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16. Abstract

Polymer concrete has been used for several years to repair concrete bridges. This report summarizes research performed to develop materials and procedures for repairing concrete pavements. Optimization studies were performed to develop monomer formulation which would cure in one hour or less over a wide range of ambient temperatures and still provide good flexural strength. Methyl methacrylate was the primary monomer. The effects of aggregate size and type, casting temperature and testing temperature on strength were investigated. The use of thickener and colorants was studied to provide a polymer concrete similar in workability and appearance to commercially-available materials. The use of steel fiber reinforcement was investigated.

A large number of field repairs are reported. Repairs included cracks, spalls and punchouts. Several methods of placing polymer concrete were used, saturation of preplaced aggregate by pouring or injecting monomre, and mixing commercially-available and user-formulated materials in concrete mixers. Costs for many of the repairs are shown. Repair evaluations, including before and after deflection measurements, were made.

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POLYMER CONCRETE FOR PAVEMENT REPAIR AND REHABILITATION

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Research Project 3-18-79-246

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PREFACE

The work reported herein was possible because of the excellent cooperation of many people: John Nixon and Jon Underwood, D-10; Gerald Peck, D-8; Donald O'Connor, D-9; Ray Brown and Ralph Banks, D-18; and John Nichols, Federal Highway Administration. The field tests were possible because of the very good cooperation of many districts thoughout the state. The help of all of the state and federal personnel is greatly apprieciated.

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ABSTRACT

Polymer concrete has been used for several years to repair concrete bridges. This report summarizes research performed to develop materials and procedures for repairing concrete pavements. Optimization studies were performed to develop monomer formulation which would cure in one hour or less over a wide range of ambient temperatures and still provide good flexural strength. Methyl methacrylate was the primary monomer. The effects of aggregate size and type, casting temperature and testing temperature on strength were investigated. The use of thickener and colorants was studied to provide a polymer concrete similar in workability and appearance to commercially-available materials. The use of steel fiber reinforcement was investigated.

A large number of field repairs are reported. Repairs included cracks, spalls and punchouts. Several methods of placing polymer concrete were used, saturation of preplaced aggregate by pouring or injecting monomer, and mixing commercially-available and user-formulated materials in concrete mixers. Costs for many of the repairs are shown. Repair evaluations, including before and after deflection measurements, were made.

SUMMARY

Polymer concrete for use in repair of portland cement concrete pavements is described. Methyl methacrylate monomer is used in all of the polymer concrete systems used. Formulations are given which will cure in less than one hour over a wide range of ambient temperatures. Mechanical properties are given for several variables. A polymer concrete system was developed which has similar workability and appearance characteristic to commercially available materials. Field repairs are described, and material cost and performance evaluations are presented.

IMPLEMENTATION

Polymer concrete has already been used as a repair material in many districts for several years. Repairs include cracks, spalls, and punchouts. Several large repair jobs have been performed by contractors using the results of this research. the cost and performance of the methyl methacrylate polymer concrete has been shown to be reasonable in comparison with other rapid repair materials.

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CHAPTER 1

INTRODUCTION

1.1 Use Of Polymer Concrete

Polymer concrete has been used for many repair applications of portland cement concrete, including bridge decks and pavements. Both user-formulated and commercially-produced systems are available. Methyl methacrylate (MMA) is the primary monomer used although other monomers and polymers, including polyesters and epoxies, have been used (Refs 1, and 2).

The strength properties of polymer concrete used for repair are superior to ordinary portland cement concrete; the compressive strength ranges from 7000 to 10,000 psi, and the modulus of rupture ranges from 1500 to over 2000 psi. However, shrinkage and coefficient of thermal expansion are higher.

Polymer concrete has been made by saturation of preplaced aggregrate and by premixing the materials in concrete mixers or batching equipment. Commercially-available polymer concretes must be premixed because of their higher binder viscosity. The curing time of most polymer concrete ranges from 30 to 60 minutes, which permits the repaired area to be turned back to traffic in a very short time.

1.2 Scope of Study

This study had the following objectives:

1. Determine the optimum amounts of initiator and promoter required to provide a cure in less than one hour over a wide

temperature range.

2. Determine mechanical properties of user-formulated polymer concrete.
3. Develop a user-formulated prepackaged polymer concrete.
4. Perform field tests and evaluate the preformance.

The polymer concretes in the study used methyl methacrylate (MMA) monomer, trimethylolpropane trimethacrylate (TMPTMA) cross-linking agent, benzoyl peroxide (BzP) initiator, and dimethyl-p-toluidine (DMT) promoter. Some polymer concrete included polymethyl methacrylate (PMMA) powder.

Table 1.1. Chemicals for Polymer Concrete

CHEMICAL	ABBREVIATION	PURPOSE
Methyl Methacrylate	MMA	MMA is a monomer which is a basic component of polymer concrete. Monomer molecules are joined together in a process called polymerization, or curing, to form a solid called a polymer. MMA is a clear liquid with the same viscosity as water.
Trimethylol Propane Trimethacrylate Tetraethylene Glycol Diacrylate	TMPTMA TTEGDA	TMPTMA and TTEGDA are cross-linking agents which increase the rate of polymerization. TMPTMA and TTEGDA are more viscous than MMA. TMPTMA is nearly always used.
Benzoyl Peroxide	BzP	BzP is an initiator which decomposes into free radicals, which are responsible for the initiation of the polymerization (or curing). BzP is used in the form of a dispersion which is a white, viscous liquid which dissolves quickly in MMA.
Dimethyl-p-toluidine	DMT	DMT accelerates, or promotes, the decomposition of the initiator into free radicals. DMT, also called an accelerator or promoter, is used to provide faster cure times. DMT is a liquid.
Polymethacrylate Powder	PMMA Powder	PMMA powder is a powder form of MMA which has been polymerized, or cured. It thickens the polymer concrete during mixing and placing, resulting in better workability. It also results in a film being formed on the surface, minimixing evaporation of the MMA. PMMA powder results in less shrinkage of the polymer concrete during polymerization.

CHAPTER 2

OPTIMUM MONOMER SYSTEMS

2.1 Introduction

This chapter describes the research to determine a rational mix design proportioning procedure for polymer concrete and the factors that could influence the quality and behavior of this material. These factors include casting temperature and testing temperature. Curves for optimum valued promoter and initiator are presented.

2.2 Optimization Program

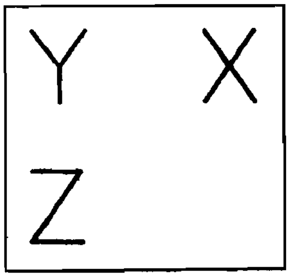
The optimization of the monomer formulation at different temperatures was carried out in two phases. The testing temperatures were 30, 50, 70 and 100°F (-1, 10, 21 and 38°C). The first phase consisted of tests to identify the relative proportions of BzP to DMT which constitute the most effective combinations at the different casting temperatures. The tests consisted of polymerizing 10 cc volumes of the monomer formulations in test tubes. The initial monomer temperature was the same as the temperature inside the environmental chamber where the polymerization took place. The polymerization time, from the end of mixing until peak exotherm, was measured and a qualitative inspection of the polymer was conducted. Table 2.1 presents sample data from this phase (Ref 1).

The data collected in the first phase of the optimization program were used to select the BzP:DMT ratios for the different casting temperatures in the second phase. The selection criteria includ-

Table 2.1 Polymerization of 95% MMA: 5% TMPTMA at 100°F (38°C).

% BzP % DMT	0.125	0.25	0.5	0.75	1
0.125		56 I 249°F		32 I 308°F	25 I 332°F
0.25				25 G 263°F	20 F 318°F
0.375				18 G 275°F	
0.5	46 I 134°F	38 I 178°F	25 B 229°F	20 F 217°F	15 G 292°F
1	32 I 123°F	25 I 141°F	22 B 193°F	19 F 240°F	10 F 274°F

Legend:



X - Qualitative description:
- G - Good
- F - Fair
- B - Bad
- I - Incomplete polymerization

Y - Polymerization Time (minutes)

Z - Peak Exotherm (°F)

ed the quality of the polymer produced, the polymerization time and the formulation cost. It was found that at temperatures between 30 and 70°F (-1 and 21°C), a BzP:DMT ratio of 2:1 was the most effective while a ratio of 3:1 was necessary at 100°F (38°C) (Table 2.2).

The second phase of the optimization program consisted of casting 2-in. x 2-in. x 12-in. (51-mm x 51-mm x 305-mm) beams using monomer formulations containing different levels of BzP and DMT at the different casting temperatures. The relative proportions of the two chemicals were kept constant for each temperature, as indicated in Table 2.2. Three specimens were prepared to represent each PC. The work time was obtained by observing when a 150 cc volume of the monomer became unpourable. The initiator and promoter levels were increased until either it was evident that the quality of the PC was reduced or the work time was approximately 10 minutes or less. The aggregate system consisted of 55 percent 3/8-in. pea gravel and 45 percent sand. The sand was a 50:50 (wt.) mixture of no. 2 and no. 3 blasting sands.

Ten hours after casting, the specimens were placed in a 70°F (21°C) room and kept there for 14 hours. They were then tested in flexure by third point loading. The results of these tests, summarized in Tables 2.3 through 2.6, indicate that significant variation of the flexural strength of polymer concrete, do not cause wide variations in the BzP and DMT levels at the same casting temperature. They also suggest that the variation of the optimized flexural strength as a function of casting temperature is insignificant. Figure 2.1 shows the BzP and DMT concentrations which yielded the highest average moduli of rupture for the different casting temperatures.

2.3 Temperature Effects

2.3.1 Effect of Casting Temperature on Compressive Behavior

To study the effect of casting temperature on the compressive

Table 2.2 BzP:DMT Ratios Used at the Different Casting Temperatures.

Casting (°F)	Temperatures (°C)	BzP:DMT Ratio	Reason for Choice
100	38	3	Cost, longer polymerzation time
70	21	2	Cost, longer polymerzation time
50	10	2	Cost, longer polymerzation time
30	-1	2	Cost, shorter polymerzation time

Table 2.3 Modulus of Rupture of PC Cast at 30°F (-1°C)[a].

% BzP	% DMT	Work Time (min)	Set Time (min)	Peak Exotherm (°F)	f_r (psi)	Average f_r (psi)
4	2	9	47 47 47	90 91 88	2228 1913 1946	2029
3.5	1.75	11.5	52 52 52	90 94 99	2244 2424 2003	2224
3	1.5	19	61 60 60	101 84 95	2278 2739 2315	2444
2.5	1.25	21	70 70 70	66 68 69	2529 2166 2432	2376

[a] NOTES:

Monomer: 95% MMA + 5% TMPTMA
Specimen Size: 2-in. x 2-in. x 12-in. (51-mm x 305-mm) beam
Temperature of specimen when mechanically tested: 70°F (21°C)
PC density: 136.6 pcf (2188 kg/m^3)
Monomer density: 26.2% by vol; 11.5% by wt.
PC age when tested: 24 hours

Table 2.4 Modulus of Rupture of PC Cast at 50°F (10°C)[a].

% BzP	% DMT	Work Time (min)	Set Time (min)	Peak Exotherm (°F)	f_r (psi)	Average f_r (psi)
2.75	1.375	12	41 41 41	97 98 94	2543 2441 2250	2411
2.25	1.125	13	45 45 46	99 95 91	2177 2205 2250	2210
1.75	0.875	18	54 54 54	101 100 98	2125 2194 2233	2183
1.25	0.625	34	72 72 72	89 85 84	2216 2025 1969	2070

[a] NOTES:

Monomer: 95% MMA + 5% TMPTMA
Specimen Size: 2-in. x 2-in. x 12-in. (51-mm x 51-mm x 305-mm) beam
Temperature of specimen when mechanically tested: 70°F (21°C)
PC density: 136.6 pcf (2188 kg/m^3)
Monomer loading: 26.2% by vol, 11.5% by wt.
PC age when tested: 24 hours

Table 2.5 Modulus of Rupture of PC Cast at 70°F (21°C)[a].

% BzP	% DMT	Work Time (min)	Set Time (min)	Peak Exotherm (°F)	f_r (psi)	Average f_r (psi)
2	1	9	31 31 31	125 124 123	2261 2244 2138	2214
1.5	0.75	12	36 38 37	126 124 119	2364 2250 2048	2220
1.25	0.625	16	43 43 43	126 124 120	2250 2244 2216	2237
1	0.50	21	50 51 51	124 118 115	2166 2100 2132	2132

[a] NOTES:

Monomer: 95% MMA + 5% TMPTMA
Specimen Size: 2-in. x 2-in. x 12-in. (51-mm x 51-mm x 305-mm) beam
Temperature of specimen when mechanically tested: 70°F (21°C)
PC density: 136.6 pcf (2188 kg/m^3)
Monomer loading: 26.2% by vol; 11.5% by wt.
PC age when tested: 24 hours

Table 2.6 Modulus of Rupture of PC Cast at 100°F (38°C)[a].

% BzP	& DMT	Work Time (min)	Set Time (min)	Peak Exotherm (°F)	f_r (psi)	Average f_r (psi)
0.6	0.2	b	58 58 58	130 131 132	2104 2138 2363	2201
0.75	0.25	24	41 41 40	145 148 150	2385 2205 1969	2186
0.9	0.3	19	38 38 38	139 140 145	1924 2250 2284	2153
1.05	0.35	12	30 30 29	141 144 151	2194 2368 2509	2357

[a] NOTES:

Monomer: 95% MMA + 5% TMPTMA
Specimen Size: 2-in. x 2-in. (51-mm x 51-mm x 305-mm) beam
Temperature of specimen when mechanically tested: 70°F (21°C)
PC density: 136.6 pcf (2188 kg/m^3)
Monomer loading: 26.2% by vol; 11.5% by wt.
PC age when tested: 24 hours

[b] was still pourable when the peak exotherm occurred in the PC

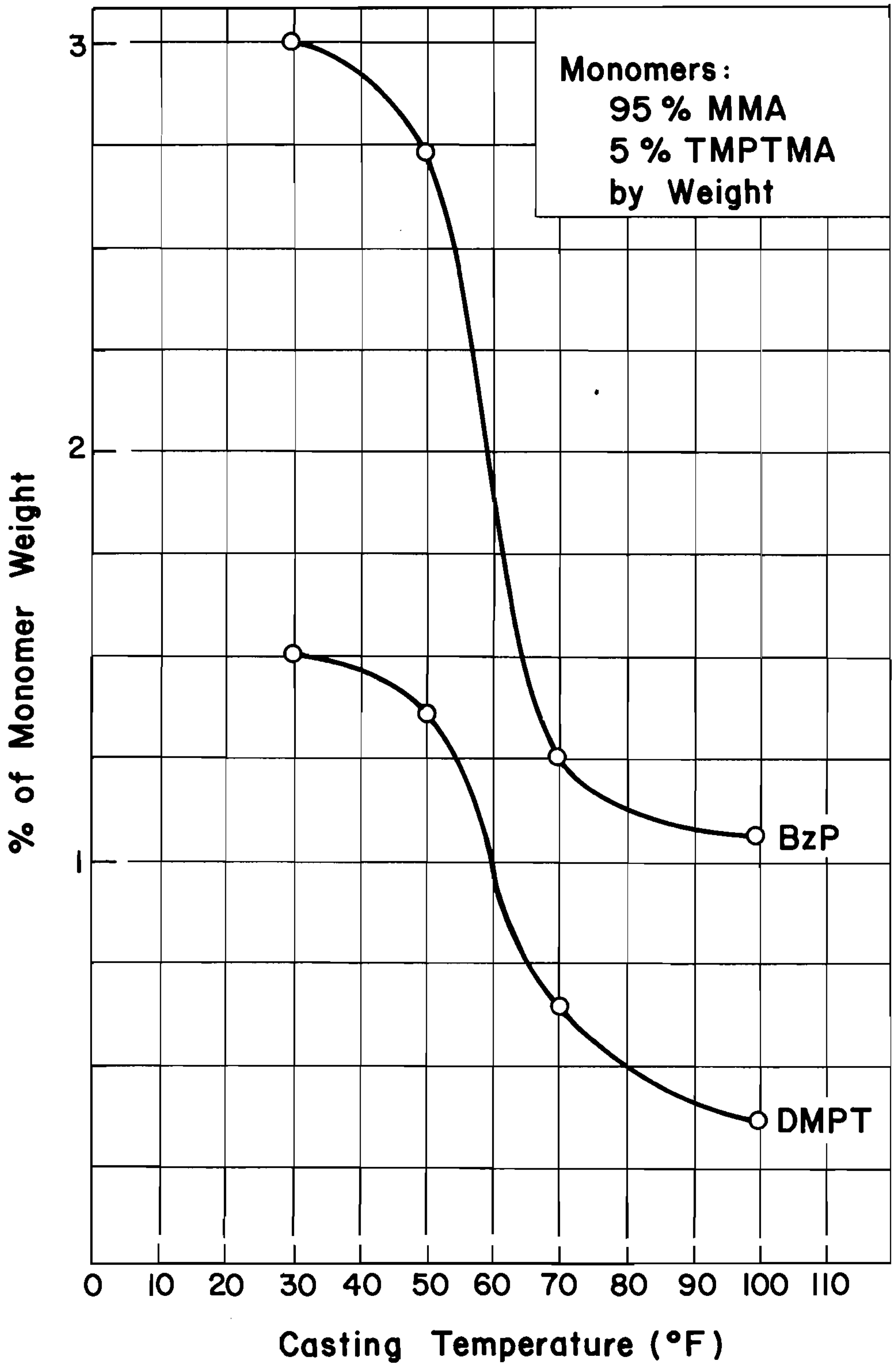


Fig. 2.1 BzP and DMT Levels in the Monomer Formulations Which Yielded the Highest Average Moduli of Rupture vs Casting Temperature.

strength and modulus of elasticity, sets of three 3-in. x 6-in. (76-mm x 152-mm) cylindrical specimens were cast at 100, 70 and 30°F (38, 21 and -1°C). The monomers consisted of 95 percent MMA plus 5 percent TMPTMA. The BzP and DMT levels were those indicated by Figure 2.1. In Table 2.7 it can be observed that the casting temperature has significant impact on the compressive behavior of PC (Ref 3).

2.4 Testing Temperature

2.4.1 Effect on Flexural Strength

Tests were conducted to study the variation of the flexural strength of the polymer concrete produced in the optimization program with testing temperature. Six 2-in. x 2-in. x 12-in. (51-mm x 51-mm x 305-mm) beams were cast at 70°F (21°C). The specimens were identical to those produced in the optimization program. They were left in the environmental chamber for 10 hours after casting. One set of three specimens was then put in an oven at 137 ± 4°F (58 ± 2°C) and the other set in an environmental chamber at 0 ± 2°F (-18 ± 1°C). The two sets were left in those locations for 14 hours, and then tested in flexure by third point loading. Figure 2.2 indicates that the flexural strength decreases as the testing temperature is increased (Ref 3).

2.4.2 Effect on Compressive Behavior

An experimental program was conducted to study the variation of the compressive behavior with the material testing temperature. Nine 3-in. x 6-in. (76-mm x 152-mm) cylindrical specimens were cast at 70°F (21°C). The aggregate was the same as that used in the optimization program. Three 3-specimen sets were cast. One set was placed in an oven at 137 ± 4°F (58 ± 2°C) and another in an environmental chamber at 0 ± 2°F (-18 ± 1°C). The specimens were kept for 14 hours at those locations before they were tested. The third set

Table 2.7 Properties of the Compressive Strength Specimens Cast at Different Temperatures[a].

Series	Casting Temp. (°F)	% BzP	% DMT	Setting Time (min)	Peak Exotherm (°F)	Compressive Strength (psi)	Average Compressive Strength (psi)	E (psi)
PC-30	30	3.0	1.5	58 59 62	101 99 90	9479 9762 9012	9418	1.66×10^6
PC-70	70	1.25	0.625	39 39 40	160 162 165	6890 7017 6791	6899	1.32×10^6
PC-100	100	1.05	0.35	27 27 26	169 170 173	6791 7130 7597	7173	1.49×10^6

[a] NOTES:

Monomers: 95% MMA, 5% TMPTMA
Monomer Loading: 26.2% by vol, 11.5% by wt.
Density: 136.6 pcf (2.88 kg/m^3)
Specimens: 3-in. x 6-in. (76-mm x 152-mm) cylinders
Testing temp: 70°F (21°C)
Age: 24 hours
Loading Rate: 47.16 psi/sec. (6.325 MPa/sec)

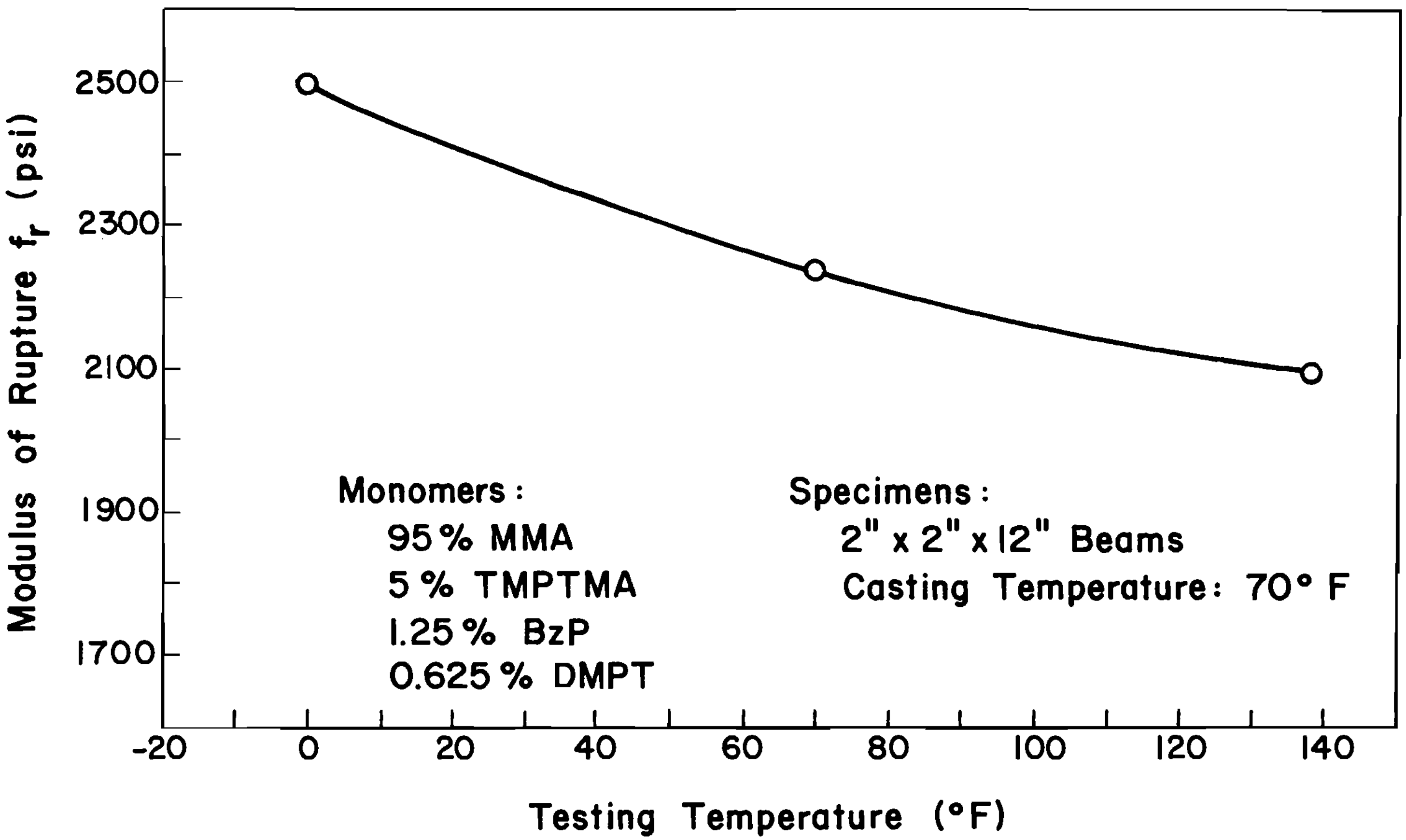


Fig. 2.2 The Variation of the Average Modulus of Rupture with the Testing Temperature.

was kept and tested at a room temperature of 70°F (21°C) (Ref 3).

It is evident from Table 2.8 that the compressive strength and modulus of elasticity decrease as the testing temperature is increased.

Table 2.8 Effect of Testing Temperature and Loading Rate on the Compressive Properties of PC[a].

Testing Temp. (°F)	Loading Rate (psi/sec)	Strength (psi)	Average Strength (psi)	E (psi)	Relative Strength	Relative Stiffness
0	47.2	7427 7682 8304	7804	1.52×10^6	1.089	1.172
	23.6	7781 7413 7639	7611	1.39×10^6	1.063	1.075
70	23.6	7074 7382 7880	7427	1.27×10^6	1.037	0.982
	47.2	6890 7017 6791	6899	1.32×10^6	0.963	1.018
138	47.2	6182 6778 6833	6597	1.23×10^6	0.921	0.950
	23.6	6394 6861 6211	6489	1.23×10^6	0.906	0.910

[a] NOTES:

Monomer Formulation: 95% MMA
5% TMPTMA
1.25% BzP
0.625% DMPT

Casting Temperature: 70°F (21°C)
Age When Tested: 24 hours
Monomer Loading: 26.2% by volume
11.5% by weight
Specimens: 3-in. x 6-in. (76-mm x 152-mm) cylinders

CHAPTER 3

EFFECT OF AGGREGATE ON USER-FORMULATED AND PREPACKAGED PC

3.1 Effect of Aggregate Mix on the Compressive Behavior of User-Formulated PC

To study the effect of varying the aggregate mixture on the compressive behavior of PC, 3-in. x 6-in. (760-mm x 152-mm) cylindrical specimens were prepared using three different aggregate mixes. Table 3.1 summarizes the properties of those mixes, which were proportioned to yield approximately the same monomer loading by volume as the mix used in the optimization program. Table 3.2 summarizes the properties of the polymer concretes produced and compares them with those of PC-70 from Table 2.7. It can be observed that the aggregate mixture had more impact on the stiffnesses of the polymer concretes produced than on their compressive strengths (Ref 3).

