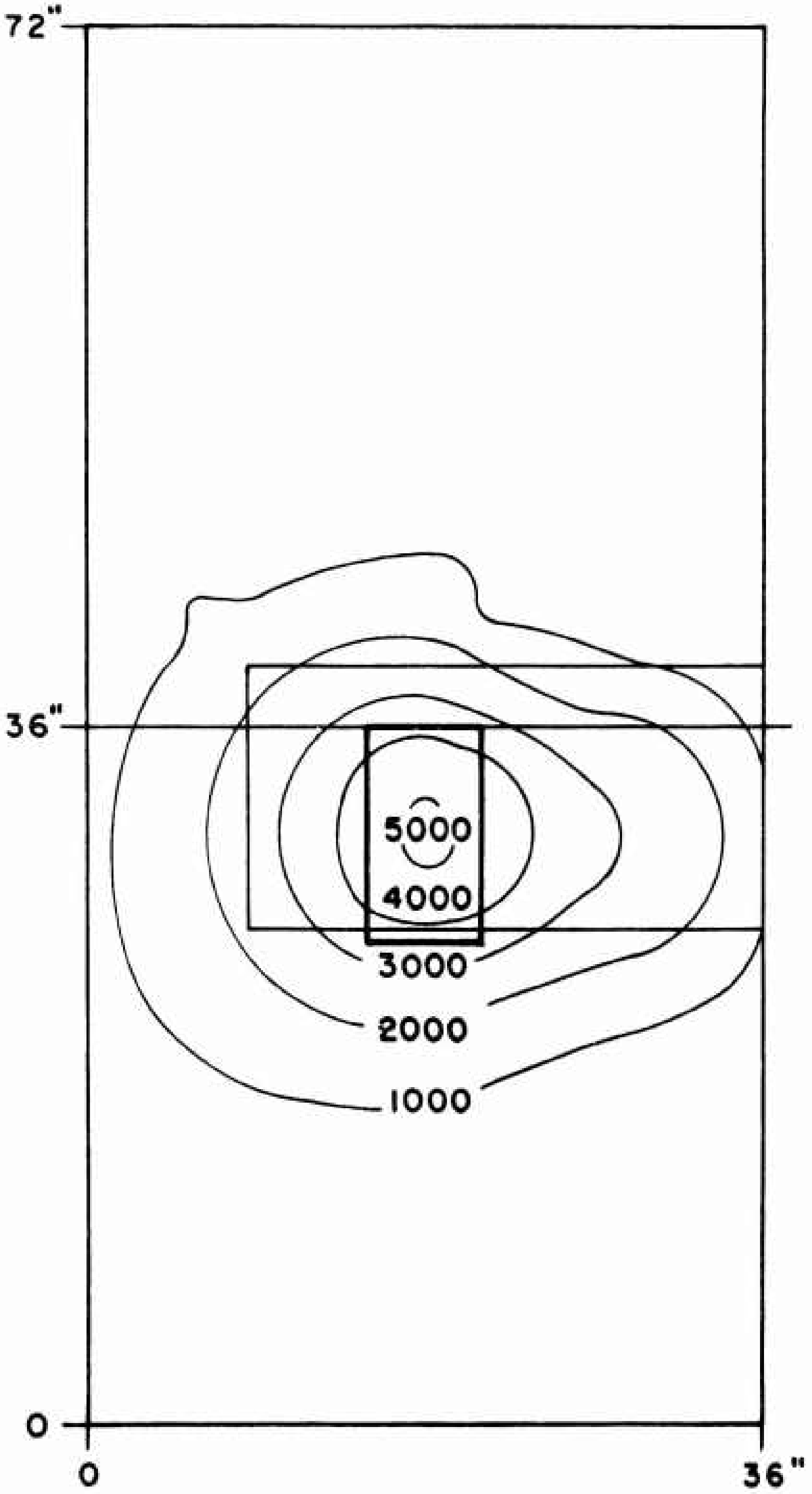


Figure 35. Tensile Stress Contours on the Bottom of Slab 2: 21 Kip Load

The 5000 psi tensile stress in the bottom of Slab 2 (Figure 35) predicted by the computer program was verified using the Westergaard corner equation on a uniform support. It seems inconsistent that the PC slab could withstand a 5000 psi tensile stress when the modulus of rupture was found to be 1500 psi from beam tests (Table 12).

The most plausible explanation is that the slab must have cracked on the bottom side allowing the steel reinforcement to limit the cracking and carry the tensile stress. This cracking continued unnoticed until the top side also reached a tensile stress across the slab of approximately 1200 psi. At this point failure occurred, and the slab cracked across the top. The theory of failure is also supported by the crack development of Slab 2. The cracking along the bottom of the slab was around the load plate and then radially outward (Figure 36). The primary cracking on the top of the slab was in a concentric circular pattern corresponding to the stress concentrations predicted by the Slab 49 program (Figure 37). This concentric pattern of cracking was only partially visible on the bottom of the slab as microcracking or discoloration of the PC. Most of the radial cracking pattern penetrated to the top of the slab.

5.7 COMPARISON TO CONCRETE SLABS

One performance comparison between PC and concrete is crack development. The PC had less cracking than concrete under identical load (Table 13). This is understandable because the flexural strength of the PC material was 300 percent higher than the concrete (Table 14). Only microcracking was observed in Slab 1 in the PC material, and no cracks exceeded 6 inches in length. No cracking was observed in Slab 2 until failure occurred. In concrete Slab 177-3, a major crack developed across the full width of the slab after only 120,000 applications.

One finding was that after the load on Slab 1 was increased to 18 kips, no new cracking occurred in the PC material at the bottom of the slab, although additional microcracking of 11 inches was observed on the top.

TABLE 12. RESULTS OF MAXIMUM FLEXURAL STRESS ANALYSES*

Slab	Void Size (inches)	Thickness (inches)	Load (kips)	Maximum Tensile Stress Westergaard Corner Equation (psi)	Maximum Tensile Stress Slab 49 Computer Program (psi)
177-2	27x14	4	5	514	451
177-3	27x14	2	5	1437	1424
Slab 1	27x14	4	5	510	558
			18	1837	2008
Slab 2	27x14	2	5	1132	1239
			18	4076	4460
			21	4755	5204

*stresses as a result of axial force are not included

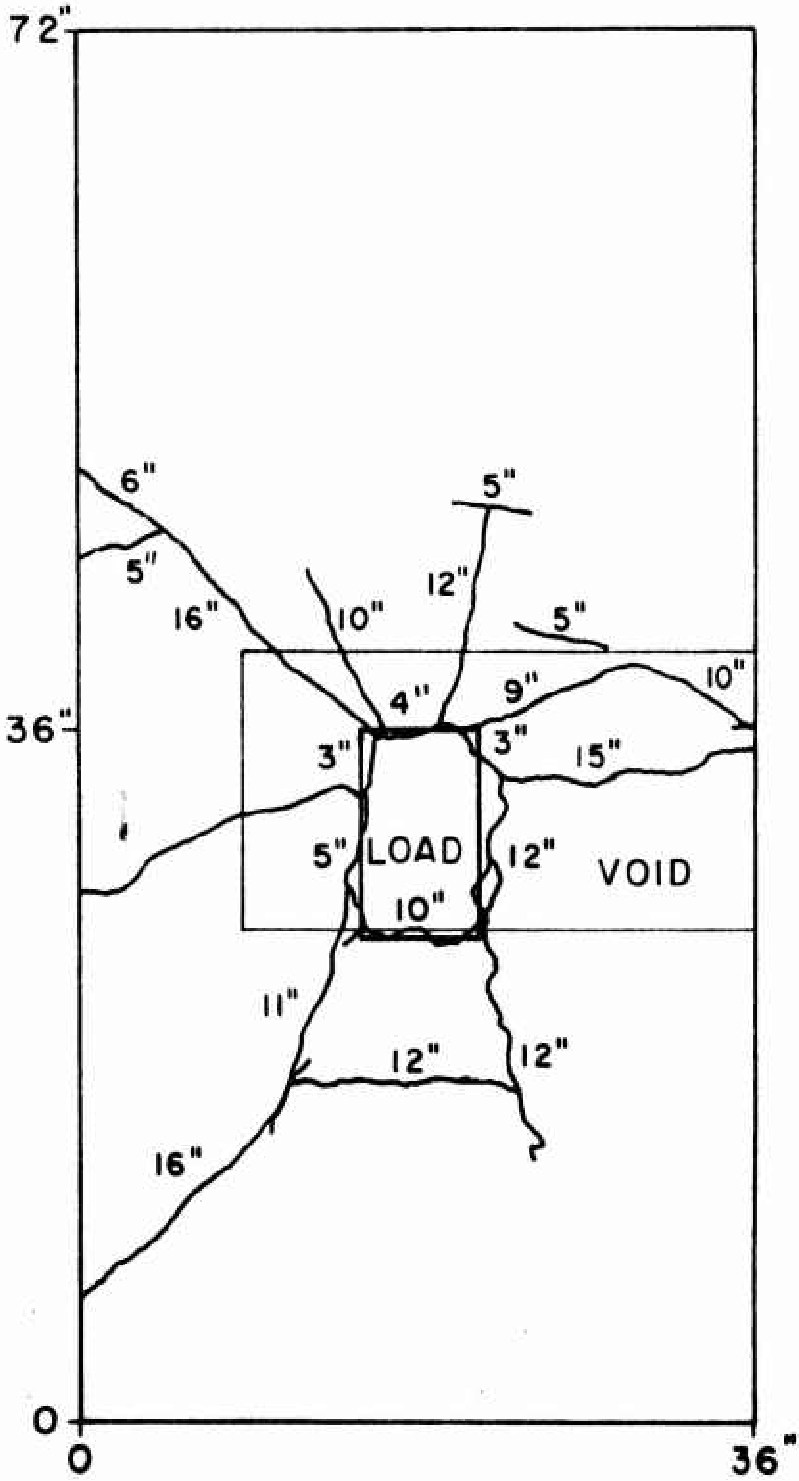


Figure 36. Crack Development on the Bottom of Slab 2

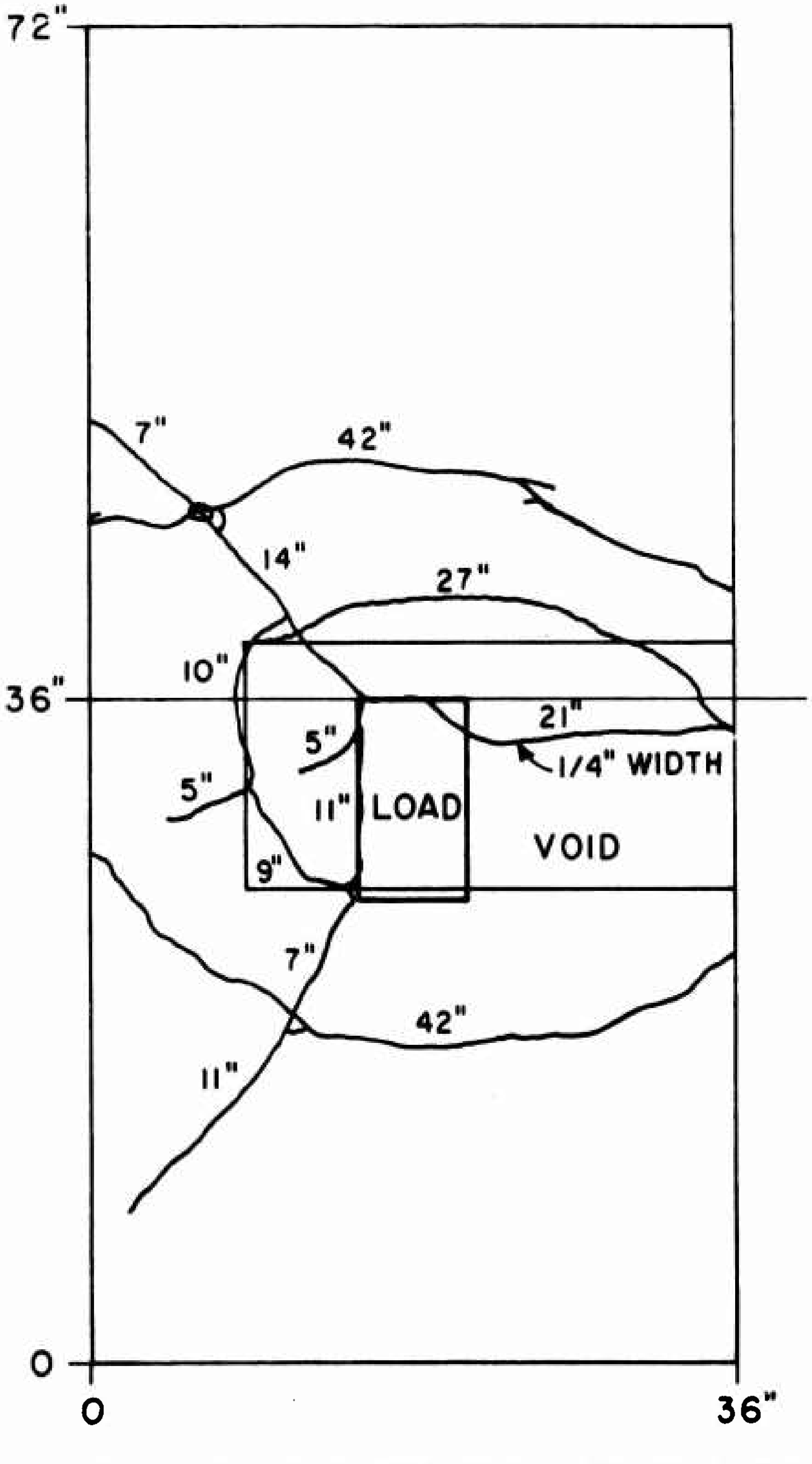


Figure 37. Crack Development on the Top of Slab 2

TABLE 13. CRACK DEVELOPMENT IN TEST SLABS

Slab	Void (inches)	Thickness (inches)	Load (kips)	Crack Development (inches)		
				Top	Bottom	Total
177-1	27x26	4	5	302	235	537
177-2	27x14	4	5	80	76	156
177-3	27x14	2	5	535	449	984
Slab 1	27x14	4	5	9	30	39 (PC)
				55	64	119 (Concrete)
Slab 2	27x14	2	5	0	-	-
Slab 1	27x14	4	18	11	0	11 (PC)
				5	15	20 (Concrete)
Slab 2	27x14	2	18	204	198	402

