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16. Abstract

Cracking in portland cement concrete pavements and bridge decks causes many problems including reduced stiffness which leads to greater deflections and additional cracking. Water and chlorides are able to penetrate cracks resulting in freeze-thaw deterioration and corrosion of reinforcement. Several methods of repairing cracks were investigated in the study. One method consisted of using polymer concrete in enlarged cracks in pavements. The cracks were enlarged with a crack cutter. Sand was placed in the crack and saturated with monomer to form a strong polymer concrete which bonded well to the portland cement concrete. Evaluations of many miles of repaired cracks on I-610 indicate very good performance. The disadvantage of the method is the length of time required to enlarge the cracks. Epoxy injection was investigated in the laboratory using different crack widths and three different ambient temperatures in cracked slabs. The slabs were recracked to determine recracking strength and location of the second crack. For the epoxy used, the recracking strength was good for 70 degrees F and higher; the results at 40 degrees F reflected the slow curing of the epoxy. Generally epoxy injection provided a good bond but crack preparation was found to be very important. Limited field tests were conducted. High molecular weight methacrylate monomer systems (HMWM) were investigated for brushing on the surface of cracked concrete. The monomer filled the cracks in dry laboratory slabs to 95 percent of the crack length for cracks as narrow as 0.2 mm. Moisture in the crack reduced the penetration but more than adequate filling was observed. Recracking strength was good. Some success was achieved with spraying cracked concrete overhead.

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portland cement concrete, cracks, repairs, polymers, enlarged cracks, epoxy injection, field tests

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by

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Research Project 3-18-84-385

conducted for
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U. S. Department of Transportation
Federal Highway Administration

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The University of Texas at Austin

November 1986

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

The authors wish to express their appreciation to Larry Buttler, D-18, for his role as techincal coordinator of Research Study 385 and to Jerry Daleiden, D-8, associate technical coordinator. Thery were always available to provide suggestions and advice and accompanied the study supervisors on trips to visit the districts.

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LIST OF REPORTS

Report No. 385-1, "Improved Method for Sealing Joints in Portland Cement Concrete Pavements," by Alexander Collins III, Wayne D. Mangum, David W. Fowler, and Alvin H. Meyer, describes methods and laboratory evaluations for the most commonly used joint sealing materials in Texas. September 1986.

Report No. 385-2, "Repairing Cracks in Portland Cement Concrete Using Polymers," by Wayne D. Mangum, Alejandro J. Bermudez-Goldman, David P. Whitney, David W. Fowler, and Alvin H. Meyer, details the methods and materials involved in repairing cracked portland cement concrete decks with polymers. November 1986.

ABSTRACT

Cracking in portland cement concrete pavements and bridge decks causes many problems including reduced stiffness which leads to greater deflections and additional cracking. Water and chlorides are able to penetrate cracks resulting in freeze-thaw deterioration and corrosion of reinforcement.

Several methods of repairing cracks were investigated in the study. One method consisted of using polymer concrete in enlarged cracks in pavements. The cracks were enlarged with a crack cutter. Sand was placed in the crack and saturated with monomer to forn a strong polymer concrete which bonded well to the portland cement concrete. Evaluations of many miles of repaired cracks on I 610 indicate very good performance. The disadvantage of the method is the length of time required to enlarge the cracks.

Epoxy injection was investigated in the laboratory using different crack widths and three different ambient temperatures in cracked slabs. The slabs were recracked to determine recracking strength and location of the second crack. For the epoxy used, the recracking strength was good for 70 degrees F and higher; the results at 40 degrees F reflected the slow curing of the epoxy. Generally epoxy injection provided a good bond but crack preparation was found to be very important. Limited field tests were conducted.

High molecular weight methacrylate monomer systems (HMWM) were investigated for brushing on the surface of cracked concrete. The monomer filled the cracks in dry laboratory slabs to 95 percent of the crack length for cracks as narrow as 0.2 mm. Moisture in the crack reduced the penetration but more than adequate filling was observed. Recracking strength was good. Some success was achieved with spraying cracked concrete overhead.

Numerous field studies were performed, mostly with HMWM. Good results were obtained except in the cases where the cracks were filled with debris.

SUMMARY

Research was conducted to indentify improved methods for sealing cracks in portland cement concrete bridge decks and pavements. The use of polymer concrete in pavement cracks enlarged with a crack cutter proved to be effective although the method is labor intensive. The method has been used extensively on I 610 with good results. Epoxy injection was tested in the laboratory with crack width and temperature as the variables. Good results were obtained for recracking strength and filling cracks except at low temperature. Limited field studies were performed. The use of high molecular weight methacrylate monomers proved successful in laboratory tests with cracked concrete with variable crack widths and variable moisture. Field tests were successful except when cracks were filled with debris.

IMPLEMENTATION STATEMENT

The methods for repairing cracks that were investigated in this study have already been implemented. Many miles of the polymer concrete-filled enlarged cracks have been successfully used on I 610. Epoxy injection has been used in limited cases where cracks are small and where restoration of structural integrity is essential. The use of high molecular weight methacrylate monomer has been used successfully on several bridge decks in Texas. The simplicity of application and the low relative cost make it a viable repair method.

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Chapter 1
Introduction

1.1 Background

Cracking in concrete pavements and bridge decks is a continuing problem. Cracking is usually the result of either overstressing of the concrete or improper curing. Overstressing is the result of thermal contraction, restriction of movement, overloading, fatigue, and, in the case of pavements, development of voids beneath the concrete. Improper curing can lead to the development of shrinkage cracks.

Cracks in concrete permit the intrusion of moisture, chlorides, and other contaminants, which can result in freeze-thaw deterioration, corrosion of the reinforcing steel, and other problems. Cracking also results in a loss of stiffness in the pavement or bridge deck, which causes additional deflection, which in turn may result in additional cracking.

The need for suitable repair methods, therefore, is very desirable. The primary need is to seal the crack from intrusion of contaminants. A secondary need is to restore structural integrity of the concrete.

Current crack repair procedures have primarily utilized epoxy injection. Epoxy injection has proven to be an effective method for repairing cracks in concrete. However, the main disadvantages of epoxy injections are (1) the length of time required to prepare the crack and to perform the injection and (2) the cost.

The cracks must be sealed along the surface with injection ports spaced 6 to 12 in. apart. The cost is relatively high; for example, one pavement repair project involving several thousand feet of epoxy injection cost nearly $10/ foot of crack. Because of the time and cost, epoxy injection can generally be justified only for major structural repairs.

1.2 Scope of Study

The objective of this study was to identify improved methods of repairing cracks. The investigated methods included

1. routing cracks and filling with polymer concrete,
2. epoxy injection, and
3. high molecular weight methacrylate treatment.

Chapter 2

Filling Cracks With Polymer Concrete

2.1 Introduction

In 1980 researchers at the Center for Transportation Research (CTR) assisted the Urban District (now part of District 12) in developing a repair procedure for the extensive longitudinal cracking that was present on I-610 in Houston (Fig. 2.1). From numerous cores which had been taken, it had been found that the cracks always occurred above longitudinal bars, apparently because of poor consolidation of the concrete below the reinforcing steel. The objective was to seal the cracks to prevent water intrusion into the crack. Although the field work was not performed as part of this investigation, the method is within the scope of the study objectives. The procedures, performance, and cost are discussed.

2.2 Repair Procedures

The procedures developed for the repair of the longitudinal cracks involved enlarging the crack to permit the placement of polymer concrete. Polymer concrete (PC) consisting of aggregate with a polymer binder had been previously investigated and reported for the repair of portland cement concrete (1-4). PC develops very good bond to portland cement concrete.

Several methods for enlarging the crack were investigated. Sawing was not feasible for following the irregular cracks. High pressure water jetting was not feasible since polymer concrete does not bond well to wet surfaces and it would have been necessary to permit the cracks to dry before placing the PC.

A single-piston pneumatic crack router was selected as the best available piece of equipment to enlarge the cracks (Fig. 2.2). The bit usually has a 0.75-in. diameter, and the crack is usually enlarged to a width of one in. in a single pass (Fig. 2.3). The depth is variable, but is usually one to two in. (Fig. 2.4)

The polymer concrete is placed by filling the enlarged crack with clean dry concrete sand and pouring methyl methacrylate (MMA) monomer system over the sand until it is completely saturated.