3.2 Effect of Addition of Coarse Aggregate to Prepackaged PC Systems

An experimental program was carried out to study the effect of extending commercially-available PC mortars with coarse aggregate. The program consisted of comparing the moduli of rupture of a commercially-available PC mortar, Silikal®, extended by different amounts of 3/4-in. (20-mm) limestone aggregate. Figure 3.1 indicates that a significant decrease in the modulus of rupture occurs as the aggregate to mortar weight ratio is increased from 0 to 0.33. However, the rate of decrease in flexural strength decreases as this ratio is increased from 0.33 to 1.0 (Ref 4).

Table 3.1 Properties of the Aggregate Mixes Used to Investigate the Effect of Aggregate Type and Gradation on Polymer Concrete.

Series	Coarse Aggregate Type	Aggregate Proportions		
		bulk moduls	%CA (by wt)	%FA[a] (by wt)
PC-T	3/8" Angular Trap Rock	3.07	65	35
PC-D	3/8" Angular Dolomite	2.67	65	35
PC-G	3/8" Longitudinal Granite	2.65	37	63

[a] Colorado sand

Table 3.2 Variation of PC Properties with Aggregate Type and Gradation[a]

Series	Density of PC (pcf)	Monomer Loading (%)		Peak Exotherm (°F)	Setting Time (min)	Compressive Strength (psi)	Average Strength (psi)	E (psi)	Relative Strength	Realative Stiffness
		Vol.	wt.							
PC-70	136.6	26.2	11.5	160 162 165	39	6890 7017 6791	6899	1.32 x 10^6	1.0	1.0
PC-G	139	25.9	11.2	131 128 134	39	5715 6211 5659	5862	0.98 x 10^6	0.85	0.741
PC-D	139	26.0	11.2	133 130 129	43	6762 6055 6027	6281	1.46 x110^6	0.910	1.102
PC-T	150	26.4	10.6	118 119 119	44	7356 6932 6904	7064	1.67 x 10^6	1.024	1.261

[a]NOTES:
Monomer Formulation: 95% MMA, 5% TMPTMA, 1.25% BzP, 0.625% DMT
Specimens: 3-in. x 6-in. (76-mm x 152-mm) cylinders
Casting Temp.: 70°F (21°C)
Testing Temp.: 70°F (21°C)
Age When Tested: 24 hours
Loading Rate: 47.16 psi/sec. (0.325 MPa/sec.)

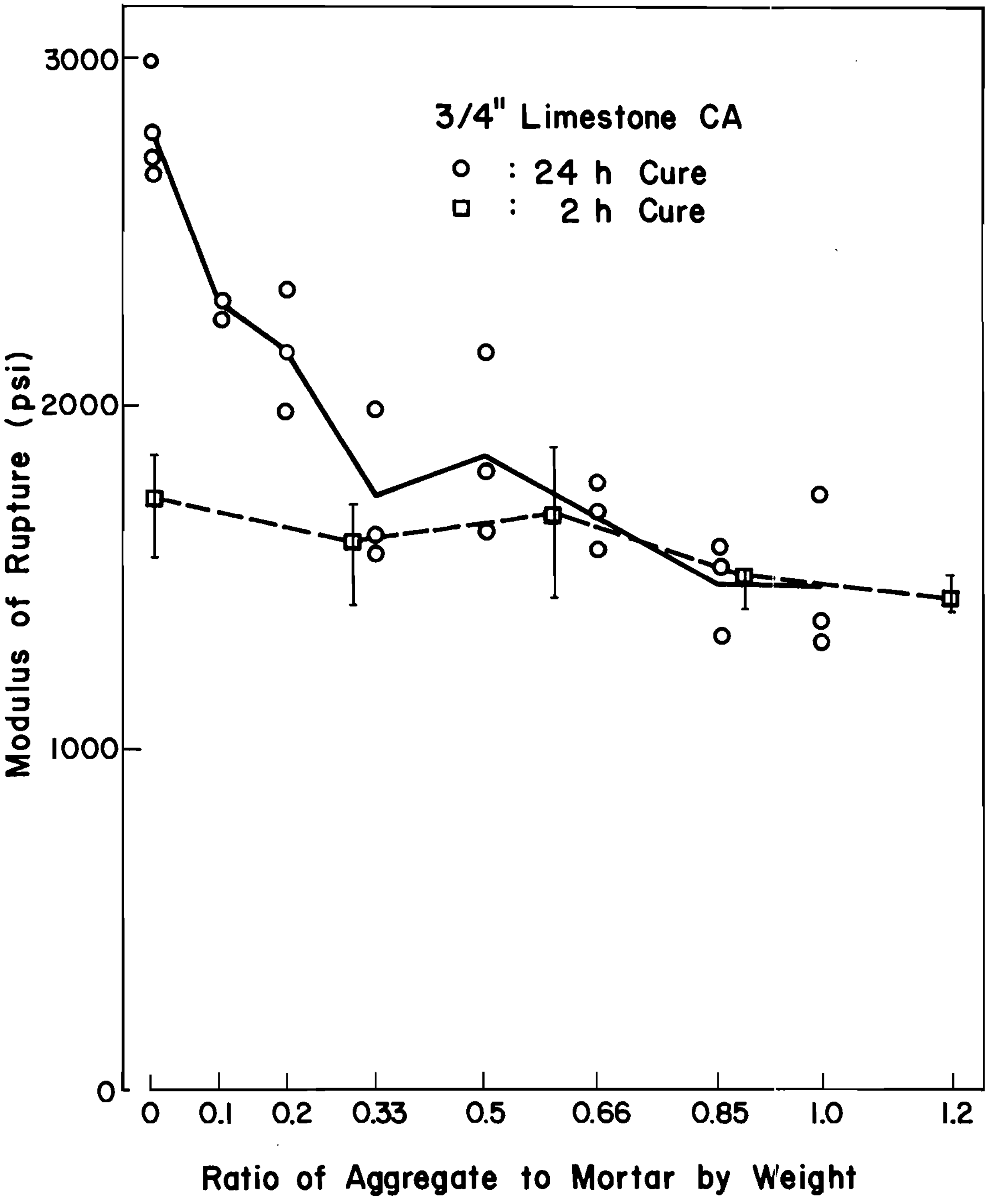


Fig. 3.1 Effect of Varying Aggregate Content on Modulus of Rupture for Silikal®.

CHAPTER 4

USER-FORMULATED PREPACKAGED SYSTEM

4.1 Introduction

One of the objectives of the research was to develop a polymer concrete with appearance and workability more similar to portland cement concrete. Since these are characteristics inherent in the commercially prepackaged systems, this material will be referred to as the user-formulated prepackaged system (Ref 4).

The primary difference between the user-formulated system described in the previous chapter and the user-formulated prepackaged system is the addition of (1) polymethyl methacrylate (PMMA), which serves as a thickening agent, and (2) colorant to provide a gray appearance. The PMMA powder eliminates segregation during placement, decreases shrinkage, and provides a film on the surface which minimizes evaporation.

This chapter describes the effect of PMMA on the behavior and properties of PC and the colorant recommended. It should be noted that the introduction of PMMA requires premixing of the PC before placement; without PMMA, preplaced aggregate can be saturated with monomer, which eliminates the necessity of premixing of aggregate and monomer.

4.2 Effect on the Evaporation of the Monomers

To study the effect of PMMA on monomer evaporation, polymer concrete samples made with a monomer formulation of 97 percent MMA and 3 percent TMPTMA were prepared in 8-1/2-in. (216-mm) aluminum foil cans. Three samples were produced. The first contained no

PMMA, the second contained 3 percent PMMA and the third, 5 percent PMMA. Based on total aggregate weight, the weight of the samples was measured as a function of time to determine the amount of monomer that evaporated. Figure 4.1 summarizes the test results. It is evident that monomer evaporation is significantly reduced by adding PMMA to fresh PC (Ref 4).

4.3 Effect on Peak Exotherm Time and Temperature

A study was conducted to investigate the effects of adding PMMA to the PC mix on the peak exotherm time and temperature. The 3-in. x 7-in. (76-mm x 178-mm) cylindrical specimens were cast at room temperature. Figure 4.2 summarizes the test results. It indicates that the setting time is decreased and the peak exotherm is increased with increased PMMA content (Ref 4).

4.4 Effect on PC Strength

To study the effect of PMMA on the strength of polymer concrete, 3-in. x 6-in. cylindrical specimens were prepared using different monomer formulations. They were then tested for splitting tensile strength and compressive strength. Figures 4.3 and 4.4 summarize the test results. It is evident that PMMA increases the splitting tensile strength while having an insignificant impact on the compressive strength (Ref 4).

4.5 Effect on Shrinkage

An experimental program was carried out to determine the effect of PMMA on the setting shrinkage of polymer concrete. An apparatus developed by Ohama and Demura (Ref 8) was used (Fig. 4.5). The test specimens were 1-1/2 in. x 1-1/2 in. x 6-in. (38-mm x 38-mm x 152-mm) prisms. A direct current differential transformer (DCDT) was used at each end to measure the contraction of the specimens during polymerization. The specimens were prepared using equal

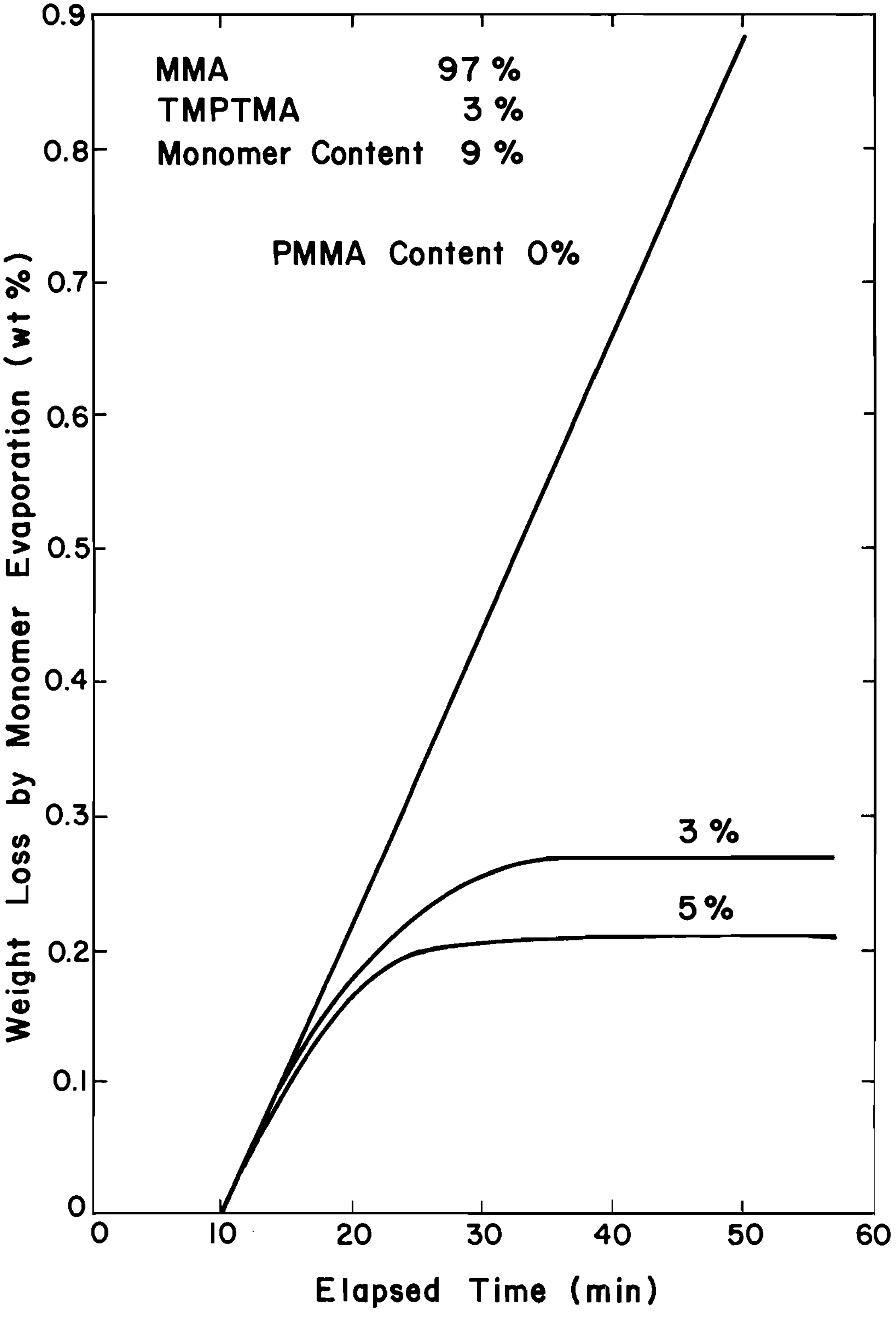


Fig. 4.1 Weight Loss by Monomer Evaporation Versus Elapsed Time for PC with Varying PMMA Content.

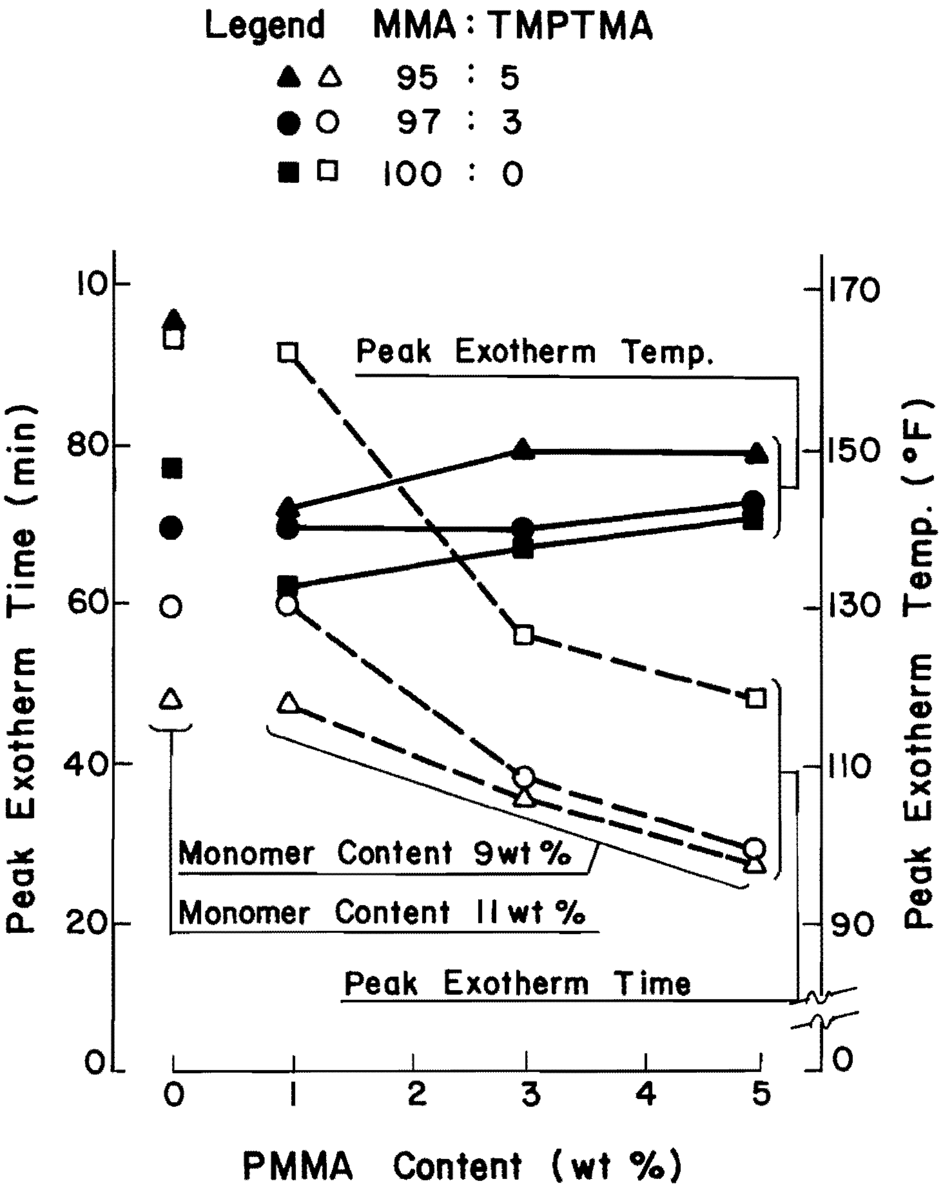


Fig. 4.2 PMMA Content Versus Peak Exotherm of PC.

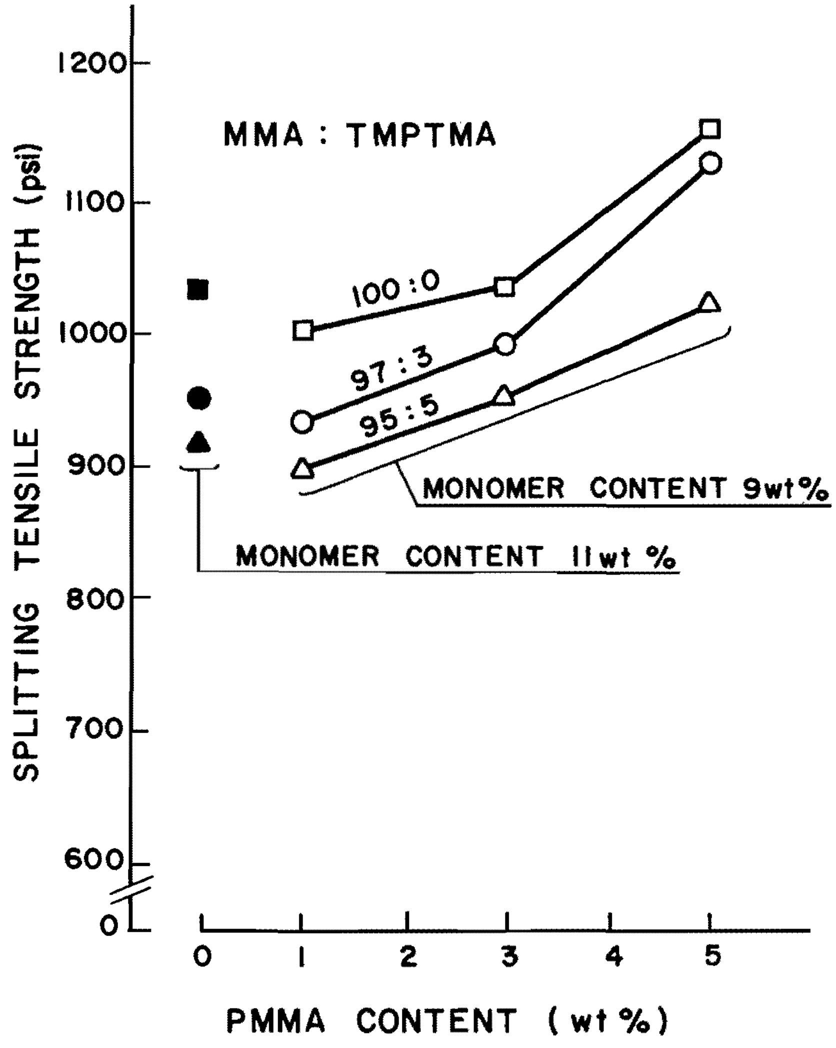


Fig. 4.3 Splitting Tensile Strength Versus PMMA Content of PC.

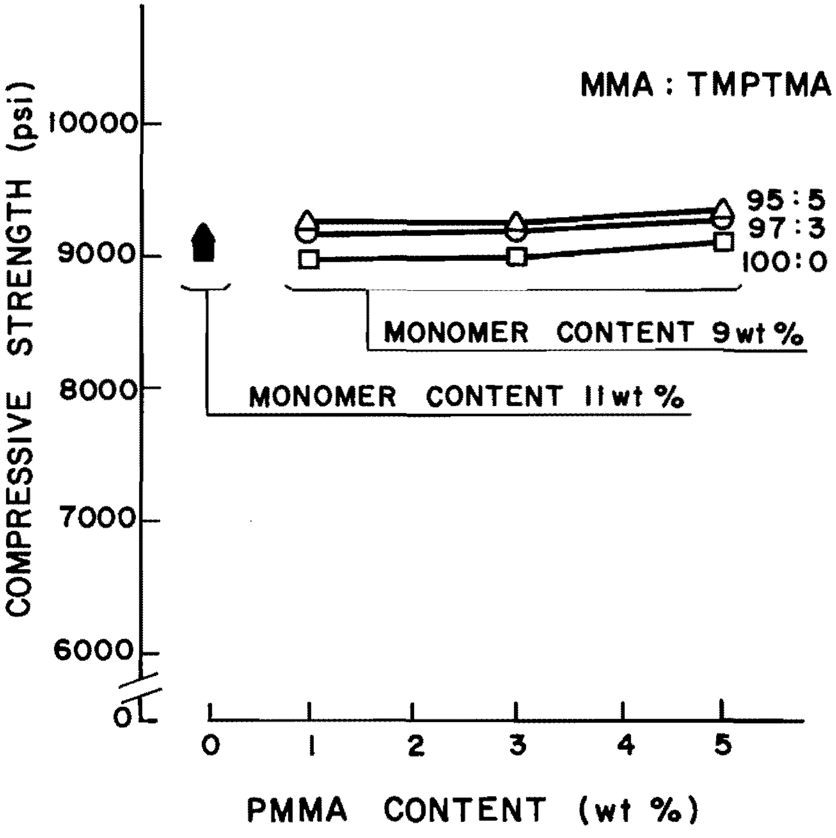
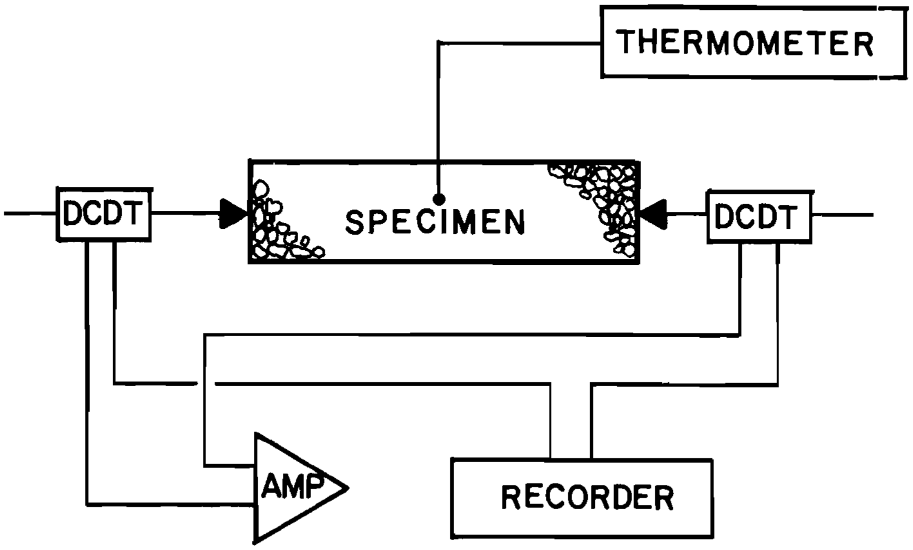
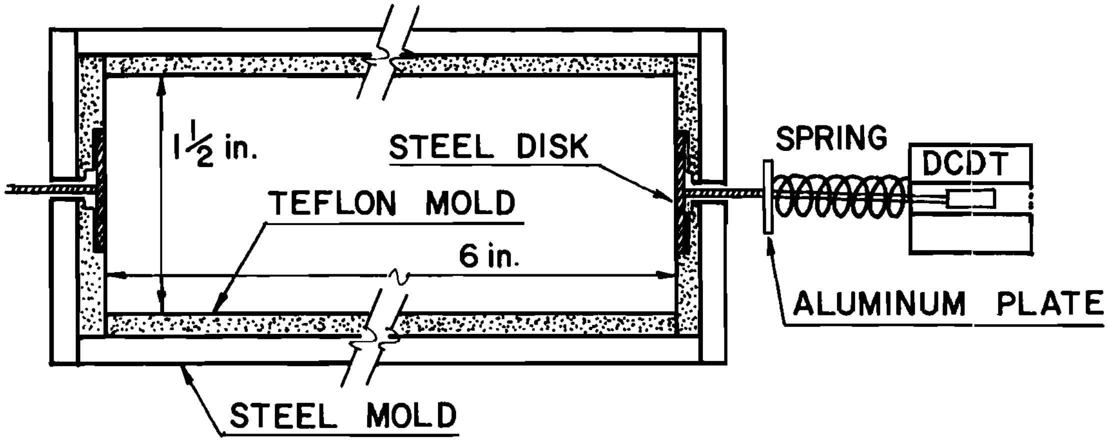


Fig. 4.4 Compressive Strength Versus PMMA Content of PC.



Block Diagram for Instrument System



Detail of Strain Detection Part

Fig. 4.5 Shrinkage Measuring Apparatus.

parts of concrete sand and 3/8-in. silicious pea gravel (Ref 4).

The monomer system consisted of 97 percent MMA, 3 percent TMPTMA, 0.6 percent DMPT and 1.2 percent BzP. The casting was done at room temperature. The PMMA was mixed with the aggregate as a percent of the aggregate total weight. The aggregate was then placed in the mold and the monomer was added until the aggregate was fully saturated. The DCDTs were then placed in contact with the steel discs at each end of the mold. As the specimen contracted during polymerization, the spring-loaded plungers forced the steel discs to maintain contact with the PC. The output from the DCDTs was converted into displacement readings. Figure 4.6 summarizes the test results. Apparently, the setting shrinkage is reduced significantly for PMMA in amounts up to 3 percent of the total weight of the aggregate.