TABLE 14. MATERIAL PROPERTIES OF THE SLABS

Slab	Material	Compressive Strength (psi)	Flexural Strength (psi)	Splitting Tensile Strength (psi)	Modulus of Elasticity (10^6 psi)
177-1	Concrete[a]	3888	577		
177-2	Concrete[a]	4187	563		
177-3	Concrete[a]	2856	481		
Slab 1	PC[b]	7016	1911	1179	3.57
Slab 2	PC[b]	6288	1558	934	1.75

a - 7-day test value

b - 75°F test temperature

SECTION VI
FIELD TESTS

6.1 INTRODUCTION

This section will report on the use of polymer-concrete for field repairs. The Center for Highway Research at the University of Texas in conjunction with the Texas State Department of Highway and Public Transportation has conducted numerous field repairs throughout the state of Texas with concrete-polymer materials. This section will discuss only three of the pavement repairs with polymer-concrete that were performed during the course of this research. A map of Texas is provided in the Appendix to show the location of the repairs.

6.2 INTERSTATE 35 -- WACO, TEXAS

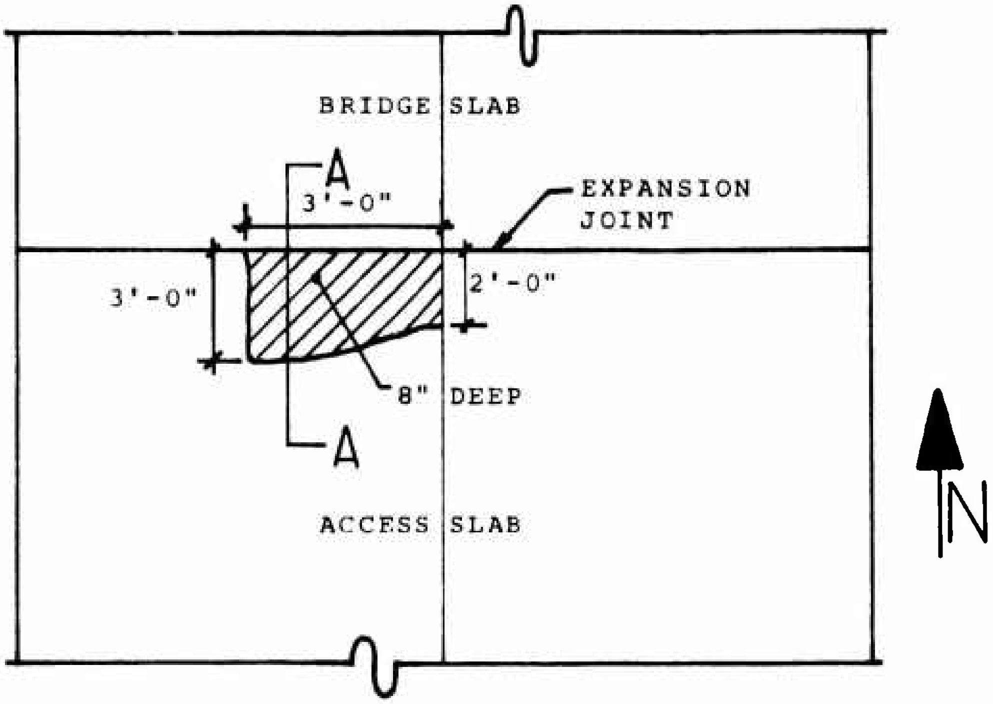
6.2.1 Conditions

On March 31, 1977 several PC patch repairs were performed on the outside, southbound lane of Interstate Highway (IH) 35 on the south side of Waco, Texas. The weather was partly cloudy in the morning with a 15 mph wind and temperatures ranging from 60° to 70°F. In the afternoon, work was performed under sunny skies and a temperature range of 70° to 80°F. Four areas were repaired on the 8-inch continously reinforced concrete pavement. The first repair area was at the joint between a bridge slab and an approach slab (Figure 38). The second repair area was a transverse crack with spalling. The third repair area was a punch-out at the shoulder between several longitudinal and transverse cracks. The fourth repair was a typical spalled area (Figure 39). The concrete was in good condition and was moderately difficult to remove with an air hammer.

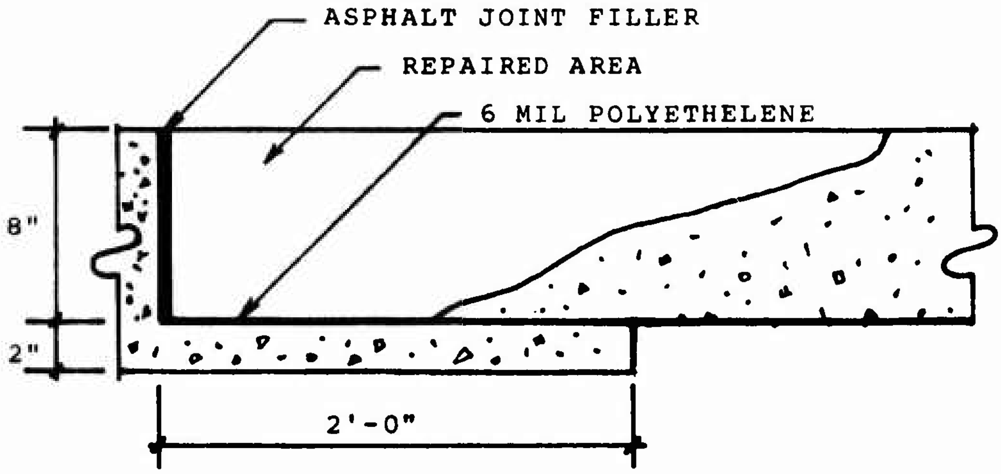
6.2.2 Procedure

The procedure used to repair the concrete pavement was slightly different in each of the repair areas.

Area 1. The repair measured 66 x 30 inches by 8 inches deep and was bounded by an expansion joint to the north side. Unsound concrete and asphalt joint filler were removed with an air hammer, and loose debris was cleaned out with compressed air (Figure 40). The concrete was then dried with a portable butane heater to remove possible moisture due to the rain which had fallen the previous day. The bottom of the repair was coated with polyester putty to preserve the expansion joint. Polyester putty was also applied to the vertical face of the adjoining slab, and a 1 x 8-inch board was placed vertically to maintain the expansion joint. A sand and gravel mixture of dried aggregate (40:60 ratio by weight) was placed in the void and screeded to grade. The aggregate was then saturated with the monomer system and finished with concrete trowels at 11:00 AM (Figure 41). There was some leakage at



REPAIR AREA 1



SECTION A-A

Figure 38. Repair Area 1 on Interstate Highway 35

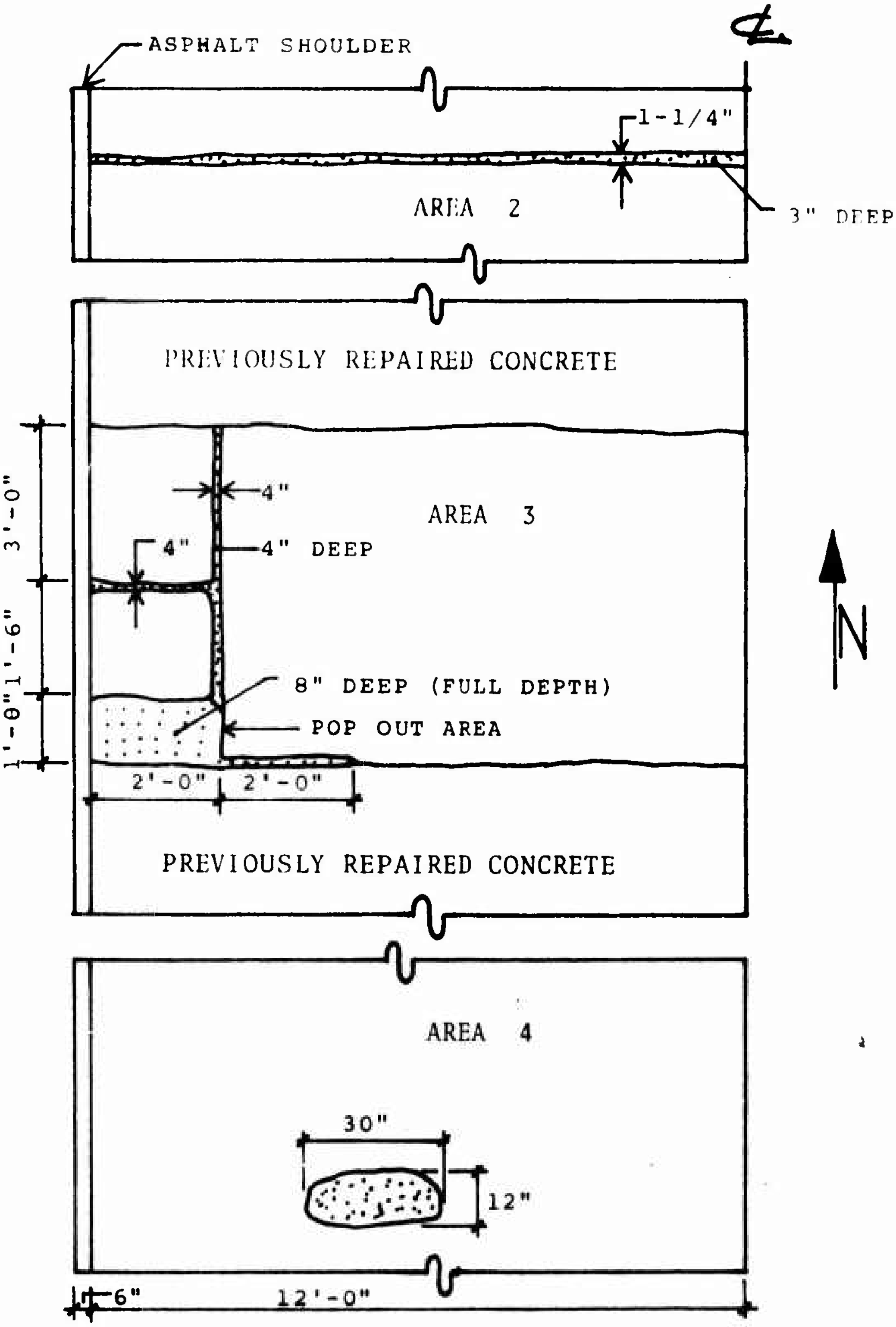


Figure 39. Repair Areas 2, 3, and 4 on Interstate Highway 35

Figure 40. Repair Area 1 After Removal of Concrete

Figure 41. Repair Area 3 Interstate Highway 35

the expansion joint and some runoff due to the slope of the repair which necessitated periodic monomer replenishment. The repair was covered with polyethylene to prevent monomer evaporation. Because of the low ambient temperature and leakage of monomer, the repair did not polymerize until 1:20 PM and was opened to traffic at 2:00 PM. A total of 60 liters of monomer was used to complete the repair.

Area 2. The transverse crack was air hammered with a spade bit to produce an opening about 1-1/4-inches deep and 3-inches wide the entire length of the 12-foot lane. The crack was filled with dry sand and then saturated with the monomer system. The surface was troweled smooth and the repair polymerized in approximately 1 hour.

Area 3. The third repair consisted of a punch-out and multiple cracks approximately 1/16-inch wide. The punch-out was a full-depth repair approximately 1 x 2 feet by 8 inches. The cracks were air hammered to a depth of 4 inches. The bottom of the full-depth area had standing water. Portland cement was sprinkled on the bottom to absorb the excess water since the monomer is practically insoluble in water. Vertical concrete cracks were coated with polyester putty to prevent leakage. Aggregate was placed in the void and at 3:45 PM saturated with a monomer system with increased promoter and initiator concentrations (Table 15). A faster-setting monomer system was used in an attempt to reduce monomer leakage into the subgrade. The repair was rodded to remove entrapped air. At 3:40 PM, additional monomer was added to keep the repair saturated. The surface was troweled smooth and covered with polyethylene. The repair polymerized at 4:00 PM and was opened to traffic before 5:00 PM. A total of 48 liters of monomer was used to complete Repair Areas 3 and 4 simultaneously.