Fig. 2.1 Crack router in operation

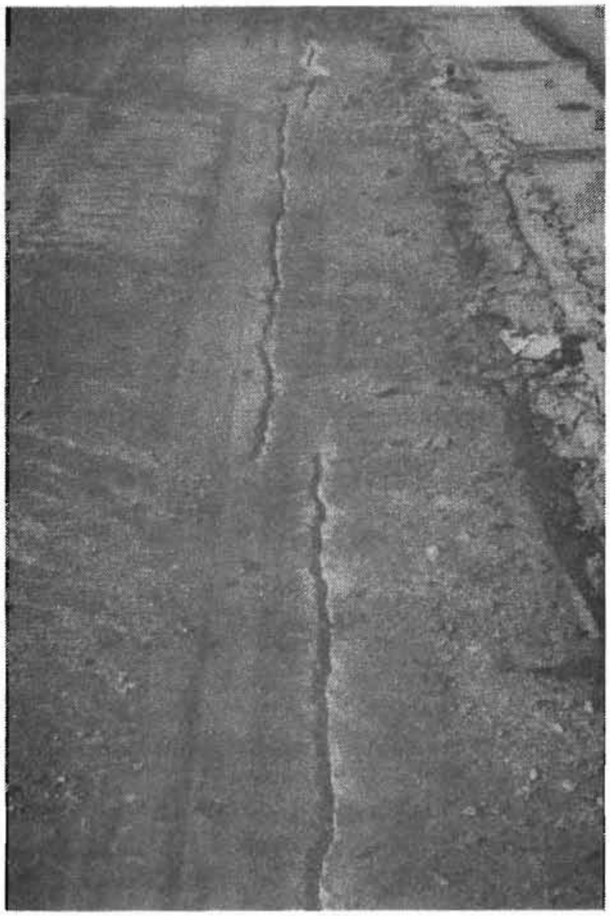


Fig. 2.2 Enlarge cracks

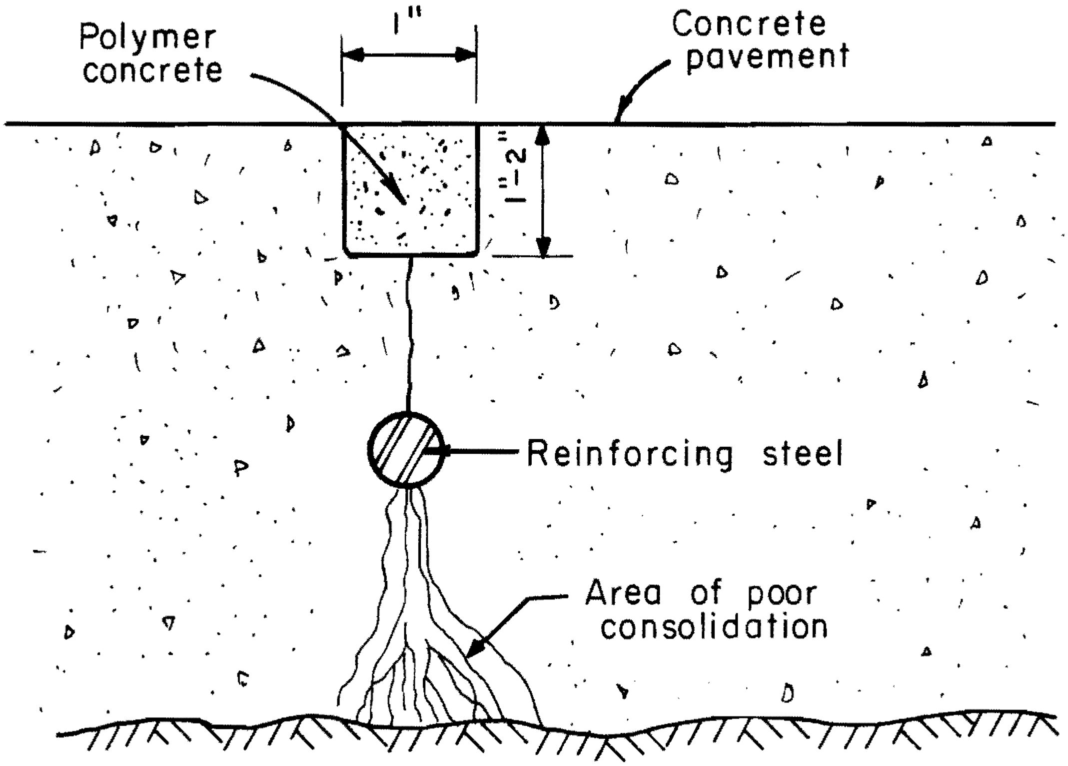


Fig. 2.3 Cross-section of repaired crack

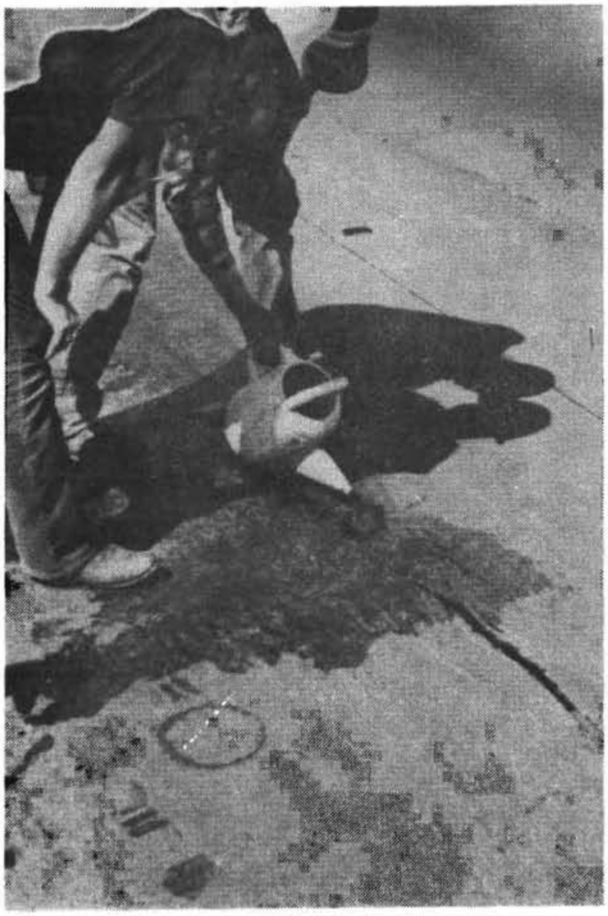


Fig. 2.4 Pouring monomer over sand

The monomer system consists of 95 percent MMA and 5 percent trimethylol propane trimethacrylate (TMPTMA). Benzoyl peroxide (BzP) initiatior, in dispersion form, is added at a level of about one percent (2.5 percent for 40 percent dispersion) and a promoter, dimethyl-para-toluidine (DMPT), is added at a level of 0.5 percent, both by weight of the MMA system. The levels of BzP and DMPT are dependent upon the ambient temperature (3).

It is essential that monomer be reapplied to keep the sand saturated since Monomer is lost due to evaporation and due to leakage in the crack at the bottom of the enlarged crack.

In some repairs silicone caulking was used to seal the crack below the PC to minimize monomer loss. In other repairs polymethyl methacrylate (PMMA) powder was mixed with the sand before it was placed in the crack. PMMA powder acts as a thickner and prevents leakage of the monomer.

Most repairs, however, have been made without the silicone sealant or PMMA powder. The objective has been to have monomer penetrate into the crack and bond the concrete.

2.3 Performance of Repair

Over 100,000 linear feet of pavement cracks on I-610 have been repaired by enlarging them and filling them with polymer concrete. Generally the repairs have performed very well.

In 1981, approximately one year after the first crack repairs were made on the West Loop (I 610), a visual examination was made by district and CTR personnel. Of the 14,066 feet of repaired cracks, 55.8 percent were found to be in good condition, 43.2 percent in fair condition, and only one percent in poor condition.

Generally the repairs rated fair or poor showed evidence of wear on the surface, apparently due to evaporation of monomer from the surface or depletion of the monomer caused by leakage into the crack below the enlarged crack.When a portion of the West Loop was scarified in preparation for placement of bonded portland cement concrete overlays, many of the repaired cracks could easily be observed. In nearly every case, the repairs appeared to be very sound, with the bond to each face of the concrete still intact.

An inspection of repaired cracks on the South Loop (I-610) in 1985 on repairs made approximately two years earlier, indicated that 80 to 90 percent were in good condition. In a few cases continued lateral movement of the pavement caused longitudinal cracks to reopen either in the repaired areas or adjacent to them. Some wear was observed in a few repaired cracks, probably due to the reasons observed on the West Loop.

2.4 Cost

All of the repairs on I 610 have been performed under contract by several contractors. The cost of the crack repairs has ranged from $6 /ft. to $8 /ft.

The repair process is labor intensive. The crack routing is performed at the rate of 25 ft./hr. The bits must be sharpened or replaced every 175 ft. The sand and monomer are placed manually and the sand must be rewetted several times to maintain a saturated condition. To make the repair procedure more economical, two improvements are needed: (1) a more rapid procedure for enlarging the cracks and (2) a less labor-intensive method for filling the crack with polymer concrete.

Chapter 3
Laboratory Investigation of Crack Repair With Epoxy Injection

3.1 Introduction

Epoxy injection has been used for many years to make structural repairs in cracked concrete. The procedures have been well developed over the years for many applications (5).

Epoxies used for injection are usually considerably more viscous than the monomers used in this study. They have to be injected under considerable pressure, usually 25 psi or more. Epoxy injection has been found to be particularly effective for deep, narrow cracks; cracks which are wet or filled with water; cracks containing debris; and cracks which must be bonded to produce a structural repair. It should be emphasized, however, that the proper epoxy and the proper techniques must be utilized to insure a sound repair.

The disadvantages to epoxy injection are length of time required to make repairs and the cost. The cost reflects the labor intensiveness of the process. For some types of repairs, it is the only viable repair method, however. A limited laboratory investigation was made on the crack sealing and bonding characteristics of epoxy injection (6). This chapter describes the test program and summarizes the results.

3.2 Materials and Preparation

3.2.1 Concrete Specimens

3.2.1.1 Material

The concrete mix used throughout the testing program, expressed as percentage by weight, was cement, 22 percent; sand, 38 percent; coarse, 30 percent; and water, 10 percent. Both ASTM Type I and ASTM Type III cements were used. Type III high-early strength cement was used at times to decrease the time required between the concrete pour and initial cracking. A minimum of seven days curing was used when Type III cement was used and 28 days when Type I was used. Both the natural sand and the coarse aggregate used in the mix were from the Colorado River near Austin, Texas.

3.2.1.2 Size

A number of requirements had to be considered when determining the dimensions of the concrete specimens to be used in the testing program. First, and probably most important, the thickness of the specimen had to be large enough to allow simulation of the crack depths experienced in the field. Next, the length of the specimen between the points of load application had to be large enough for the specimen to crack in flexure rather than in shear. Finally, the width of the specimen had to be large enough to approach the length of the cracks experienced in the field. As a result of these considerations, specimen dimensions of 12 in. wide x 5-1/2 in. thick x 14 in. long (30 cm x 14 cm x 36 cm) were selected. However, the manufacturer of the epoxy used in the study suggests that the distance between injection ports be limited to between 4 and 8 inches (10 cm and 20 cm). Therefore, the width of the specimen was decreased to 7 inches (18 cm).

3.2.1.3 Preparation

Four strands of 10-gauge wire were placed in each specimen so that the specimen would not break apart when cracked. These strands of wire ran along the 14-in. (36-cm) length of the specimens and were evenly spaced along its 12-in. (30-cm) width.

The concrete specimens were cracked by center point loading to produce different crack widths. After they were cracked, a polyester putty was placed over the sides of the specimens along the crack depth. This putty, when cured, restricted the flow of the crack sealant out of the side of the crack during the epoxy injection process.

3.2.2 Epoxy

Niklepoxy Concrete Injection Resin #3, which is produced by Rocky Mountain Chemical Company, was used in the epoxy injection tests. This low viscosity epoxy is supplied as a two-component system. It is designed to restore complete structural integrity of the cracked concrete. Niklepoxy Injection Resin is 100 percent solids and conforms to ASTM C881 Type 1 Grade 1.

3.3 Testing Procedure

Tests were performed at three temperatures: 40 degrees F, 70 degrees F, and 100 degrees F. The specimens were divided into three crack width categories: small (0.008 to 0.02 in.) (0.2 to 0.6 mm); medium (0.03 to 0.04 in.) (0.7 to 1.1 mm); and large (0.05 to 0.08 in.) (1.2 to 2.0 mm).

In each test the specimens were first saturated with water. They were then allowed to dry for periods of 12 hours, one day, and two days. Some specimens were injected immediately after being saturated with water. The drying took place at the designated temperatures so that the temperature of the specimens would correspond to the recorded ambient temperature of the test. The zero drying time specimens were placed under their respective testing temperatures 12 hours before injection and then filled with water immediately before injection.

Two types of injection ports were used in this experiment. The epoxy manufacturer suggests that drilled ports be used with cracks with widths smaller than 0.015 in. (0.034 mm). Therefore, these drilled ports were used for all of the small cracks (0.2 to 0.6 mm). The placement of these ports was accomplished by first drilling a hole at the ends of the crack with a hollow core drill bit. A vacuum-attached swivel drill chuck was used in the drilling process in order to assure that the concrete dust from the drilling did not clog the crack. The drilled ports were then placed in the hole and recessed 1/2 in. A small reservoir below the port was provided in order to aid in the resin flow. A further description and photographs of these ports may be seen in Section 5.3.1, which describes the McLean, Texas, field study.

Surface ports were used for all medium (0.7 to 1.1 mm) and large (1.2 to 2.0 mm) cracks. These ports were placed directly over the surface of the crack and held in place by placing polyester putty over their attached tabs. These ports are also further described in the McLean field study.

Putty was placed over the entire length of the crack after the ports were in place in order to prevent the epoxy from flowing out of the crack. This step in the injection preparation process is very important. If the putty is not applied properly, the epoxy will leak out of the crack, thus making the pressure injection impossible.

In the 40 degrees F tests, specimens were dried in a cooler which was set at 49 degrees F. The average relative humidity in the cooler was measured to be 65 percent. The surface temperature of the blocks at the time of injection was 42 degrees F. The time required for the injections in this test varied from less than one minute for large cracks (1.2 to 2.0 mm) to up to 10 minutes for the small cracks (0.2 to 0.6 mm). The epoxy was allowed to cure for two days before the specimens were removed and cut.

The 70 degrees F tests were performed in the lab at an average temperautre of 72 degrees F and a realtive humidity of about 50 percent. The epoxy was allowed to cure for 24 hours before the specimens were cut.

The 100 degrees F tests were performed in a temperature chamber which maintained this temperature throughout the experiment. The relative humidity inside the chamber was 25 percent. The specimens remained in this chamber 24 hours following the injection, before they were removed and cut.

After the specimens were removed from the temperature chambers they were cut lengthwise, perpendicular to the direction of the crack. The resulting segments of the original specimen had widths of 3 and 4 in. The 3-in.-wide segment was further sliced across the crack. The percentage of the crack filled by the epoxy was determined from these samples.

The 4-in.-wide portion of the original specimen was recracked under the center point loading conditions that were used for the initial cracking. The recracking stress was then calculated and compared with the initial cracking stress.

3.4 Results

3.4.1 Recracking Strength

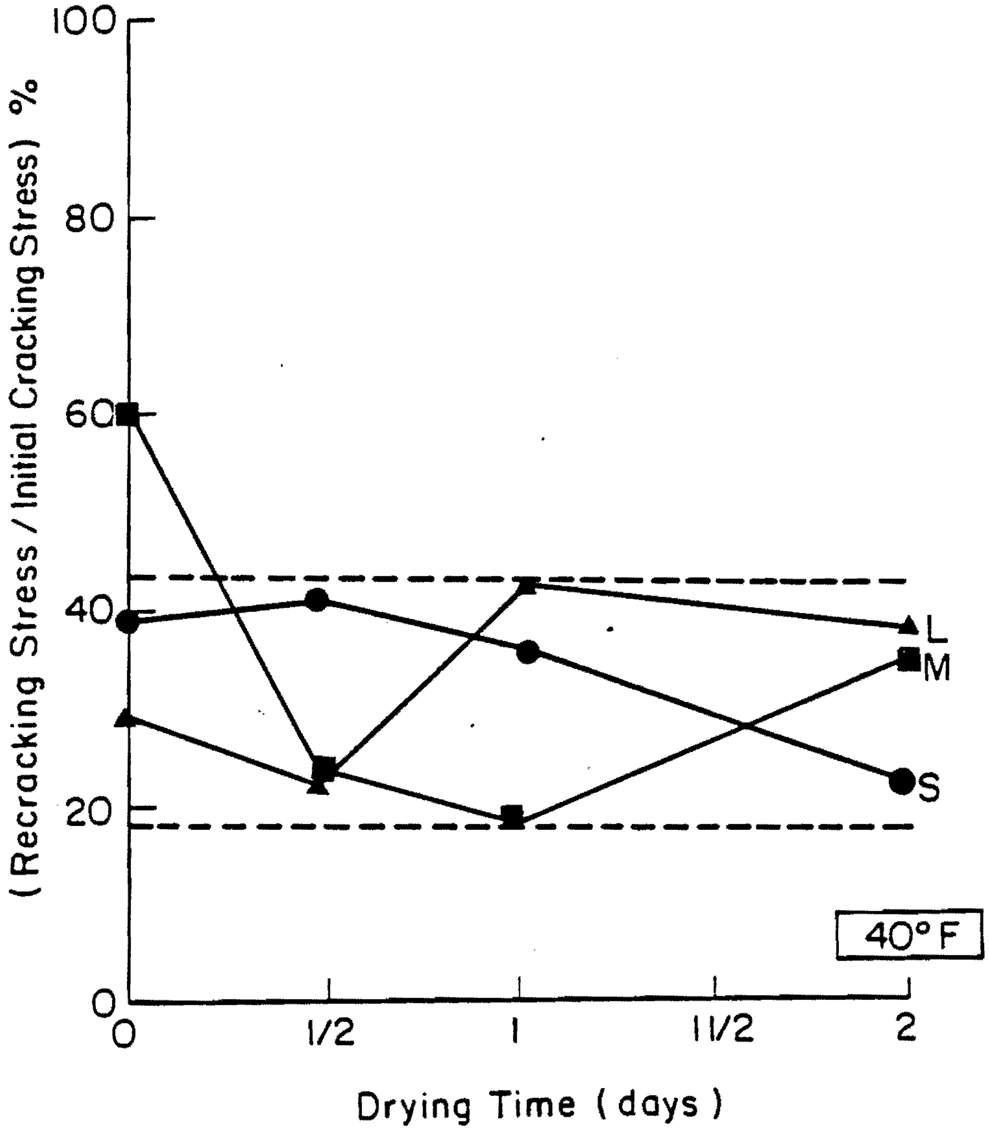
Table 3.1 and Figs. 3.1 through 3.3 show the relationship between the ratio of recracking to initial cracking stress and drying time for the various temperatures. In general, for the tests performed at 40 degrees F, the ratio fell within the range of 0.2 to 0.4. For the 70 degrees F tests, the range for this stress ratio rose to a range of between 0.3 to 0.5. And for the tests performed at 100 degrees F, the ratio of recracking to original cracking stress rose to a range of between 0.4 and 1.0. This general rise in recracking strength with increased temperature is shown in Table 3.2 and Fig. 3.4, in which the recracking stress to original cracking stress values for the small, medium, and large crack widths were averaged for each drying time and temperature.