4.6 Colorants for User-Formulated PC

Generally, MMA-based PC without a colorant exhibits the color of its aggregates, since MMA polymer has a relatively clear color. For aesthetic reasons, it is usually desirable that the repair material have a color similar to that of the surrounding portland cement concrete (Ref 4).

A number of materials were investigated for possible use as coloring agents. It was found that relatively large amounts (20 to 30 percent of the total PC weight) of calcium carbonate powder and portland cement were required to achieve a satisfactory color. Consequently, a mixture of titanium dioxide and carbon black was tried. The weight ratio of carbon black to titanium dioxide was varied from 1/10,000 to 1/100 and the weight of the mixture was varied from 0.50 to 3.0 percent of the aggregate weight. It was found that a weight ratio of carbon black to titanium dioxide of 1/300 to 1/500 and a mixture weight of 0.5 to 1.0 percent of aggregate weight were necessary to yield a color similar to that of portland cement concrete.

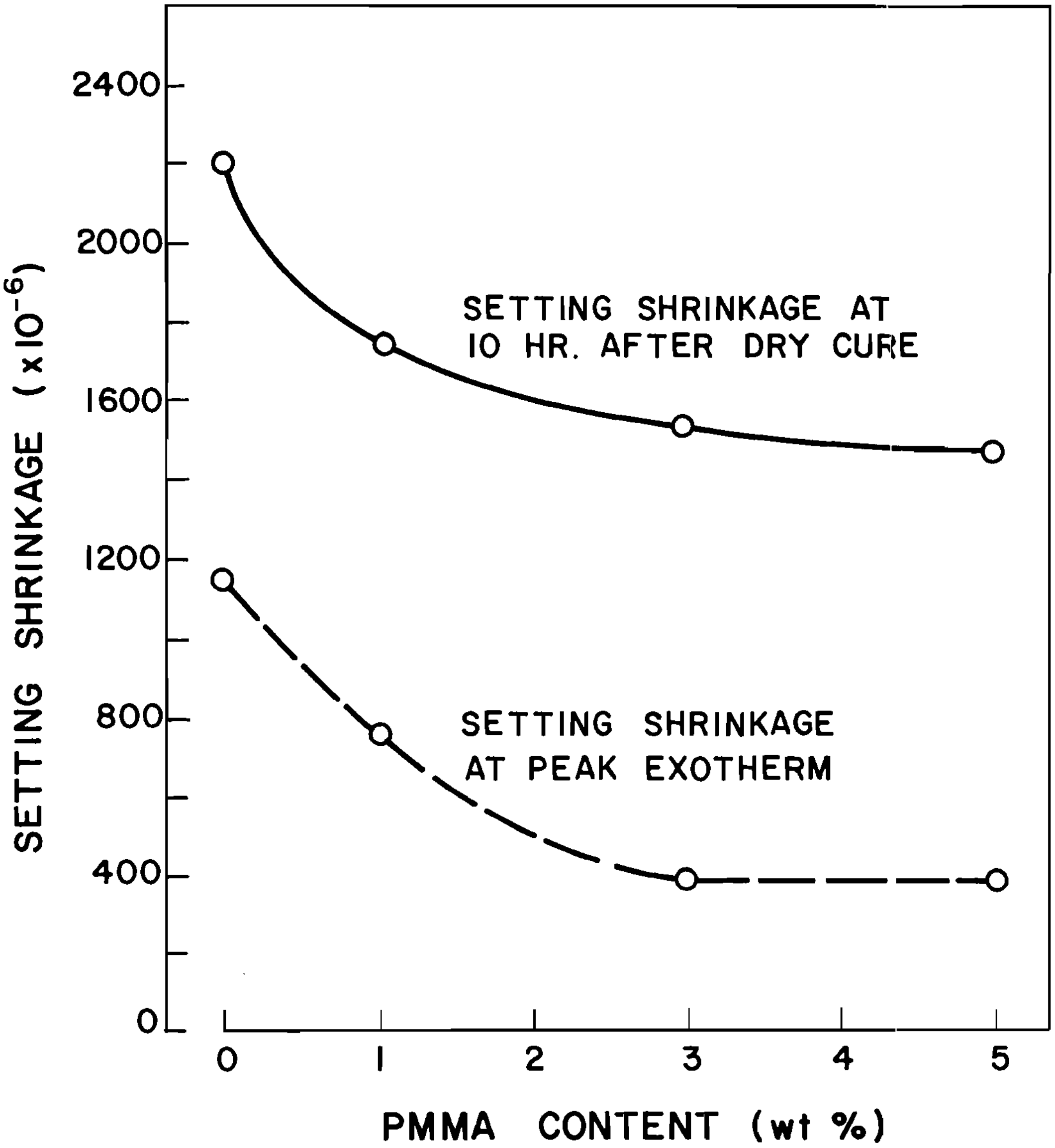


Fig. 4.6 Setting Shrinkage at Peak Exotherm and 10 hrs after Dry Cure as a Function of PMMA Content of PC.

CHAPTER 5

EFFECT OF MOISTURE IN THE AGGREGATE

5.1 Effect on User-Formulated PC

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-in.) and 50 percent oven-dried concrete sand was selected. Water was added to the sand in three different amounts and stirred by hand until uniform color was achieved. Six PC cylinders 3 in. by 6 in. (76 mm by 152 mm) were prepared using each variation of moisture content. Three PC cylinders each were tested in compression and splitting tension. The three specimens with the highest moisture content (5.65 percent) were too weak to be removed from the molds undamaged. Only three specimens could be removed from the molds at a moisture content of 1.64 percent. For higher moisture contents, the specimens bonded to the steel molds even though the molds were well-coated with the most effective mold release agent tested (Ref 2).

Results of the tests show that relatively small amounts of moisture reduce the compressive and tensile strengths by as much as 40 percent (Figures 5.1 and 5.2). At a moisture content of 0.78 percent, the sand was noticeably wet in color yet good strengths were obtained. This indicates that if the sand can be dried until it appears to be surface dry, 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

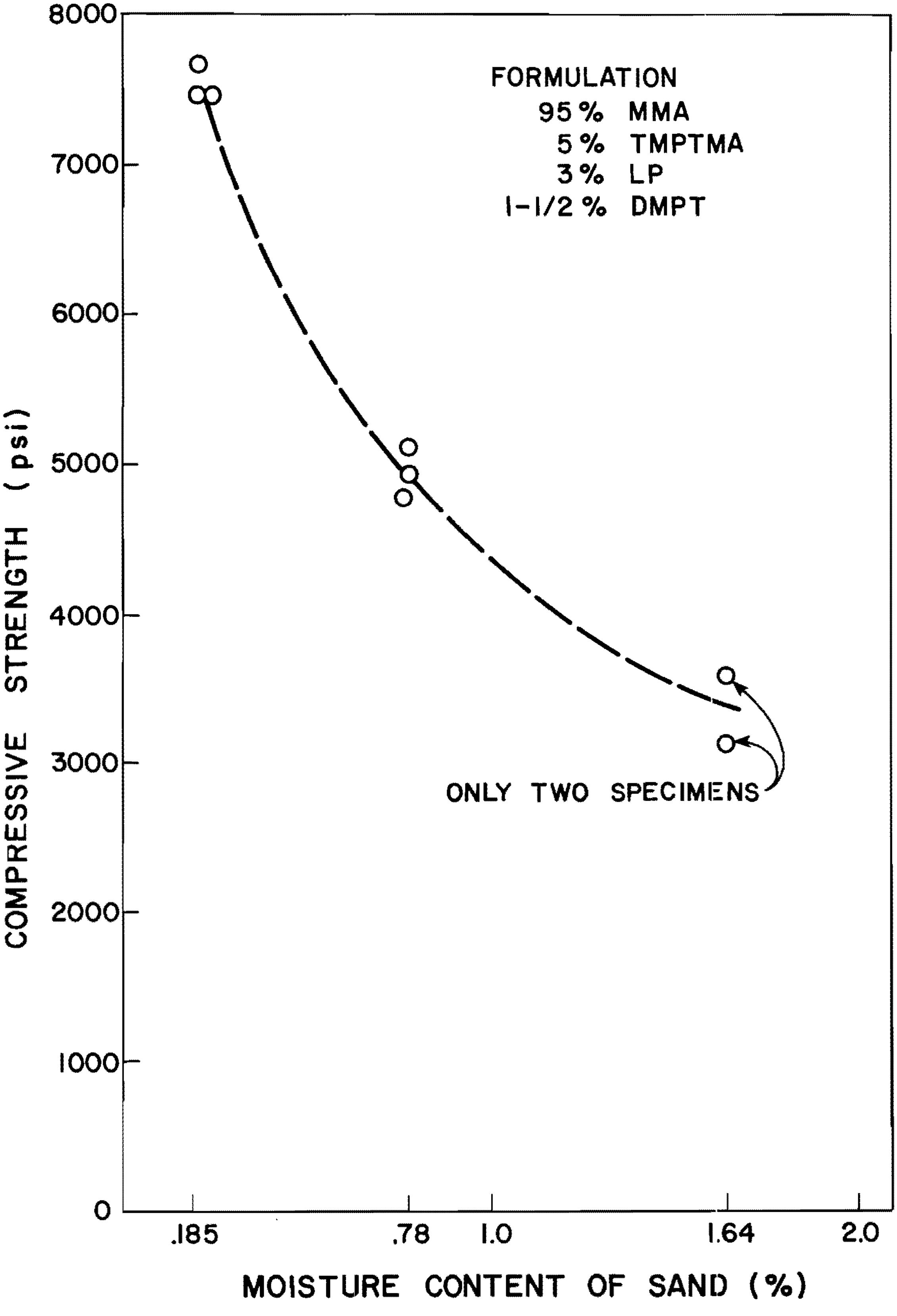


Fig. 5.1 Effect of Moisture Content of Sand on Compressive Strength.

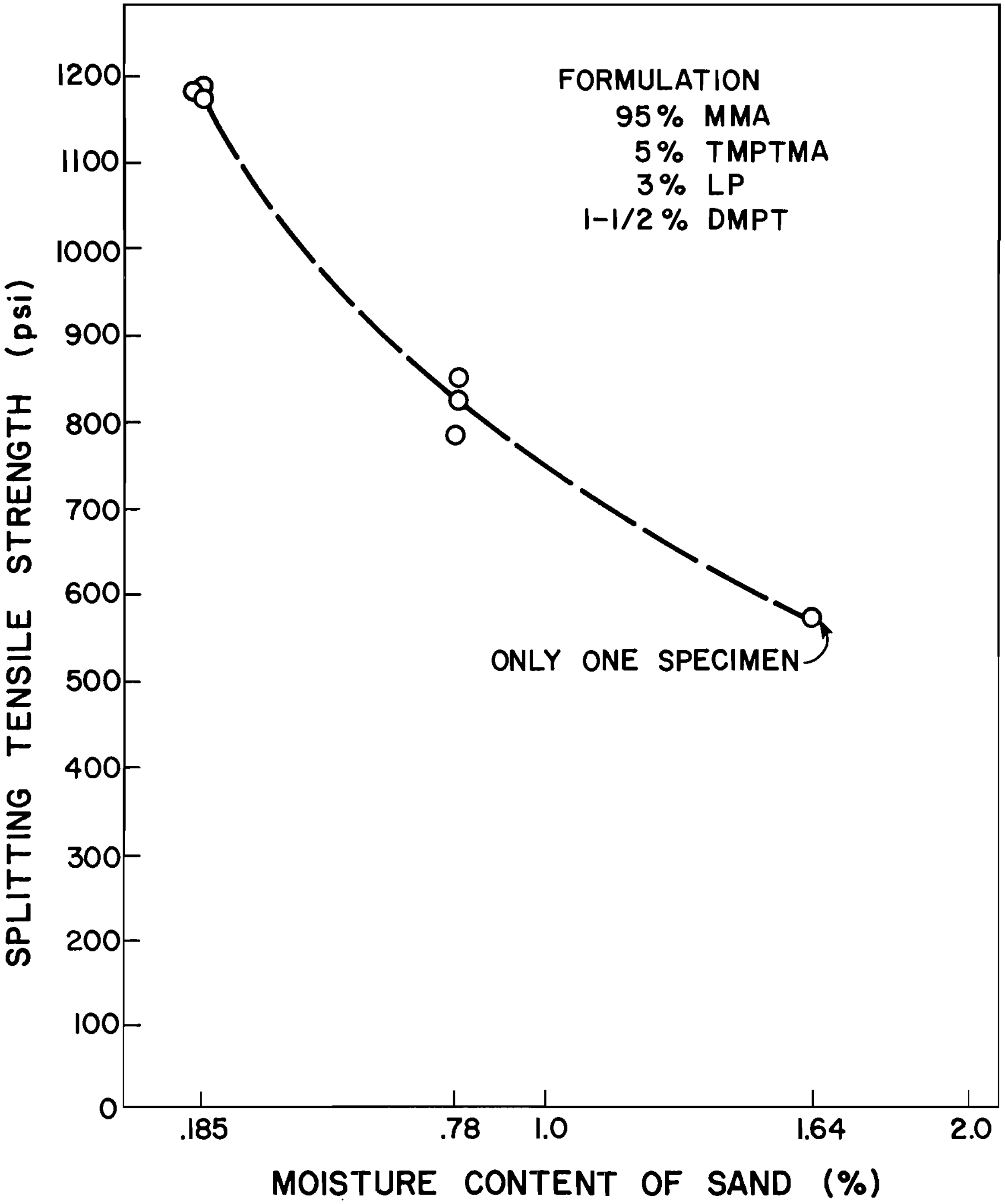


Fig. 5.2 Effect of Moisture Content of Sand on Splitting Tensile Strength.

and stored indoors in an air-conditioned laboratory.

5.2 Effect of Moisture in Coarse Aggregate on the Mechanical Properties of Commercially-Available PC

Test were performed on Silikal® to determine the effect of moisture in the coarse aggregate on its mechanical properties. The test results are summarized in Figure 5.3. The same results are expressed as percentages of the dry aggregate PC strengths in Figure 5.4 (Ref 4).

5.3 Effect of Addition of Fibers to PC Made with Wet Aggregate

The use of fibers in the PC mix to improve the strength when moisture is present was investigated. Based upon workability, a value of 5 percent by weight of the aggregate was selected. The PC was made using equal weights of all-purpose sand and 3/8-in. coarse aggregate. The monomer formulation was 95 percent MMA, 5 percent TTEGDA, 1.33 percent BzP and 0.70 percent DMPT. The fibers were Bekaert ZL 30/50 (0.5 mm x 30 mm). Figure 5.5 shows a comparison in strengths for PC with and without fibers for 2.5 and 5.0 percent moisture. Modest increases in strength were observed for splitting tensile strength and compressive strength for 2.5 percent moisture content when fibers were included. Very significant increases in strength were found for the modulus of rupture with 2.5 percent moisture content and for all strength tests when 5.0 percent moisture was present (Ref 4).

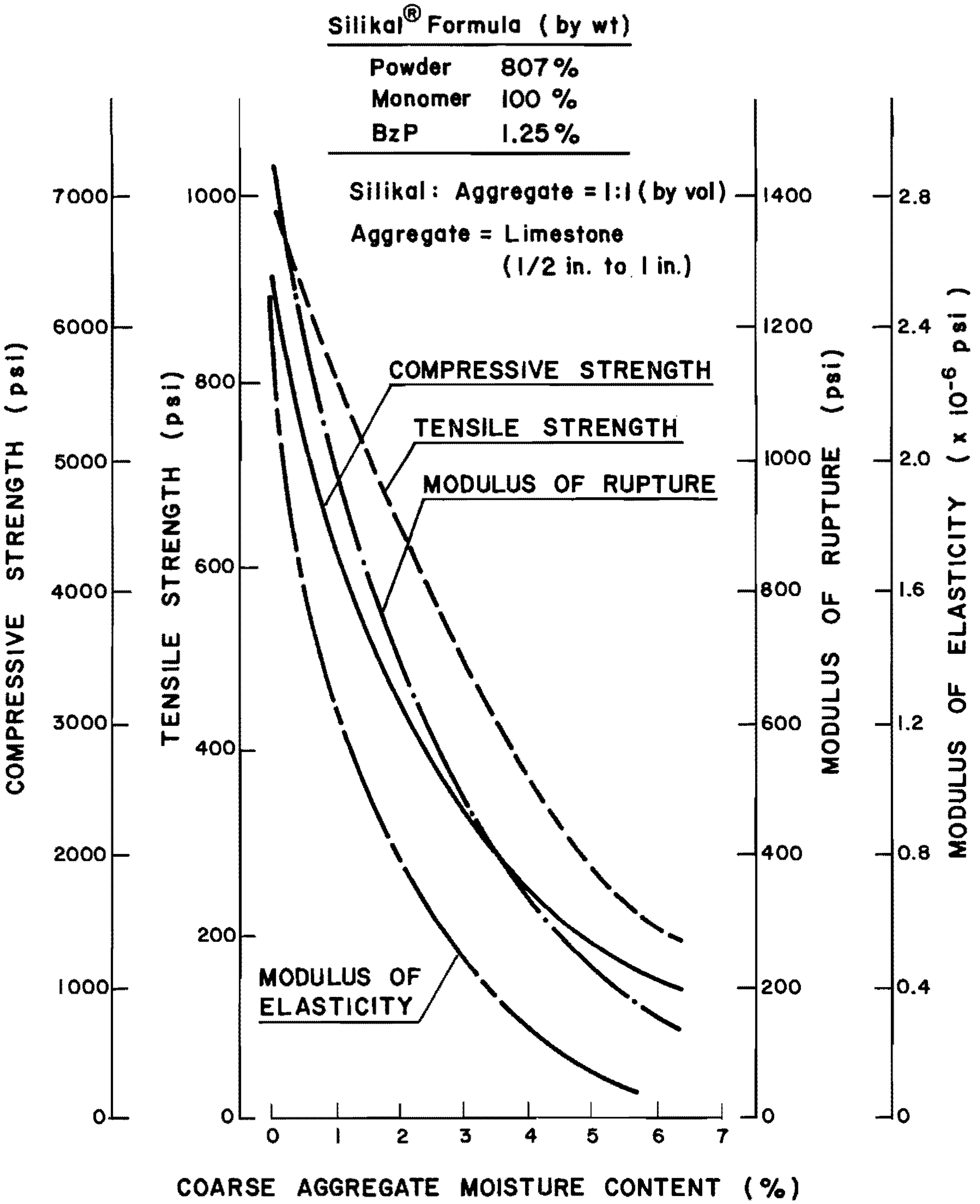


Fig. 5.3 Effect of Coarse Aggregate Moisture Content on Tensile, Compressive and Flexural Strengths, and Modulus of Elasticity of Silikal®.

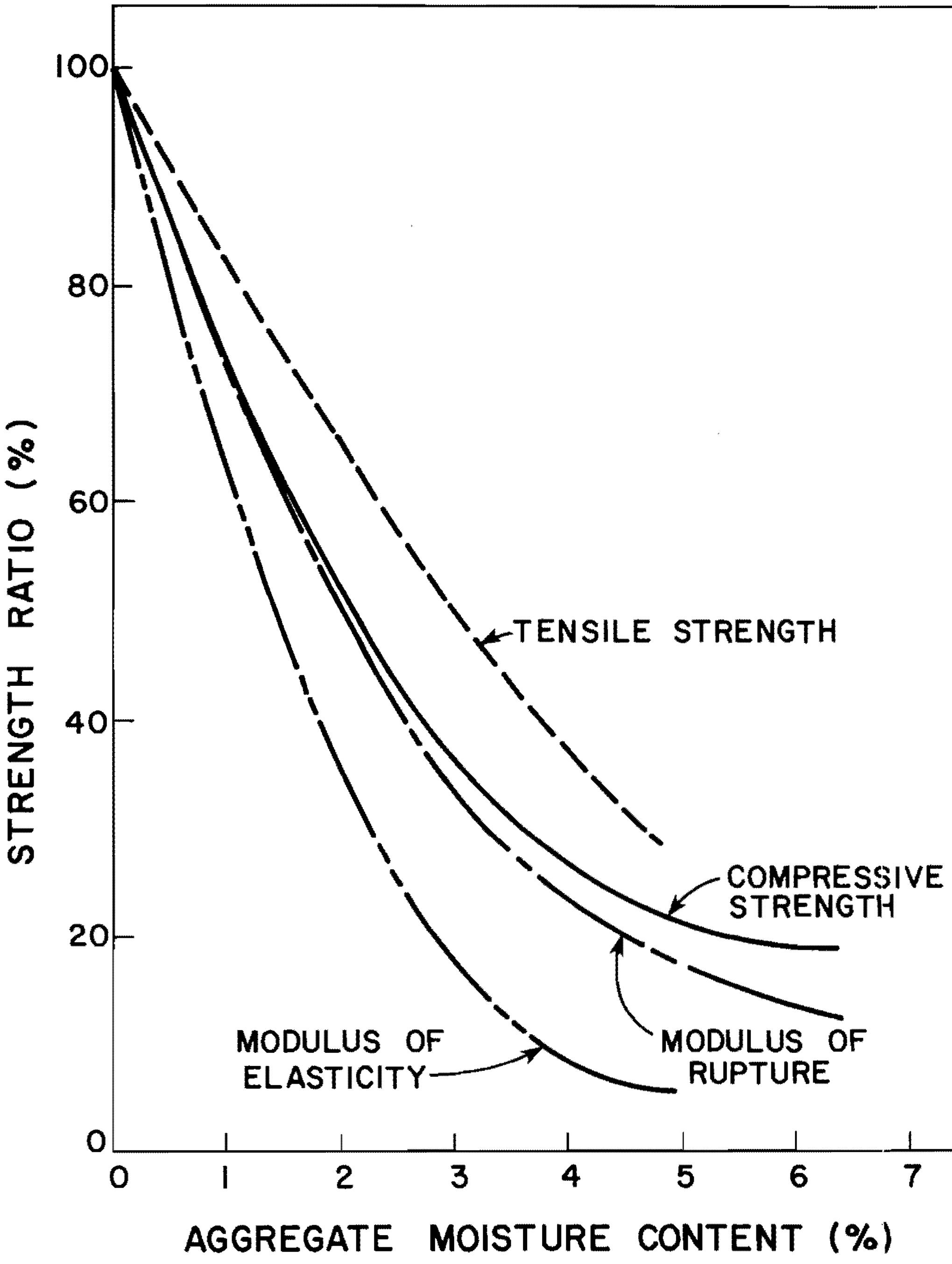


Fig. 5.4 Percentage of Residual Compressive, Tensile and Flexural Strengths, and Modulus of Elasticity versus Coarse Aggregate Moisture Content of Silikal®.

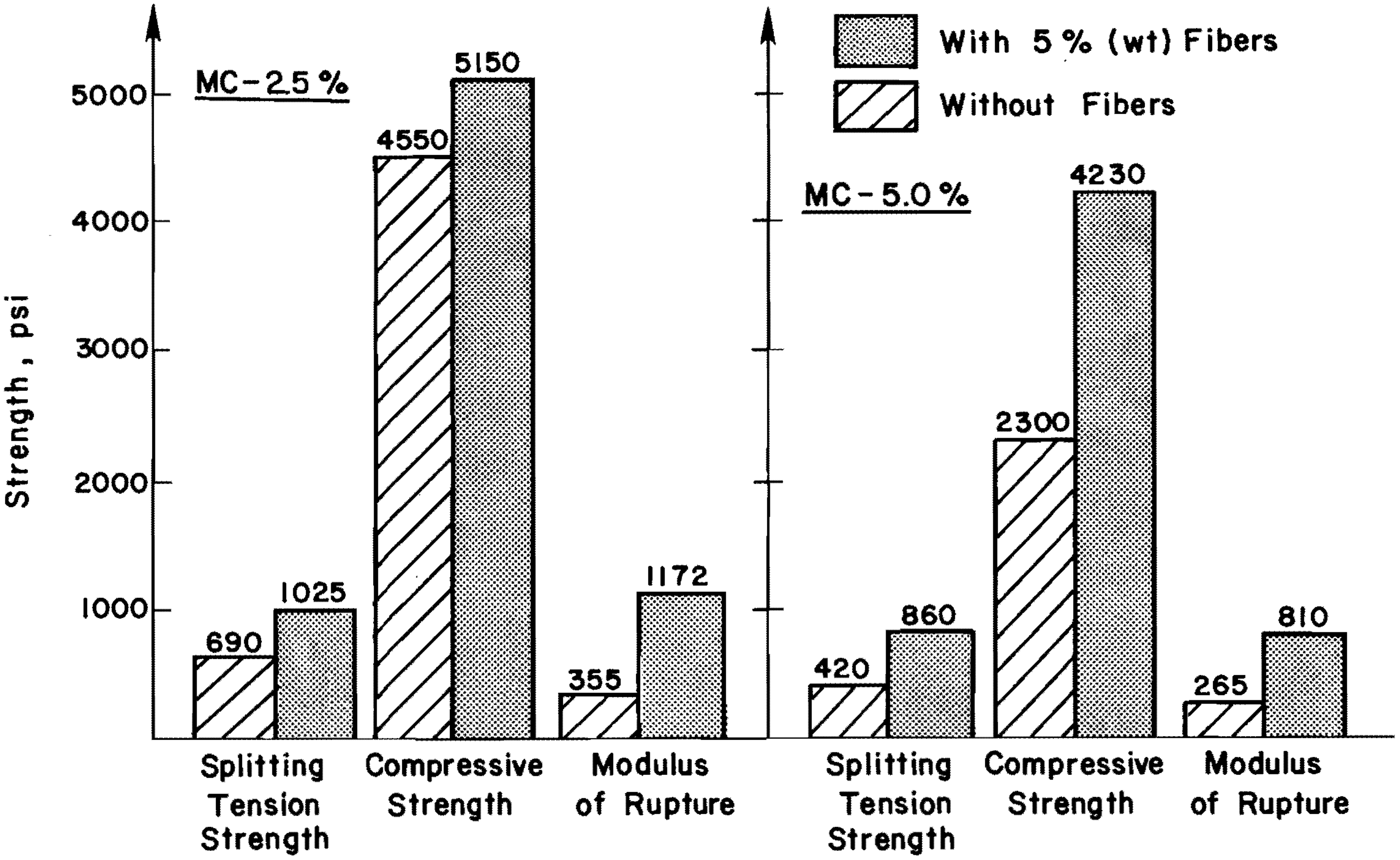


Fig. 5.5 Comparison of Properties of PC Made With and Without Fibers.