Area 4. The fourth repair was a spall 30 x 12 x 4 inches after removing unsound concrete with an air hammer. Loose debris was blown free with compressed air and the area was filled with dry aggregate. The monomer was added at 3:30 PM and polymerization was completed by 4:00 PM.

6.2.3 Results

All repairs were structurally sound and opened to traffic immediately. The polymerization time of Area 1 was 2 hours and 20 minutes, but the other three areas were polymerized in 1 hour or less. The longer polymerization time of Area 1 was due to cool ambient temperature, leakage of monomer, and insufficient concentrations of promoter and initiator. A slightly rough texture was noticed in the third repair due to slight blistering on the surface of the PC. This was considered insignificant since it became smooth after exposure to traffic. A total of 116 liters of monomer was mixed for all repairs counting the excess not used.

TABLE 15. MONOMER FORMULATIONS - WACO INTERSTATE HIGHWAY 35

Area	Formulation (Percent)	Volume of Components
1 and 2	90 MMA	21,000 cc
	10 BA	2,400 cc
	4 LP	2 lb
	2 DMPT	480 cc
	1 SILANE	240 cc
		24,720 cc
3 and 4	90 MMA	21,600 cc
	10 BA	2,400 cc
	6 LP	3 lb
	3 DMPT	720 cc
	1 SILANE	240 cc
		24,960 cc

Three standard 3 x 6 inch concrete test cylinders were cast on the site and later tested. The average compressive strength was found to be 6710 psi with an average modulus of elasticity of 3.21×10^6 psi.

6.3 INTERSTATE 45 -- MADISONVILLE, TEXAS

6.3.1 Conditions

On May 24, 1977 several PC repairs were performed on the outside, southbound lane of Interstate Highway 45 near Madisonville, Texas. The weather condition in the morning was fair and warm after early morning rain. The afternoon was hot with temperatures in the range of 80° to 90°F.

All five areas repaired with PC were in a section of highway that was in constant need of repairs. The first four areas were located at mile post 140.5 (Figure 42). The first repair area was located at mile post 147.0, just north of the intersection with US 75 (Figure 43).

The 8-inch thick continuously reinforced concrete pavement was generally in poor condition. It was suspected that poor subgrade resulted in voids under the concrete, causing crack spacing only a few feet apart in some sections. The concrete was 15 years old and was easily air hammered.

6.3.2 Procedure

General Procedure. The preparation and repair of all the areas were performed in the following general method:

1. Unsound concrete was removed with an air hammer at least to the depth of steel, then loose debris was removed with compressed air (Figure 44).

2. The repair was sealed with polyester putty to seal cracks or protect asphalt shoulder (Figure 45).

3. The repair was filled with a sand and gravel mixture of dried aggregate (40:60 ratio by weight) (Figure 46).

4. Monomer was added to saturate the aggregate (Table 16) (Figure 47).

5. The PC was vibrated to remove entrapped air (Figure 48).

6. The surface was finished by screeding and then troweling to achieve the desired texture.

7. The repair was covered with polyethylene to prevent evaporation of monomer.

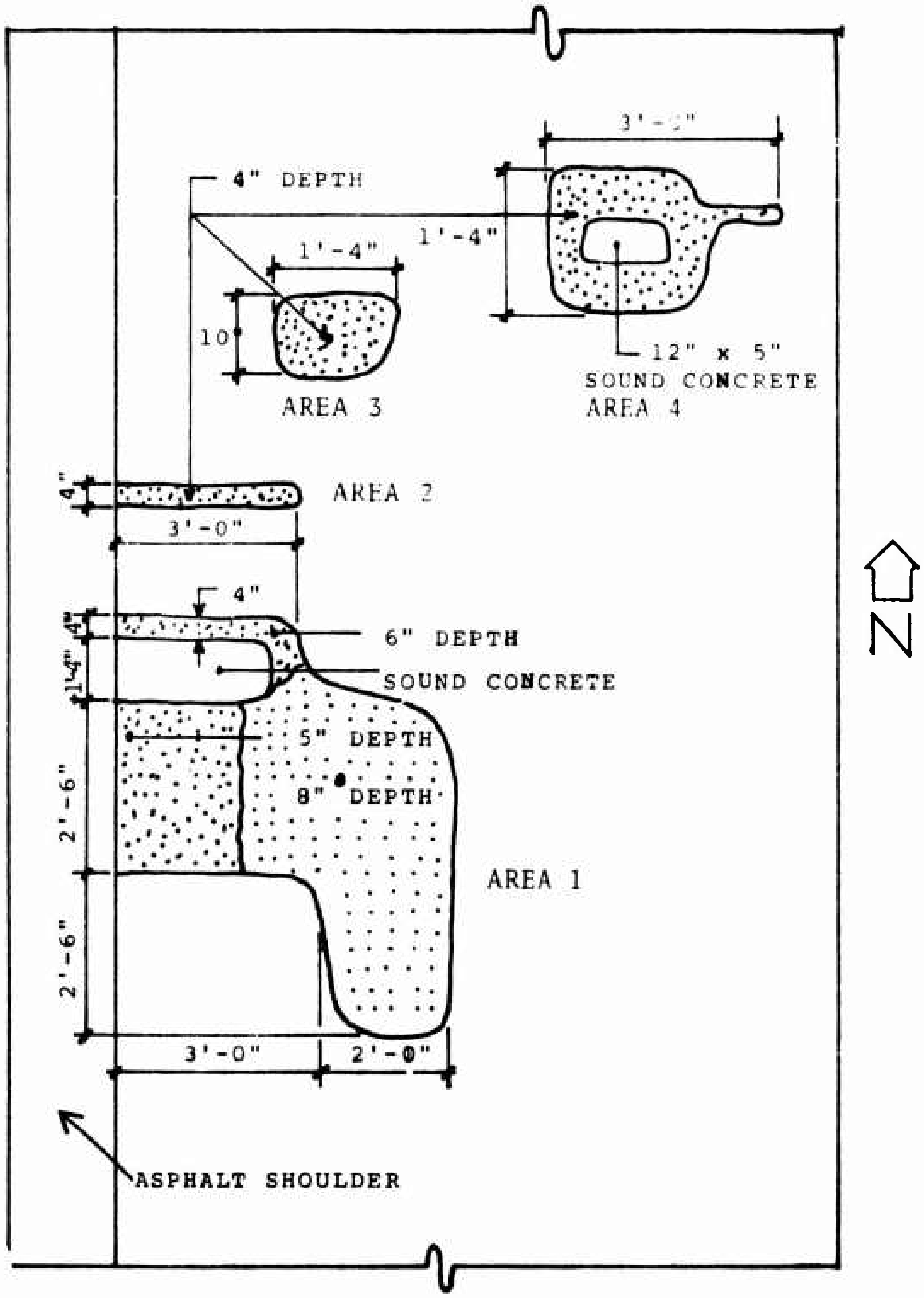


Figure 42. Areas 1 to 4 on Interstate Highway 45 (Milepost 140.6)

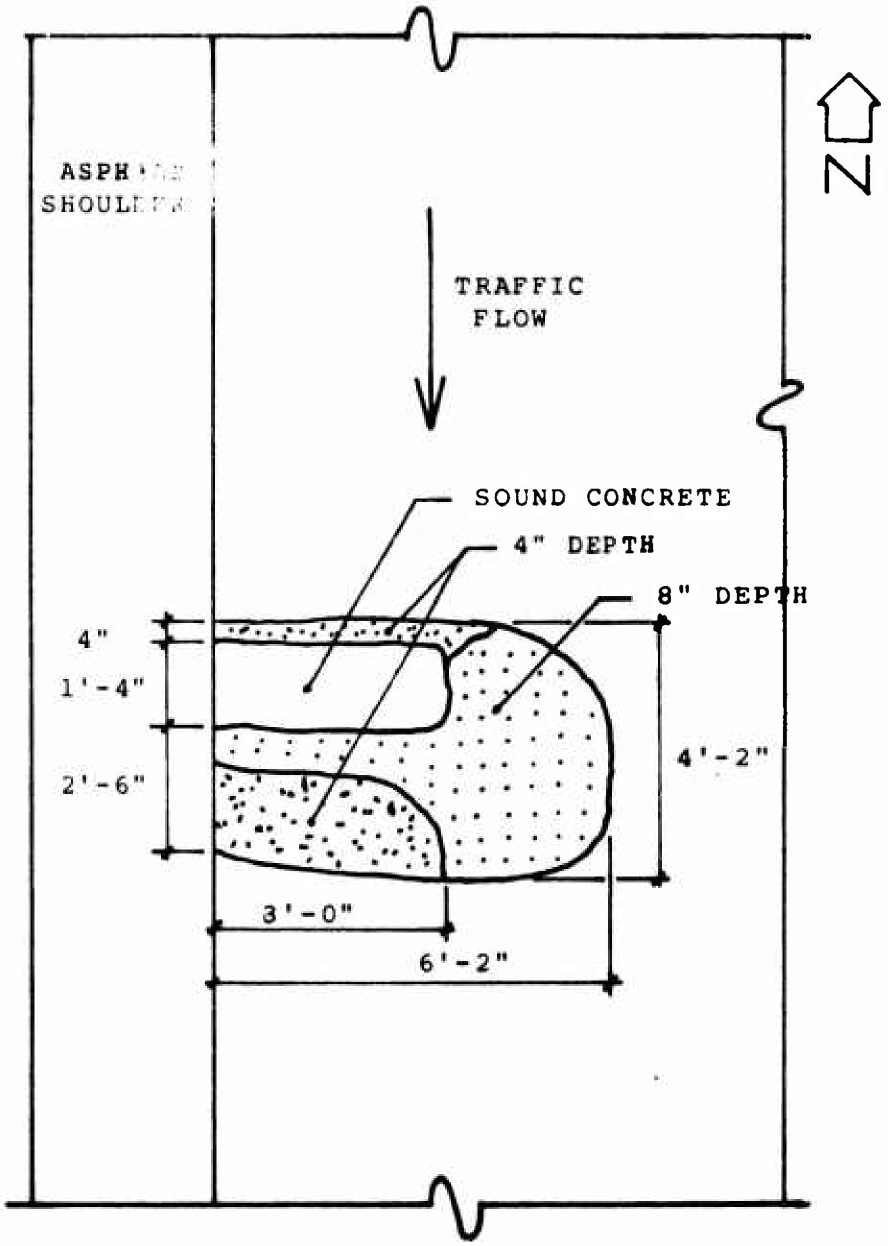


Figure 43. Area 5 on Interstate Highway 45 (Milepost 147)

Figure 44. Concrete Preparation

Figure 45. Polyster Putty Applied to Asphalt Should

TABLE 16. MONOMER FORMULATION - MADISONVILLE INTERSTATE HIGHWAY 45

Formulation (Percent)	Volume of Mix
90 MMA	21,600 cc
10 BA	2,400 cc
4 LP	2 lb
2 DMPT	480 cc
1 SILANE	240 cc
	24,720 cc

Figure 46. Dry Aggregate Added to Area 1

Figure 47. Addition of Monomer: Area 1

Figure 48. Vibration of PC: Area 1

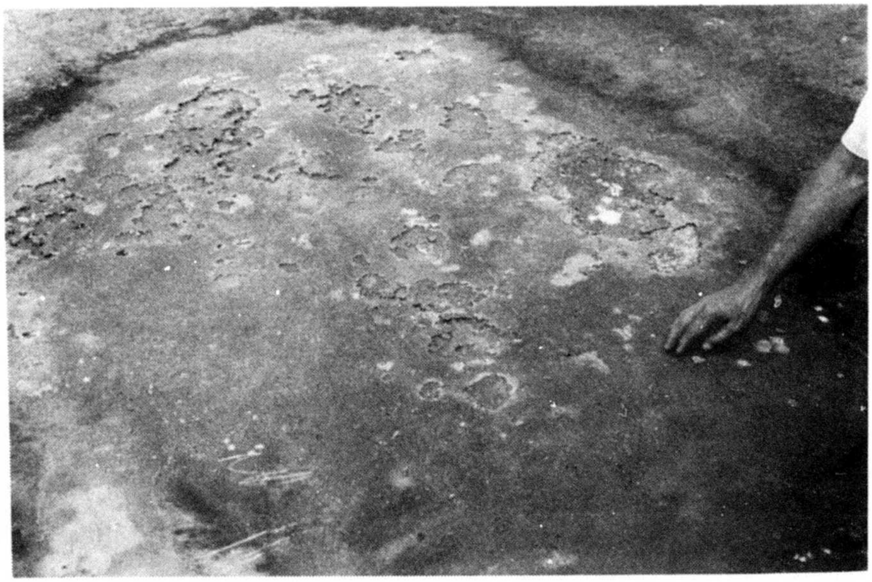


Figure 49. Screed Finish on Area 5

Area 1. By 8:00 AM all unsound concrete had been removed by highway department crews. The repair was bordered by an asphalt shoulder which had to be protected from the dissolving action of the monomer with polyester putty. The depth of the repair was 5 to 6 inches adjacent to the asphalt shoulder and in the cracked area at the north edge. The other parts of the repair were full depth (8 inches). This repair was performed in two lifts. Aggregate was added to about half depth, saturated (Figure 47), vibrated, then another layer of aggregate was added to grade, and the process repeated. The repair polymerized approximately 1 hour later.