Although there was a general increase in recracking strength with corresponding increases in temperature at application, no trend was recognizable concerning the effects of changes in moisture and crack width. The recracking strength-to-original cracking strength ratio generally fell within a given range for a particular temperature, regardless of the crack width or the drying time.

Table 3.1 Recracking-to-Initial Cracking Stress Ratio

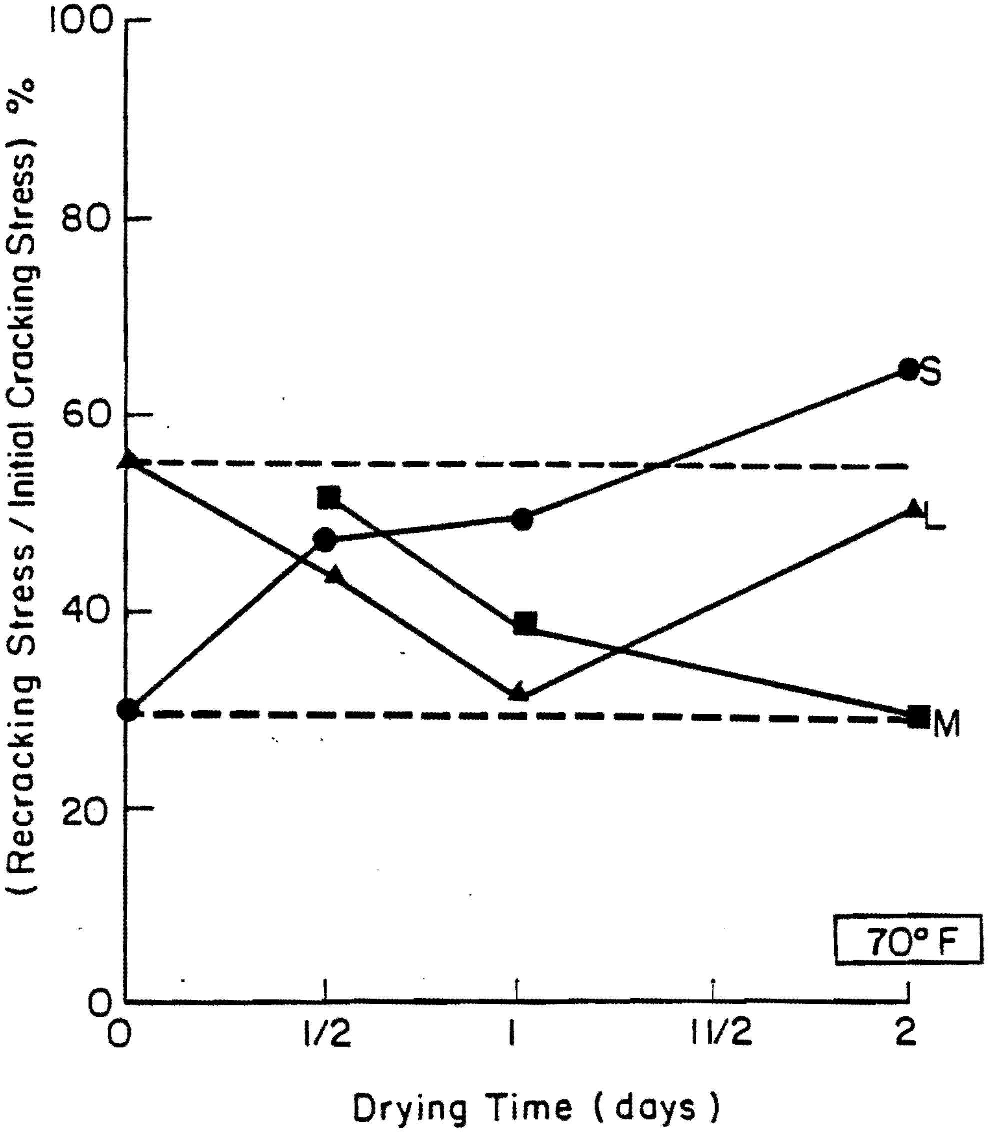
Drying Time (days)	Crack Width[a]	(Recracking Stress/ Initial Cracking Stress) % 40 °F	70 °F	100 °F
0	S	39	30	35
0	M	61	--	--
0	L	29	55	64
1/2	S	41	47	78
1/2	M	23	52	78
1/2	L	22	44	44
1	S	36	49	103
1	M	18	38	128
1	L	42	31	83
2	S	22	64	68
2	M	35	29	102
2	L	38	50	89

[a]S = small crack width = 0.008 to 0.02 in. (0.2 to 0.6 mm)
M = medium crack width = 0.03 to 0.04 in. (0.7 to 1.1 mm)
L = large crack width = 0.05 to 0.08 in. (1.2 to 2.0 mm)



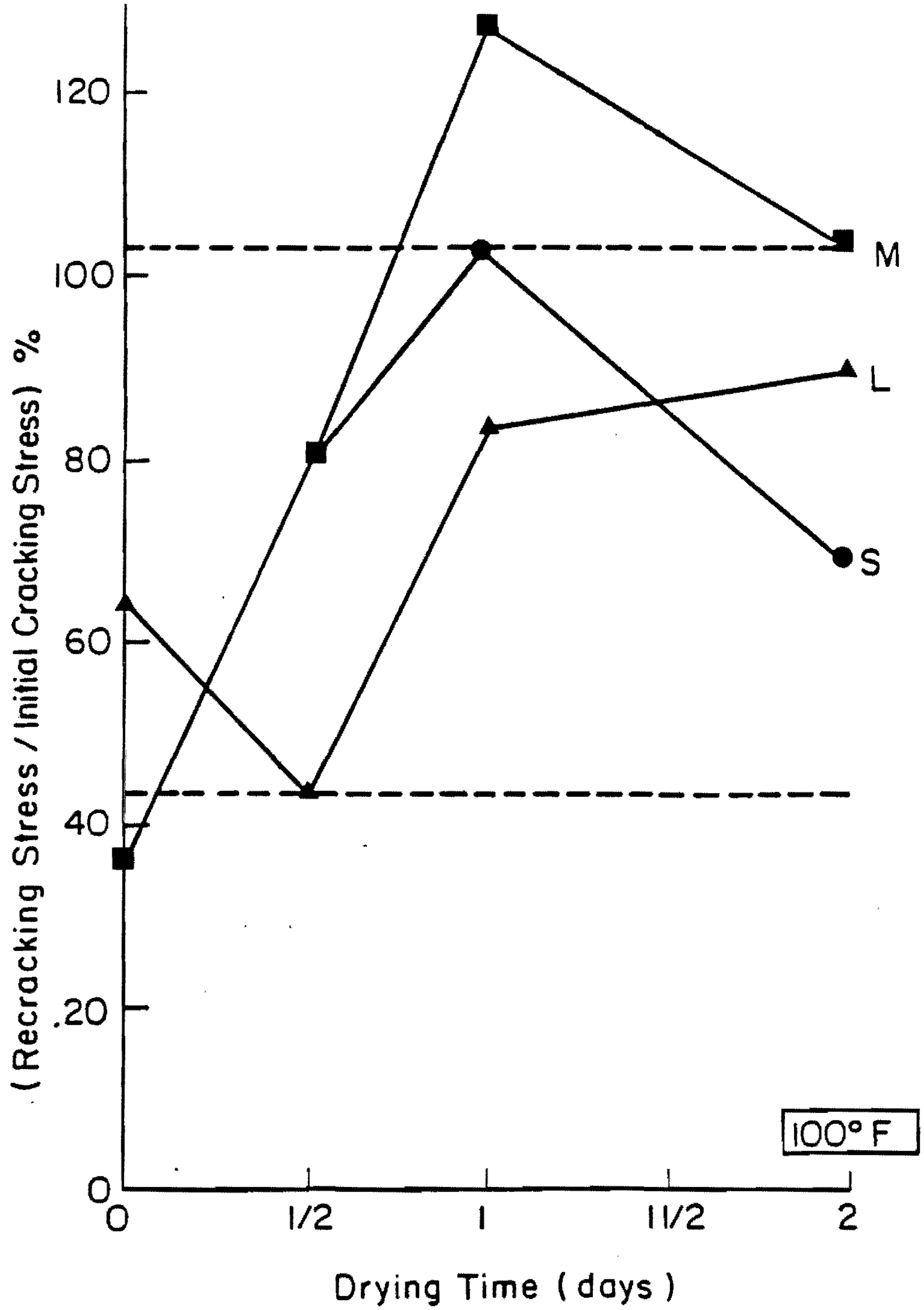
Legend:
S=Small Crack Width (0.2 to 0.6mm)
M=Medium Crack Width (0.7 to 1.1mm)
L=Large Crack Width (1.2 to 2.0mm)

Fig. 3.1 Ratio of Recracking Stress to Initial Cracking Stress vs. Drying Time at 40°F



<u>Legend:</u>
S=Small Crack Width (0.2 to 0.6mm)
M=Medium Crack Width (0.7 to 1.1mm)
L=Large Crack Width (1.2 to 2.0mm)

Fig. 3.2 Ratio of Recracking Stress to Initial Cracking Stress vs. Drying Time at 70°F



Legend:
S=Small Crack Width (0.2 to 0.6mm)
M=Medium Crack Width (0.7 to 1.1mm)
L=Large Crack Width (1.2 to 2.0mm)

Fig. 3.3 Ratio of Recracking Stress to Initial Cracking Stress vs. Drying Time at 100°F

Table 3.2 Average Recracking-to-Initial Cracking Stress Ratio

Drying Time (days)	Temperature (°F)	Average $\left(\frac{\text{Recracking Stress}}{\text{Initial Cracking Stress}}\right)$ (%)
0	40	43
0	70	43
0	100	50
1/2	100	29
1/2	40	48
1/2	70	67
1	40	32
1	70	39
1	100	105
2	40	32
2	70	48
2	100	86