CHAPTER 6

FLEXURAL BOND STRENGTH OF POLYMER CONCRETE

6.1 Polymer Concrete to Portland Cement Concrete

The flexural bond of PC to PCC results from the penetration of the monomer into the latter material. Consequently, it can be expected to be influenced by the permeability and moisture content of the adjacent PCC, the initial viscosity of the monomer, and the change of monomer viscosity with time during the polymerization process (Ref 3).

An investigation was carried out to determine PC-to-PCC flexural bond strength. The procedure consisted of nine low-water-cement-ratio PCC beams 2-in. x 2-in. x 12-in. (51-mm x 51-mm x 305-mm). Six of the beams were cut at midspan using a water-cooled saw and then placed, together with the remaining three, in an oven at 250°F (121°C) for two days. After their removal from the oven, the cut halves were put back in the molds. The molds were then put in environmental chambers at the desired casting temperatures, covered with polyethylene membrane and left for 24 hours. Polymer concrete was cast in the empty halves of the molds and thermocouples were inserted. The aggregate used in the PC was the same as that used in the optimization program. After casting, the specimens were left inside the environmental chambers for 10 hours. They were then placed at room temperature for 14 hours. Later, they were removed and placed with the uncut PCC specimens in an oven for 24 hours at 136 ± 4°F (58 ± 2°C). The specimens were then taken out of the oven and tested in flexure by third point loading. The uncut PCC beams were used as control specimens. The testing temperature of 136 ± 4°F (58 ± 2°C) was used to simulate the maximum temperatures that might occur in exposed concrete structures in the summer. For lower temperatures, higher bond strengths would probably be anticipated. Table 6.1 indicates that the flexural bond strength of PC to PCC decreases as the casting temperature increases.

6.2 Bond of PC to PC

An investigation was carried out to determine the feasibility of repairing damaged PC with the same material. The program consisted of comparing the flexural strengths of non-monolithically cast 2-in. x 2-in. x 12-in. (51-mm x 51-mm x 305-mm) beams to those of monolithically cast ones (Ref 3).

Three kinds of specimens including controls were used. The first set (A) of three specimens was cast to simulate a vertical cold joint. Half the length of each specimen was cast after dividing the mold horizontally with a piece of sheet metal which was caulked on its second side to the adjacent mold walls. Six days later, the second half of the specimen was cast after removing the sheet metal divider.

The second set (B) of three specimens simulated a horizontal cold joint. The upper 1-in. thick half was cast 6 days after casting the lower half. The interface between the two halves was smooth and level. Two monomer batches were used in the casting of all specimens. Three control specimens were cast from each batch. The aggregate used was Colorado River silica sand. Set (A) and the control sets were tested by third point loading. The location of the cold joint in set (B) specimens suggested that shear stress might control their behavior. Consequently, they were tested by single point x7 loading at midspan. Testing took place when the new and old polymer concretes were 1 and 7 days old, respectively. Table 6.2 suggests

Table 6.1 The Effect of Casting Temperature on the Minimum PC-PCC Concrete Flexural Bond Strength[a].

PC Casting Temp. (°F)	% BzP	% DMT	f_r (psi)	Average f_r (psi)	Mode of Failure
100	1.05	0.35	360 371 366	366	Inter-face
70	1.25	0.625	596 641 557	598	PCC
50	2.75	1.375	815 939 731	828	PCC
30	3.0	1.5	900 968 923	930	PCC
Control PCC Specimens			939 963 951	951	PCC

[a]Notes:

Monomers:	Specimens:	Age When Tested:
95% MMA 5% TMPTMA	2-in. x 2-in. x 12-in. (51-mm x 51-mm x 305-mm) beams	48 hours

Testing Temperature: 136°F (± 4°) (58°C ± 2°)

Table 6.2 Testing Results of PC to PC Bond Strength.

Series	f_r (psi)	Average f_r (psi)
A - Beams with a Vertical Cold Joint at Midspan-Third Point Loading	939 894 1029	945
B - Beams with a Horizontal Cold Joint at Middepth-Single Point Loading	2093 2227 2152	2157
7 - Day-Old PC Control Specimens	2076 1974 1991	2014
1 - Day-Old PC Control Specimens	1536 2014 2306	1952

that casting polymer concrete in successive lifts does not reduce its flexural strength. It also indicates that beams with vertical cold joints have significantly lower flexural strengths than monolithically cast PC.

CHAPTER 7

FIELD APPLICATIONS

7.1 Introduction

This chapter describes the procedures used for making polymer concrete repairs and reports the behavior of the major repairs made in coordination with the Texas State Department of Highways and Public Transportation (SDHPT).

In some of the earlier repairs chemicals were used that are no longer being recommended. They include 2-ethylhexyl methacrylate (EHMA), a monomer; butyl acrylate (BA), a monomer; tetraethylene glycol diacrylate (TTEGDA), a cross-linking agent; and lauroyl peroxide (LP), an initiator.

Costs are shown for most of the repairs and represent 1983 costs of chemicals, unless otherwise noted. Labor and aggregate are not included.

7.2 Repair Procedures

The repair procedures for the most common highway applications can be identified in three major processes.

7.2.1 Preplaced Aggregate

This procedure is illustrated in Fig. 7.1. The repair area is first cleaned of all delaminated portland cement concrete; the surface is dried if wet. A mixture of dry aggregate and sand is placed in the repair area and flooded with the monomer system. The

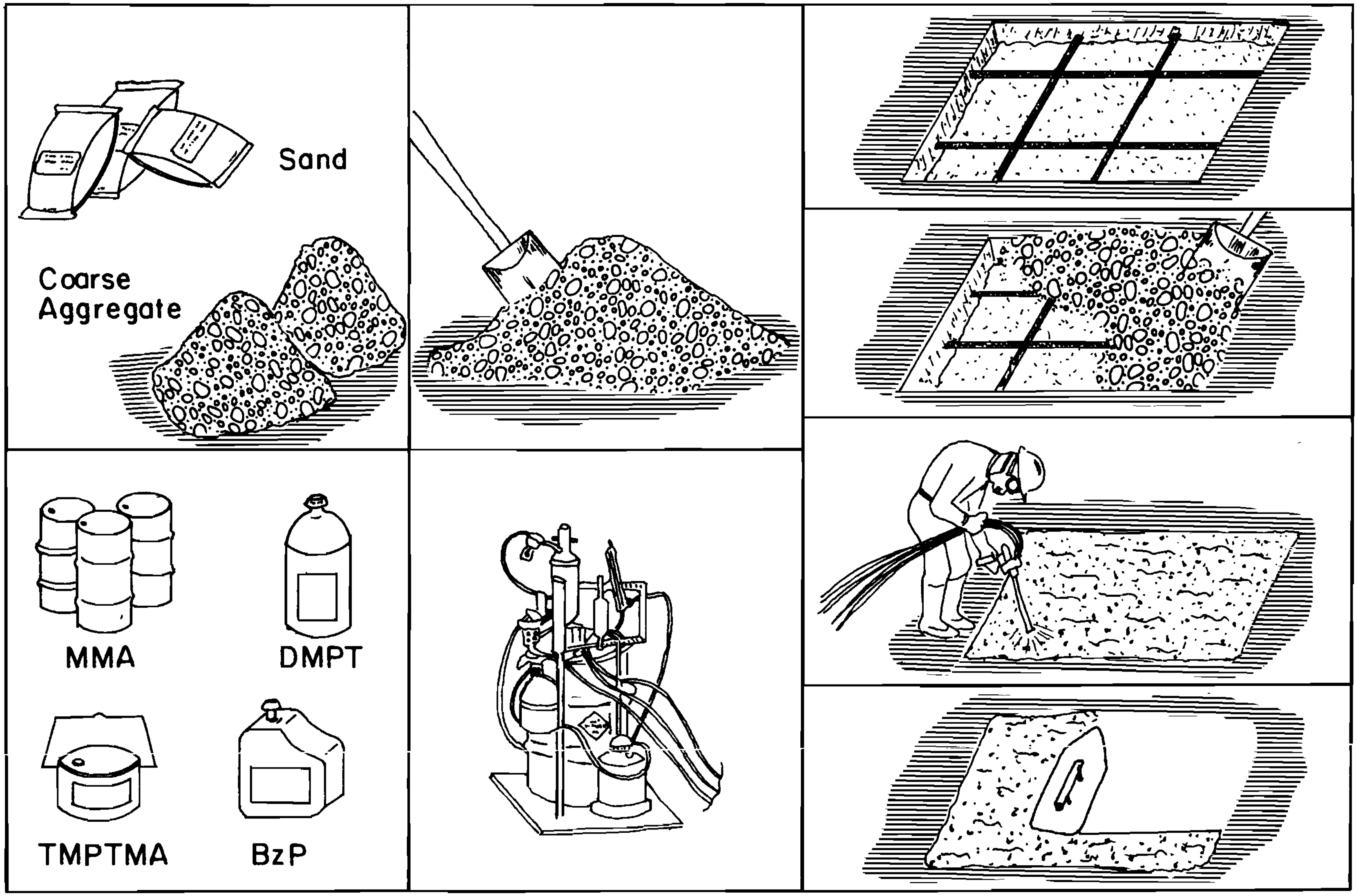


Fig. 7.1 Repair Procedure for User Formulated PC (Pump Injection System).

chemicals can either be premixed or nozzle-mixed. However, in both cases, care must be exercised to prevent the initiator and promoter from contact with each other while they are still in their pure forms. Finally, the repair is trowelled and finished (Ref 2).

7.2.2 User-Formulated Prepackaged System

This process is illustrated in Fig. 7.2. The repair area is first cleaned of all delaminated portland cement concrete and its surfaces dried out. The user prepackages the chemicals in two components: liquid and powder. The liquid component should contain the monomers and the desired percentage of promoter. The powder component should contain the desired amounts of initiator, colorant and PMMA powder. The two components are added to the mixture of dry aggregate and sand and mixed either by hand or in a concrete mixer and placed into the repair area. Finally, the repair is trowelled and finished (Ref 4).

7.2.3 Commercially-Available Systems

The use of commercially-available polymer concrete systems is similar to the user-formulated processes, except that the liquid and powder components are formulated and packaged by the producer who specifies their mix proportioning. They may be extended up to 100 percent by volume with dry coarse aggregate. This process is illustrated in Fig. 7.3 (Ref 4).

7.3 Field Tests

A number of repairs were made with polymer concrete in coordination with the SDHPT. This section reports on those repairs and their behavior.

7.3.1 IH-10, Columbus, Texas

On August 22 and 23, 1979, a team from the Center for

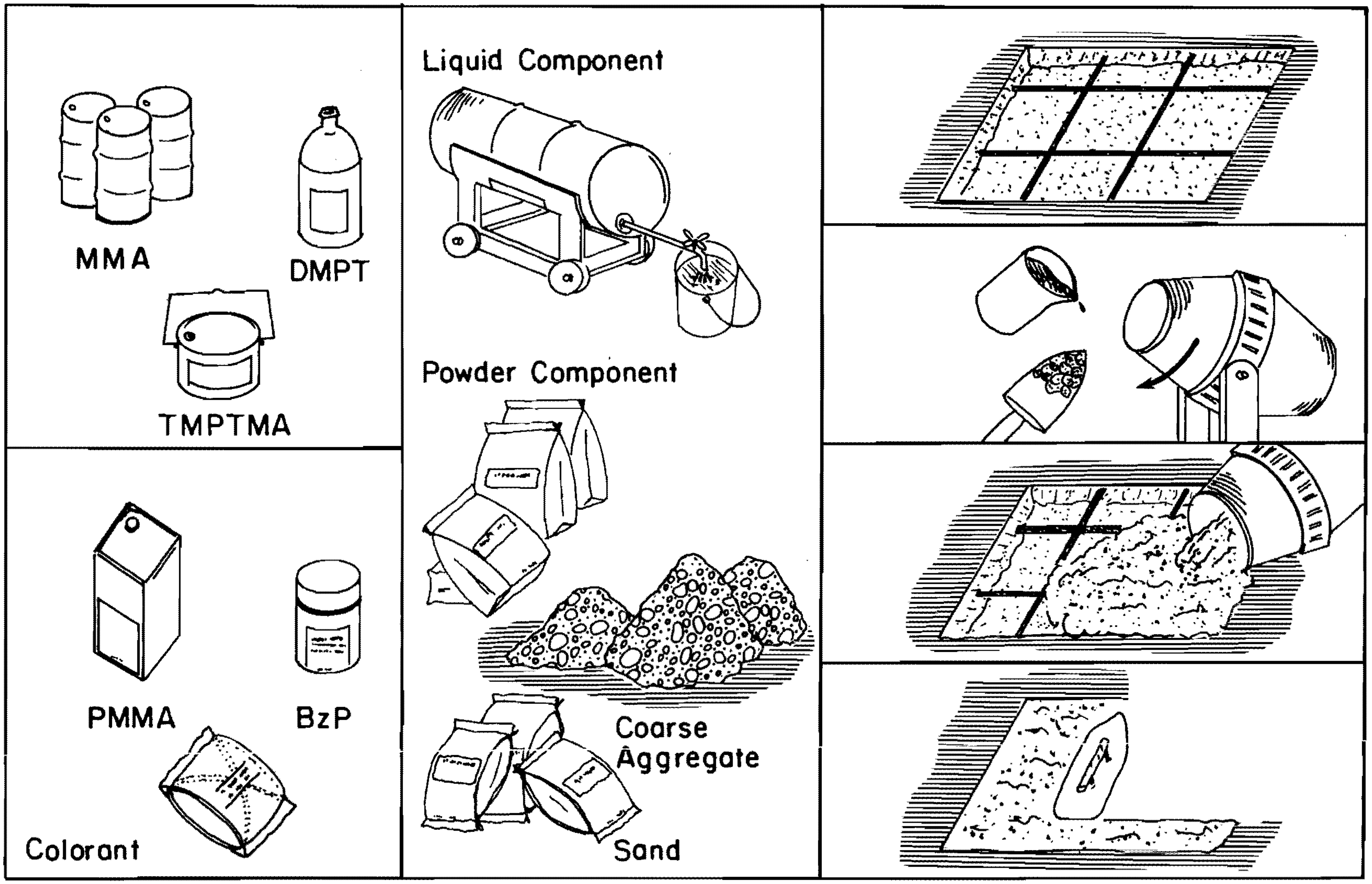


Fig. 7.2 Repair Procedure for User Formulated Prepackaged PC.

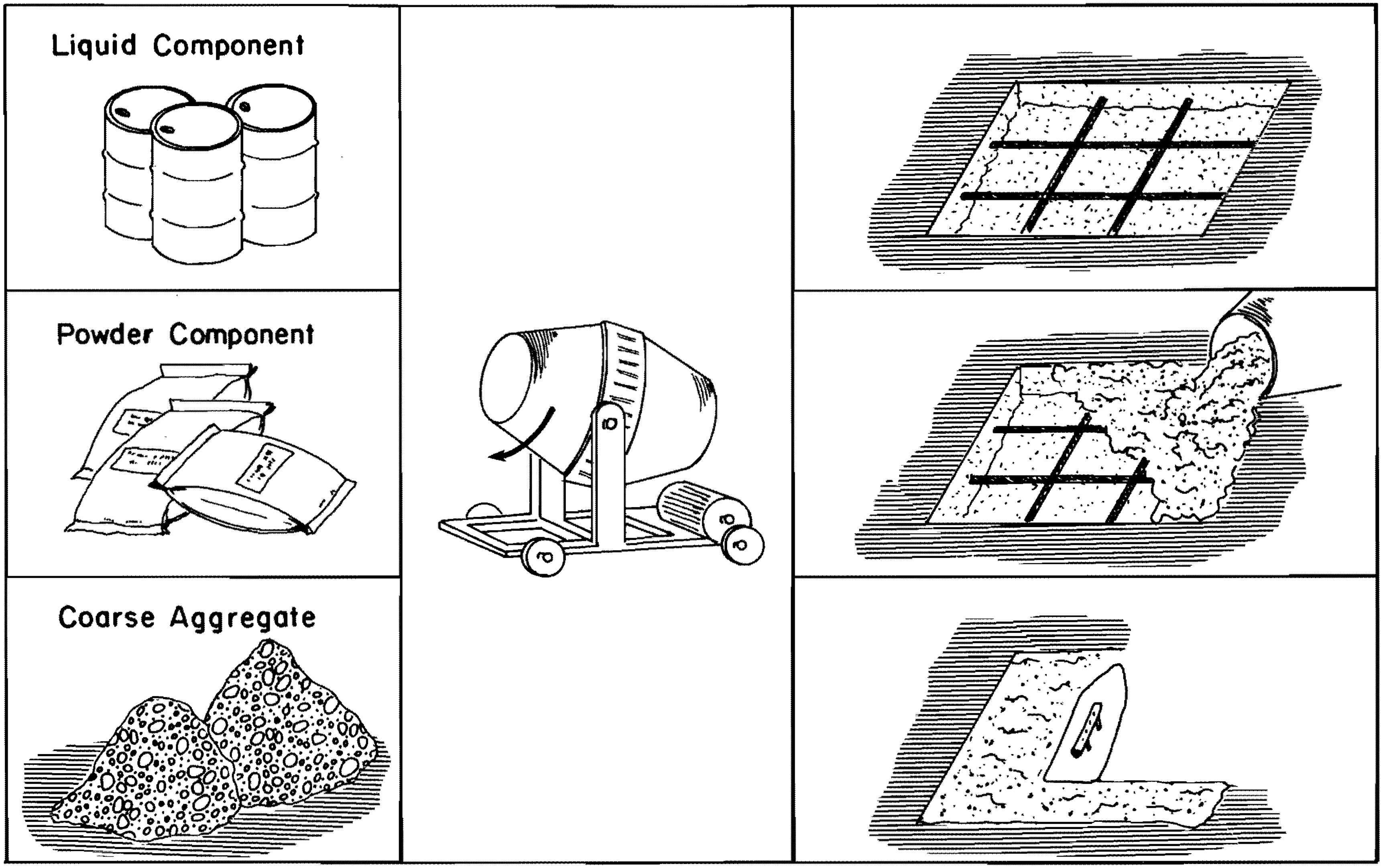


Fig. 7.3 Repair Procedure for Commercially-Available Prepackaged PC.

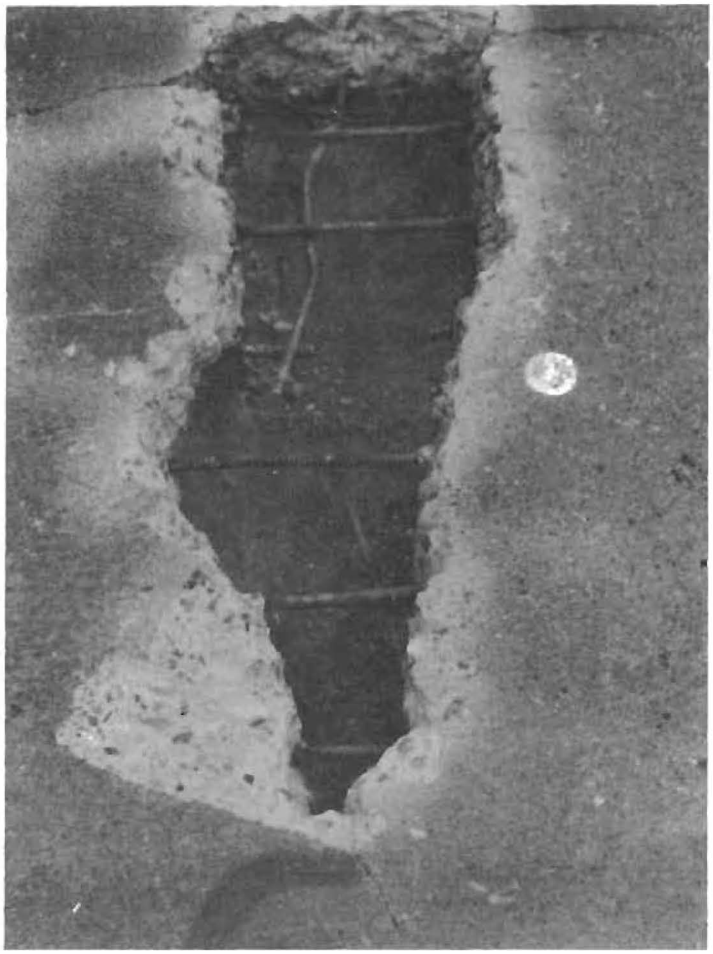
Transportation Research (CTR) made three polymer concrete repairs on IH-10, in the west bound lane between mileposts (MP) 700 and 703. The repairs were designated by numbers 6, 11, and 12. Figures 7.4, 7.5, and 7.6 show the areas before repairs were made (Ref 5).

7.3.1.1 Repairs No. 11 and 12

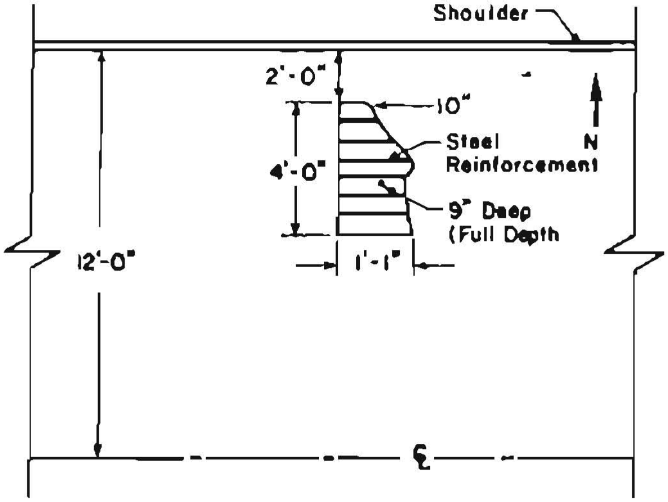
Repairs 11 and 12 were performed on the first day, August 22. The temperature was about 95°F (33°C). It rained for 30 min., about three hours before the repairs were performed (Ref 3).

The 9-in. (229-mm) CRCP had developed a series of transverse and longitudinal cracks. Repairs No. 11 and 12 consisted of punchouts with cracks extending to the centerline of the highway (Figs. 7.5 and 7.6). The unsound concrete in the punchouts was jackhammered out to full depth, and the holes were then sand blasted and cleaned with compressed air (Figs. 7.7 and 7.8). A crack chaser was used to open the cracks to 2 in. (51 mm) deep and 1 in. (25 mm) wide out to the centerline of No. 12 (Fig. 7.8). The crack chaser hammers out the loose particles in and around the crack and leaves a crack of uniform width and depth for repair.

In the punchouts, a dry mixture of sand and aggregate (50:50 ratio by weight) was placed in two layers. Each layer was rodded and saturated with monomer. A thin layer of sand was spread on top and trowelled to a smooth finish. A mixture of sand and powder PMMA (90:10 ratio by weight) was sprinkled on the surface to provide a skin surface that would help reduce evaporation of the monomer as it cured. The cracks were first filled to about 1/4 in. (6.4 mm) with monomer; then a dry mixture of sand and pea gravel (50:50 ratio by weight) was placed in two layers. Each layer was rodded and saturated with monomer. A thin layer of sand was spread on top and then a mixture of sand and PMMA (90:10 ratio by weight) was sprinkled to seal the surface. Tables 7.1 and 7.2 show the formulations and quantities of monomer and aggregate used.