Areas 2 and 4. Repairs in Areas 2 and 4 were identical to Area 1 with the exception of the aggregate being placed in only one lift due to the 4-inch depth.

Area 2 was crack approximately 3-feet by 4-inches. Area 4 was a spalled area with cracking, approximately 1 foot 4 inches by 2 feet.

Area 3. The repair in Area 3 was a spalled area approximately 1 foot 4 inches by 10 inches by 4-inch depth. This repair differed from the previous repairs because air hammering was needed. The sand was the only aggregate used. This repair was opened to traffic approximately 1 hour after the start of the repair.

Area 5. The repair in Area 5 was almost identical in size and shape to the first area repaired. The procedure was the same as for Area 1 with the exception that some of the cracked concrete was left in place to test the bonding of the PC. An attempt was made in this repair to leave a rougher surface texture by screeding the patch but not troweling it (Figure 49).

6.3.3 Results

All repairs polyermized in less than 1 hour and were structurally sound. The surface of Repair Area 1 exhibited surface blisters which were theorized to be caused by expanding air from the exotherm reaction being trapped below the semi-hard surface of PC (Figure 50). The effect is only cosmetic and the "blistered" skin is quickly worn away by traffic. The reason for a preliminary surface hardening was the high ambient temperature and rapid cure time. The surface of Area 5 which was screeded rather than troweled contained less blistering of PC. The blistering was absent in Repair Areas 2, 3, and 4 which suggested that blistering was more of a problem in the deeper repairs (Figure 51). Both Areas 1 and 5 indicated a slight volumetric expansion resulting in the surface being 1/8 to 1/4 inch above concrete grade.

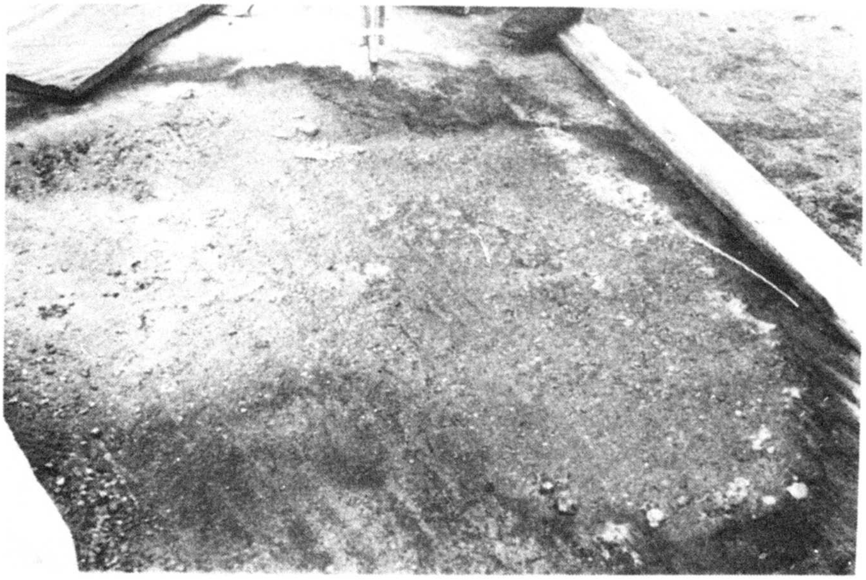


Figure 50. Blistering of Area 1

Figure 51. Finished Repair of Areas 3 and 4

Three standard 3 x 6-inch test cylinders of PC were cast on the site and later tested. The average compressive strength was found to be 6100 psi with a modulus of elasticity of 2.13×10^6 psi. Approximately 123 liters of monomer were used in all the repairs.

6.4 HOUSTON INTERCONTINENTAL AIRPORT

6.4.1 Conditions

On July 6, 1977, several PC repairs were performed on taxiway K of Intercontinental Airport in Houston, Texas. The morning repairs were performed under sunny skies as the temperature rose from 85° to 90°F. Repairs were halted in early afternoon by a 45 minute cloudburst. Repairs were continued in the afternoon with cooler temperatures of 75° to 80°F.

Taxiway K is a primary taxiway parallel to runway 8L-26R. Normal traffic includes air carrier operations up to and including FAA Designation Group III Aircraft (Boeing 747). Taxiway K is a rigid pavement 75 feet wide, divided into three equal slabs 25 feet wide, 25 feet long, and approximately 12 inches thick, with welded-wire fabric reinforcement. Repair Area 1 was a pop-out of a corner of the center slab which had temporarily been filled with asphalt. Repair Areas 2, 3, and 4 were on a single spalled longitudinal crack following the centerline of the taxiway from end to end of the slab. The concrete in all areas was in good condition and was difficult to remove with an air hammer.

6.4.2 Procedure

Area 1. The first repair was located at station 57 + 00 to 57 + 04, 12.5 feet south of the centerline (Figure 52). The repair measured 45 x 9 inches with depths varying up to 6 inches and was bounded by two expansion joints (Figure 53). A temporary asphalt repair was removed with an air hammer (Figure 54) and sandblasting (Figure 55). The repair was then cleaned of loose debris with compressed air. The removal of all asphalt was deemed necessary because asphalt tends to retard the curing of the monomer system. Wood strips were fitted along the two edges to maintain the expansion joints. An approximate 50:50 mixture by weight of oven-dried 3/8-inch topping rock and sandblasting was placed in the repair and leveled to grade. The monomer system (Table 17) was added until the aggregate was saturated (Figure 56). The repair was troweled with concrete trowels to produce a smooth finish (Figure 57). The total repair time of Area 1 was longer than normal because of several equipment breakdowns of the air hammer and sandblasting equipment. The monomer was not added until 12:00 noon, with final polymerization occurring by 1:10 PM (Figure 58). A total of 24,000 cc's of monomer was used to complete the repair, approximately twice the estimated amount because of severe leakage in the expansion joint.

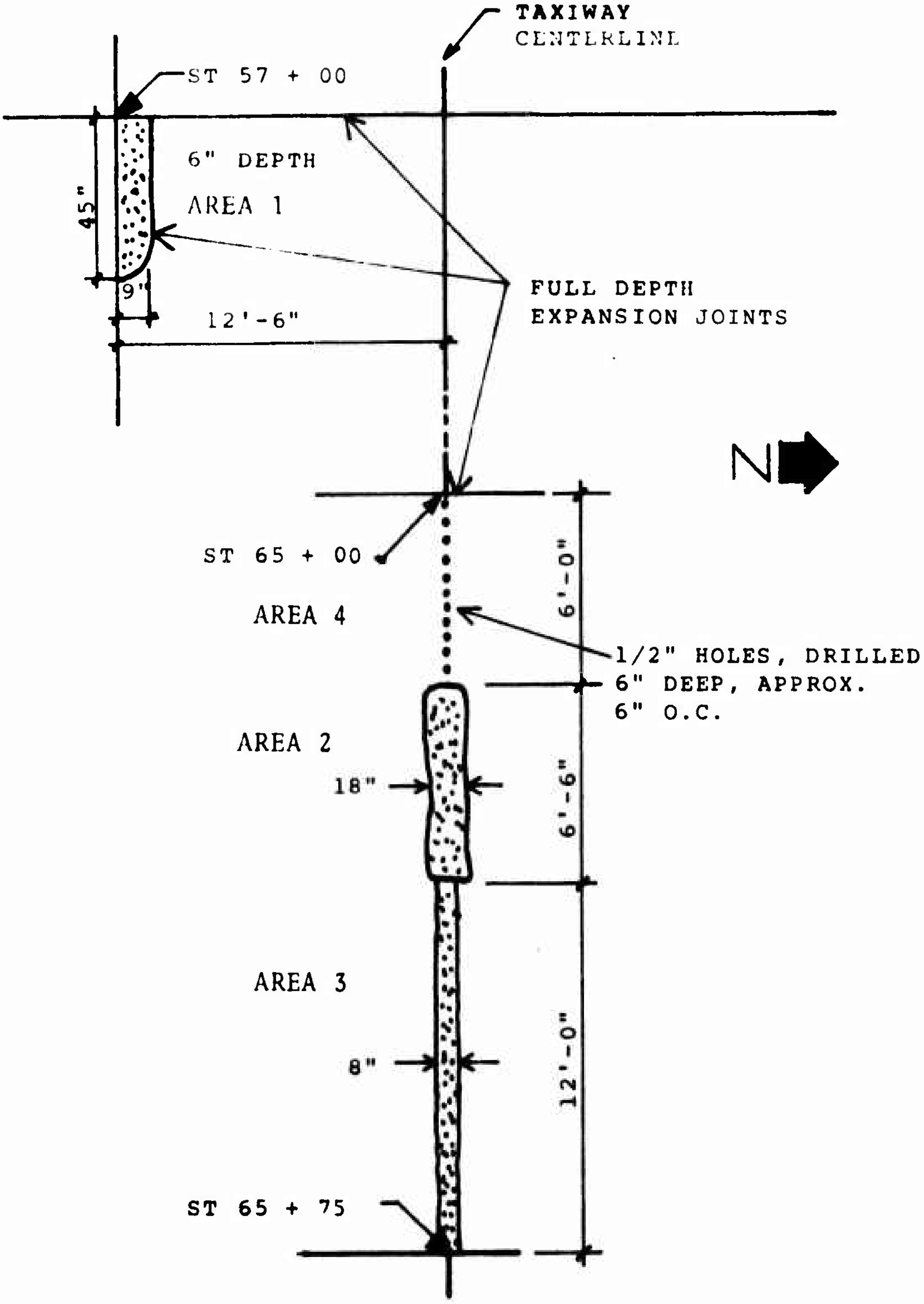


Figure 52. Repair Locations at Houston Intercontinental Airport

Figure 53. Repair Area 1

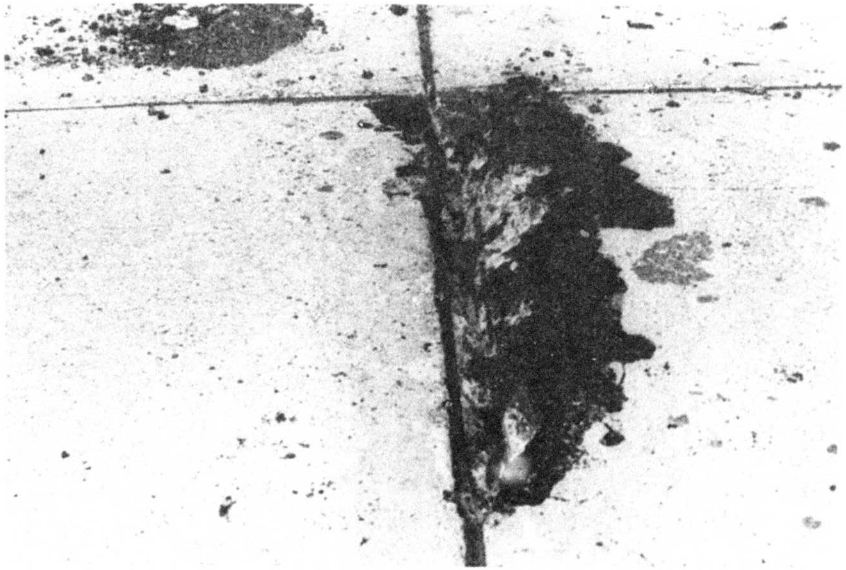


Figure 54. Repair Area 1 After Removal of Asphalt

Figure 55. Sandblasting Area 1

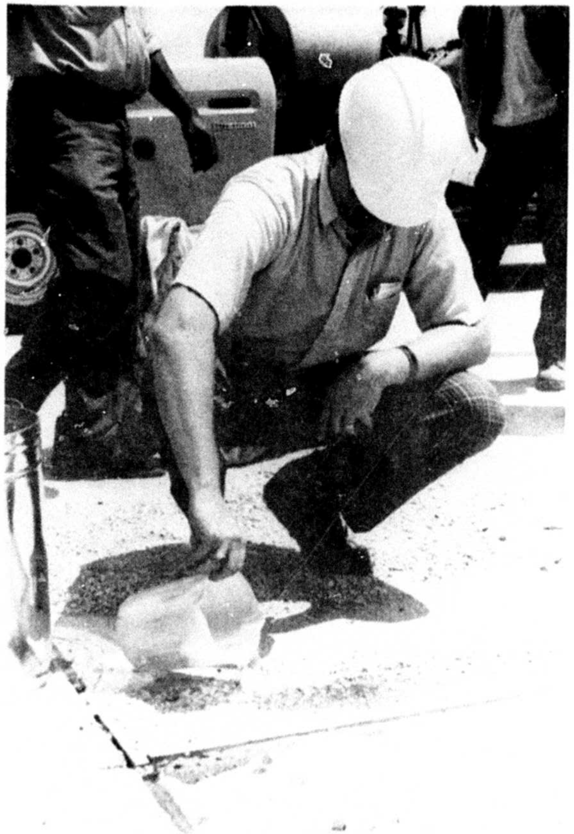


Figure 56. Adding Monomer to Repair Area 1

TABLE 17. MONOMER FORMULATION - HOUSTON INTERCONTINENTAL AIRPORT

Formulation (Percent)	Volume of Mix
90 MMA	21,600 cc
10 BA	2,400 cc
4 LP	2 lb
2 DMPT	480 cc
	24,480 cc