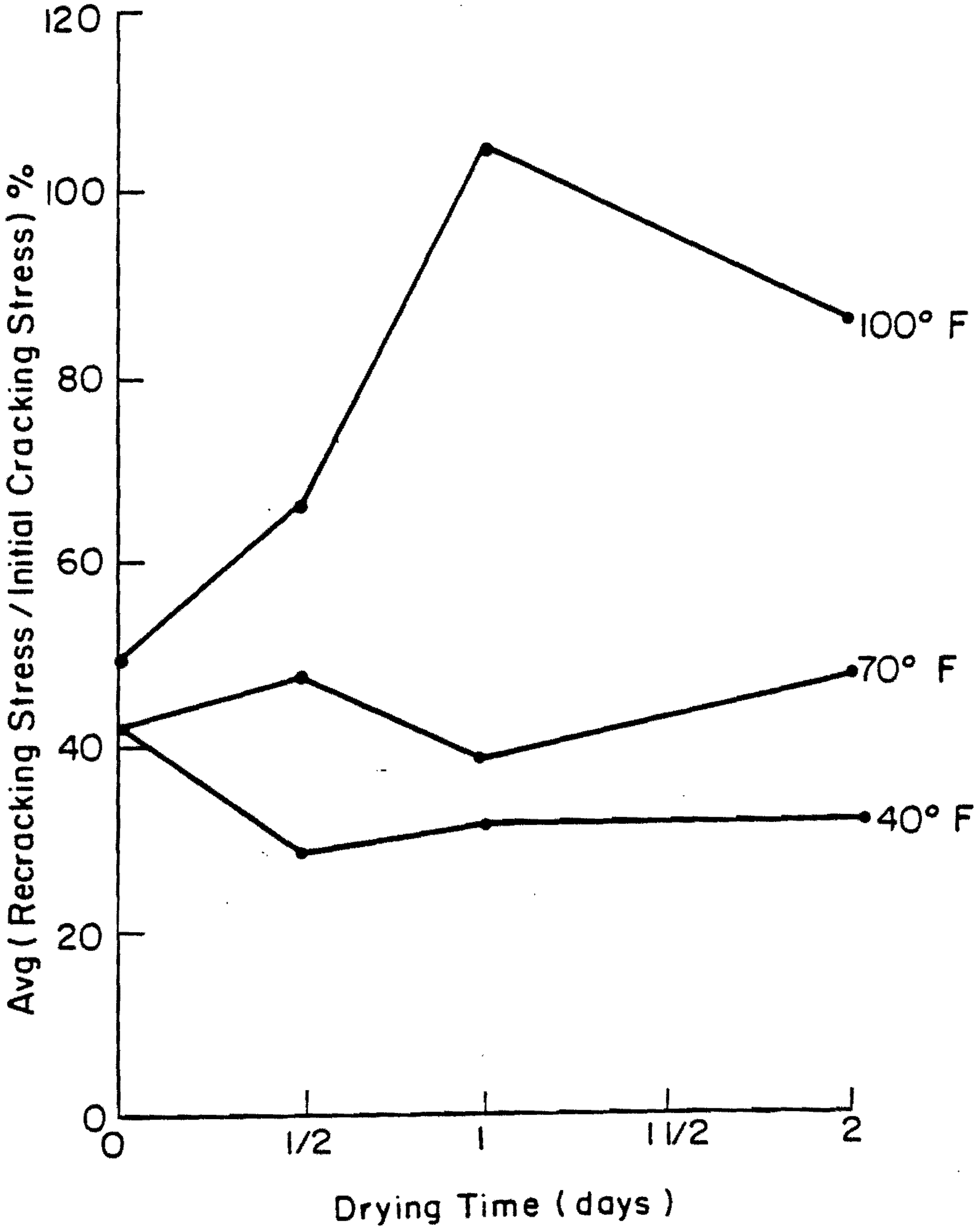


Fig. 3.4 Average Ratio of Recracking Stress to Initial Cracking Stress vs. Drying Time

3.4.2 Percentage of Crack Length Filled

The percentage of the crack length filled for each specimen is recorded in Table 3.3 and plotted in Figs. 3.5 through 3.7. In general, when the specimens were prepared properly, between 95 and 100 percent of the total crack length was filled by the epoxy. However, as can be seen in Fig. 3.5, proper preparation is critical. The decrease in percentage filled shown in Fig. 3.5 was due to insufficient sealing of the crack with putty around the injection port or underneath the specimen if the crack extended through its depth. This allowed the epoxy to escape from the crack during the injection, either from around the injection port or from underneath the specimen.

Initially, it was thought that the lower filling percentage values were responsible for the low recracking values of the 40 degrees F test. However, as shown in Fig. 3.8, the recracking-to-initial-cracking stress ratio decreased only slightly with decreases in percentage of the crack depth filled. These decreases were probably due to incomplete curing of the epoxy at low temperatures. The epoxy in the 40 degrees F specimens was still tacky when they were cut.

3.5 Summary

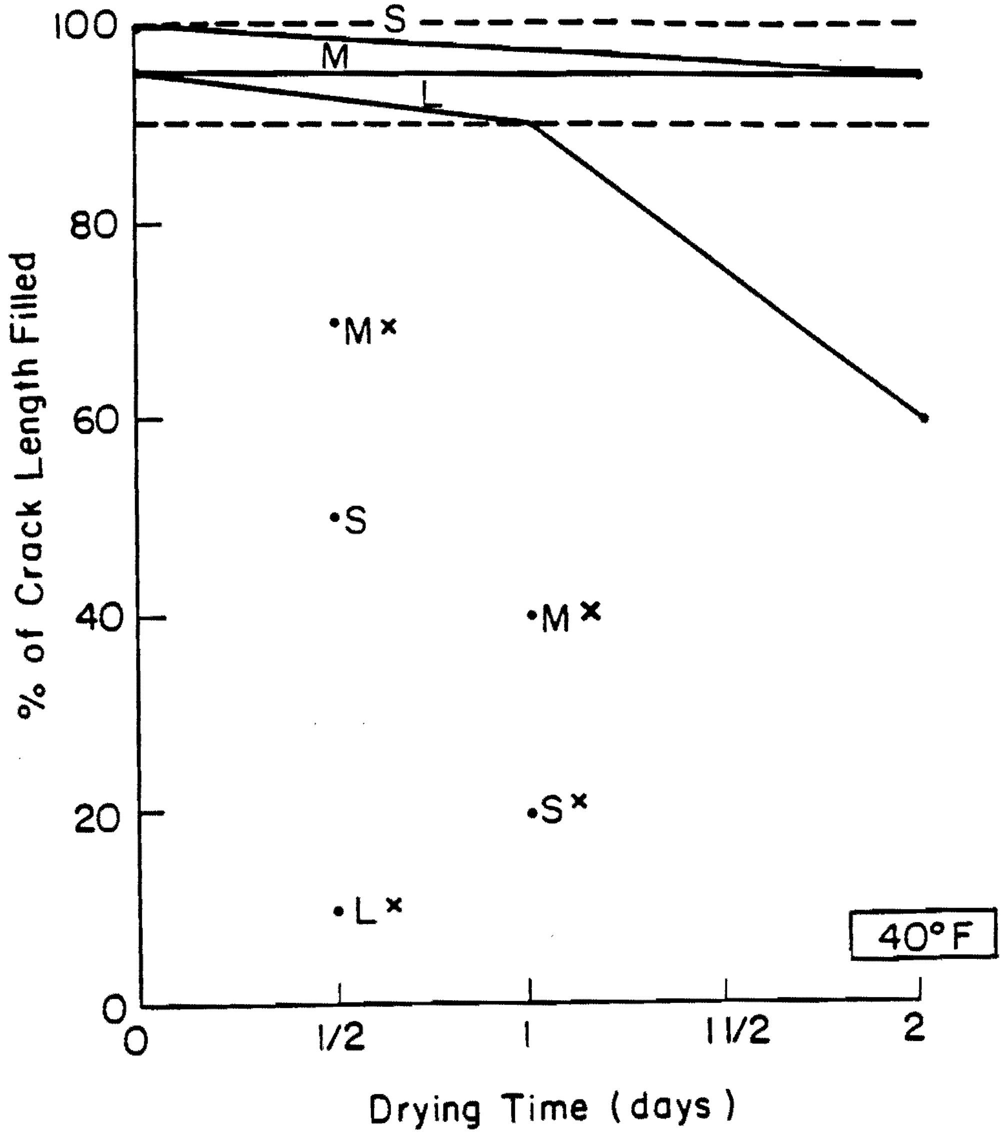
These tests would suggest that the epoxy will generally fill a crack almost entirely, regardless of its width and whether or not it is wet. As was observed during these tests, the epoxy displaced any water present within the crack when it was injected. When a great deal of water was present in the specimens, it would flow out of the injection port first, followed by the epoxy. However, the success of the injection depends greatly on proper preparation of the crack.

Table 3.3 Percent of Crack Length Filled

Drying Time (days)	Crack Width[a]	Percent of Crack Length Filled 40 °F	70 °F	100 °F
0	S	100	95	100
0	M	95	--	--
0	L	95	95	90
1/2	S	50	95	95
1/2	M	70	95	100
1/2	L	10	95	95
1	S	20	85	100
1	M	40	100	100
1	L	90	85	95
2	S	95	95	100
2	M	95	90	100
2	L	60	100	100

[a] S = small crack width = 0.008 to 0.02 in. (0.2 to 0.6 mm)
M = medium crack width = 0.03 to 0.04 in. (0.7 to 1.1 mm)
L = large crack width = 0.05 to 0.08 in. (1.2 to 2.0 mm)

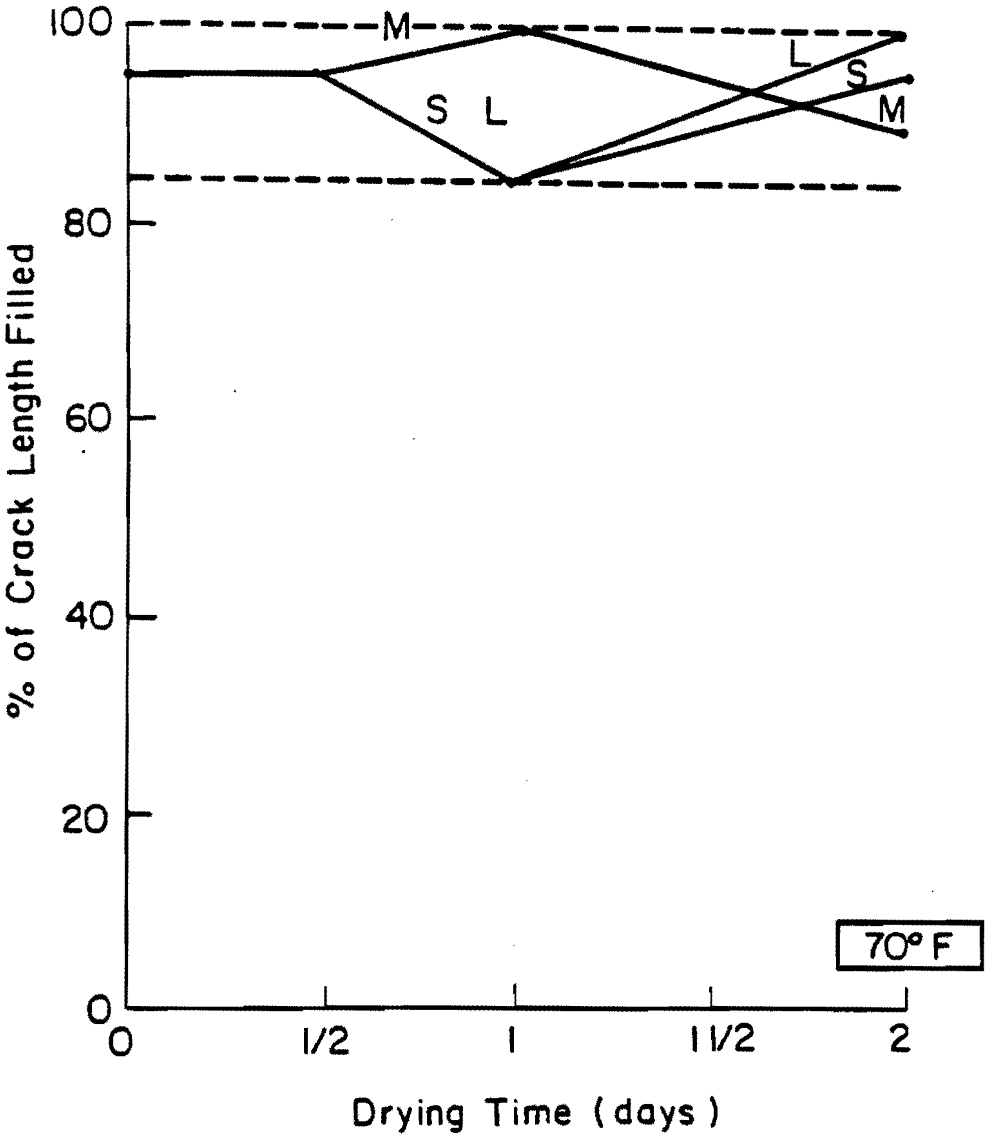
* Noticeable epoxy leakage due to improper cracking sealing prior to injection