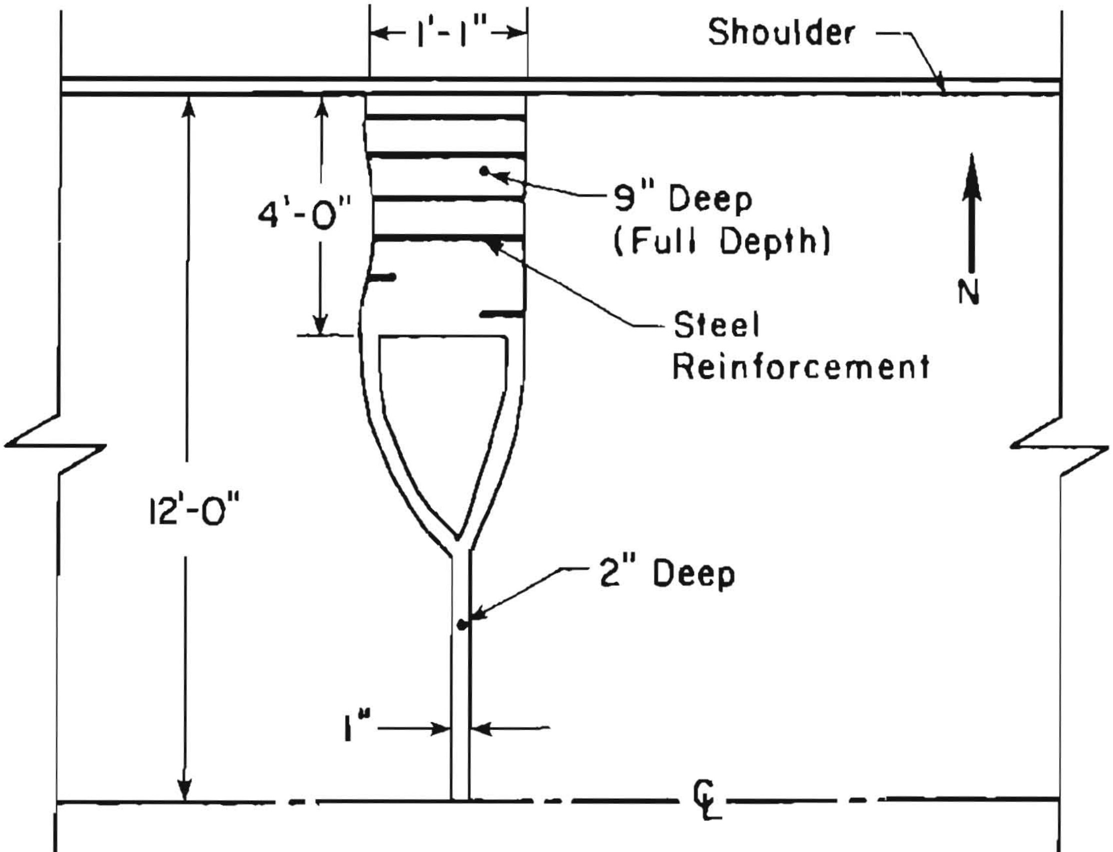
A. Photo



B. Dimensions

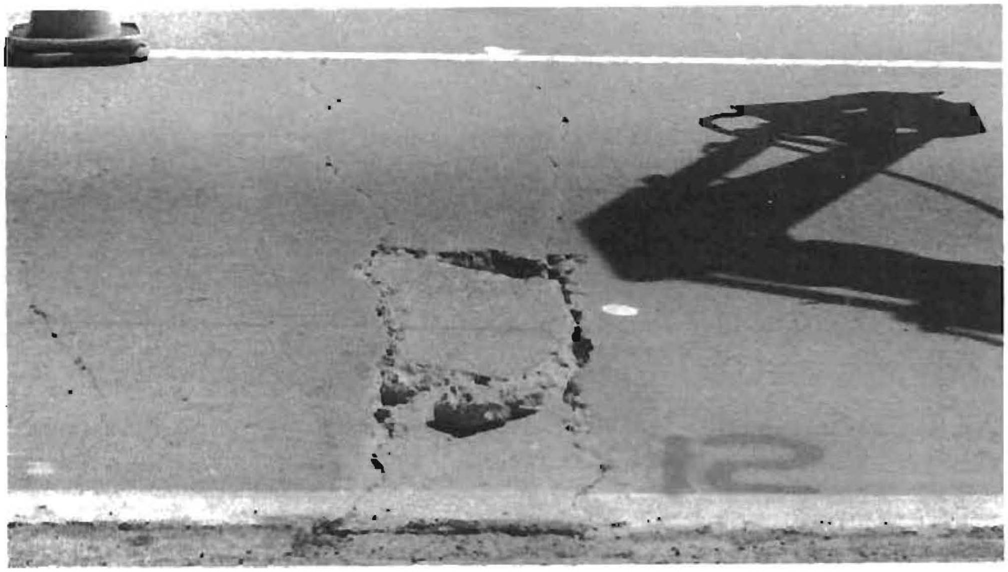
Fig. 7.4 Columbus Repair No. 6

A. Photo

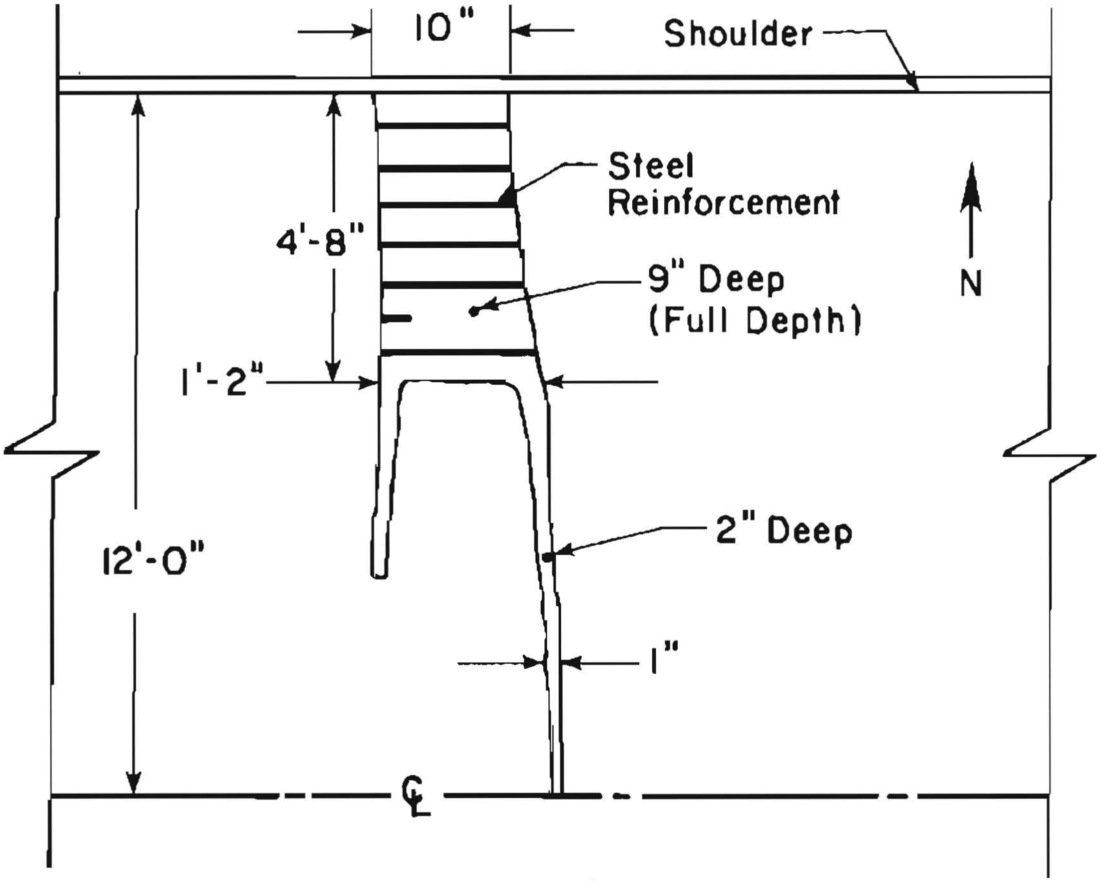


B. Dimensions

Fig. 7.5 Columbus Repair No. 11



A. Photo



B. Dimensions

Fig. 7.6 Columbus Repair No. 12

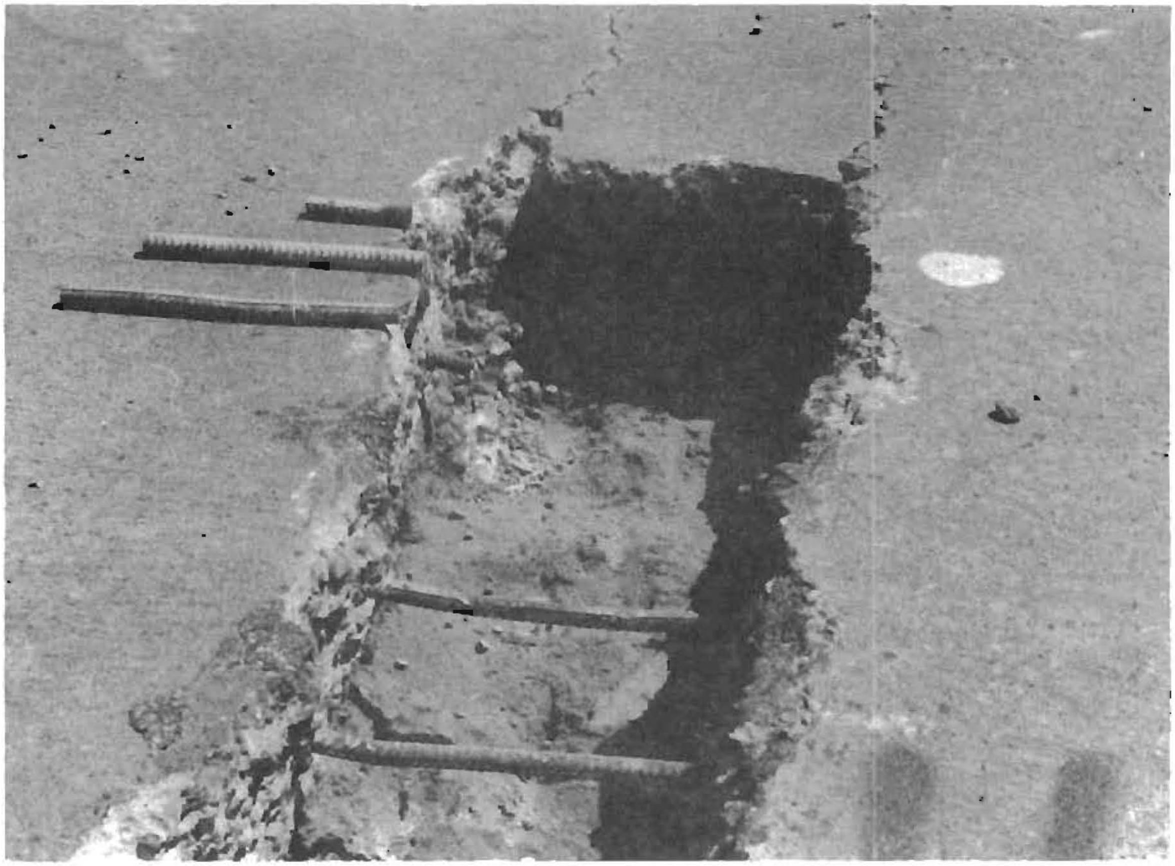


Fig. 7.7 Repair No. 11 Before the PC was Placed

Fig. 7.8. Repair No. 12: Concrete Removed and Crack Opened with Crack Cutter to Centerline

Table 7.1 Materials Used in Repair No. 11.

Chemical, etc.	Price ($/lb)	Punchouts (3.25 ft^3)			Cracks (0.16 ft^3)		
		Percent by Weight	Weight (lb)	Cost ($)	Percent by Weight	Weight (lb)	Cost ($)
MMA	0.71	90	72	51.12	90	7.2	5.11
BA[a]	0.55	10	8	4.40	10	0.8	.44
LP[b]	3.50	4	3.2	11.20	4	0.32	1.12
DMT	5.00	2	1.6	8.00	2	0.16	.80
Total Cost				74.72			7.47
				$23.00/cu.ft.			$46.68/cu.ft.

[a] Butyl acrylate; no longer used so price may be inaccurate

[b] Layroyl peroxide; no longer used so price may be inaccurate

Table 7.2 Materials Used in Repair No. 12.

Chemical, etc.	Price ($/lb)	Punchouts ($3.5\ ft^3$)			Cracks ($0.16\ ft^3$)		
		Percent by Weight	Weight (lb)	Cost ($)	Percent by Weight	Weight (lb)	Cost ($)
MMA	0.71	85	68	48.28	80	6.34	4.50
MMA Syrup	1.02[b]				15	1.19	1.21
EHMA[b]	0.70	10	8	5.60			
TTEGDA[c]	1.69	5	4	6.76			
TMPTMA	1.78				5	0.40	.71
BzP (40% concentration)	2.07	2.4[a]	1.9	3.93	2.4[a]	0.19	.39
DMT	5.00	0.3	0.24	1.20	0.3	0.024	.12
Total Cost				65.77			6.93
				$18.79/ft^3$			$43.31/ft^3$

[a] 0.95 percent concentration BzP required

[b] 2-ethylhexyl methacrylate; no longer used so price may be inaccurate

[c] Tetraethylene glycol diacrylate; no longer used so price may be inaccurate

As the monomer cured in repair No. 11, some blistering appeared on the surface of the PC, which might tend to indicate that the percentages of initiator and promoter were too high for the temperature on that day. It might also be noted that this formulation had no TMPTMA, which tends to reduce blistering. The blistering was not observed in the cracks extending from the punchout, although the same monomer formulation was used. The reason might be the smaller mass of PC in the crack repair. The overall quality and finish of repair No. 11 was good (Fig. 7.9). Figure 7.10 shows repair No. 12. Curing time on both repairs was less than 30 minutes. All repairs were structurally sound and were opened to traffic in two hours.

An inspection the next day indicated that repair No. 11, including all repaired cracks, was sound, with no evidence of cracking. Repair No. 12 had a crack at the interface between the PC and the concrete pavement.

The repairs were inspected in April 1981. It was found that a part of repair 11 had broken away and it was replaced with asphalt concrete. Repair 12 developed thin cracks at the interface with portland cement concrete.

7.3.1.2 Repair No. 6

Repair No. 6, which was of a punchout (Fig. 7.4), was performed on August 23, at 5 PM. The temperature was around 90°F (32°C) with partly cloudy skies. The vertical sides of the concrete were dried with a butane torch. Table 7.3 shows the formulations and quantities of monomer and aggregate used. After the concrete had cooled, the sides were primed with monomer formulation No.1. The mixture of dry sand and gravel (50:50 ratio by weight) was then placed in three layers. Each layer was rodded and saturated with

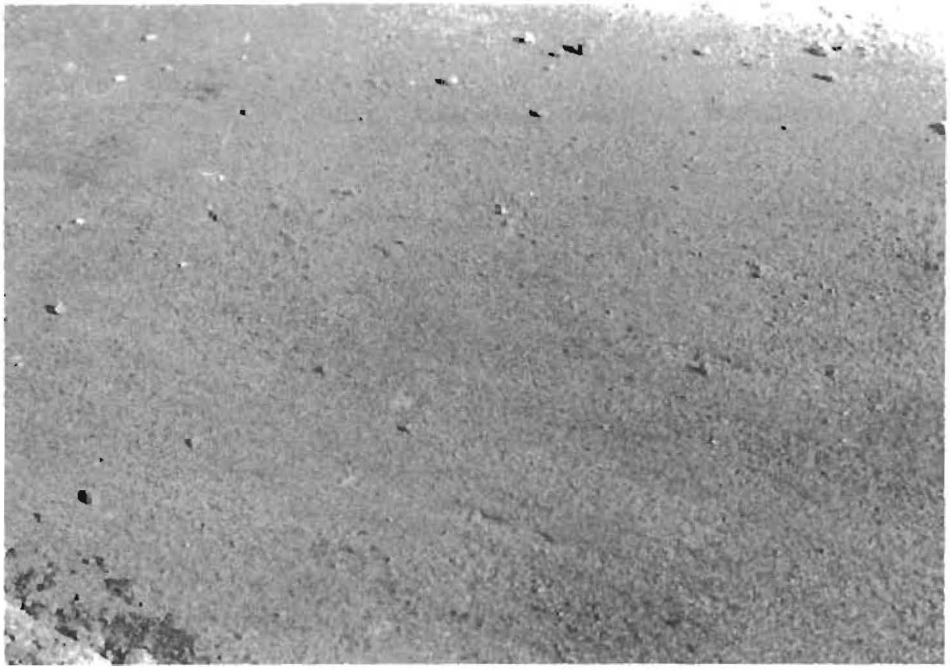


Fig. 7.9 Columbus Repair No. 11 After Finishing

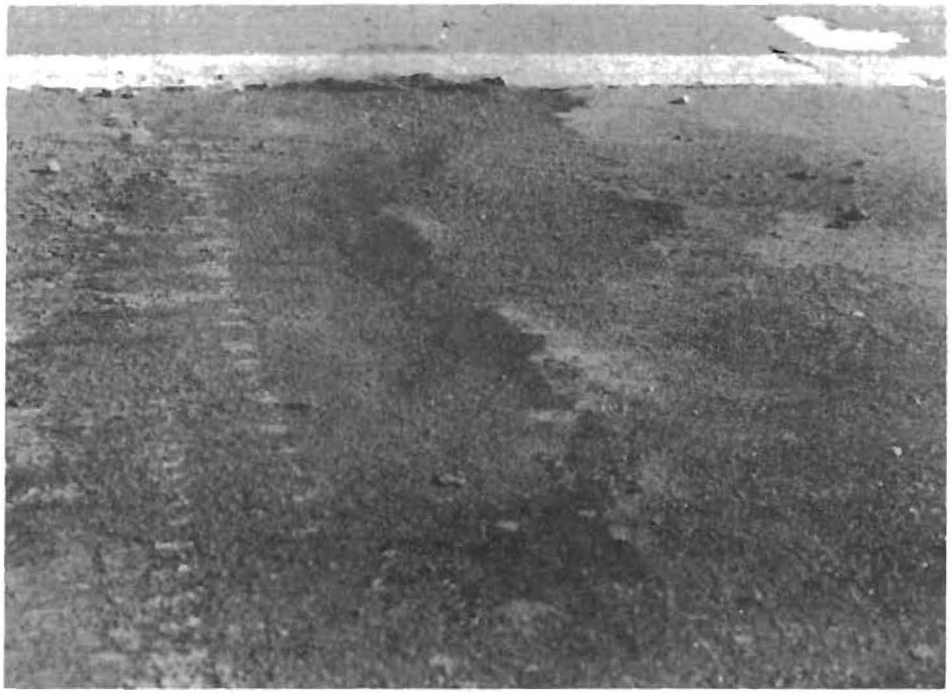


Fig. 7.10 Columbus Repair No. 12 After Completion

Table 7.3 Materials Used in Repair No. 6.

Chemicals	Price ($/lb)	Formulation No. 1			Formulation No. 2[d]		
		Percent by Weight	Weight (lb)	Cost ($)	Percent by Weight	Weight (lb)	Cost ($)
MMA	0.71	85	27.2	19.31	15	1.19	.84
MMA Syrup	1.02[c]				80	6.34	6.46[c]
EHMA	0.70[c]	10	3.2	2.24[c]			
TTEGDA	1.80[c]	5	1.6	2.88[c]			
TMPTMA	1.78				5	0.40	0.71
BzP (40% concentration)	2.07				2.4[a]	0.19	0.39
LP	3.50[c]	4	1.28	4.48[c]			
DMT	5.00	2	0.64	3.20	0.3	0.024	0.12
Total Cost				32.11			8.52
Estimated Volume (ft^3)				2.92			
Fine Aggregate (ft^3)		50	180				
Coarse Aggregate (lb)		50	180[b]				

[a] 0.95 percent concentrated BzP required

[b] 3/4-in. aggregate

[c] These materials no longer used so prices may be inaccurate.

[d] Formulation No. 2 was only and for surface finishing of the repair.

monomer No. 1. The top 1/4 in. (6.4 mm) of the repair was filled with sand and monomer formulation No. 2 was used to saturate the top layer. The repair area was then trowelled to a smooth finish. The surface with the thick monomer formulation was very workable and produced a good finish (Fig. 7.11). The monomer polymerized in about 20 min., and the area was opened to traffic in two hours (Ref 5).

7.3.1.3 Deflection Measurements

To determine the improvement that the PC repair made in the damaged concrete pavement, deflection readings with a Dynaflect were taken at the edge of the holes a few days before and after the repair was performed. Figure 7.12 shows a drawing of the Dynaflect system. Cyclic force is generated by a pair of unbalanced fly wheels which rotate in opposite directions at 480 rpm. This produces a cyclic vertical force of 1,000 lb on the loading wheels. The resulting deflections are picked up by the five geophones, each 12 in. apart, on the surface of the pavement. Figures 7.13, 7.14, and 7.15 show plots of the deflection profiles for Columbus repairs 6, 11, and 12. The deflections were considerably reduced after the repairs, indicating that the PC improved the stiffness of the pavement. For a sound pavement, the deflections range from 0.5 x 10^{-3} in. to 0.8 x 10^{-3} in. (13-mm to 20-mm) (Ref 5).

7.4 IH-10, Sealy, Texas

On October 2, 1979, a team from the Center for Transportation Research made three polymer-concrete joint repairs at Sealy. The joints repaired were on IH-10 just east of the westbound Exit 713 sign (Fig. 7.16) and were designated as numbers 4, 7, and 9. Figures 7.17 to 7.19 show the dimensions of the repairs. The weather was sunny with clear skies and temperature around 85°F (Ref 5).