Figure 57. Troweling Area 1

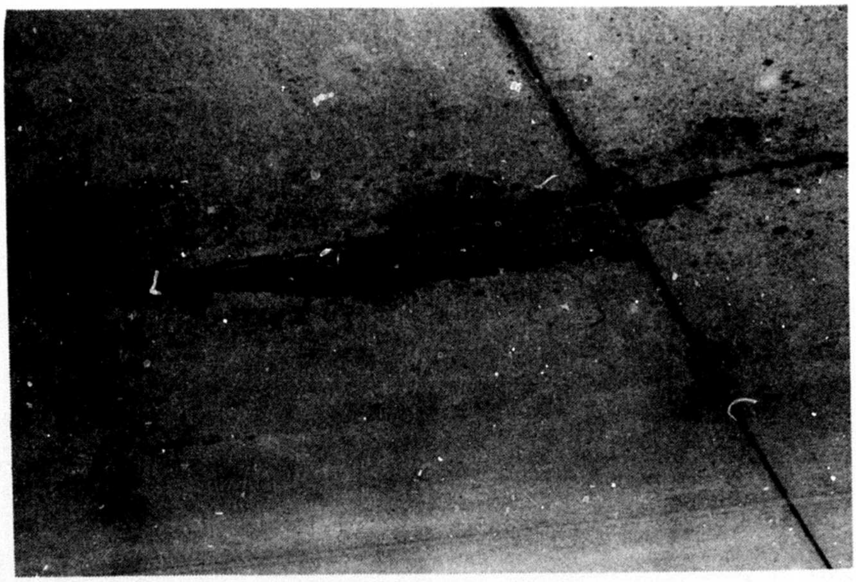


Figure 58. Completed Repair of Area 1

Area 2. The second repair was located at station 65 + 63 on the taxiway centerline. The same general preparation was used in Area 2 which measured 6.5 feet by 1.5 feet by 4 inches, with the exception that no asphalt had to be removed and no joints had to be sealed. The crack was air hammered to reach sound concrete, and debris was removed with compressed air (Figure 59). The sand and rock were mixed and placed in the repair (Figure 60). A total of 14,000 cc's of monomer was added and then the surface was troweled smooth (Figure 61). The total repair time was 1 hour. Removal of loose concrete was started at 1:15 PM, and aggregate and monomer were added at 1:45 PM, final polymerization occurred within 25 minutes due to the high ambient temperature. At 2:15 PM the repair was completed.

Area 3. Both the third and fourth repairs were located on the centerline adjacent to the second repair, station 65 + 63 to 65 + 75, and station 65 + 50 to 65 + 56, respectively (Figure 52). Area 3 repair was performed after a cloudburst using the same preparation. The repair had to be dried with a portable butane heater before adding monomer since water would reduce monomer penetration into the sound concrete voids thus reducing the bond strength (Figure 62). The repair area was 12 feet by 8 inches by 4 inches and required a total of 16,000 cc's of monomer to complete the repair. Work was started at 3:40 PM, monomer was added at 4:00 PM and polymerized in 35 minutes (4:35 PM), for a total elapsed time of approximately 1 hour.

Area 4. It was noticed during the removal of loose concrete from Area 3 that monomer from Repair Area 2 flowed into the crack up to 3 feet away and had polmerized, bonding the concrete together on each side of the crack. This discovery led to experimenting with a new technique for repair in Area 4. It was decided, rather than air hammer out the crack concrete, to drill 1/2-inch diameter holes 6 inches deep along the crack at approximately 6-inch intervals (Figure 63). The holes were filled with sand and saturated with monomer (Figure 64). The monomer cured in approximately 1/2 hour and appeared to have good penetration into the crack.

6.4.3 Results

All repairs were structurally sound and polymerized rapidly. Repair Area 1 polymerized in 70 minutes and the others in about 30 mintues each. Blistering of PC was observed in repairs of Areas 2 and 3 but not in Areas 1 and 4. By the time Areas 2 and 4 were repaired, the monomer, which was stored in a black drum and exposed to the sun, was relatively warm. Area 1 did not have blistering because of a longer polymerization time due to the leakage of monomer. Area 4 did not have blistering because of the small size of the repair. Area 2 did have volumetric expansion above grade of approximately 1/4 inch.

After all repairs were completed the taxiway was swept with a motorized sweeping machine, then opened to traffic at approximately 4:00 PM.

Figure 59. Repair Area 2

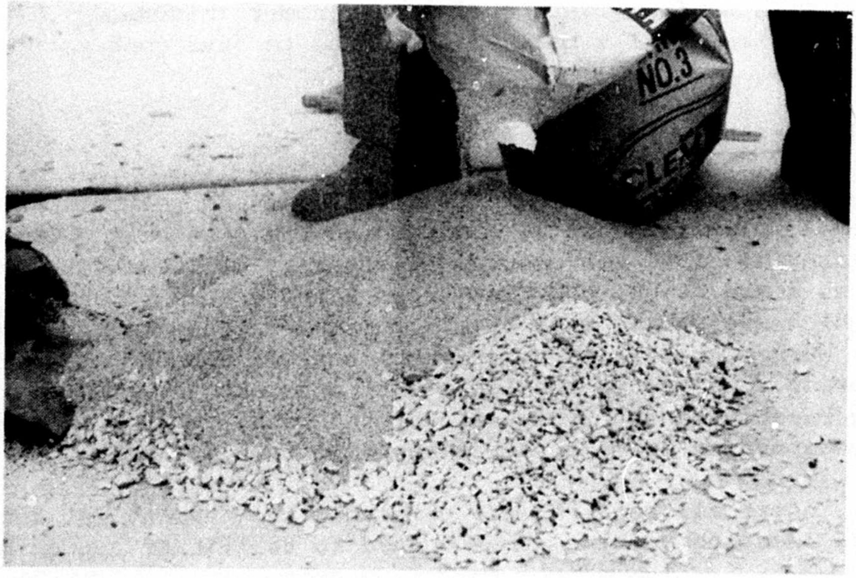


Figure 60. Mixing of Sand and 3/8-inch Topping Rock

Figure 61. Troweling Area 2

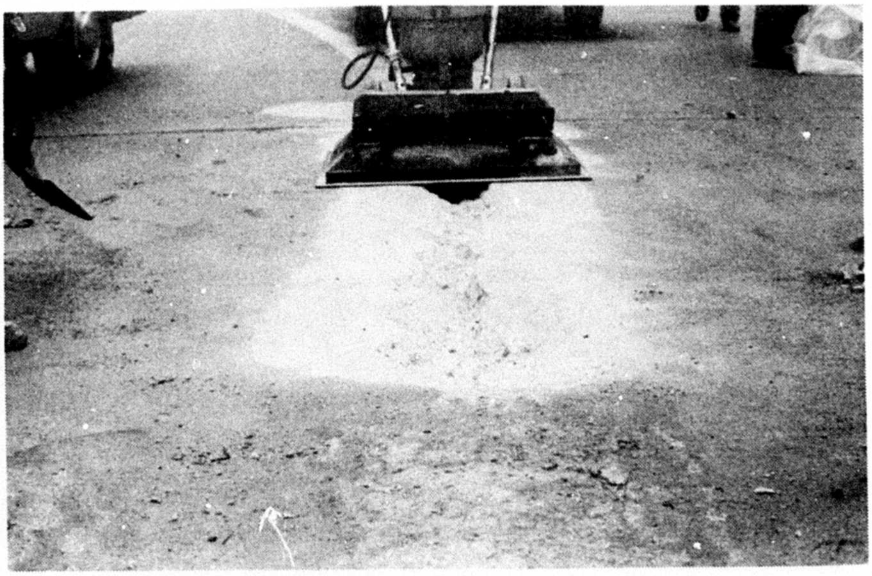


Figure 62. Drying Concrete of Area 3

Figure 63. Drilling Holes Along Crack in Area 4

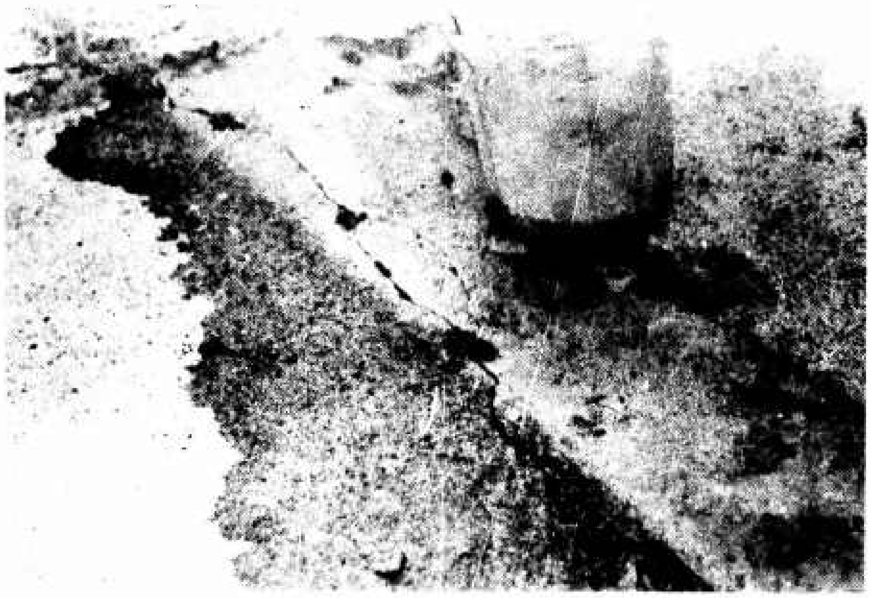


Figure 64. Saturating Area 4 with Monomer

6.5 SUMMARY

Three polymer-concrete field repairs were successfully polymerized in a very short time. All repairs were structurally sound and immediately opened to traffic. In some of the repairs during high ambient temperature, a blistering was noted on the surface but quickly wore away due to traffic. As of December 1977, the three described repairs and all other polymer-concrete repairs performed by the CFHR were still in service without any problems or signs of deterioration.

SECTION VII
ANALYSIS OF FIELD AND LABORATORY TESTS

This section analyzes the data and experience gathered in the laboratory tests and field repairs of Sections V and VI. The analyses of strength, rapidity of repair, problems and environment are discussed relative to large PC repairs of airfield pavements.

7.1 PROBLEMS ENCOUNTERED IN FIELD TESTS

7.1.1 Blistering of Polymer-Concrete

Blistering was a phenomenon observed in the field tests of PC at high ambient temperatures. This was potentially significant problem for airfield pavements because of the possibility of pieces of PC flaking off and being ingested into jet engines. A test was conducted to duplicate the conditions of the field tests and then to attempt to eliminate the blistering. The test was conducted at an ambient temperature of 100°F and the monomer was set in the sun to warm. Specimens were cast using 6 x 12 inch cylinders, one with the field test formulation and one with an identical formulation except the addition of 5 percent TMPTMA, a cross-linking agent. The experiment showed that blistering can be controlled with the addition of small amounts of TMPTMA (Figures 65 and 66). TMPTMA was then included as part of the standard formulation.

7.1.2 Leakage of Monomer

Leakage is a problem that has not been completely solved. The loss of monomer has been controlled in the laboratory by using watertight forms sealed with a commercial sealant. This is not always feasible in the field. Some success has been achieved with polyester putty in field applications that called for sealing joints and shoulders. It seems feasible to place polyethylene on the ground to act as a sealant for large PC repairs cast on grade. This method has not been attempted in the field on any large scale. However, leakage is not viewed as a major problem. It is probable that future research into this area will provide suitable answers for quick and efficient methods of casting large PC repairs on grade without excessive leakage. The use of an initial application of a more viscous formulation or a very rapid setting formulation would be effective in sealing the bottom of a hole.

Leakage alone does not cause a major structural problem if additional monomer is added to keep the PC saturated until it hardens. Leakage is not desirable because of the possibility of honeycombing occurring and because of the increased cost of both labor and material.

Figure 65. Test Cylinders with TMPTMA (Left) and Without TMPTMA (Right)

Figure 66. Close-up View of Blistered Speciment

7.2 Strength Analysis

Laboratory tests have shown that even under adverse conditions polymer-concrete has a higher compressive strength than concrete used for pavements. There are many factors that affect the strength of PC, with set time being the most significant.