Note:
X Imprcper Crack Sealing Preparation Prior to Injection

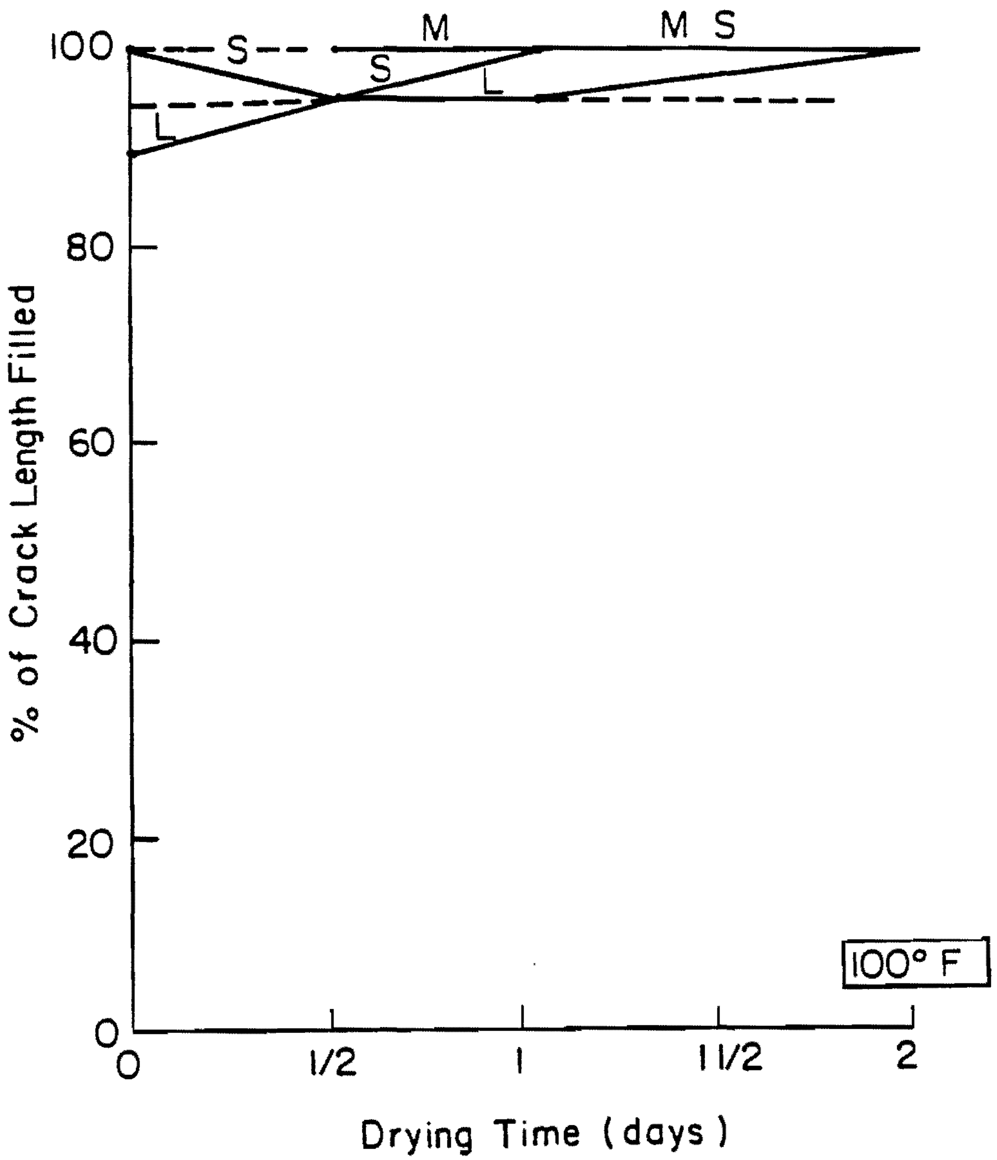
Legend:
S=Small Crack Width (0.2 to 0.6 mm)
M=Medium Crack Width (0.7 to 1.1mm)
L=Large Crack Width (1.2 to 2.0mm)

Fig. 3.5 Percentage of Crack Length Filled vs. Drying Time at 40°F



Legend:
S=Small Crack Width (0.2 to 0.6mm)
M=Medium Crack Width (0.7 to 1.1mm)
L=Large Crack Width (1.2 to 2.0mm)

Fig. 3.6 Percentage of Crack Length Filled vs. Drying Time at 70°F



Legend:
S=Small Crack Width (0.2 to 0.6mm)
M=Medium Crack Width (0.1 to 1.1mm)
L=Large Crack Width (1.2 to 2.0mm)

Fig. 3.7 Percentage of Crack Length Filled vs. Drying Time at 100°F

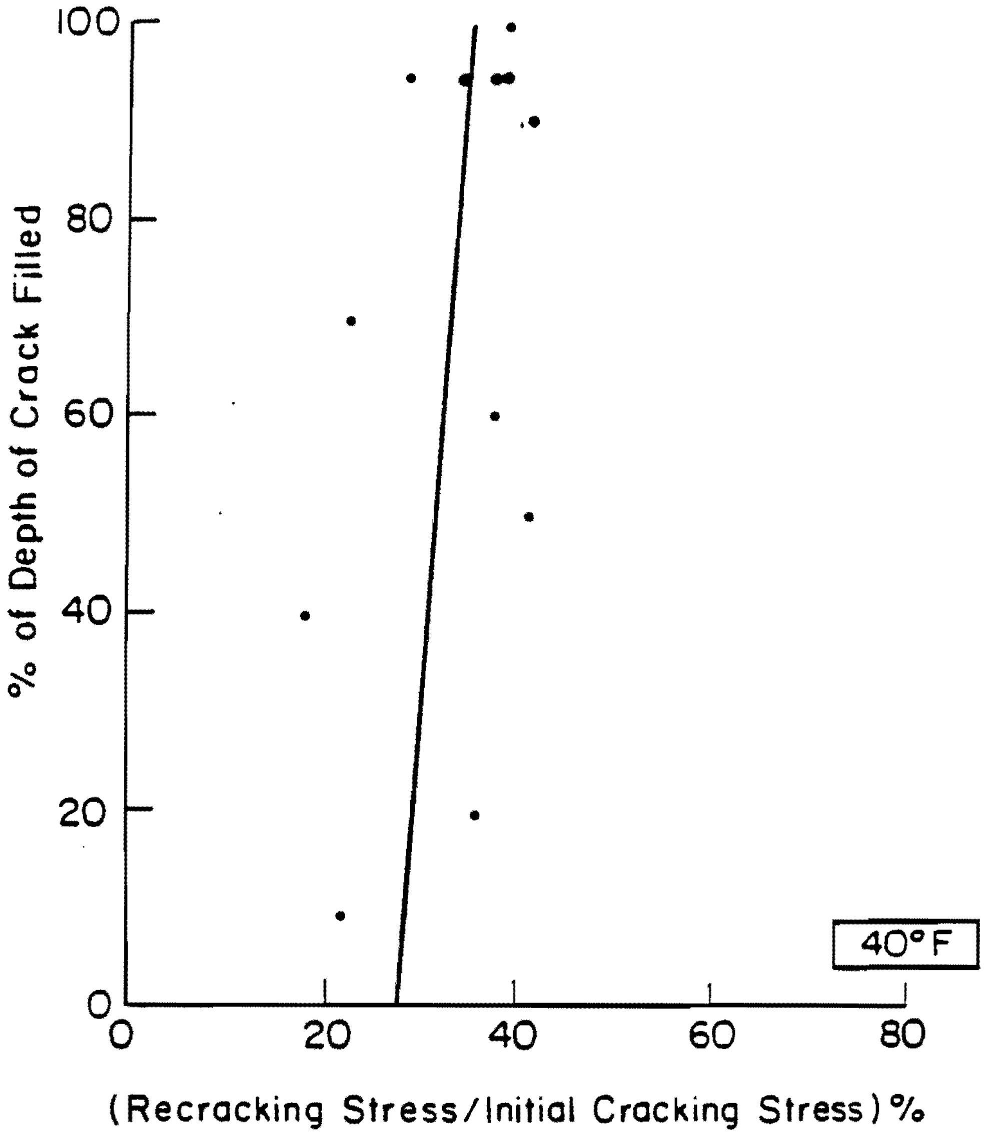


Fig. 3.8 Percentage of Crack Length Filled vs. Ratio of Recracking Stress to Initial Cracking Stress for 40° F.

Chapter 4
Laboratory Investigation of Crack Repair with Monomers

4.1 Introduction

Finding a way to use low viscosity monomer to seal cracks in portland cement concrete has been the objective of CTR researchers for several years. In the 1970s, several attempts were made to broom MMA monomer into bridge deck cracks. The Harbor Bridge in Corpus Christi was treated, but cores indicated that none of the monomer polymerized in the cracks. A bridge deck at an interchange in Dallas adjacent to the district office developed shrinkage cracks over an area of about 2600 sq. ft. during construction . MMA was broomed into the cracks in a small test area. Cores taken from test area indicated that little polymer was present in the cracks even though the silicone sealant dikes were placed around some of the cracks to cause ponding of the MMA. The bridge was eventually repaired using epoxy injection at a cost of approximately $95,000.

It was theorized that the MMA, which has a viscosity about the same as water, penetrated the cracks but either leaked out the bottom or into the side walls of the crack or evaporated. MMA was never found to be a suitable material for the repair of narrow cracks.

In the 1970s the Rohm and Haas Company developed high molecular weight methacrylate (HMWM) monomers which had many of the same qualities as MMA: low viscosity, good mechanical properties when used as a binder for polymer concrete, and rapid polymerization. In addition, the HMWM has little odor and a significantly higher flash point than MMA. It was used at first to produce PC overlays.

In November 1981 HMWM was used in an attempt to seal cracks on the lift span of the Rio Vista Bridge near Sacramento, California. The concrete was worn and cracked, and during rainy weather the deck absorbed so much water that the counter-weights had to be adjusted so that the span could be lifted properly. HMWM was mopped onto the surface and allowed to cure. In the five years following, the bridge has functioned properly without the need to adjust the counter-weights, which indicates that the bridge was sealed and has remained sealed.

The success of the sealing of the Rio Vista Bridge led to the investigation of HMWM in this research. Laboratory studies were conducted to determine the effectiveness of HMWM for sealing cracks and for bonding the concrete.

4.2 Initial Investigation

An initial investigation was conducted to perform a comparative evaluation of four high molecular weight methacrylate monomer systems (6).

4.2.1 Materials and Preparation

4.2.1.1 Concrete Specimens

Concrete specimens, 12 in. wide, 5-1/2 in. thick, and 14 in. long (30 cm x 14 cm. x 36 cm.) were prepared. Four strands of 10-gauge wire were placed along the length to prevent the specimens from breaking apart when cracked. The wires were placed at different depths to cause different crack widths when subjected to flexural loads. The concrete mix consisted of:

Material	Weight Percent
cement	22
sand	38
3/4-in. coarse aggregate	30
water	10

The specimens were cured at room temperature for 24 hours and then cured in a moist room for 30 days when Type I cement was used and seven days when Type III was used.

Using a 10-in. span and center point loading the specimens were cracked. Crack widths were varied as a result of the wire placement and by the amount of loading applied after the initial crack development. Crack widths ranged from 0.008 in. (0.2 mm) to 0.08 in. (2.0 mm). Polyester putty was placed along the sides of the cracks to prevent monomer from escaping.

4.2.1.2 Monomers

Four Rohm and Haas high molecular weight monomer systems were used: Monomer 200, Monomer 400, Monomer 1100, and Monomer 1300. Monomers 200 and 400 were identical except for the initiator/ catalyst system. Monomers 1100 and 1300 produced polymers with decreasing moduli of elasticity. The initiator/ catalyst systems and moduli of elasticity for polymer concrete made from the different monomer systems are shown in Table 4.1.

Table 4.1 Monomer Systems
Using High Molecular Weight Monomers

Monomer	Catalyst [a]	Initiator [a]	Modulus of Elasticity [b]
200	4% Cumene Hydroperoxide	12% Cobalt Napthenate	3 x 10^6 psi
400	4% Benzoyl Peroxide	12% Cobalt Napthenate	3 x 10^6 psi
1100	4% Benzoyl Peroxide	12% Cobalt Napthenate	1.5 x 10^6
1300	4% Benzoyl Peroxide	12% Cobalt Napthenate	1.0 x 10^6

---

[a] Weight percent of monomer

[b] Modulus of elasticity of polymer concrete made from monomer systems (References 7 and 8)

It should be noted that during this study the Rohm and Haas Company reported that some of the monomers had indicated high levels of toxicity in a laboratory test program. Testing proceeded with caution, with protective clothing use to minimize skin contact with the monomer. Within the past year, monomers having properties similar to those of the original monomers but with acceptable levels of toxicity were developed .

4.2.1.3 Application of Monomer

After cracking, the concrete slabs were typically air dried in the laboratory for a minimum of 24 hours. The monomer system to be used was mixed just prior to use and brushed onto the concrete surface until the crack was filled with monomer. The monomer was permitted to cure for a minimum of 24 hours before the slabs were recracked.

One specimen was saturated with water prior to the monomer application in order to give some indication of the effect of water on the success of the application. The specimen was placed in a wet chamber for eleven days following its initial cracking. The specimen was prepared and treated with monomer immediately upon removal from the chamber. It was totally saturated with water and its crack was entirely full of water when the monomer was applied. One specimen was filled with the monomer, outside, at a temperature of over 90 degrees F.