The jointed pavement had developed spalls at the joints,

Fig. 7.11 Repair No. 6 After PC Placement

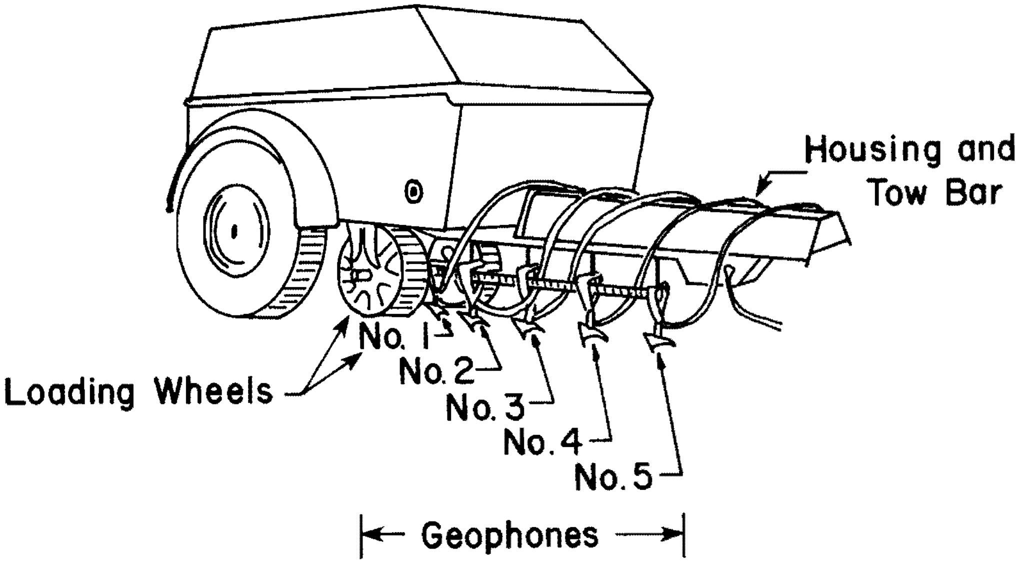


Fig. 7.12 The Dynaflect System in Operating Position

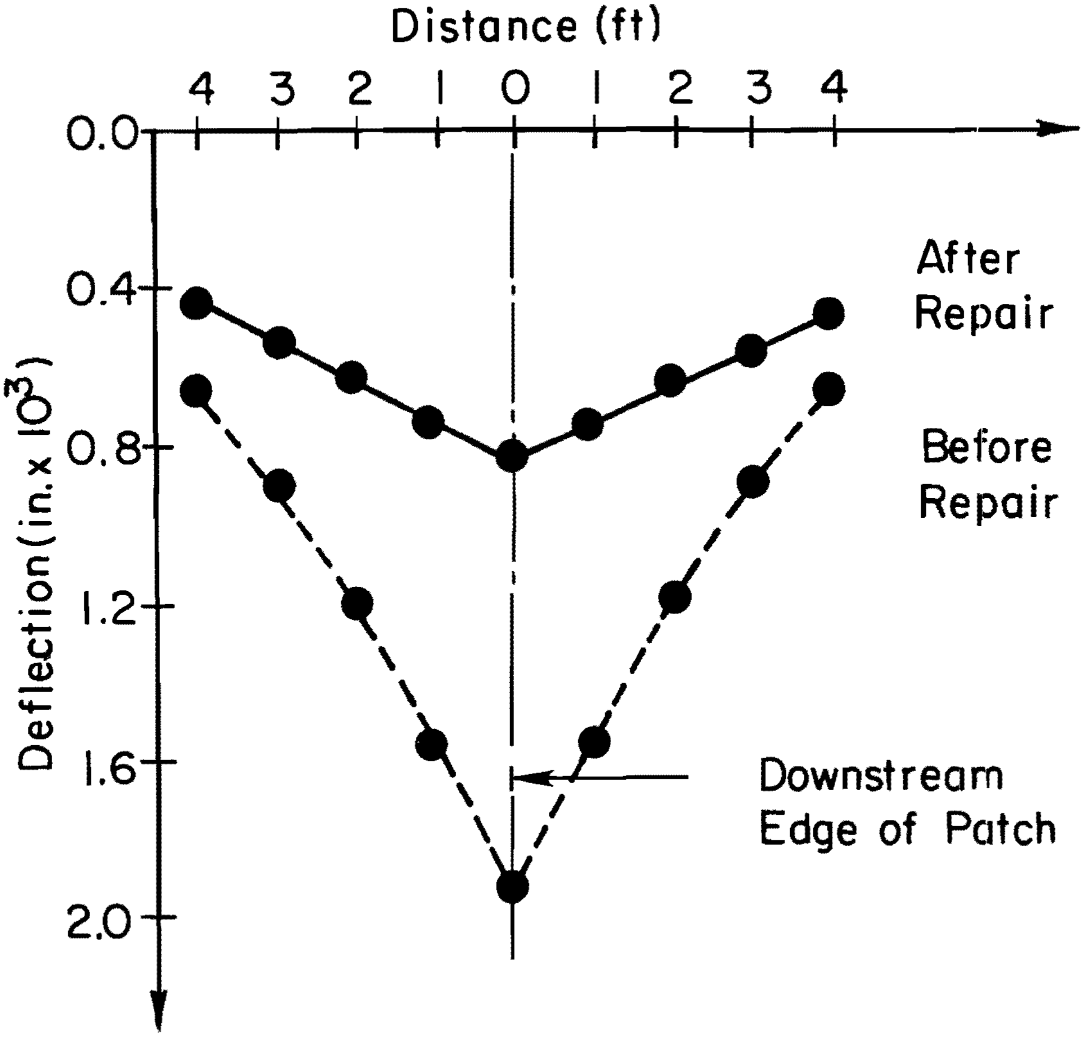


Fig. 7.13 The Deflections at Downstream Edge of Repair No. 6

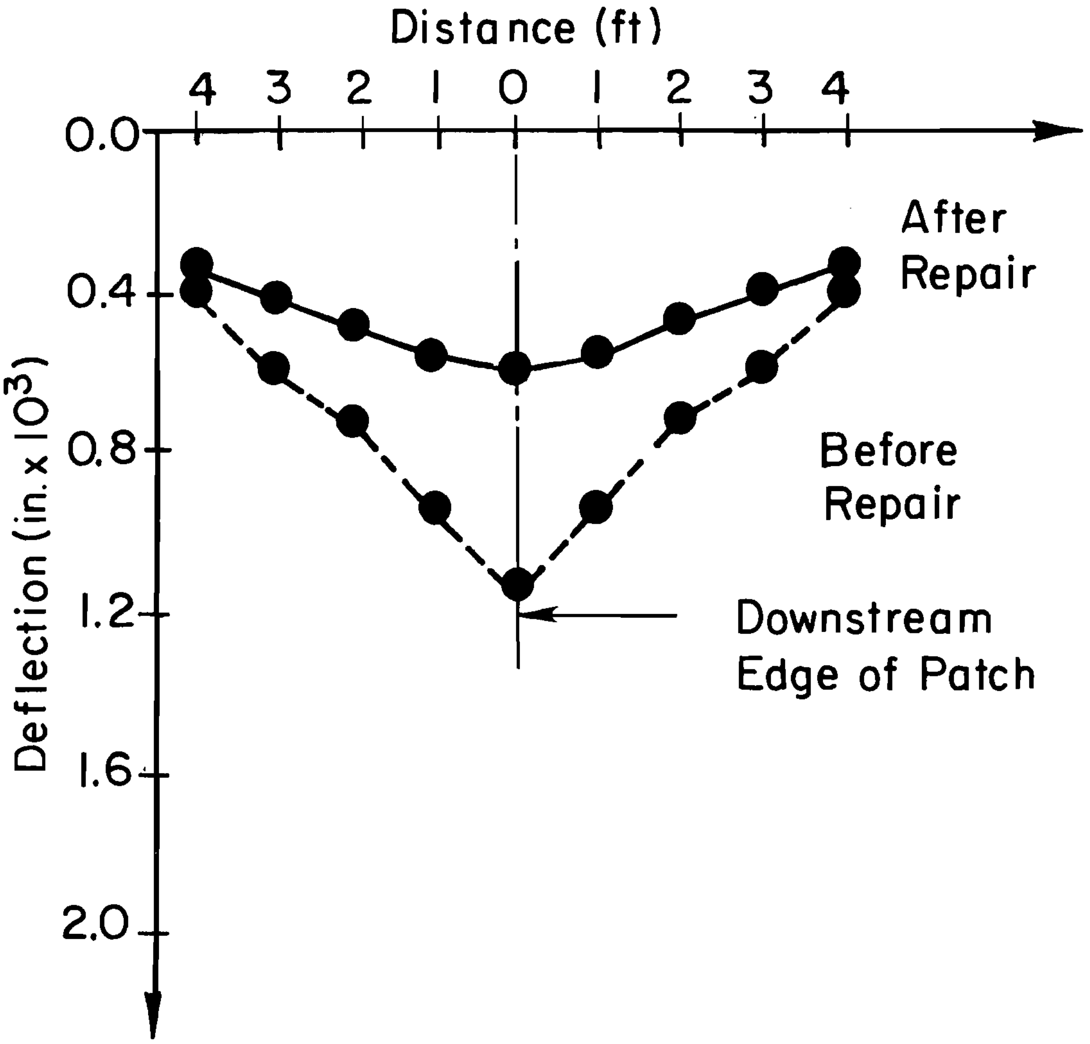


Fig. 7.14 The Deflections at Downstream Edge of Repair No. 11

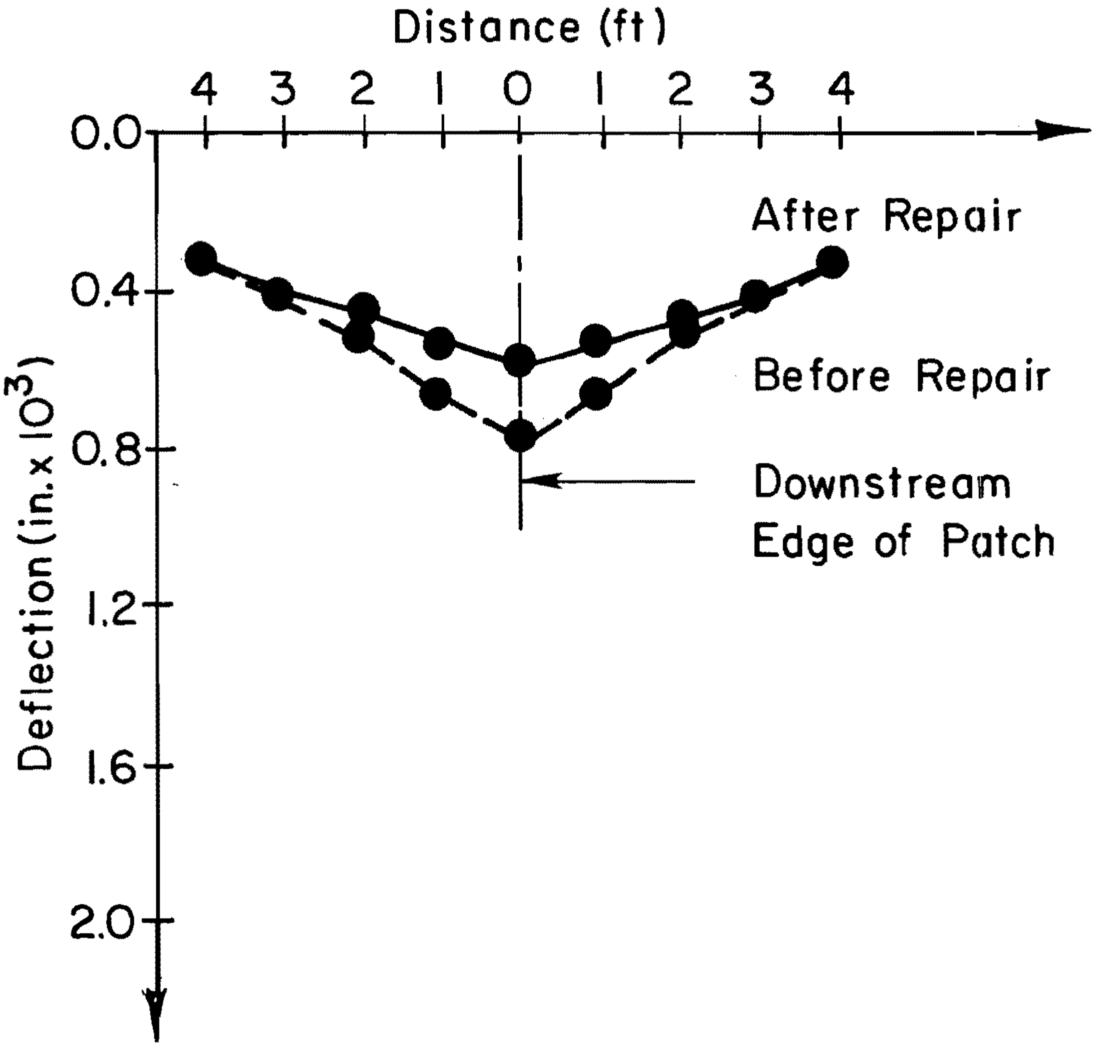


Fig. 7.15 The Deflections at Downstream Edge of Repair No. 12

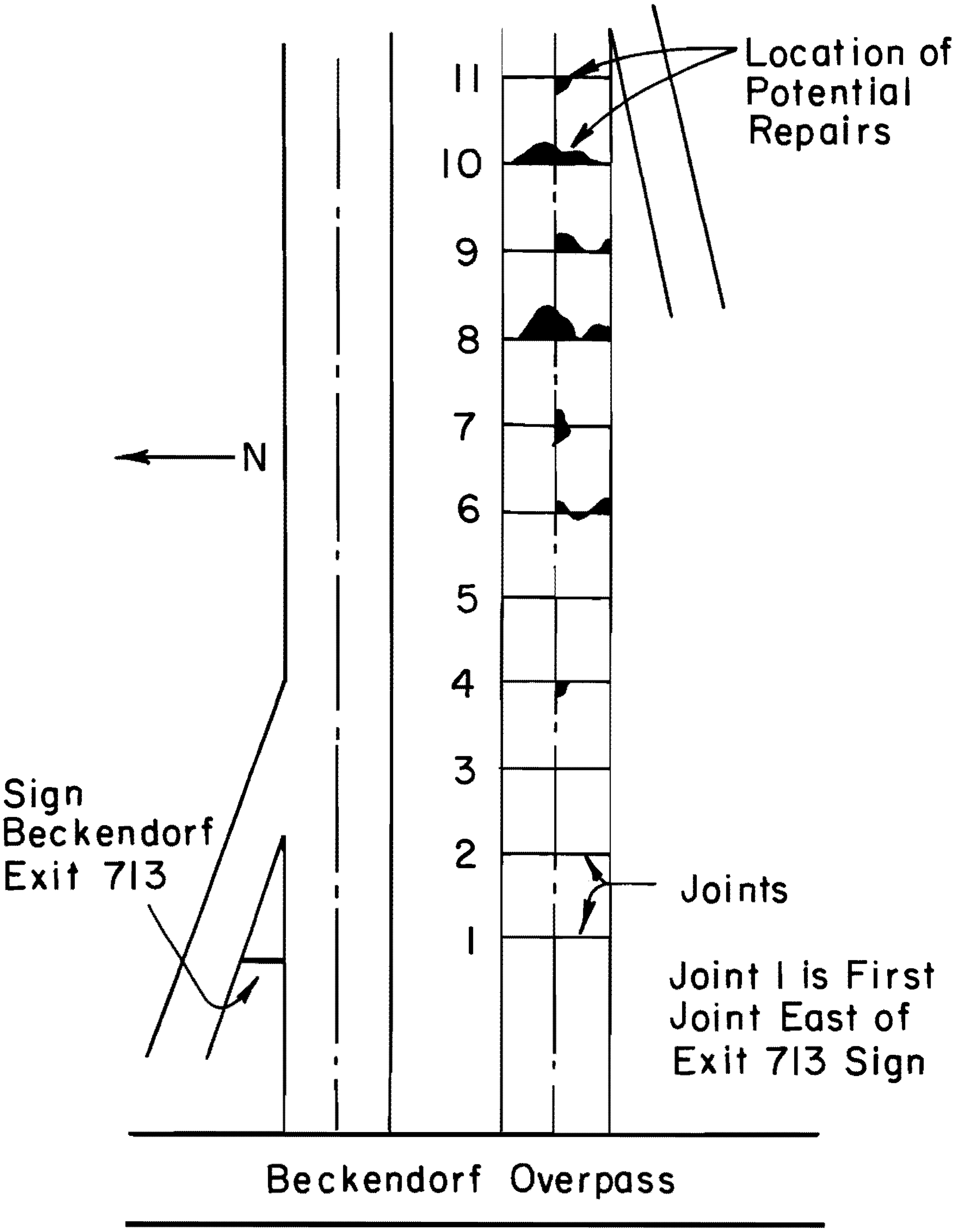
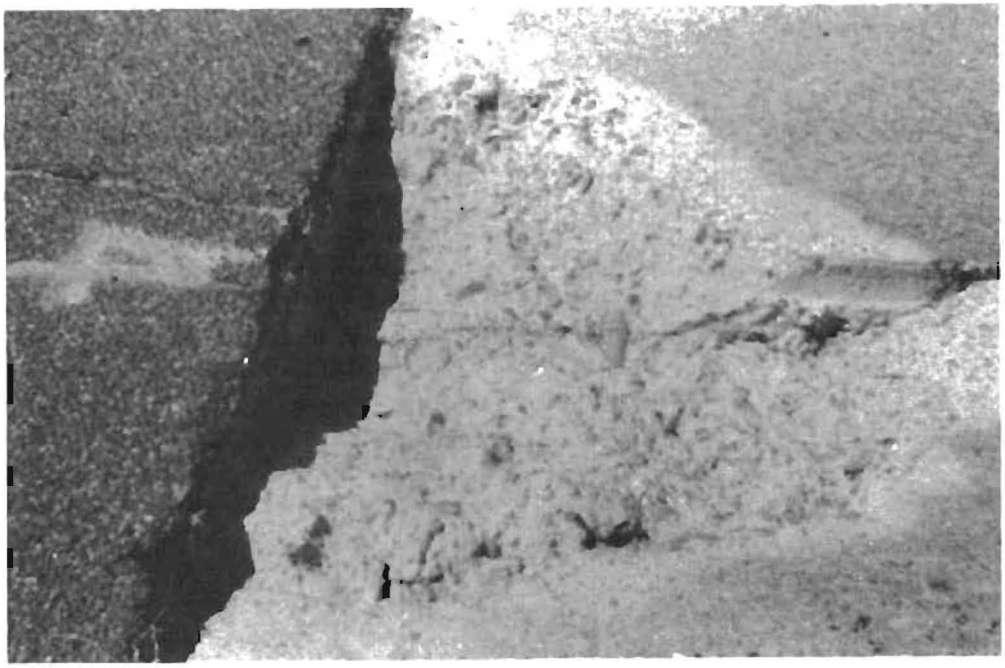
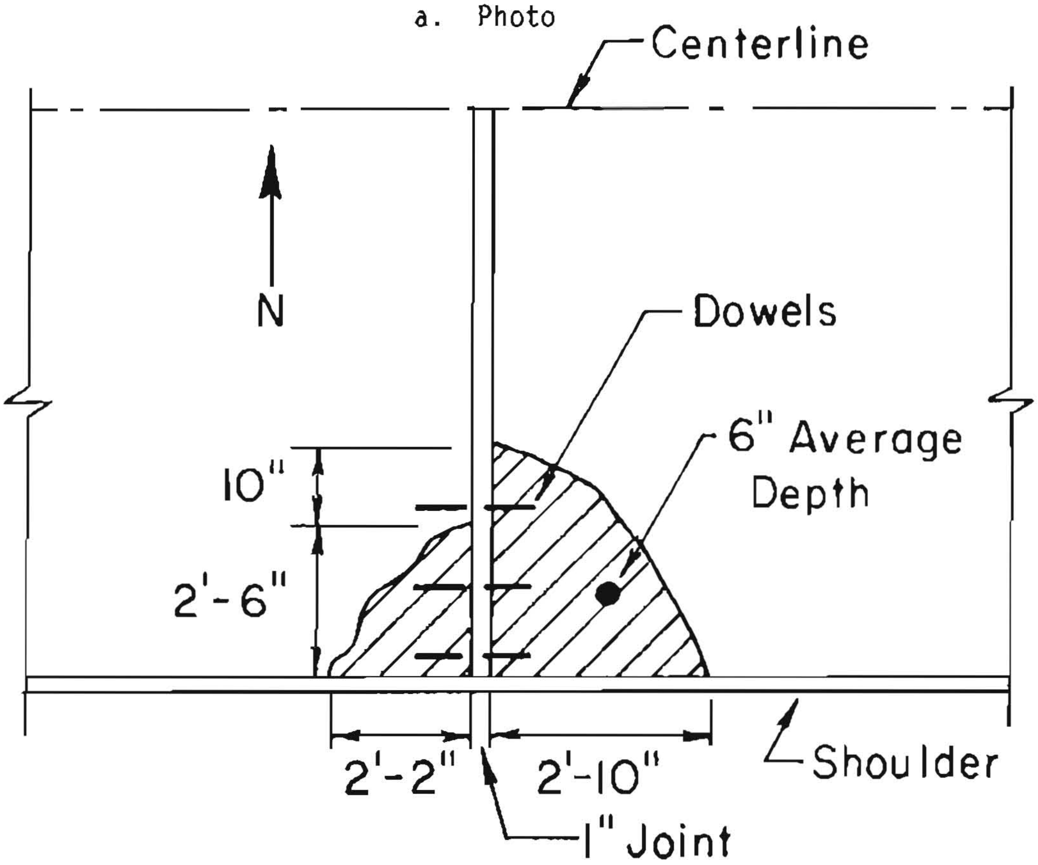


Fig. 7.16 Location of Joint Repairs in District 12

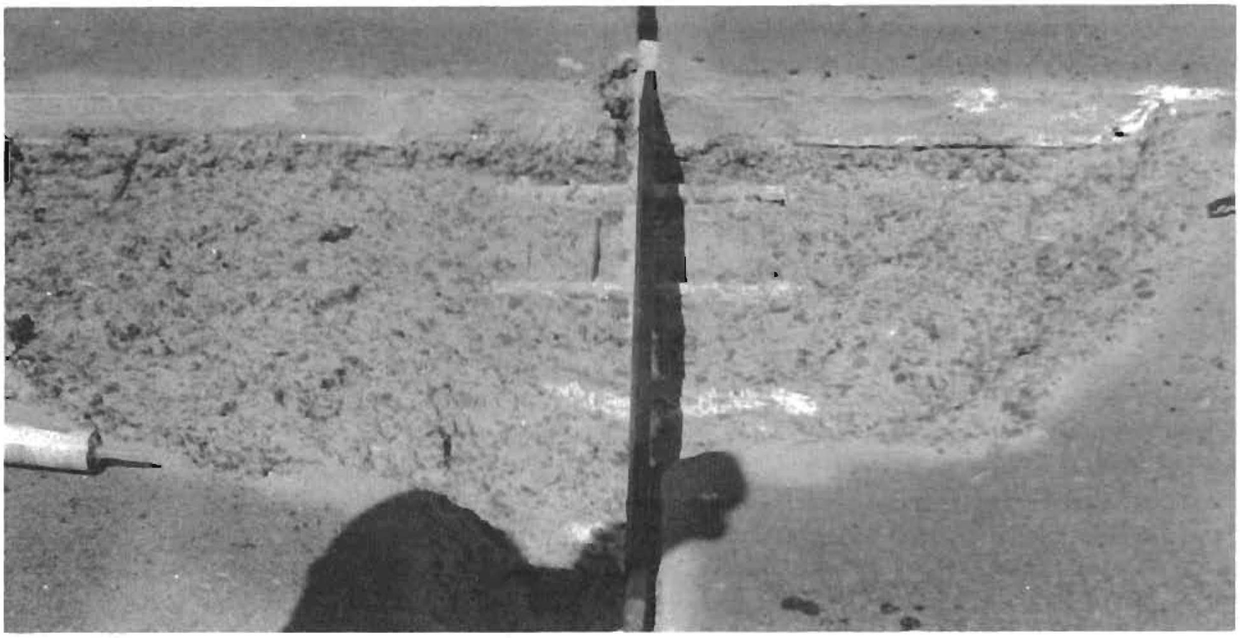


a. Photo



b. Dimensions

Fig. 7.17 Sealy Repair No. 4



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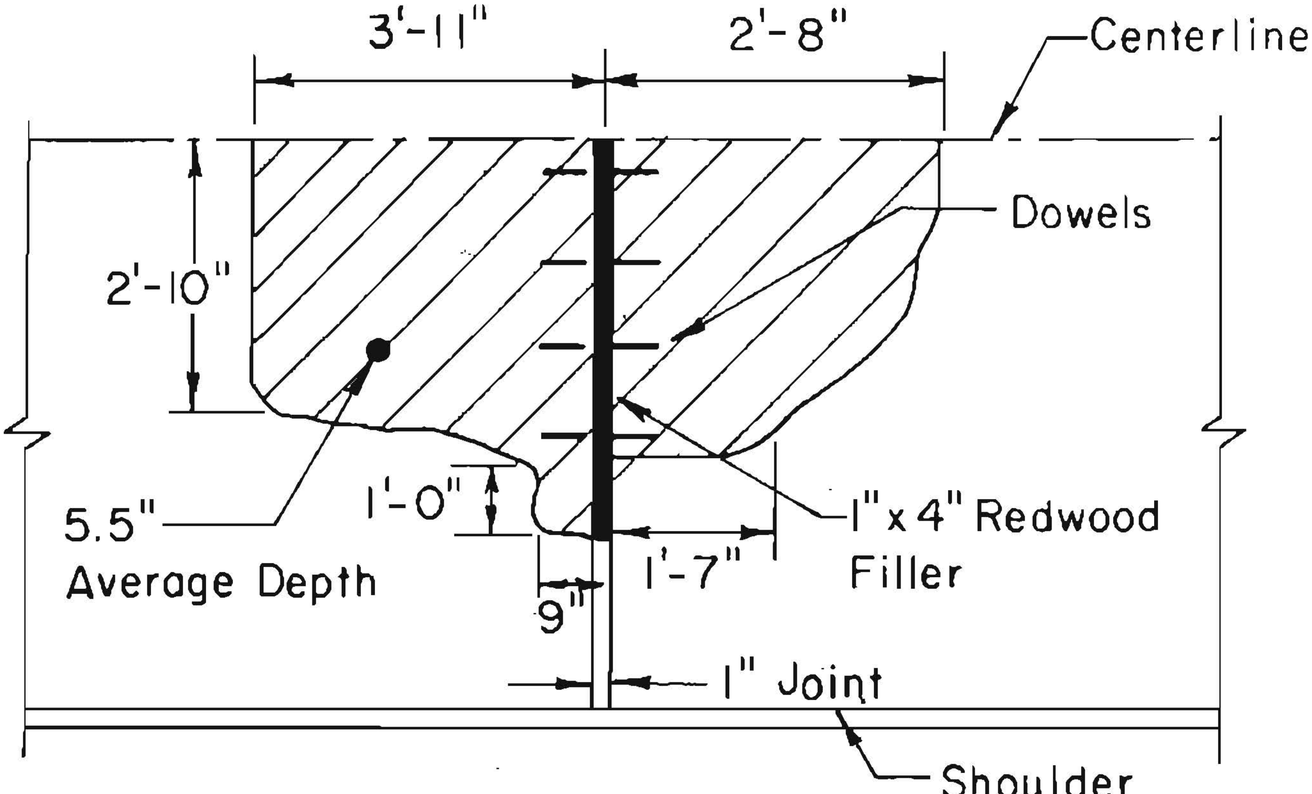
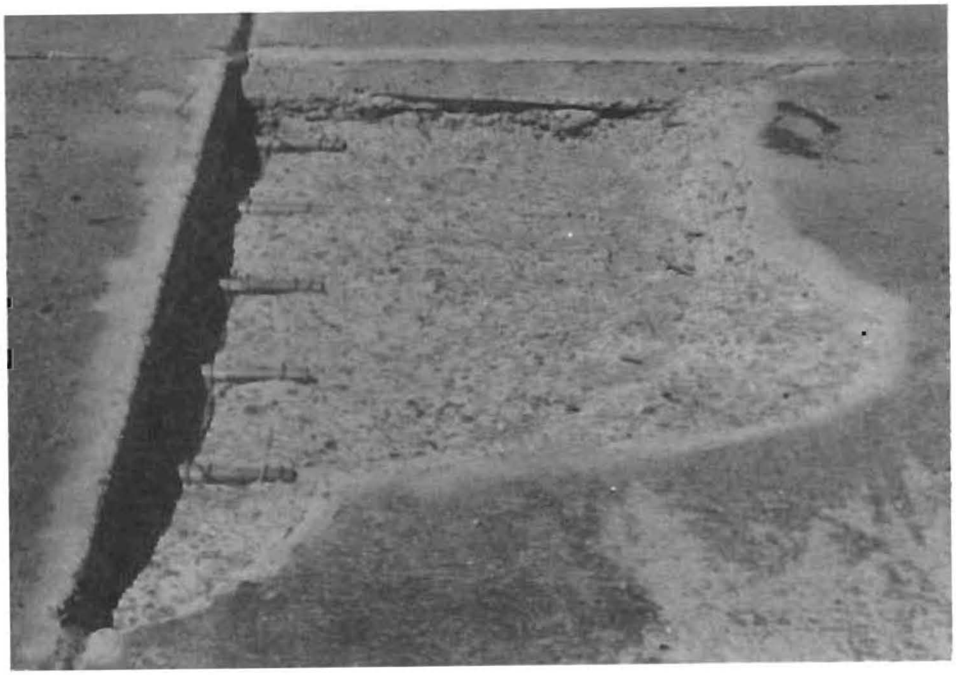


b. Dimensions

Fig. 7.18 Sealy Repair No. 7



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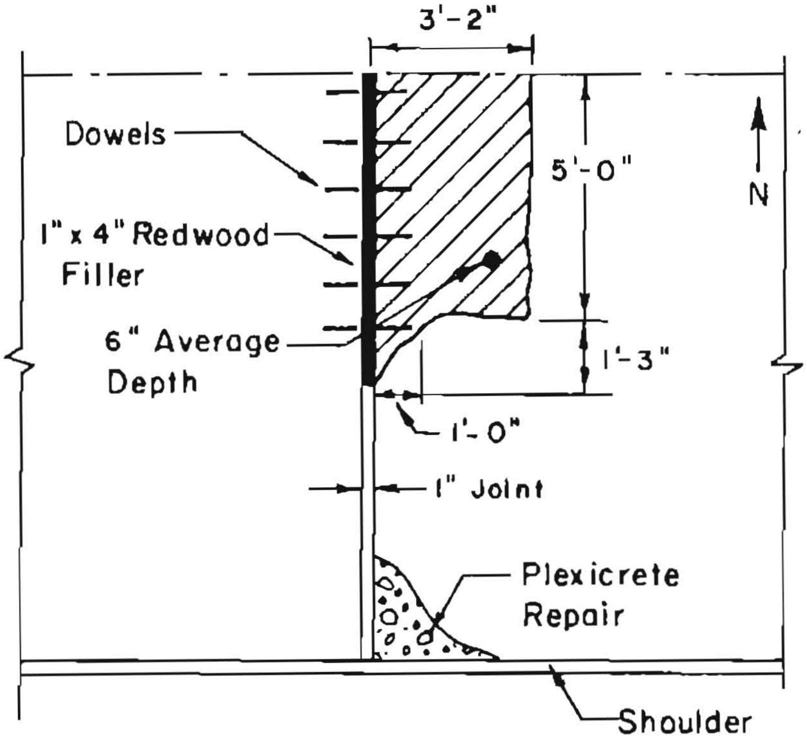

b. Dimensions

Fig. 7.19 Sealy Repair No. 9

which were located 60 ft apart. On all of the repairs, the unsound concrete and asphalt filler was jackhammered out and the hole was then sandblasted and cleaned with compressed air. The depths of the holes were 5.0 in. to 6.0 in. It was noted that some of the dowels at the spalls had been placed so that they were slighty out of alignment with the centerline of the pavement, and this may have contributed to the spalling. The correctly aligned dowels were left in the pavement. The open joints were sealed with latex caulking to prevent leakage of the monomer, and the dowels were coated with caulking to prevent bonding to the polymer concrete. At joint No. 9 a horizontal crack was noted in the concrete at the north side of the repair. The concrete in the left hand lane appeared to be delaminated. To maintain the integrity of the joints, 1-in. x 4-in. redwood filler strips were used on repairs 7 and 9.