The stress analysis showed that Slab 1 and Slab 2 withstood without damage considerably higher stresses than are normally subjected to concrete pavements. Slab 1 withstood 89,000 cycles of 18-kip dynamic loading without noticeable damage. The 2000 psi tensile stress associated with the 18-kip load which it withstood would be equivalent of 89,000 passes of an F-4 aircraft over a 4.5-inch thickness of PC on a subgrade with modulus of subgrade reaction, k , equal to 120 pci. The ratio of stress to modulus of rupture (stress-ratio) was 1.05. The stress-ratio of concrete required to carry the same number of repetitions would be 0.56 according to the Portland Cement Association (Reference 20). In other words, according to the PCA, concrete would be required to have a modulus of rupture equal to 3571 psi or roughly five times the normal values of high strength concrete. Or a concrete thickness of approximately 9 inches would produce the required stress for an unfactored stress ratio of 0.56 to achieve 100,000 equivalent applications of the 18-kip loading.

There are limitations to these comparisons of the slab tests and expected field conditions. The laboratory model was tested only at a temperature of 75°F and it has been shown that a reduction of strength and modulus of rupture would be present under higher ambient temperatures. It is quite feasible that under sunny conditions the surface of the PC could reach 130°F and the modulus of rupture would be reduced to approximately 1000 psi. Any temperature less than 75°F would increase strength, and theoretically increase the number of repetitions.

Another limitation in the strength comparison between PC and concrete is the variability of strengths in both the specimens cast in the field and laboratory. The variation of strengths between the PC in Slab 1 and Slab 2 is significant (Table 18). The only differences in construction between Slab 1 and Slab 2 were ambient temperature and aggregate gradation. The sand used in Slab 2 was more angular and had less fines which could make a significant difference in strength (Table 19).

In general it can be said that polymer-concrete has excellent strength properties, particularly tensile strength. However, to properly analyze and construct a design procedure for PC is beyond the scope of this study.

TABLE 18. COMPARISON OF PC PROPERTIES OF SLAB 1 AND SLAB 2

	Slab 1		Slab 2		Reduction (Percent)
Ambient Temperature during construction	72°F Indoors		80°F Outdoors		
Polymerization Time	1 hr 40 min		60 min		40
		Avg		Avg	
Compressive Strength (psi)	7369 7313 6365	7016	6337 6238	6288	10
Splitting Tensile Strength (psi)	1154 1198 1186	1180	925 943	934	21
Flexural Strength (psi)	1800 2044 1899	1911	1733 1467 1475	1558	18
Modulus of Elasticity (10^6 psi)	3.71 3.88 3.13	3.57	1.72 1.79	1.75	51

TABLE 19. COMPARISON OF SAND GRADATION IN SLAB 1 AND SLAB 2

Sieve Size	Percent by Weight	
	SLAB 1	SLAB 2
No 4 to 3/8-inch	0	6.3
No 8 to No 4	7.5	11.9
No 16 to No 8	13.4	12.3
No 30 to No 16	26.3	21.9
No 50 to No 30	31.4	31.2
No 100 to No 50	16.0	12.7
PAN	5.4	3.7
	100	100

Future research into the stress-ratio fatigue failures of PC beams and slabs would contribute significantly to the understanding of the behavior of this material. The predicted response of this material is slightly different than concrete because of its ability to take high compressive strains and deform without cracking. The behavior of PC in some ways is more similar to plastic than concrete which is reasonable because of the polymer binder.

If a design procedure was developed, it would have to include the temperature of the pavement when subjected to the design load. Tests would have to be made that would set an allowable stress-ratio for the number of repetitions desired. The results of the Slab 1 and Slab 2 tests tend to support a conclusion that a PC slab can support load for large number of repetitions of an apparent stress-ratio greater than one.

Failure in PC, based on the results of this study, seems to occur without prior cracking until failure. Modulus of rupture beams failed without visible prior cracking. The failure in Slab 2 was also without prior cracking. The absence of cracking and the large deflections seem to indicate a redistribution of stresses in the slab. It seems likely that Slab 2 started to crack on the bottom side when the modulus of rupture stress was exceeded. However, the steel apparently carried the tensile force and the top of the slab remained uncracked and continued carrying the load. The load continued until the top of the slab began to exceed its tensile stress, and then failure occurred at first crack.

If the load at failure in Slab 2 is considered to be the ultimate strength, it could be used in a factored design. This would indicate that PC can exceed its predicted modulus of rupture stress by over 300 percent. Conventional concrete analysis by Miner's hypothesis would require that the design stress ratio be approximately 0.71 for 1500 repetitions (Reference 20). The difference in these methods of analysis would give results between a 2.5-inch pavement and a 6.5-inch pavement for 1400 passes of the design F-4 aircraft. The large difference between the observed tests and the expected analysis supports the need for further research in this area.

7.3 ANALYSIS OF RAPIDITY OF REPAIRS

One of the primary advantages of this material is the relatively short time required to reach high strength. Unfortunately, as the time required for polymerization is reduced so is the strength. Therefore the time for polymerization must be optimized with respect to the design strength and the time required. In situations where high strengths are required and the set time required is relatively unimportant, the longer polymerization times would be preferable. In situations where time is the most critical factor a short polymerization time would be used, but depth may have to be increased to compensate for lower strength of the PC. Formulations have been developed that polymerized in only 14 minutes at 75°F and still have a compressive strength of over 6000 psi.

Ambient temperature is the major variable in the polymerization time of PC. Laboratory tests have proven that PC can be polymerized successfully at temperatures from -30° to 100°F. There is no reason to believe that these are limiting values, but rather they represent the limits of study. The low temperature study did suggest that benzoyl peroxide was the desired initiator for temperatures of 50°F or lower. Lauroyl peroxide does not readily dissolve in sufficient quantities at low temperatures. The limits of lauroyl peroxide in MMA seem to be approximately 6 percent at 75°F and less than 4 percent at 50°F. No problems were encountered in this study dissolving 50 percent benzoyl peroxide paste in sufficient quantities to polymerize MMA at temperatures as low as -30°F. If dissolving BP paste were a problem, the possibility exists of using a liquid form of benzoyl peroxide now commercially available.

Another way that the time to complete repairs could be reduced would be to have the monomer system premixed to only two components. It seems feasible to store MMA with TMPTMA and promoter already added. This premixing would permit polymerization by adding only initiator.

7.4 ENVIRONMENTAL CONDITIONS

Environmental conditions affect the ability to repair airfield pavements. As discussed earlier, the ambient temperatures affects the strength of PC, as well as the time required, for a particular formulation to harden. As previously discussed, PC can be successfully polymerized and adequate strength maintained in the normal range of temperatures. In fact, the ability of PC to be successfully polymerized at temperatures below 32°F is an advantage not shared by normal concrete or any other mixture that uses water. This advantage should be researched more fully and its possible applications fully developed.

One other environmental condition that usually plays havoc with most concrete pavement repair is rain. Although it is not likely that pavement repairs would be attempted in a pouring rain, it is possible that a repair will get rained upon while in progress. There is an incompatibility of water with monomers, but there seems to be a feasible solution. The monomer needs only to be protected from the rain during the polymerization process. If this time is kept short and the rain is intermittent, then the repair can be made if the adjacent concrete is dry. If there is no adjacent concrete or the area is small, a portable heater is adequate to dry the concrete surface. The Houston Intercontinential Airport repair was successfully polymerized by drying the concrete immediately after the thunderstorm. It is important for strength that the aggregate be kept reasonably dry.

SECTION VIII
MATERIAL CONSIDERATIONS

This section discusses the feasibility of concrete-polymer materials for rapid repair of airfield pavements. The safety, storage, and cost of monomers is discussed as well as the advantages and disadvantages of polymer-concrete.

8.1 SAFETY

8.1.1 General Precautions

Personnel using concrete-polymer materials must be knowledgeable of the safety requirements. Most monomers are generally volatile, combustible and toxic liquids. The training of workmen in the storage and handling requirements and other hazards is of greater importance. The use of these materials without the proper knowledge of safety procedures could lead to disaster and possible loss of life. Experience has shown that safety can be achieved if sound procedures are carefully followed. The manufacturers' instructions and safety procedures should be carefully followed (Reference 18).

One of the primary hazards is flammability and combustibility. MMA has a Tag closed cup flash point below $100^{\circ}F$ and is, therefore, a Class I flammable liquid as defined by the National Fire Prevention Association (NFPA) (Reference 19).

Care should be taken to avoid premature polymerization of monomers. Generally, catalyzed monomer should be added just prior to use. This is especially important when the promoter has already been added to the monomer. Care should be exercised during the handling of certain chemicals since excessive contact can cause ill effects and, in the case of some promoters, even death by absorption through the skin or inhaling the vapors. Care should also be taken that <u>promoters and initiators are never mixed directly together</u> as an explosive reaction could occur.

Disposal of waste or excess monomer can be hazardous unless accomplished by knowledgeable personnel. References 23 and 24 provide guidelines for disposal.

Although MMA and other monomers are hazardous, to place this in proper perspective a comparison must be made with other materials. Table 20 gives the "Sax" ratings of MMA and gasoline (Reference 21). The ratings show that MMA has a lower fire hazard rating than gasoline and lower acute local and acute systemic ratings. Although MMA requires trained and knowledgeable personnel to use it, the hazard level is acceptable. All the polymer-concrete materials are readily available and safely used in industry today.

TABLE 20. RATINGS OF INDUSTRIAL MATERIALS

	MMA	BA	GASOLINE	TURPENTINE
Flash Point	50°F	120°F	-45°F	95°F
Toxic Hazard Rating:				
Acute Local	Irritant 1	Irritant 2 Ingestion 2	Irritant 2	Irritant 2 Allergen 1
Acute Systemic	Ingestion 2 Inhalation 1	Ingestion 2 Inhalation 2	Ingestion 2 Inhalation 2	Ingestion 3 Inhalation 2 Skin Absorbtion 2
Chronic Local	U	U	U	Irritant 2 Allergen 2
Chronic Systemic	Ingestion 1 Inhalation 1	U	U	Ingestion 1 Inhalation 1 Skin Absorbtion 1
Fire Hazard	Moderate	Slight	Dangerous	Moderate
Explosion	Moderate		Moderate	Moderate

Toxic Hazard Rating Code

0 None - No harm under conditions.

1 Slight - Cause readily reversible changes which disappear after end of exposure.

2 Moderate - May involve both irreversible and reversible changes not severe enough to cause death or permanent injury.

3 High - May cause death or permanent injury after very short exposure to small quantities.

U Unknown - No information on humans considered valid by authors.

8.1.2 Storage and Handling Precautions

In general, the guidelines furnished by the manufacturer should be followed. For protection of personnel, it is recommended that each operator be provided with neoprene gloves and safety goggles. Personnel should be properly clothed and wear suitable footwear.

It is advisable that chemcial fire extinguishers be available. All spark-producing equipment must be kept away from monomer or be grounded or equipped with explosion-proof motors. As with all flammable materials, smoking should not be permitted. Initiators should not be stored in the same room as the monomers and promoters.

8.1.3 Personnel Training

Crews should be given the necessary training and knowledge of the chemicals they work with. It is important that crews be able to work confidently and properly while learning to respect rather than fear the chemicals. For example, dry benzoyl peroxide is extremely hazardous to work with because it is shock-sensitive, friction-sensitive, and in large quantities, self-confining, but benzoyl peroxide is also available in less hazardous forms. The proper knowledge of the chemical used is important in its handling characteristics. Several large construction projects using concrete-polymer materials have beeen completed without injury to workmen.

8.2 STORAGE

Storage of monomers and other chemicals can be safely accomplished for various lengths of time. MMA can be stored for longer than 1 year at 68°F with small inhibitor concentrations (Reference 19). It is recommended that MMA be checked periodically for inhibitor concentrations and additional inhibitor added if necessary. At normal temperatures, the shelf life of each chemical used in PC is at least 6 months and generally more. It is strongly recommended that monomer containing initiator not be stored for more than a very short time.

8.3 COST ANALYSIS

The initial cost of materials is often an important characteristic in the use of the material. The current prices of the individual components of PC are listed in the Appendix. Based on the formulation of 95 percent MMA, 5 percent TMPTMA, 3 percent LP, and 1-1/2 percent DMPT, the cost is approximately $0.73 per pound based on buying the materials in relatively small quantities. It could be reduced to $0.61 per pound by buying in large quantities. This could be reduced to $0.55 per pound by purchasing the MMA in bulk shipments.

Using the $0.73 per pound figure, the repairs made in the field cost approximately $10 to $13 per cubic foot of repair for the chemicals alone based on 25 to 30 percent by volume. This figure could be reduced by using an aggregate gradation that had a smaller pore volume and, thereby, using a lower percentage of monomer. Proper sealing to prevent leakage of monomer would reduce this cost even further.