A decrease in cure time with increased temperature had been noticed in earlier tests. It was thought that the decreased cure time would inhibit the flow of the monomer into the finer portions of the cracks. The continual lowering of the surface level of the monomer in the crack throughout the duration of its cure in earlier tests was believed to be due to the monomer's penetrating into the finer widths of the cracks prior to its cure.

After the monomer cured, the specimens were cut lengthwise in the center of the specimen (perpendicular to the crack). One of the specimen halves was cut into thin slices perpendicular to the crack to determine the percentage of crack length filled, and the other half was recracked to determine the load (and stress) required to crack the specimen and to determine the location of the crack with respect to the repaired crack.

4.2.2 Percentage of Crack Length Filled

4.2.2.1 Test Procedure

After the monomer had cured, the specimens were sliced perpendicular to the length of the cracks. Slices of the cracked cross section were viewed and the percentage of the crack filled by the monomer was estimated. The monomer almost never terminated at any single depth. Instead, air pockets usually formed in the monomer, making the polymer discontinuous along the length of the crack. The percentage of the crack filled was estimated by dividing the summation of the lengths of the segments of the depth of the crack filled by the monomer by the total depth of the crack. The crack widths recorded in these tests were the widths at the surface of the slab. Since the crack width and the percentage of the crack which was filled by the monomer varied slightly along the length of the crack, the values from the various slices of each specimen were used to calculate average crack width and percentage filled values for the specimen.

4.2.2.2. Results

The results of this test are tabulated in Table 4.2 and plotted in Fig. 4.1. Figure 4.1 reveals that the percentage of the crack filled by the monomer increased as the crack width increased. No specimen (besides the wet specimen) was filled less than 60 percent. This indicates that, although the expected success of the monomer application is directly related to the crack width, the majority of the depth of even very narrow cracks can be filled under dry and clean conditions.

Table 4.2 Percentage of Crack Length Filled by Monomer Systems

Specimen	Crack Width (mm)	Monomer System	Percent of Crack Depth Filled
1	1.5	200	95
2	1.0	200	95
3	1.0	200	50
4	2.0	200	97
5	0.4	1300	80
6	0.2	400	90
7	0.4	1100	95
8	0.2	400	60
9	0.7	200	80
10	0.5	1100	90
11	0.8	1300	90
12	0.3	200	90
	Average (excluding specimens 3 and 9)		88

* Wet Specimen

** Applied outside under hot conditions

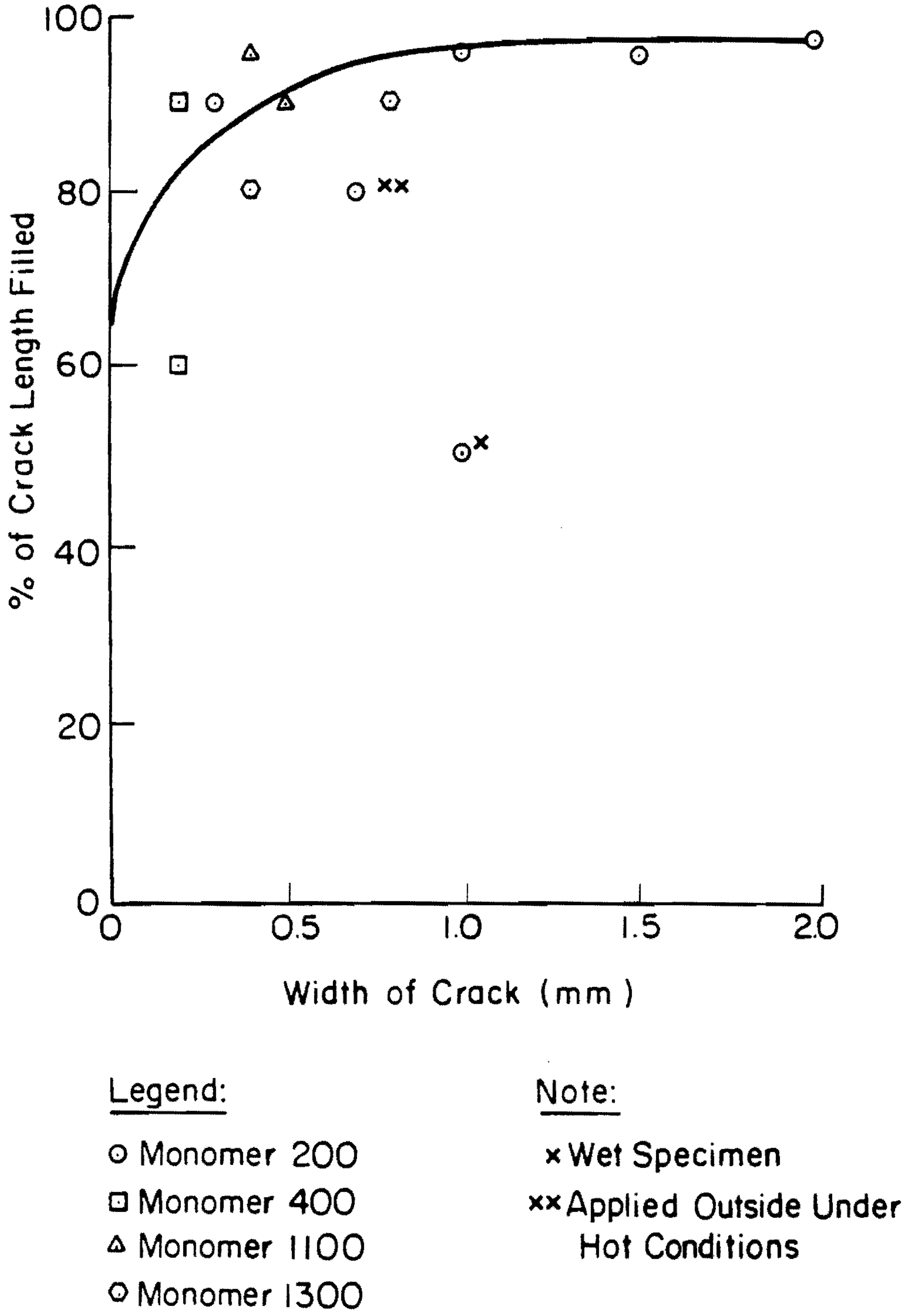


Fig. 4.1 Width of Crack vs. Percentage of Crack Length Filled

The single data point for the wet specimen indicates that the presence of standing water in the crack greatly affects the performance of the monomer. The cross sections of the wet specimen used in this test revealed that only 50 percent of the crack length contained monomer. This is compared to an expected value of 95 percent (Fig. 4.1) for dry cracks of the same width. Apparently the monomer could not displace the water and fill the crack properly. The effect of moisture is more thoroughly investigated in Section 4.2.4.

The performance of the monomer seemed to also be adversely affected by hot conditions during its application. The percentage of the length of the crack filled for the specimen treated outside was 80 percent. This is slightly lower than the 94 percent value for cracks with the same width filled at 72 degrees F.

The four monomer systems did not exhibit a significant difference in their crack filling capabilities.

4.2.3 Recracking Strength and Crack Location

4.2.3.1 Test Procedure

The second half of the specimen was recracked under loading conditions indentical to those used for the initial cracking. The recracking loads were recorded and initial cracking and recracking stresses were calculated for each specimen. These values are tabulated in Table 4.3 and plotted in Fig. 4.2. After each specimen was recracked, it was examined to determine the amount of the length of the crack from this test that coincided with the initial crack. These observations are recorded in Table 4.4. Figure 4.3 shows typical cracking patterns.

4.2.3.2 Results

The data plotted in Fig. 4.2 reveal that the ratio of recracking stress to initial cracking stress for specimens repaired under cool, dry conditions in general follows the line of equality between initial stress

Table 4.3 Initial and Recracking Stresses

Specimen	Crack Width (mm)	Monomer Used	Percent of Crack Depth Filled	Initial Cracking Stress (ksi)	Recracking Stress (ksi)	Recracking Stress Initial Cracking Stress
1	1.5	200	95	0.298	0.238	0.80
2	1.0	200	95	0.278	0.322	1.16
3	1.0	200	50	0.254	0.105	0.41
4	2.0	200	97	0.302	0.298	0.83
5	0.4	1300	80	0.278	0.218	0.78
6	0.2	400	90	0.245	0.232	0.94
7	0.7	1100	95	0.241	0.324	1.32
8	0.2	400	60	0.227	0.243	1.07
9	0.7	200	80	0.248	0.287	1.16
10	0.5	1100	90	0.221	0.211	0.96
11	0.8	1300	90	0.240	0.248	1.03
12	0.3	200	90			
13	1.3	200	---	0.308	0.298	0.97
					Avg.	0.99

* Wet Specimen

** Applied outside under hot conditions

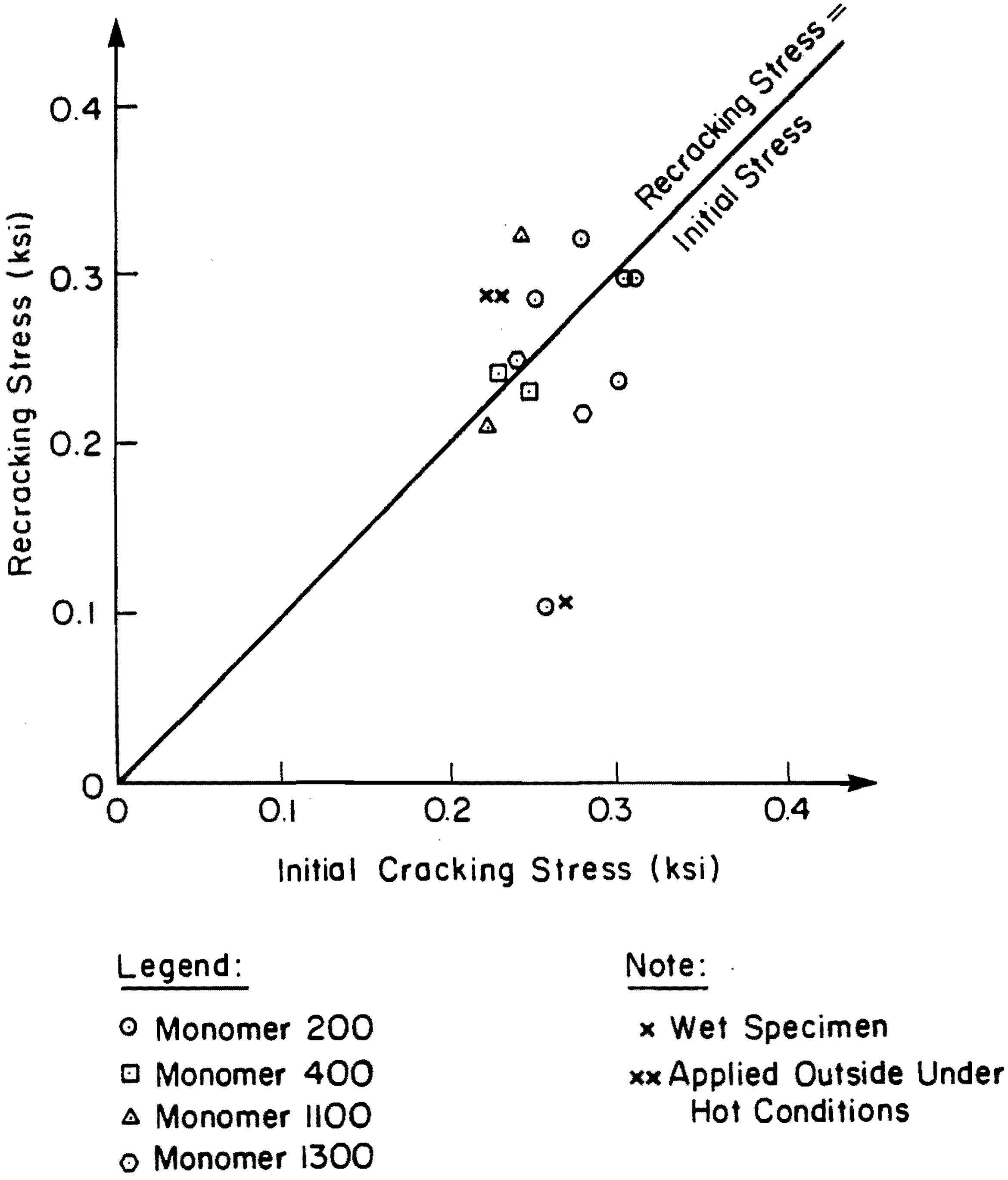


Fig. 4.2 Recracking Stress vs. Initial Cracking Stress

Table 4.4 Location of Recracking Crack

Specimen	Crack Width (mm)	Recracking Stress Initial Cracking Stress	Position of Recracking Crack in Relation to Original Crack*
1	1.5	0.80	Parallel
2	1.0	1.16	Partially inside
3	1.0	0.41	Partially inside
4	2.0	0.83	Totally inside
5	0.4	0.78	Parallel
6	0.2	0.95	Parallel
7	0.4	1.34	Parallel
8	0.2	1.07	Partially inside
9	0.7	0.16	Mostly parallel
10	0.5	0.96	Mostly inside
11	0.8	1.03	Totally inside
12	0.3	–	–
13	1.3	0.97	Totally inside