A 55-gal. drum of premixed monomer system consisting of MMA (95 percent by weight), TMPTMA (5 percent by weight), and DMT (0.35 percent by weight) had been prepared in the laboratory. For each repair the needed amount of monomer system was emptied into a 5-gal. container and mixed with BzP (1.0 percent by weight).

The concrete surface in the repair hole was first wetted with the monomer. Next the hole was filled with dry sand and gravel (50:50 ratio by weight) and fully saturated with the monomer. A thin layer of sand was spread on top and trowelled to a smooth finish. Finally, a mixture of sand and PMMA powder (90:10 ratio by weight) was sprinkled on the surface to develop a skin that would help reduce evaporation of the monomer as it cured.

Approximately 50 minutes were required for the monomer to fully polymerize. All of the repairs appeared to be of good quality and structurally sound. The repair work began at 11:15 AM and was completed by 3:34 PM. Traffic was returned by 4:30 PM.

On repair No. 7, a crack developed on top of the 1-in. x 4-in. filler, which assured that the separation at the joint would be maintained. The quantities of aggregates and monomer used for each repair are shown in Table 7.4. The cost ranged from \$268 to \$346/yd^3.

In April 1981, the repairs were inspected and found to be in a good condition.

7.5 Repairs at Marshall, Texas

7.5.1 Conditions

On July 15, 1980, several crack and punchout repairs were performed with PC on Interstate 20 near Marshall, Texas. The weather throughout the day was hot and dry. The ambient temperature recorded was 90°F, and winds were recorded at 10 mph. Four areas were repaired on the 8-in. thick continuously reinforced concrete pavement (Ref 6).

The first repair area, No. 1, was a large spall and punchout on the eastbound outside lane at milepost (MP) 638.5. This area had been repaired with asphalt cement concrete. Figure 7.20 shows the repair after the asphalt had been removed. The second repair area, No. 2, was also on the eastbound outside lane at MP 639.5. This repair area showed longitudinal and transverse cracking (Fig. 7.21). The third and fourth repair areas were on the westbound lane at MP 646.8 and 641.5, respectively. The third repair area showed a little spalling at the intersection of the two transverse cracks (Fig. 7.22). The fourth area was a "V" shaped punchout close to the shoulder (Fig. 7.23).

7.5.2 Procedure

The repair procedure in each case is described in this section. The monomer formulation used for all repairs was

MMA	95 percent
TTEGDA	5 percent
DMPT	0.75 percent
BzP	1.5 percent

Table 7.4 Materials Used in Joint Repairs on IH 10 (Sealy).

			Repair Site Numbers					
			No.4 (4.75 ft^3)		No.7 (10 ft^3)		No.9 (8ft^3)	
Chemical, etc.	Price ($/lb)	Percent by weight	Weight (lb)	Cost ($)	Weight (lb)	Cost ($)	Weight (lb)	Cost ($)
MMA	0.71	95	68.0	48.28	120.8	85.77	90.63	64.35
TMPTMA	1.78	5	3.58	6.37	6.4	11.39	4.77	8.49
BzP (40% concentration)	2.07	2.5[b]	2.4	4.97	3.18	6.58	2.4	4.97
DMPT	5.00[b]	0.35	0.25	1.25	0.45	2.25	0.33	1.65
Total Cost				60.87		105.99		79.46
Cost/yd^3				$346.00		$286.00		$268.00

[a] Cost in 55-gal drums

[b] 1% concentrated BzP required; use 1.0/4 - 2.5% of 40% concentration

Fig. 7.20 Marshall Repair No. 1 After Removal of Asphalt

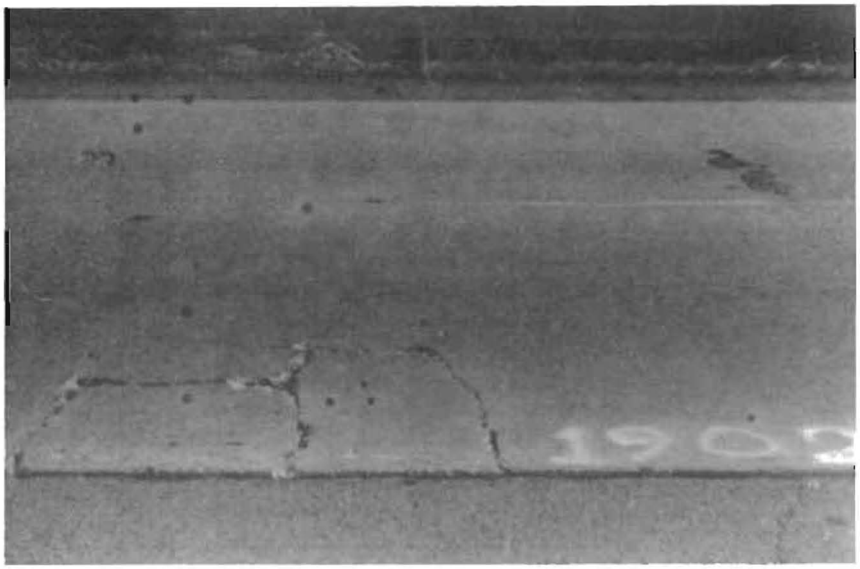

Fig. 7.21 Marshall Repair No. 2 Before Cracks Widened

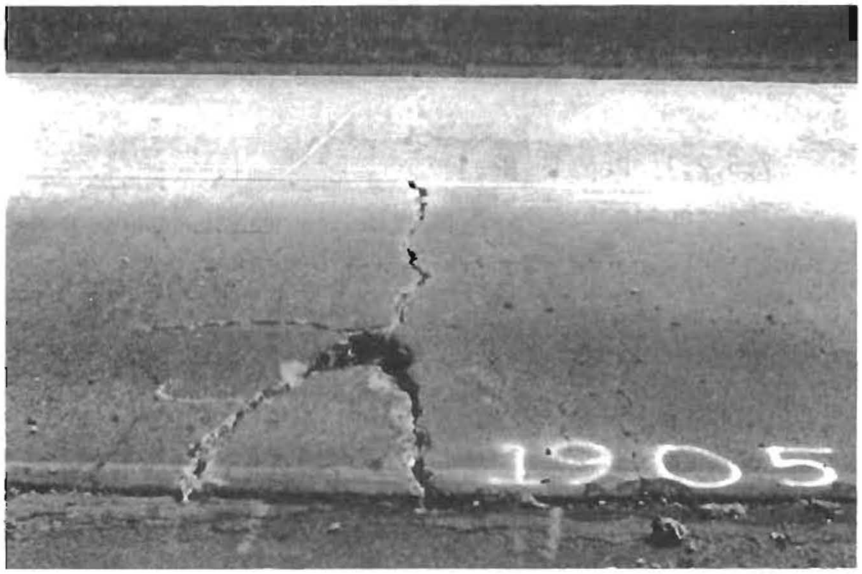

Fig. 7.22 Marshall Repair No. 3 Prior to Widening Cracks

Fig. 7.23 Marshall Repair No. 4 Prior to Removal of Concrete

The aggregates used were a mixture of 50 percent all-purpose sand and 50 percent 3/4-in. crushed limestone (Ref 4).

7.5.2.1 Repair No.1

The repair had been previously made with asphalt. Transverse cracks originated from the spall (Fig. 7.20). Major cracking in the slab could be noticed on the upstream end of the spall. The exisiting asphalt and about 6 inches of existing concrete were removed from the repair area to expose the steel reinforcement. Replacement bars were welded in place. The repair area was then thoroughly cleaned, and all loose particles were removed to expose a clean hard concrete surface. After the monomer was prepared, a small amount was poured into the repair area to wet the concrete. The aggregate, which consisted of a mixture of 50 percent concrete sand and 50 percent 3/4 in. crushed limestone, was then placed to one-half the depth of the repair area. The monomer was poured over it, and the repair area was rodded. This process was repeated until the entire repair area was filled. The top of the repair area was trowelled to the level of the existing pavement to provide a smooth riding surface (Ref 6).

7.5.2.2 Repair No. 2

The longitudinal and transverse cracks in repair No. 2 (Fig. 7.21) were traced with a crack chaser. The cracks were opened to a 3/4-in. width and a 2-in. depth. Monomer was poured into these cracks. The crack was filled with dry sand and then saturated with the monomer system. The surface was trowelled smooth to the level of the existing pavement (Ref 6).

7.5.2.3 Repair No. 3

The procedure for this repair area was similar to the one performed on repair Area 2. The cracks in repair No. 3 (Fig.

7.22) were opened with a crack chaser (Fig. 7.24) and then filled with sand which was saturated with monomer (Ref 6).

7.5.2.4 Repair No.4

The "V" shaped punch out, previously repaired with asphalt was excavated to expose a clean concrete surface. The aggregates consisted of a mixture of 50 percent dry sand, 50 percent 3/4-in. crushed limestone, and two percent 0.5 x 30-mm-long bent steel fibers. The repair area was completed as described before (Ref 4).

7.5.3 Results

The SDHPT measured deflections with a Dynaflect at each repair area before and after the repairs were performed. All Dynaflect readings were made at 3 ft from the edge of the pavement. Figures 7.25 to 7.28 show the plots of the deflections measured across the four repairs. In all cases, it was observed that PC partially restored uniformity of stiffness in the pavement. In the case of repair No. 2 (Fig. 7.26), it was observed that there was a redistribution of stiffness across the crack. The stiffness coefficient at the crack before the repair was measured to be 0.92 and after the repair was measured to be 1.18. The increase in stiffness at the crack partially restored uniformity of stiffness across the crack. From the deflection curves of the repaired pavement (Fig. 7.26), the pavement was restored to act as one unit. The redistribution of stiffness across the repair area indicates a redistribution of stresses across the area, which indicates that the bond between PC and PCC was good. This pattern was observed for all the repairs (Figs. 7.26, 7.27, and 7.28). The stiffness of the cracked area could not be fully restored to the original stiffness of the slab because of the low modulus of elasticity of PC as compared to PCC. The reduction in stiffness, in fact, helps, by reducing large stresses at the joint and thus preventing further cracking (Ref 6).

Fig. 7.24 Cracks in Repair No. 3 Opened with Crack Chaser

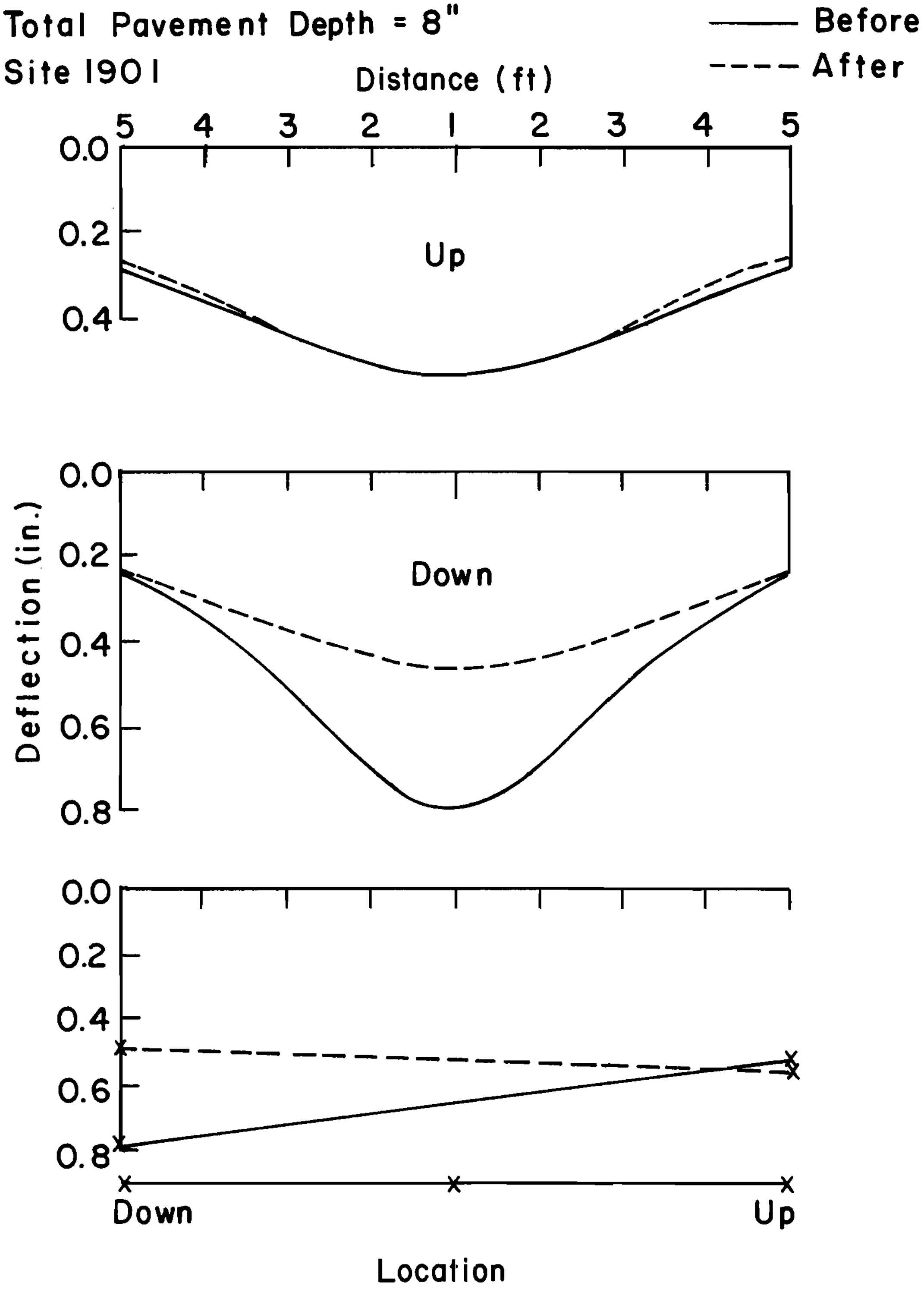

Fig. 7.25 Deflection of Repair No. 1
Before and After Repair

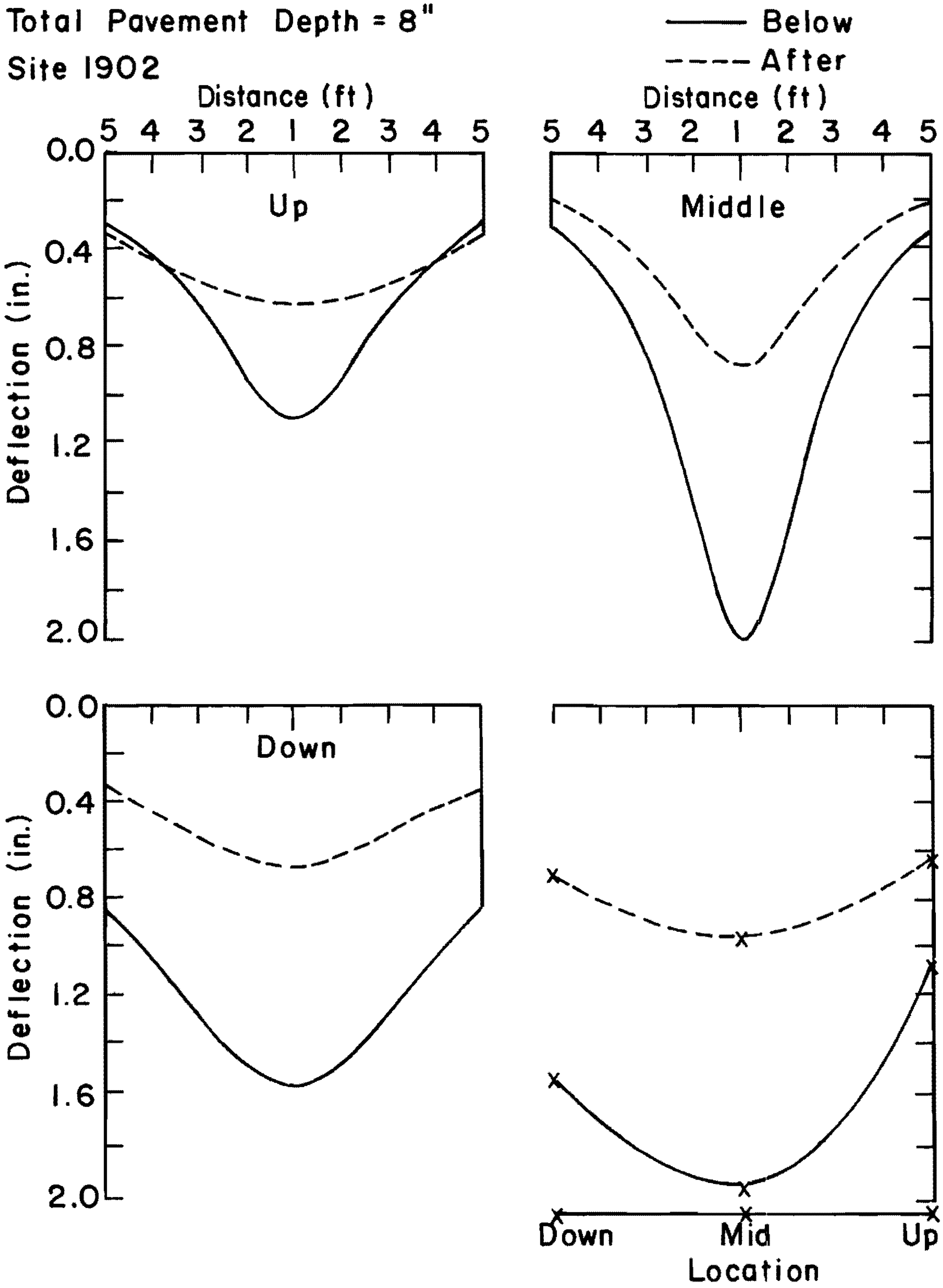

Fig. 7.26 Deflection of Repair No. 2
Before and After Repair

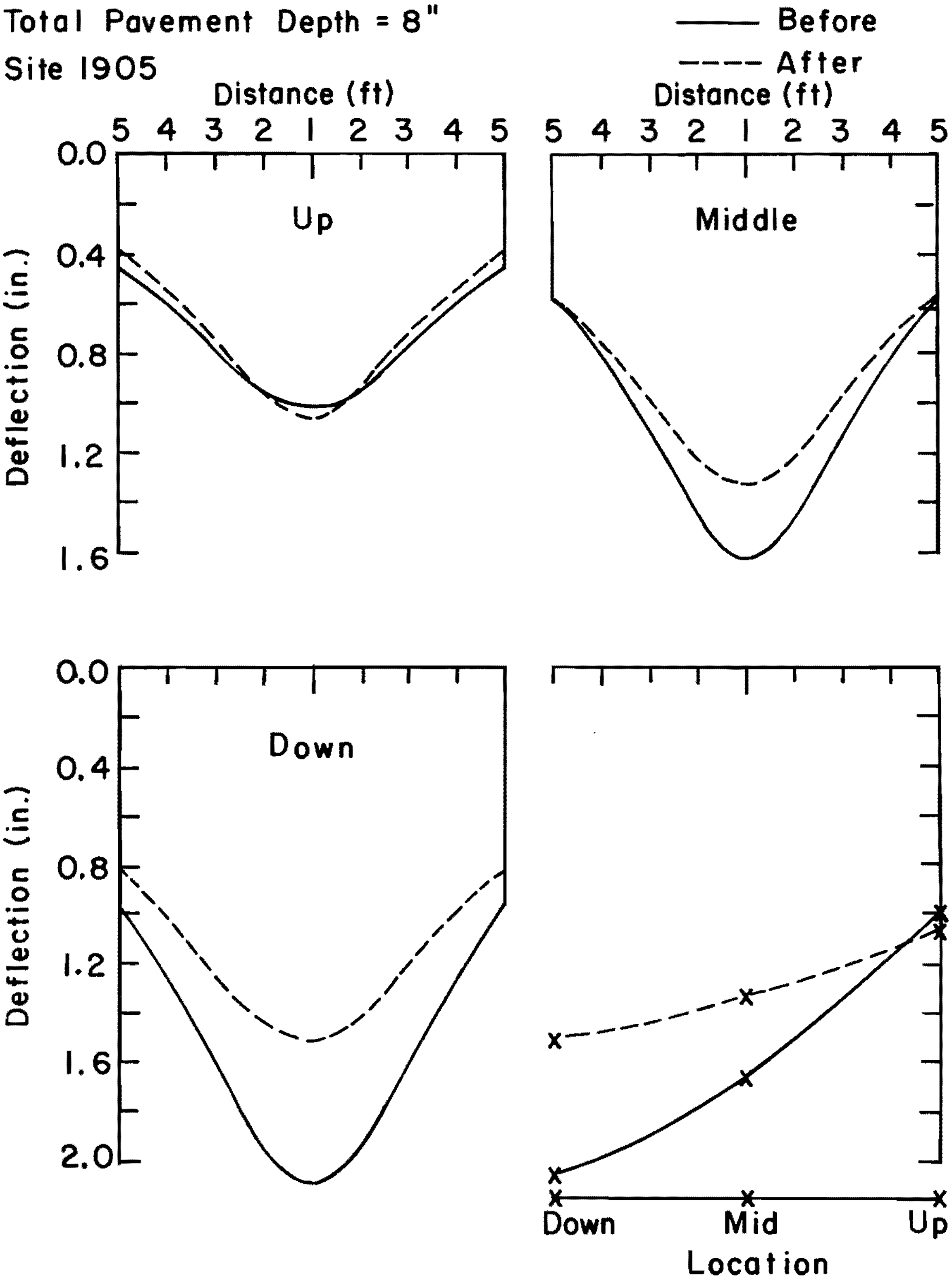

Fig. 7.27 Deflection of Repair No. 3
Before and After Repair

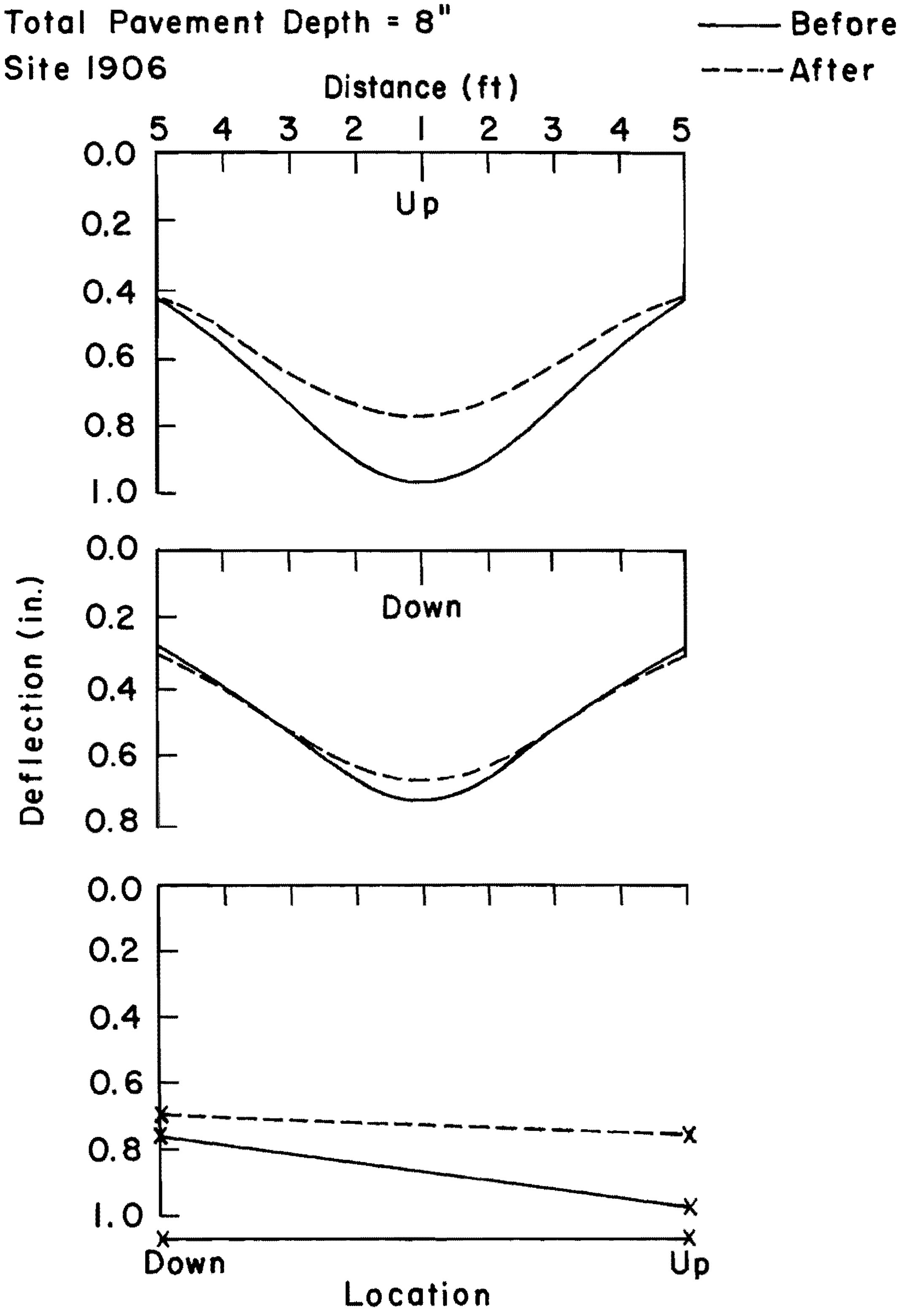

Fig. 7.28 Deflection of Repair No. 4
Before and After Repair

7.6 Fiber Reinforced PC at Marshall, Texas

An additional repair was made at Marshall, Texas, using fiber-reinforced polymer concrete (FRPC). The repair was on the outside edge of the westbound lane of IH 20 0.7 mile west of US 80 and 3.7 mile east of FM 2199. The pavement was 8 in. thick. Aggregate used in the repair was 50 percent crushed limestone (3/4-in. max) and 50 percent all-purpose sand. The monomer formulation consisted of 95 percent MMA and 5 percent TTEGDA. Steel fibers, 3 percent by weight of aggregate, were added. The weather was clear and sunny with a 10 mph wind and temperatures in the mid 90s (°F) (Ref 7).