The total cost of a repair depends on the volume repaired. A 70-foot diameter repair could be repaired at a depth of 4.5 inches for a cost of $6050 to $7560 for the monomer system alone. This is a conservative range and could probably be reduced. The labor cost should be no more and perhaps less than for ordinary concrete repairs, since the premixing of monomer and aggregate is not required. Finishing is just as fast, and the clean-up is negligible.

8.4 ADVANTAGES OF POLYMER-CONCRETE

PC has many advantages as a repair material. One of the most obvious advantages is its high compressive and tensile strength. PC has approximately 300 percent of the tensile strength of normal concrete.

Another important advantage is the speed and relative simplicity of the repair procedure. The procedure is very similar to the placement of normal concrete. Total repair times from start to finish of small areas can be kept to less than 30 minutes.

Another advantage of PC repairs is the extremely good bond to existing concrete. The low viscosity of the monomer permits it to penetrate into dry concrete and the resulting polymerization strengthens the concrete.

PC has also been shown to be both durable and highly fatigure resistant (Reference 5). Tests have shown that PC has a much better resistance to freeze-thaw cycles than normal concrete. Tests in progress at the University of Texas include some PC specimens that have withstood over 150 freeze-thaw cycles with little or no damage. This is due primarily to the very low water absorption of PC which is less than 1 percent (Reference 11).

8.5 DISADVANTAGES OF POLYMER-CONCRETE

The primary disadvantage of PC is the initial material cost which is greater than conventional concrete. However, the savings in time and labor, the durability, and apparent longer life make PC economically feasible for many types of repairs.

Another possible disadvantage that has not been fully tested is the susceptibility to fire. Preliminary tests were conducted by BNL in accordance with ASTM D635-68: "Flammability of Self Supporting Plastics." The results of these tests indicate that PC does not sustain combustion, but is decomposed by sustained fire (Reference 5).

Another possible disadvantage that has not been fully tested is the creep characteristics of PC. Tests are under way at the Univesity of Texas, but preliminary findings seem to indicate that PC has acceptable creep characteristics for repair applications.

8.6 APPLICATIONS OF POLYMER-CONCRETE

PC seems to be a suitable material for patching spalls, cracks, and punch-outs in portland cement pavements. The quick curing time and high strength make it an ideal material for repairing bomb-damaged, portland cement pavements. The ability to polymerize at low temperature supports the possibility of making PC repairs at all temperatures.

Future applications of PC should be explored in the area of PC overlays for distressed pavements. Even the possibility of expedient, remote-airfield paving with PC could be explored. Polymer-concrete with the addition of a plasticizer such as butyl acrylate could be used as a joint sealer.

SECTION XI
CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

A liquid monomer system mixed with aggregate can be successfully polymerized to produce polymer-concrete (PC). The resulting PC has high strength, excellent bond to concrete, and is very durable. This investigation represents a continuation of earlier studies to use PC as a crack repair material.

The basic monomer system consisted of methyl methacrylate (MMA), trimethylolpropane trimethacrylate (TMPTMA), dimethyl-p-toluidine (DMPT) and either lauroyl peroxide (LP) or benzoyl peroxide (BP).

Tests were conducted to accomplish three principal objectives. First, tests were conducted to isolate the major variables that affect the polymerization time. Second, tests were conducted to define the variables that affect the strength of PC. Finally, laboratory and field tests were conducted to test the strength of PC as a repair material for concrete.

The following conclusions can be made:

1. Ambient temperature is a major variable affecting the polymerization time of PC. The polymerization time increases at an exponential rate as ambient temperature decreases.

2. Promoter and initiator concentrations can be varied to change the rate of polymerization. The promoter and initiator concentrations can be used to control the polymerization time with respect to ambient temperature.

3. Inhibitor concentrations of the monomer and sample size each have smaller affect on polymerization time.

4. Polymer-concrete gains strength as a result of the exotherm reaction and exhibits no significant increase in strength with respect to time after the reaction.

5. The strength of PC is dependent to a great extent on the temperature at testing. The higher the temperature, the lower the strength of PC.

6. As the polymerization time is decreased, the compressive strength of PC decreases.

7. The aggregate gradation should be monitored to minimize the ratio of voids to aggregate to maximize strength.

8. The moisture content of the aggregate should be kept as low as possible to maximize both compressive and tensile strengths.

9. The performance of PC slabs subjected to fatigue loadings was much better than equal thickness concrete slabs with respect to crack development and load capacity.

10. A 2-inch PC slab tested in the laboratory developed ultimate stresses at failure that were much higher than predicted by theory. Cracking was also predicted at much lower loads.

11. The poor agreement between theory and observed behavior may be indicative of much better distribution of stresses than for portland cement concrete.

12. Successful repairs have been made on concrete pavements of both Interstate Highways and airport taxiways.

13. The relative cost of PC repairs were from $10 to $13 per cubic foot of repair (1977 prices).

9.2 RECOMMENDATIONS

The rapid repair of airfield pavements with PC appears to be an excellent means of patching and restoring damaged concrete on a permanent basis. The ability to repair pavements at any temperature in a very short time makes PC an excellent prospect for repair of bomb-damaged runways and taxiways under dry conditions. For future development and acceptance of this method the following studies should be implemented immediately.

1. Investigation of ways to reduce the effect of moisture on strength of polymer-concrete.

2. Investigation of the feasibility of making polymer-concrete repairs on asphalt-overlayed pavements.

3. Development of a simple and rapid procedure for repairing large areas.

If the above studies appear favorable for future development the following studies are recommended:

4. Studies to determine the optimum monomer system to be used at specific ambient temperatures.

5. Studies to determine the optimum procedure to minimize cost and repair time.

6. Investigation of the behavior of polymer-concrete pavements over short and long-term traffic.

7. An analysis of polymer-concrete to determine a thickness design procedure for military aircraft.

8. Demonstration of the most promising materials and procedures on full-scale repairs.

APPENDIX

CHEMICALS

CHEMICALS

A. Monomers

1. Methyl Methacrylate (MMA)

Formula	Specific Gravity	(20°C) Viscosity	Flash Pt.	T_G
$C_5H_8O_2$	0.950	0.6 cps	70°F	200°C

Sources:

DuPont Company
Polymer Products Division
Wilmington, Delaware 19898

Rohm and Haas Company
Independence Mall West
Philadelphia, Pennsylvania 19105

Current Price: (Rohm and Haas)

Bulk	$0.41/pound
(54 drums) truckload	$0.47/pound
30-53 drums	$0.48/pound
15-29 drums	$0.49/pound
5-14 drums	$0.50/pound
3-4 drums	$0.52/pound
1-2 drums	$0.54/pound

2. Butyl Acrylate (BA)

Formula	Specific Gravity	(20°C) Viscosity	Flash Pt.	T_G
$C_7H_{12}O_2$	0.9003	1.0 cps	105°F	-65°F

Sources: Rohm and Haas Company

Celanese Chemical Company
1211 Ave. of the Americas
New York, New York 10036

Current Price: (Rohm and Haas)

Bulk	$0.38/pound
truckload	$0.44/pound
30-53 drums	$0.46/pound
15-29 drums	$0.47/pound
5-14 drums	$0.48/pound
3-4 drums	$0.49/pound
1-2 drums	$0.51/pound

3. Trimethylolpropane Trimethacrylate (TMPTMA)

Formula	Specific Gravity	Viscosity	Flash Pt.	T_G
$C_{18}H_{26}O_6$	1.06	50-100 cps	>200°F	>370°F

Sources: Rohm and Haas Company - (monomer X-980)

Celanese Chemical Company

Current Prices: (Celanese)

2 drums	$1.25/pound
1 drum	$1.50/pound
5 gallons	$2.50/pound
1 gallon	$5.00/pound

B. Initiators

1. Benzoyl Peroxide (BP)

Sources: Lucidol Division Pennwalt Corp
1740 Military Road
Buffalo, New York 14028

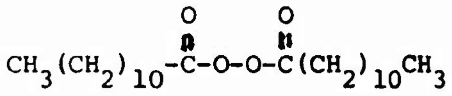
Noury Chemical Corp
Burt, New York 14028

Reichhold Chemicals Inc.
White Plains, New York 10602

Dry Powder Form	Lucidol 98 (Lucidol)	$2.55/pound	< 500 lbs
Dry Powder Form (50 percent)	Caddox BFF-50 (Noury)	$2.47/pound	< 500 lbs
Paste Form	Lucidol 78 percent	$2.20/pound	
	Lucidol 70 percent	$2.20/pound	
	Reichhold 50 percent	$1.71/pound	
	Noury 55 percent	$1.94/pound	
Liquid Form (40 percent)	Reichhold	$1.50/pound	
	Noury	$1.64/pound	

2. Lauroyl Peroxide (LP)

Formula:



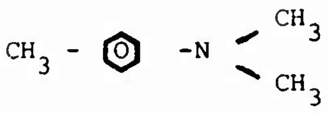
$$CH_3(CH_2)_{10}-\overset{O}{\overset{\|}{C}}-O-O-\overset{O}{\overset{\|}{C}}(CH_2)_{10}CH_3$$

Source: Lucidol Division Pennwalt Corp

Current Price: $2.30/pound (ALPEROX)

C. Promoters

1. N,N-Dimethyl-para-toludine (DMPT)

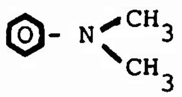
Formula: 

Source: RSA Corp
690 Saw Mill River Road
Ardsley, New York 10502

Current Price:

5 gallon	$5.00/pound
110 lb drum	$4.50/pound
450 lb drum	$4.00/pound
multiple drum orders	

2. Dimethyl Aniline (DMA)

Formula: 

Source: American Cyanamid Company
Organic Chemicals Division
Bound Brook, New Jersey 08805

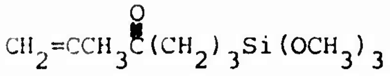
Current Price:

Bulk	$0.57/pound
(24,000) truckload	$0.63/pound
440 pound drum	$0.66/pound
40 pound pail	$1.16/pound

D. Silane Coupling Agent

1. γ-methacryloxpropyltrimethoxysilane

Formula:



$CH_2{=}CCH_3\overset{O}{\overset{\|}{C}}(CH_2)_3Si(OCH_3)_3$

Source: Dow Corning (Z-3060)

Union Carbide (A-174)
Chemical and Plastics Sales Office
2710 Stemmons Freeway Suite 700
Dallas, Texas 75207

Current Price: (Union Carbide)

1 gallon	$11.00/pound
40 pound pail	$ 8.20/pound
440 pound drum	$ 7.20/pound

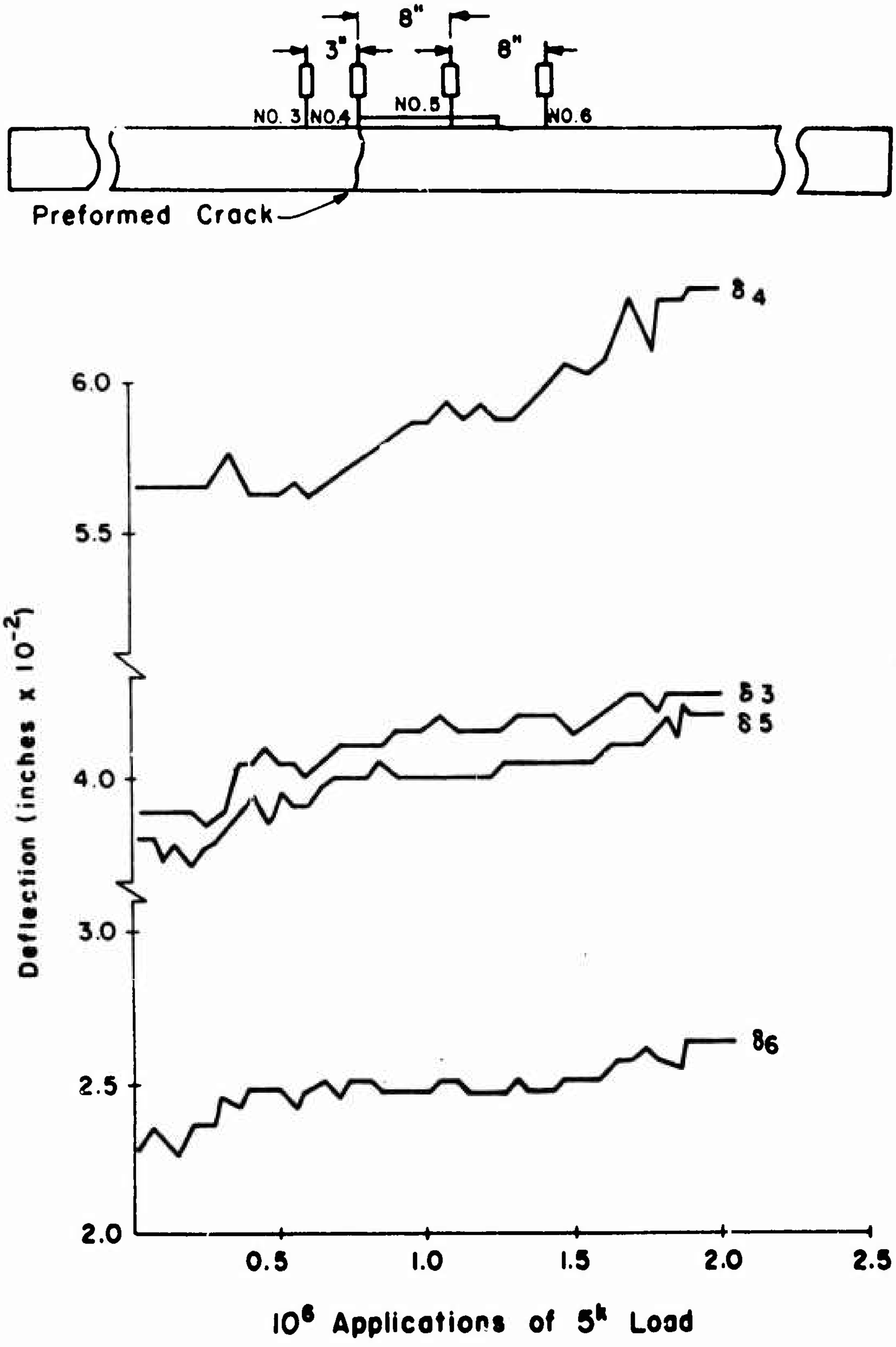


Figure 67. Deflection Profile of Slab L-5;
4-inch Concrete with Uniform Support
(Reference 20)