* Fig. 4.3 Defines cracks locations

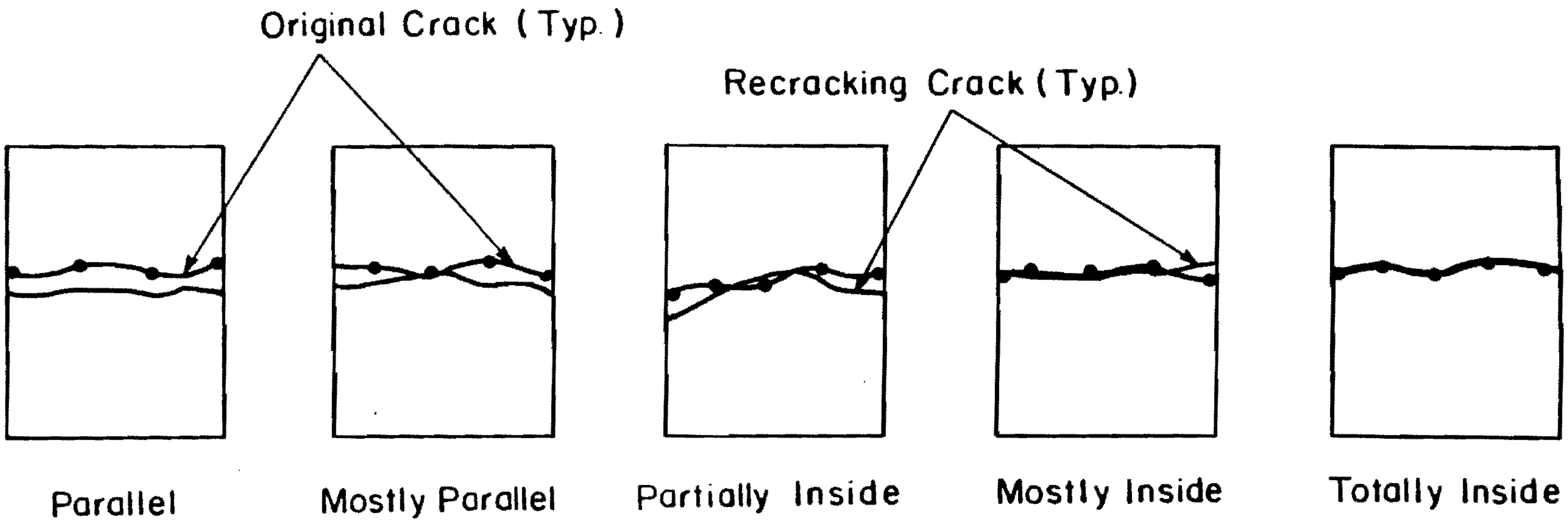


Fig. 4.3 Location of Recracking Crack Relative to Initial Crack

and recracking stress. The average variation between the initial and recracking stresses was 13 percent (Table 4.4).

The average value of the ratio of recracking stress to initial stress was 0.99. However, it should be noted that many of the lower recracking stress values were offset by values of recracking which were higher than the recorded initial cracking stress. These higher stress values could be due to slight differences in positions of the supports or the point of load application for the initial cracking and recracking loadings. However, it is quite likely that, when the initial crack was repaired, the next crack developed at a higher flexural stress.

As can be seen in Fig. 4.4, often the crack produced in this test did not coincide with the initial crack of the specimen. The observations recorded in Table 4.4 reveal that , in general, cracks resulting from the recracking test coincided with the initial crack along less than half its length in specimens where the recracking stress values are larger than the initial stress values. Even when the second crack did not coincide at all with the original crack, the recracking stress was sometimes lower. This is most likely due to the fact that during the first loading microcracking developed that resulted in cracking which caused failure at lower loads during the second loading. Although there is a significant variation in the recracking to initial stress ratio, it is apparent that the monomer treatment restores a great deal of the strength to the concrete.

The recracking stress value of the wet specimen is also plotted in Fig. 4.2. This specimen yielded a recracking to initial cracking stress ratio of less than 0.5.

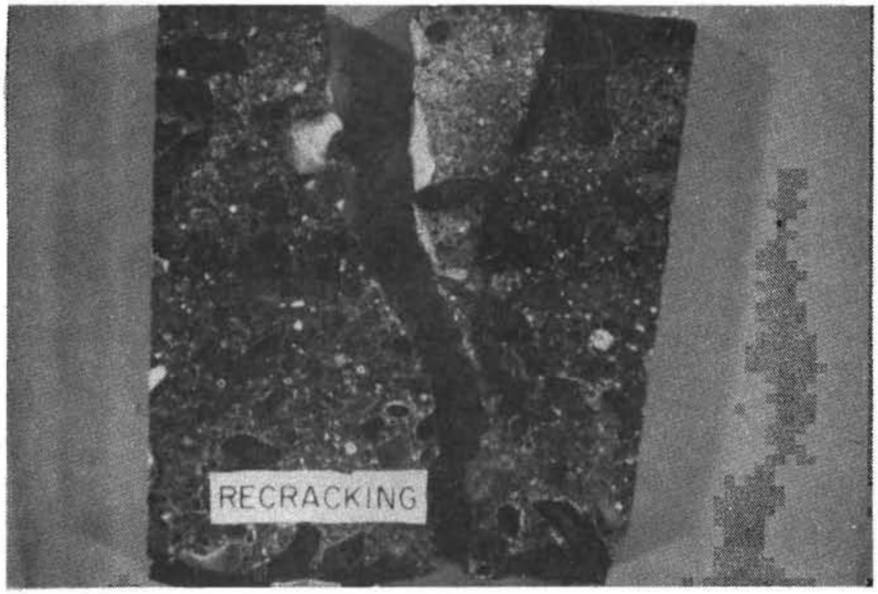


Fig. 4.4 Recracked Monomer - Filled Specimen

The presence of water in the crack at the time of monomer application decreased the recracking strength of the rehabilitated concrete. Examination of Fig. 4.6 suggests that the decrease in strength is due in part to the decrease in the percentage of the crack filled with polymer. However, the substantial decrease in the initial to recracking stress ratio of the wet specimen, as compared to dry specimens with similar filling percentages, suggests that the presence of water within a crack adversely affects both the filling capability of the monomer and the bond between the monomer and the faces of the crack.

The ratio of the recracking stress to the initial cracking stress for each specimen is plotted against the crack width and the percentage of the crack filled in order to determine if any correlation exists between these values. Figure 4.5, which shows the relationship between the recracking to initial cracking stress ratio and the crack width, shows that there is an initial increase in the ratio as the crack width increases. The stress ratio peaks at a crack width of approximately .04 in. (1.0 mm) and begins to decline with further increases in crack width.

It was noted that, in some of the specimens with larger crack widths, brittle cracking in the polymer within the crack was the mode of failure during recracking. It has been a general observation that the larger the volume of polymer, the less its strength, perhaps as a result of the more porous polymer associated with the higher exotherm during polymerization. Larger cracks should be filled with sand to minimize the effect.

The relationship of the recracking to initial stress ratio and the percentage of the crack filled by the monomer is plotted in Fig. 4.6. There is a great deal of scatter in the data. However, there is a noticeable upward trend of the recracking to initial stress ratio, with increasing percentages of the crack length filled by the monomer.

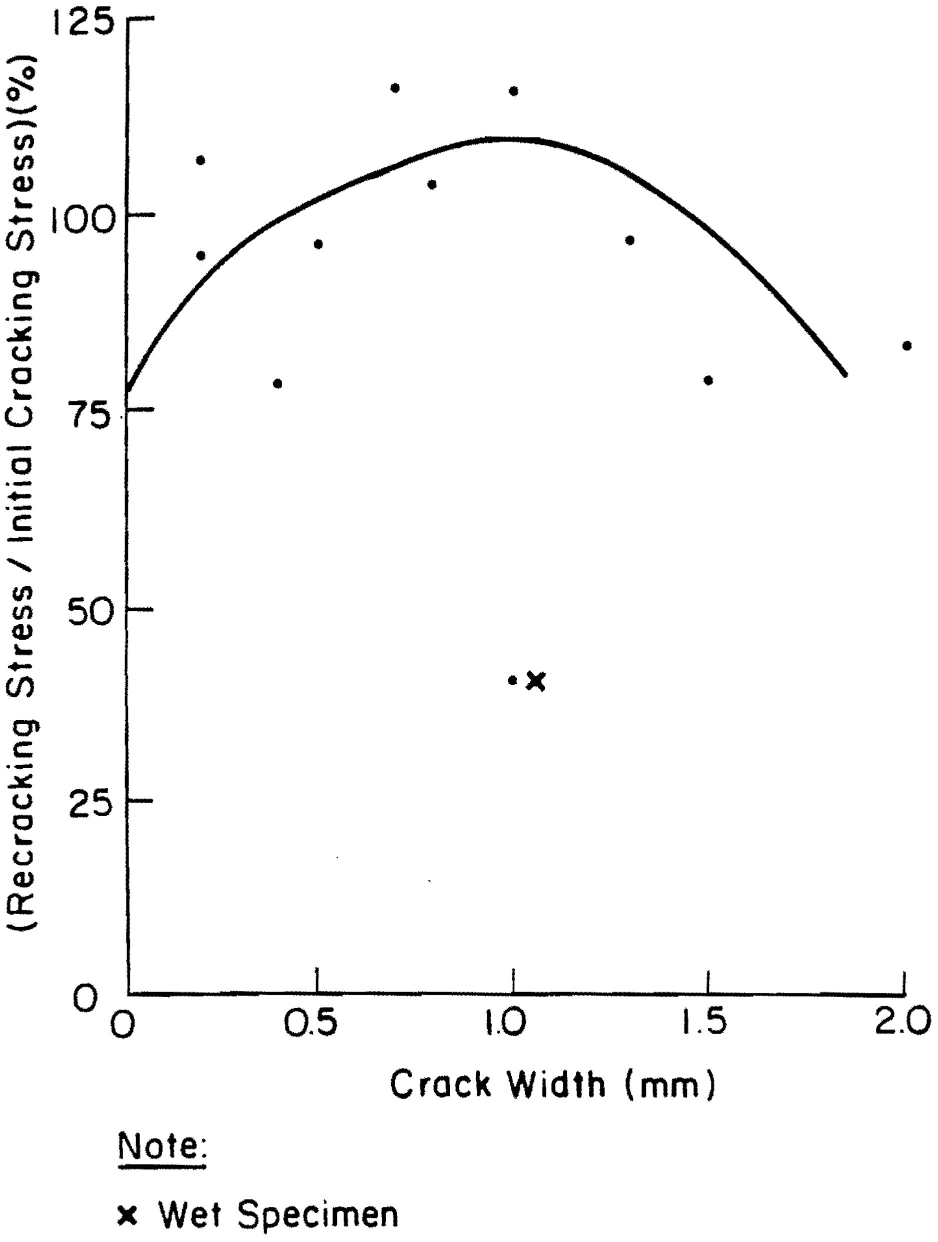
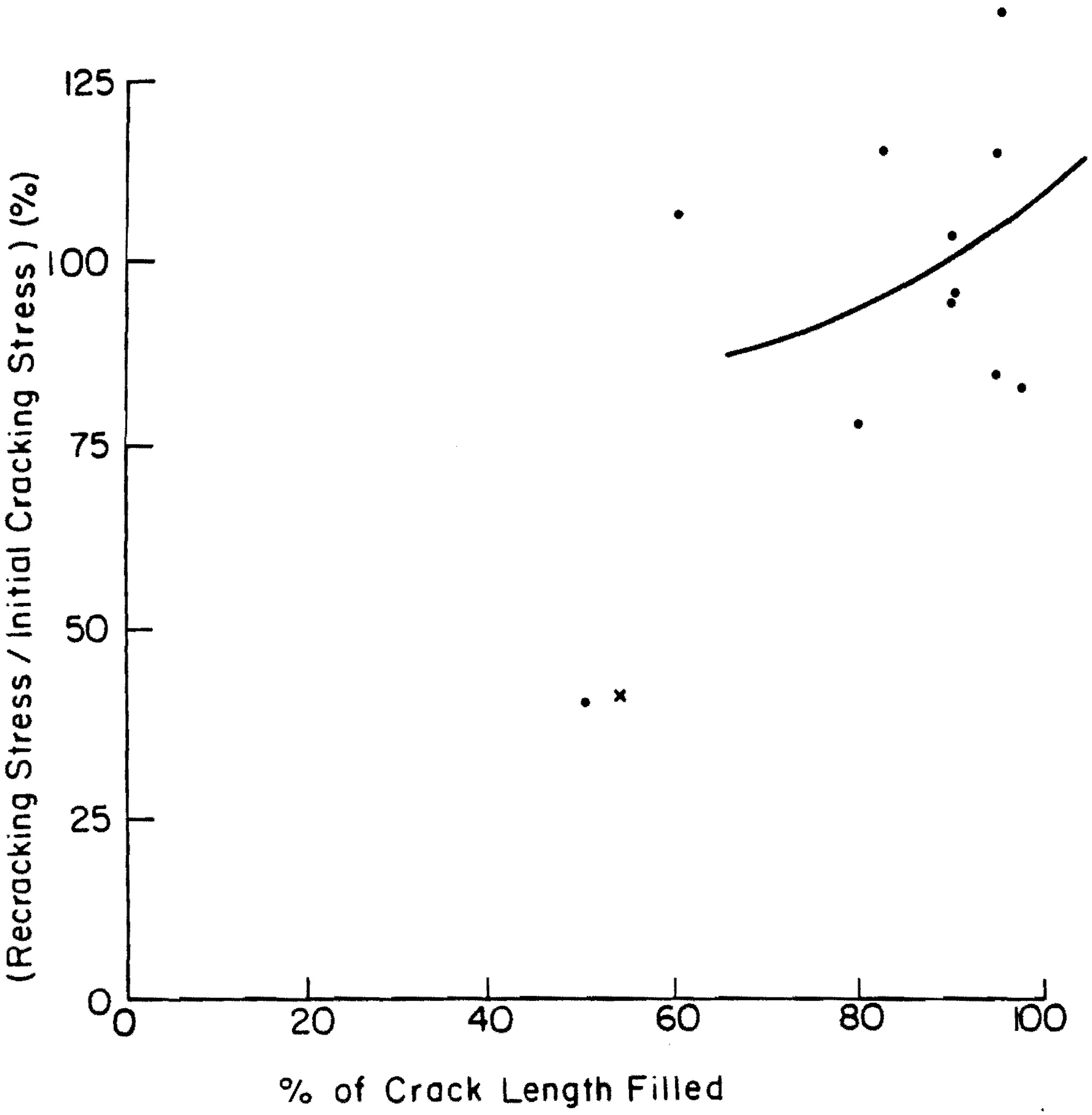