7.6.1 Procedure

The damaged area of the pavement, which was repaired previously, was cleaned out. Aggregates and fibers were mixed in a concrete mixer. The aggregate was placed in three layers, and monomer was poured on each layer. The PC was rodded until the repair was well compacted. The monomer system was mixed manually and poured over the repair.

7.6.2 Evaluation of the Repair

Evaluation of the field repair was based on deflection measurements made before and after the repairs with a Dynaflect. The deflections were measured just prior to the removal of the damaged pavement material and 3 weeks after the repair had been made (Ref 6).

Readings of the Dynaflect before and 3 weeks after the repair are presented in Table 7.5 A comparison of the stiffness coefficients shows significant improvement in pavement rigidity.

7.7 Repair at Comanche

7.7.1 Conditions

On February 12, 1981, a repair was performed with polymer concrete on a bridge deck on Highway 36 at Comanche, Texas. The

Table 7.5 Dynaflect Measurements[a]

Date of Measurement	AS2[b]	AP2[c]	Remarks
7-15-80	0.18 0.21	2.10 1.83	UP[d] DOWN[e]
8-7-80	0.18 0.20	2.50 2.15	UP[d] DOWN[e]

[a] Location of repair: Milepost 641.5 on IH 20

[b] AS2 is the stiffness coefficient of the subsgrade

[c] AP2 is the stiffness coefficient of the pavement

[d] UP is up traffic side or approach side of repair area

[e] DOWN is down traffic side or departure side of repair area

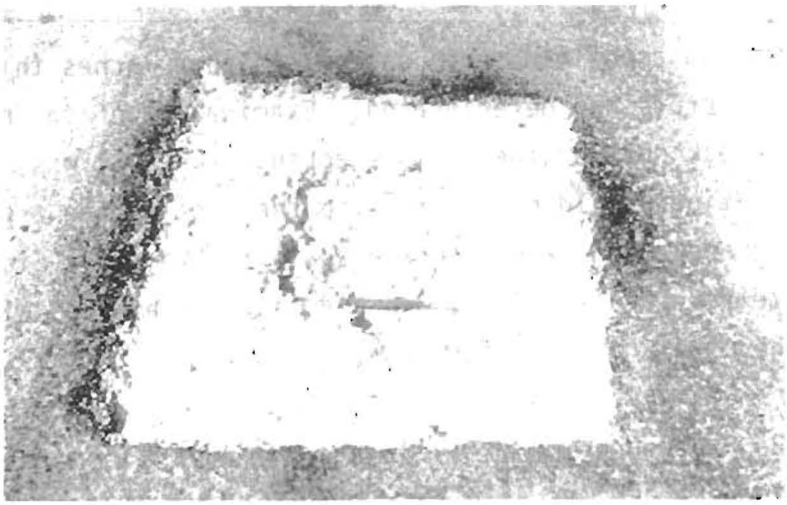

Fig. 7.29 Spall in Bridge at Comanche

Fig. 7.30 Completed Repair at Comanche

bridge deck was an asphalt-covered concrete slab 5 inches thick. The existing concrete had deteriorated. Examination of the bottom of the bridge deck showed widespread cracking. When it was hit with a hammer, vibrations could be observed to the edge of the asphalt overlay. The repair area was a square spall in the slab (Fig. 7.29). The ambient temperature was 45°F, and the weather remained windy throughout the repair operation (Ref 6).

7.7.2 Procedure

The temperature was 45°F and, hence, a higher concentration of the cross-linking agent and the initiator was used. The formula tion used was

MMA	90 percent
TMPTMA	10 percent
DMPT	1 percent
Bzp (40% dispersion)	5 percent

The repair area was cleaned and then dried with a torch. Loose chips of concrete were removed to expose a relatively clean surface. The aggregate consisted of 50 percent oven-dried allpurpose concrete sand and 50 percent oven-dried 3/8-in. pea gravel. The monomer was prepared, and a little was poured into the repair area to wet the concrete. The aggregate was then placed to one-half the depth of the repair area. The monomer was poured over it, and the repair area was rodded. This process was repeated until the entire repair area was filled. The top of the repair area was trowelled smooth to the level of the road surface. Powder MMA was sprinkled over the top of the PC to prevent loss of monomer through evaporation. Figure 7.30 shows the punchout after the repair.

7.8 Repair on Bridge Deck at Eastland, Texas (IH-20)

On October 20, 1981, a team from the Center for Transportation

Research (CTR) made PC bridge repairs at Eastland, Texas. The repairs were on the outside lane of eastbound IH-20, Bear Creek Bridge, just east of the IH-20 intersection with State Highway 16 (Ref 4).

7.8.1 Repair Procedure and Monomer Formulation

The repairs were done with four types of polymer concrete:

Method 1: Commercially-available prepackaged PC (Crylcon®: low temperature formulation)

Method 2: User-formulated prepackaged PC

Method 3: User-formulated prepackaged PC with steel fibers

Method 4: User-formulated PC (preplaced aggregate and pumped monomer)

Before PC repair started, the repair area (Fig. 7.31) was jack hammered to remove the asphalt and damaged surface concrete, dried with a butane heater, and cleaned (Fig. 7.32) by the SDHPT. After that, each repair material was cast into the dried and cleaned hole with the following procedures.

7.8.1.1 Method 1: Commercially-Available Polymer Concrete

A 33 lb package of Crylcon® 3020 powder component was transferred to a concrete mixer (Fig. 7.33), and the required amount of Crylcon® 3009 liquid component was added to the powder component in the concrete mixer. After the complete mixing of the mortar, 3/4-in. dry coarse aggregate was added into the concrete mixer and thoroughly mixed. The PC was placed into part of repair No. 1 which had been primed with Crylcon® 3040 (Fig. 7.34). The PC was compacted, screeded, and troweled using conventional techniques. A total of 4 cu.ft. of PC was required. The PC required about 2 hours to cure.

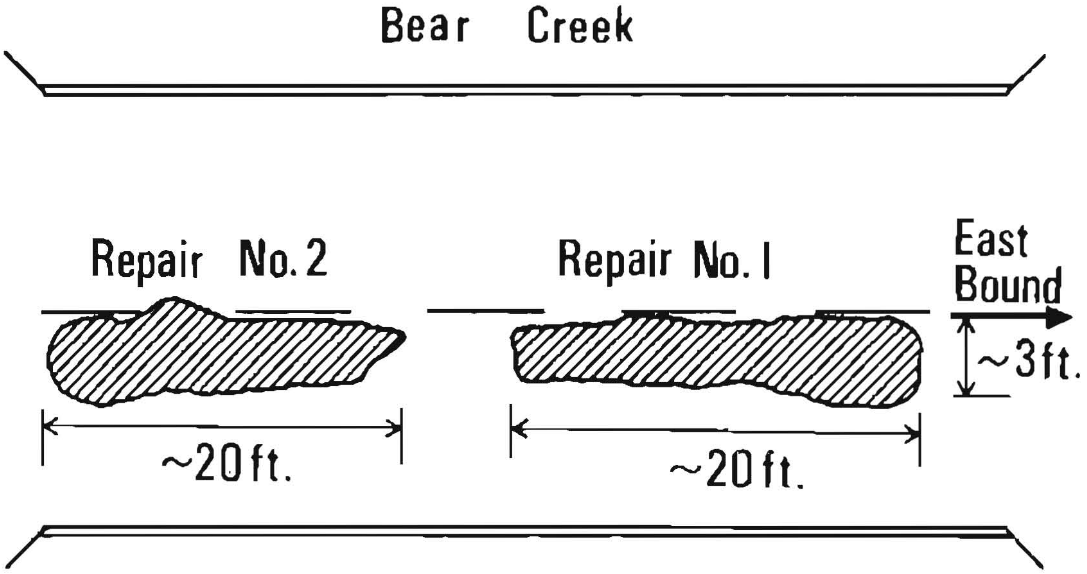

Fig. 7.31 Repair Site

Fig. 7.32 Drying of Repair No. 1

Fig. 7.33 Transfer of Powder Component into Concrete Mixer

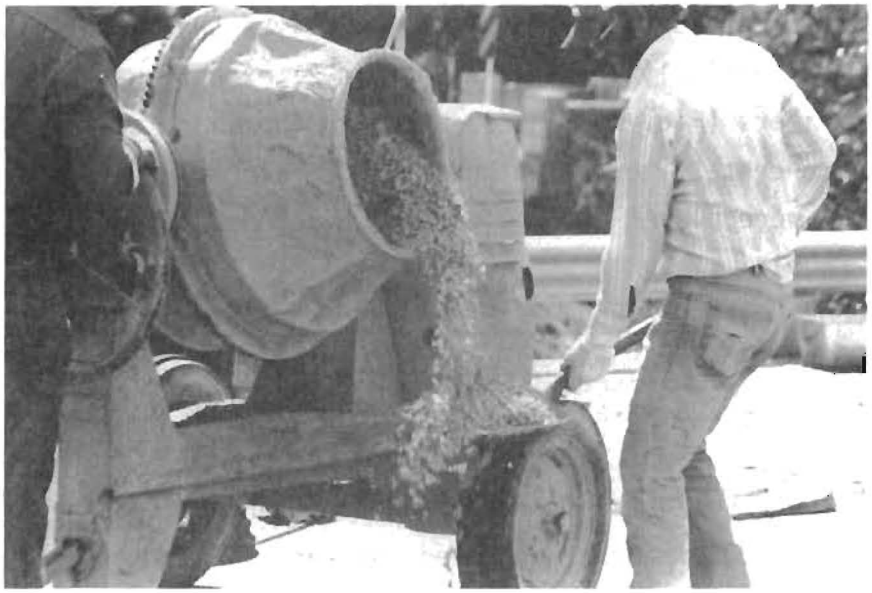

Fig. 7.34 Placing PC into the Repair Hole

7.8.1.2 Method 2: User-Formulated Prepackaged PC

Figure 7.35 shows the materials for user-formulated prepackaged PC, and Table 7.6 gives the formulations.

First, the dried sand, 3/4-in. coarse aggregate and powder component were put into a concrete mixer and mixed. Two unit packages were required. Next, premixed monomer was added into the concrete mixer. Subsequently, BzP dispersion (40 percent concentration) was added into the mixture. For this system, usually packaged BzP powder is used; however, in this repair, BzP dispersion was used as a substitute for Bzp powder. Then the PC was mixed and placed into part of repair No. 1. The compaction and trowelling were by conventional means (Fig. 7.36). The repair required about 2.5 cu.ft. of PC. Curing occurred in about 30 minutes.

7.8.1.3 Method 3: User-Formulated Prepackaged PC with Steel Fibers

The materials are the same as shown in Fig. 7.35 for user-formulated prepackaged PC, and Table 7.7 gives the formulations. This system is essentially the same as Method 2, except that 3 (wt.) percent steel fibers (Fig. 7.37) were added to the sand, gravel and powder in the concrete mixer. Two units of user-formulated prepackaged PC (2.4 cu.ft.) were placed into repairs No. 1 and 2 (Fig. 7.38).

7.8.1.4 Method 4: Preplaced Aggregate and Injected Monomer

Table 7.8 gives the monomer formulations for use with the in-line injection pump.

First, equal weights of gravel and sand were placed into the repair hole (Fig. 7.39). Next, premixed monomer (97 percent MMA: 3 percent TMPTMA) system was injected into the sand and gravel with the injection pump until slight ponding on the surface has been observed (Figs. 7.40 and 7.41). Premixed monomer (MMA + TMPTMA +

Fig. 7.35 Materials for User-Formulated Prepackaged PC

Fig. 7.36 Finishing the Surface of User-Formulated Prepackaged PC

Table 7.6 Mix Proportion for User-Formulated Prepackage PC

	for 1 unit(1.2 5cf)	for 1 batch(2.5 cf)
Premixed Monomer	2.1 gal	4.2 gal
Powder Component	1 bag (5.25 lb)	2 bag (10.5 lb)
Sand & Gravel	75 + 75 (150 lb)	300 lb

4.2 gal Premixed Monomer (for 2.5 cf)	
MMA	4 gal
TMPTMA	590 cc
DMPT	114 cc
One bag Powder Component (5.25 lb)	
PMMA	4.5 lb
Colorant	0.75 lb
BzP	---

Table 7.7 Mix Proportioning for User-Formulated Prepackaged PC with Steel Fibers

Materials	for one package (1.25 cu.ft.)	for one batch (2.5 cu.ft.)
Premixed Monomer	2.1 gal	4.2 gal
Powder Component	1 bag (5.25 lb)	2 bags (10.5 lb)
Steel Fibers [a]	4.5 lb	9.0 lb
Sand	75 lb	150 lb
Gravel	70.5 lb	141 lb

[a] Steel fibers (0.3 x 50 mm, hooked) replaced an equal weight of coarse aggregate.

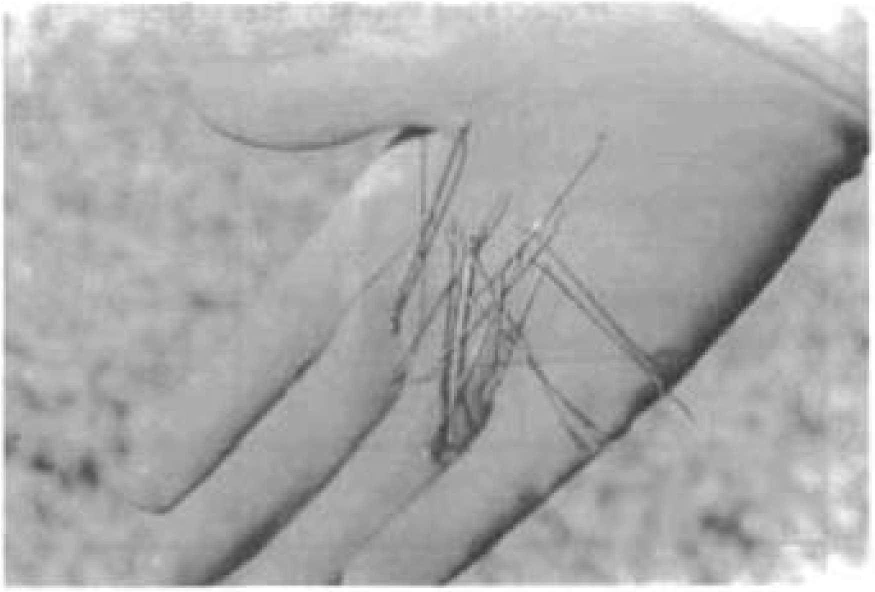

Fig. 7.37 Steel Fiber Using User-Formulated Prepackaged PC with Steel Fiber

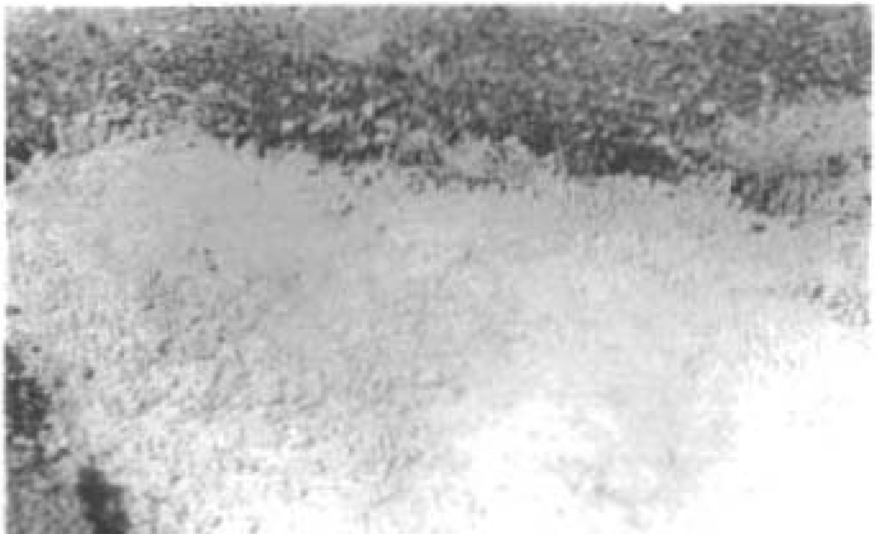

Fig. 7.38 User-Formulated Prepackaged PC with Steel Fiber

Table 7.8 Mix Proportion of Monomer for User-Formulated PC

55 gal Premixed Monomer	
MMA	53.5 gal
TMPTMA	1.5 gal
DMT	1290 cc
BzP	1 - 1/2 gal (RCI 46-742)

NOTE: BzP dispersion is mixed into monomer automatically with an in-line mixing system

Fig. 7.39 Placement of Premixed Aggregate into Repair Hole No. 2

Fig. 7.40 Injecting Monomer into Premixed Aggregate using In-Line Mixing System

Fig. 7.41 Close-up View of Monomer Injection into Premixed Aggregate

DMPT) was mixed with BzP in the pump. After the repair was compacted and trowelled, a mixture of PMMA and sand was sprinkled over the repair area to prevent surface monomer evaporation (Fig. 7.42). About 30 minutes were required for curing.

7.8.2 Repair Evaluation

After the polymer concrete hardened it was overlaid with 1-1/2 in. of asphalt concrete hot mix to bring the repair surface flush with the surrounding asphalt. Apparently the PC has held up well, but the concrete surrounding the repair is rapidly deteriorating and the entire bridge deck will probably have to be replaced.

7.9 Summary of Cost

A summary of the cost of polymer concrete as of January 1983 is given in this section. These costs do not include labor or aggregate. Costs can vary depending upon the amount of monomer required per unit volume (Ref 2).

7.9.1 Preplaced Aggregate Method

The cost for the user-formulated monomer system for the preplaced aggregate method using either sprinkling or pouring or the in-line injection system is shown in Table 7.9. The monomer content for this method is usually higher for the method than for the prepackaged, mixed systems. The monomer to aggregate ratio was assumed to be 0.15:0.85. For hot weather applications the cost of the chemicals is $484/cu.yd; for cold weather the cost is increased to $551/cu. yd. due the additional coats of promoter and initiator.

7.9.2 User-Formulated Polymer Concrete

The cost of chemicals for user-formulated prepackaged polymer concrete is shown in Table 7.10. A monomer-to-aggregate ratio of 0.11:0.89 is assumed, although for some gradations it may be possible to reduce the monomer to a ratio of 0.09:0.91. PMMA powder and

Fig. 7.42 Completed Repair using User-Formulated PC

Table 7.9 Cost of Polymer Concrete Using Preplaced Aggregate.

Material		Weight Formulation (percent)	Weight (lb)		Unit Cost ($/lb)	Cost ($/cu.ft.)
MMA	Monomer	9.5	20.14	21.2[a]	0.72	14.50
TMPTMA		5	1.06		1.88	1.99
DMT		0.3[b]	0.064		5.00	0.32
BzP[c]		2.5[b]	0.53		2.07	1.10

Total Cost $17.91/cu.ft.
or
$483.57/cu.yd[d]

[a] Based upon assumed monomer (MMA+TMPTMA) content of 15 percent of the total weight of PC; Aggregate assumed to weigh 120 lbs/cu.ft.

[b] Amount depends upon ambient temperature and is based upon monomer weight

[c] 40 percent dispersion assumed

[d] These costs assume a hot weather formulation and to not include aggregate cost. The additional cost of DMT and BzP for cold weather applications would be approximately $67/cu.yd.

Table 7.10 Cost of User-Formulated Prepackaged Polymer Concrete

Material		Weight Formulation (percent)	Weight (lb)		Unit Cost ($/lb)	Cost ($/cu.ft.)
MMA	Monomer	97	14.39	14.83[a]	0.72	10.36
TMPTMA		3	0.44		1.88	0.83
DMT		0.6[b]	0.089		5.00	0.45
BzP[c]		3.4[b]	0.5		2.07	1.04
PMMA		3	3.6		1.55	5.58
Colorant		0.5	0.6		0.89	0.53

Total Cost $18.79/cu.ft
or
$507.33/cu.yd[d]

[a] Based upon assumed monomer-to-aggregate ratio of 0.11:0.89. Aggregate assumed to weigh 120 lbs/cu.ft.

[b] Amount depends upon ambient temperature and is based upon monomer weight. Value shown is for moderate temperatures (75°F)

[c] 40 percent dispersion assumed

[d] These costs assume a formulation for 75°F and do not include cost of aggregate

colorant are included for workability and appearance, respectively. The cost is approximately $507/cu.yd. for a formulation that can be used at moderate temperatures (75°F).

7.9.3 User-Formulated Polymer Concrete for Crack Repair

The cost of monomer for crack repair is about $6.75/gal (Table 7.11). Experience has shown that, because of waste and leakage in the bottom of the crack, about one gallon of monomer is required per 10 ft. of crack, assuming a routed crack 1 in x 2 in. The cost of PMMA for the sand, assuming 3 percent PMMA by weight of sand, is $4.65/cu.ft. for sand weighing 100 lb/cu.ft. For a 1 in. x 2 in. crack, allowing for 20 percent waste, the cost of PMMA is about $0.08/ft. The cost of PMMA plus monomer system is $0.08 + $6.75/10 = $0.76/ft.

Table 7.11 User-Formulated Polymer Concrete for Crack Repair

Material	Weight Formulation (percent)	Weight (lb/gal)		Unit Cost ($/lb)	Cost ($/gal)
MMA	97	7.70		0.72	5.54
Monomer			7.94		
TMPTMA	3	0.24		1.88	0.45
DMT	0.5	0.04		5.00	.20
BzP	3.4	0.27		2.07	.56

Total Cost $6.75/gal. monomer[a]

[a] cost includes only chemicals shown; formulation is for moderate temperatures. Experience indicates that one gallon of monomer is required per 10 ft. of 1-in. x 2-in. crack.

CHAPTER 8

SUMMARY AND RESULTS

8.1 Summary

Laboratory tests have been conducted to determine monomer formulations to provide adequate strength and reasonable curing time for producing polymer concrete. Mechanical proporties were found for different casting and testing temperatures. The effect of aggregate size and type was investigated. A user-formulated prepackaged system was developed which had a workability and a color more similar to portland cement concrete. Numerous repairs were made on portland cement concrete pavements, and the repairs were evaluated. Costs of repairs were calulated.

8.2 Results

The following conclusions can be made:

1. Monomer formulations consisting of MMA, TMPTMA, DMT, and BzP and providing a set time of less than one hour were developed.
2. Flexural strength of PC beams is in excess of 2,000 psi at room temperature.
3. Flexural strength and modulus of elasticity decreased with increasing testing temperature.
4. Aggregate type influenced the modulus of elasticity more than the compressive strength.
5. The addition of PMMA to polymer concrete significantly reduced the evaporation of the MMA, decreased the setting

time, and increased the peak exotherm.

6. The addition of PMMA increased the tensile strength but had little effect on the compressive strength.
7. The addition of PMMA reduced the shrinkage of PC by about one third.
8. A weight ratio of carbon black to titanium dioxide of 1/300 to 1/500 at a level of 0.5 to 1.0 percent of the aggregate weight produced a color similar to that of portland cement concrete.
9. Moisture in the aggregate in excess of one percent can result in significant strength reduction. The use of steel fibers can reduce the strength loss for moisture content as much as 5 percent.
10. Bond failures of PC to PCC were found to occur in the PCC from tests performed at room temperature or below. At 100°F the fracture occurred at the interface.
11. The bond strength at PC-to-PC vertical joints was about half the strength of monolithically-cast PC.
12. A wide range of concrete pavement repairs were made and described. Several methods were used to place the PC, including: (a) pouring monomer over preplaced aggregate, (b) injecting monomer with an injection pump in which the initiator is mixed in the injection tube, and (c) mixing either user-formulated or commercially-available PC in conventional mixers.
13. The cost of user-formulated PC is approximately $500/cu.yd. for punchouts or spalls. For widened cracks (1-in. x 2-in.) the cost is about $0.76/ft.

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