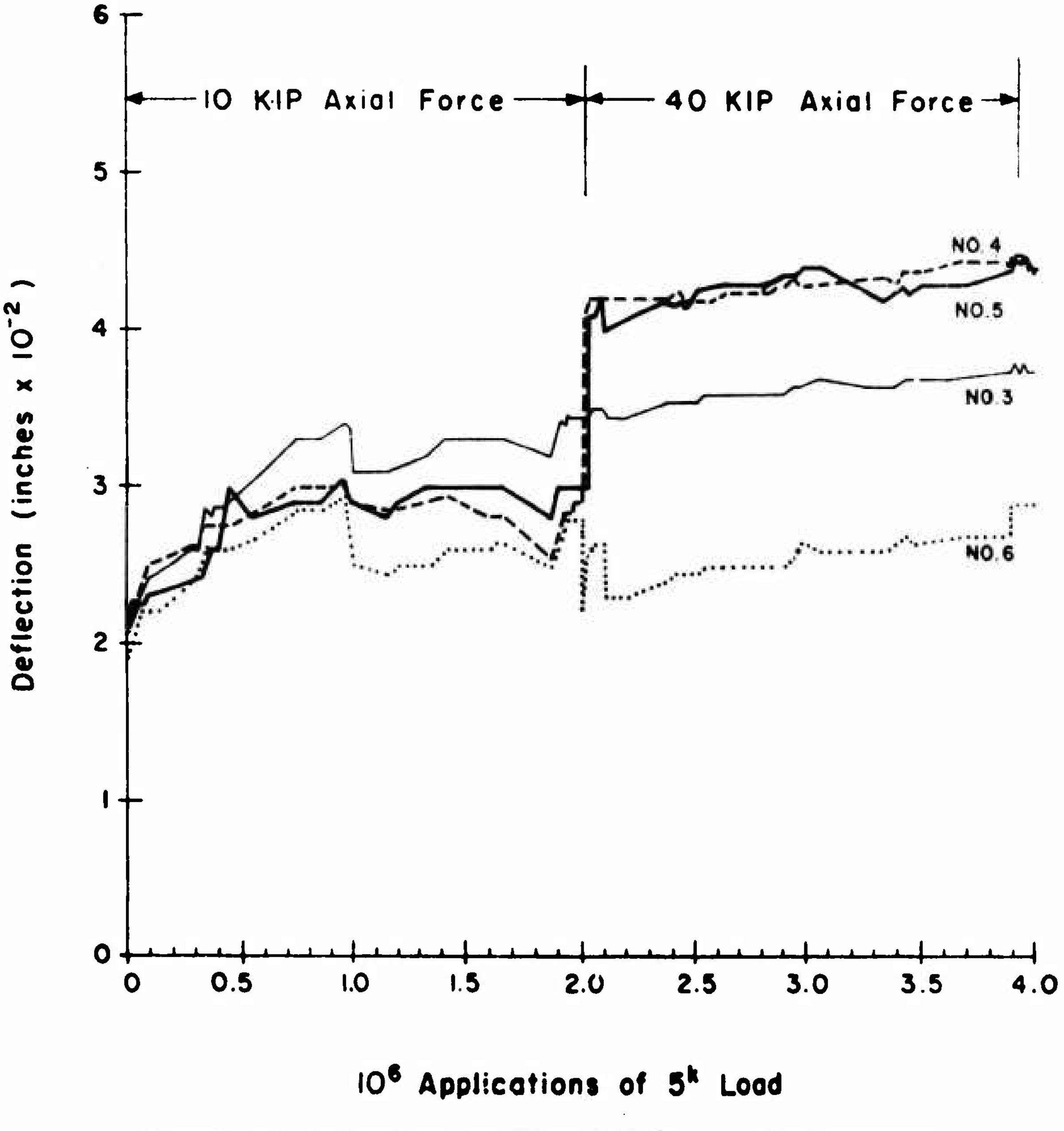


Figure 68. Deflection Profile of Slab 1: 4-inch Concrete with PC Patch, Voided Support

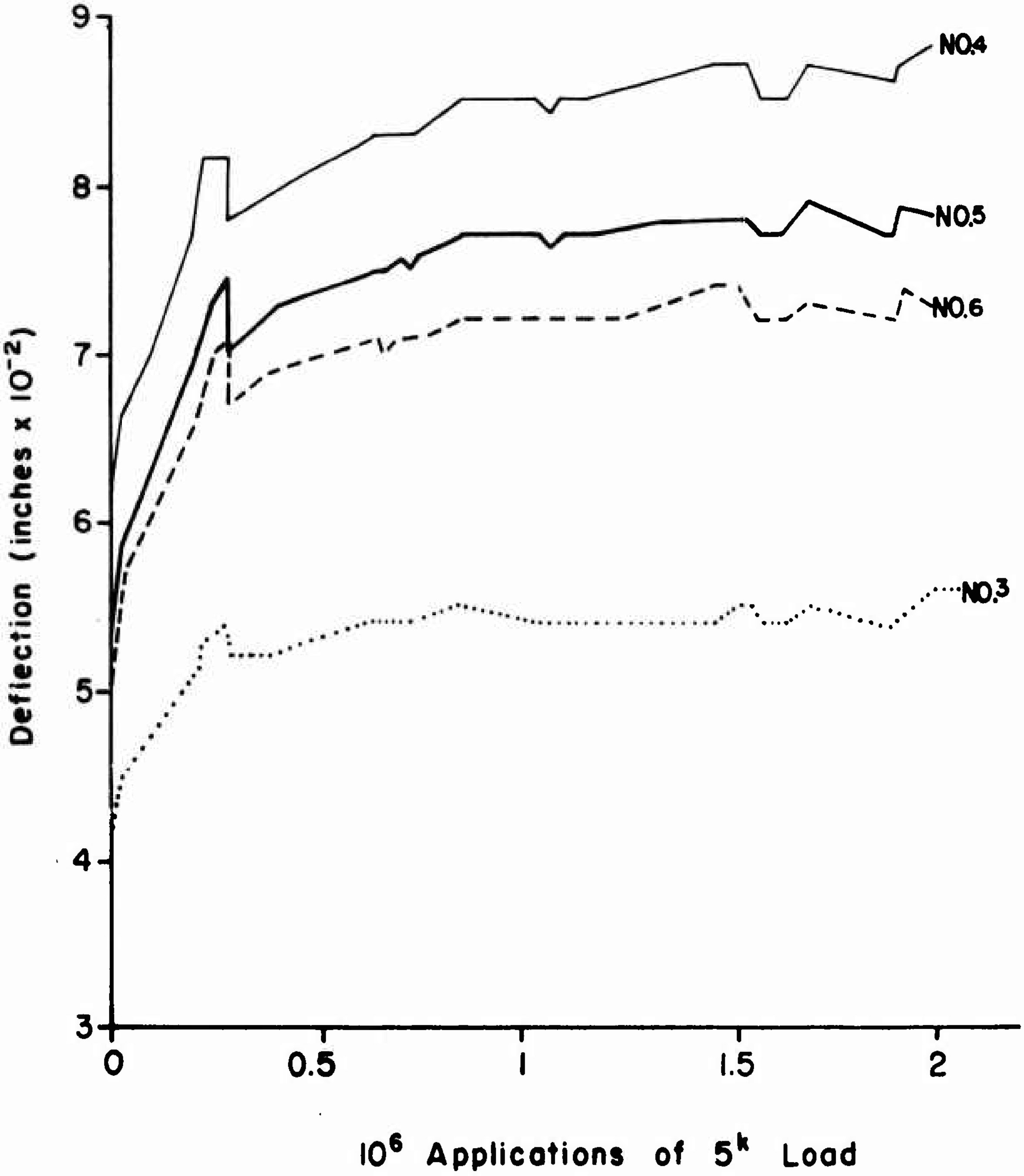


Figure 69. Deflection Profile of Slab 2:2 Inch PC Slab With Voided Support

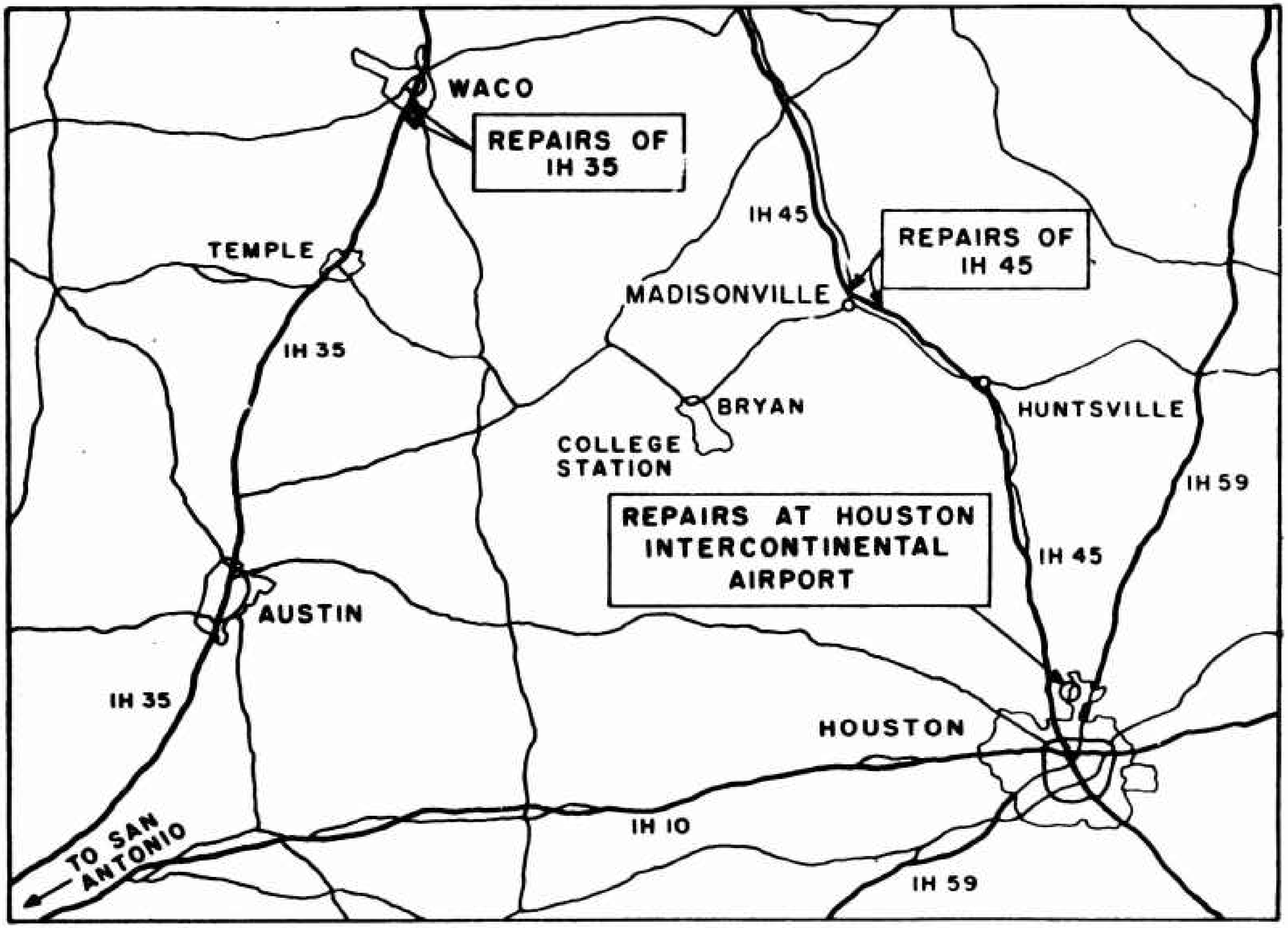


Figure 70. Location of Field Repairs

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