Fig. 4.5 Ratio of Recracking Stress to Initial Cracking Stress vs. Crack Width



<u>Note</u>:
X Wet Specimen

Fig.4.6 Ratio of Recracking Stress to Initial Cracking Stress vs. Percentage of Crack Length Filled

Visual observation of the cut specimens indicated that in several cases the level of polymer was below the surface of the concrete even though care was taken in the treatment to completely fill the crack. This was undoubtedly due to the continued but slow penetration of the monomer into the narrower part of the crack at the bottom of the specimen and perhaps wicking into the pores of the concrete. While presence of the polymer in the crack all the way to the surface is not essential for resotration of water tightness and structural integrity, it is desirable from a visual inspection standpoint. When polymer is not visible at the surface, it is difficult to determine the effectiveness of the treatment without taking cores. For that reason, it is desirable to have continued or intermittent brooming of the monomer into the cracks for 10 or 15 minutes after the initial application.

4.2.4 Effect of Moisture

As can be seen in Figs. 4.1 and 4.2, the presence of moisture in a crack can greatly affect both the amount of filling of the monomer and the resulting recracking strength of the repaired concrete. These data suggest that the presence of moisture lowered the percentage of the crack filled by approximately 50 percent and also caused a reduction of more than 50 percent in recracking strength. In other words, by allowing a crack to dry, the success of the monomer application, in terms of percent of the crack length filled and the strength of the rehabilitated concrete will be increased by approximately 100 percent.

4.2.4.1 Test Procedure

In an effort to quantify the amount of drying time necessary in order to achieve a particular level of success, drying tests were performed. Two sets of five specimens were prepared in the manner described in section 4.2.1. After the specimens were cracked, they were placed in a wet chamber for approximately two weeks, until they were saturated and the cracks were entirely full of water.

Tests run on the first five specimens were performed under nearly ideal field drying conditions. These specimens were taken out of the moist room and immediately placed outside under direct sunlight. The outside temperature during the drying of the specimens ranged from the mid-70s at night to the mid-90s under sunny to partly sunny conditions during the day. The relative humidity remained below 50 percent throughout the duration of the drying peroid. This environment is subsequently referred to as "dry conditions." Also, in an effort to create improved drying conditions, four of the five specimens contained medium sized cracks (0.7 mm to 1.1 mm). It was believed that larger crack sizes would be more conducive to rapid drying. The fifth specimen, containing a small crack (0.5 mm), was used to test the validity of this assumption. The specimens were brought inside and treated with monomer after drying times of 8 hours, 16 hours, 1 day, 2 days, and 3 days.

Five other specimens used in the second set of tests were dried under very poor conditions. They were placed in an environmental chamber upon removal from the wet chamber. This enviromental chamber was equipped with adjustable temperature and humidity controls. The specimens were dried at a temperature of 65 degrees F and 90 percent relative humidity subsequently referred to as "wet conditions." These five specimens were removed from the chamber and filled with monomer at intervals of 8 hours, 16 hours, 1 day, 2 days, and 3 days. These specimens contained small cracks (0.2 to 0.6 mm). One other specimen was filled with the monomer immediately upon removal from the wet chamber in order to determine the effect of zero drying time.

4.2.4.2 Results

The crack widths of the specimens used in these tests varied. However, there was not only variation in widths between the small and medium width cracks: there were also smaller variations within the two crack size classifications. As shown in Fig. 4.1, the percentage of the crack filled by the monomer under dry conditions is affected by the crack width. Therefore, in order to negate the effects of crack width from the wet versus dry results and yet still maintain the crack width effects in the drying time results, the filling percentages from these tests were divided by the average filling percentages for the same crack width from Fig. 4.1. These values are recorded in Table 4.5 and plotted versus drying time in Fig. 4.7. A 100 percent value in Fig. 4.7 indicates that the crack was filled as completely as if the specimen were completely dry.

It should be noted from Fig. 4.7 that the assumption that the larger cracks would lead to faster drying is affirmed by the point labeled "small crack, dry conditions." Although this point should theoretically plot above the line for the specimens dried under humid conditions, it should be recognized that it is very much below the data points for the specimens dried under dry conditions.

The results of these tests suggest that the pressence of moisture does in fact have a significant effect on the filling capability of the monomer. The monomer is obviously not able to displace the water from the crack.

These tests were performed with the intent of establishing the drying time for saturated concrete required to insure the desired level of success. The conditions under which the first set of tests were run could be considered close to ideal for field conditions. Therefore, the results of this set of tests could be used in estimating the minimum drying time required for a particular level of success. The drying conditions for the second set of tests could be considered close to the worst conditions which would be experienced. The results of this set of tests could, therefore, be used in predicting the minimum level of success which could be expected for a particular drying time. For example, if the cracks in a particular slab are subjected to dry conditions for one day after steady rain, the results obtained from applying the monomer could be expected to be 90 percent or more as good as if the monomer had been applied to a perfectly dry crack. Even for very humid, cool drying conditions, the results would be in excess of 60 percent of that expected for dry concrete. It can be concluded that long drying times in hot, dry weather are not required in order to obtain an adequately sealed bridge deck or pavement.

4.2.5 Spray Application

It is often desirable to seal cracks on a vertical surface or on the underside of a horizontal concrete slab, such as a bridge deck, as described in previous sections. Monomer applications are unsuccessful because either the surface which is cracked can not be easily reached or pouring the monomer into the crack is impossible. Therefore, it becomes necessary to examine methods of application such as spraying.

4.2.5.1 Test Procedure

In order to make preliminary estimates of the success which could be expected by using this technique, three specimens were prepared in the manner described in Section 4.2.1. These specimens contained cracks of 0.01, 0.02, and 0.08 in. (0.3 mm, 0.5 mm, and 2.0 mm).

Two of these specimens were elevated between two supports with the crack positioned on the underside of the specimen. In order to determine the effect of varying crack widths, one specimen contained a large (2.0-mm) crack and another contained a small (0.3-mm) crack. The monomer was sprayed on the cracked surfaces of the specimens using an airless electric sprayer, the same sprayer that was used to inject the monomer in the Fort Worth, Texas, bridge deck field study (Section 5.3.2).

Table 4.5 Results of Drying Tests

Crack Width (mm)	Expected Percent Filled (from Fig. 9.1)	Actual Percent Filled	Drying Time (days)	Drying Condition	Actual Percent Filled / Expected Percent Filled
1.0	96	40	0	---	42
0.8	95	75	1/3	Dry	79
0.5	91	60	2/3	Dry	66
0.8	95	95	1	Dry	100
1.0	96	95	2	Dry	99
0.8	95	85	3	Dry	89
0.5	91	35	1/3	Wet	38
0.2	82	55	2/3	Wet	67
0.4	93	60	1	Wet	65
0.3	86	60	2	Wet	70
0.5	91	75	3	Wet	82

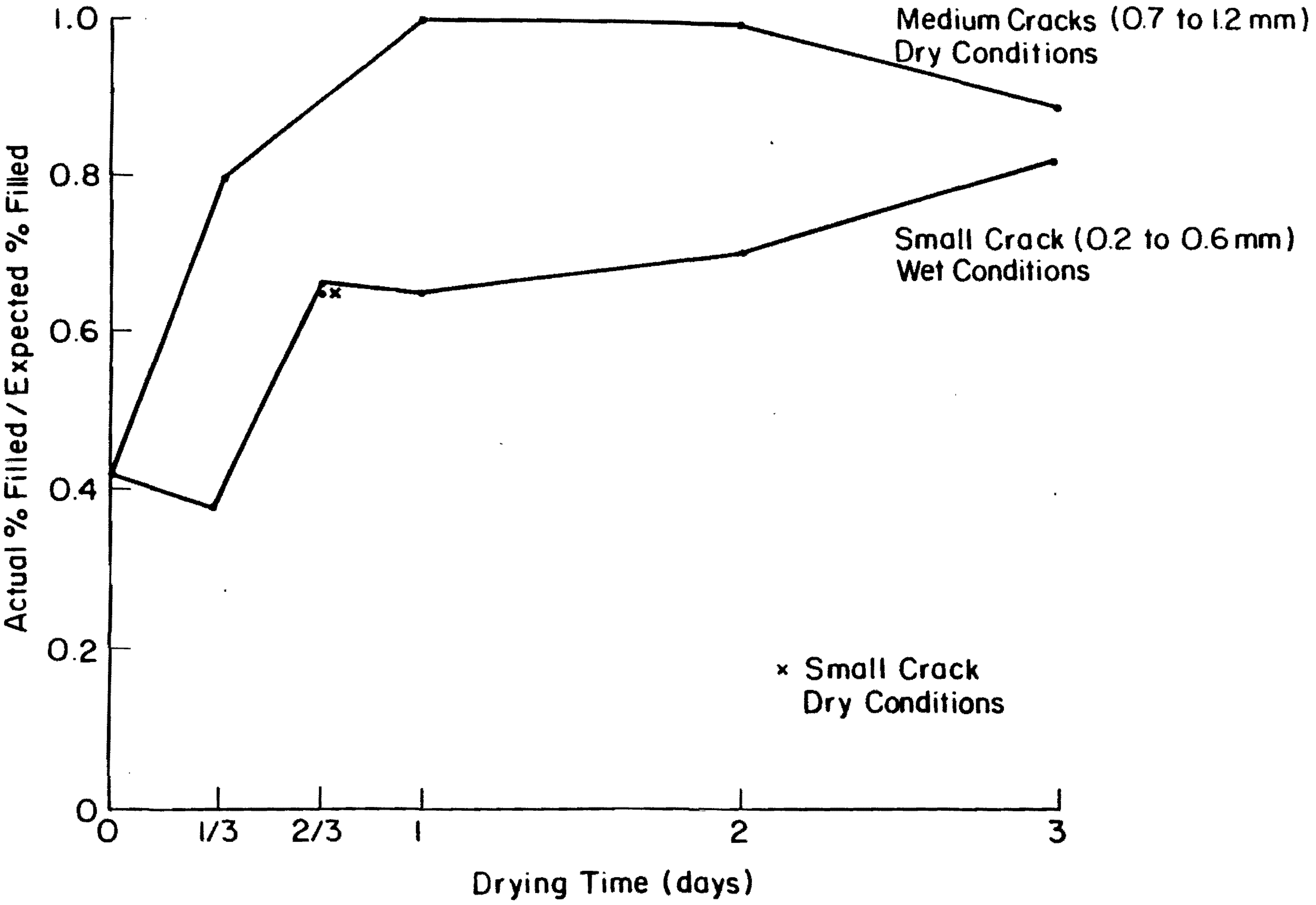


Fig. 4.7 Ratio of Actual Percent Filled to Expected Percent Filled vs. Drying Time

The third specimen was positioned so that the length of the crack ran in a vertical direction. Monomer was also sprayed on the cracked surface of this specimen with the airless electric sprayer.

It should be noted that spraying monomer requires protection clothing in cluding protection for the eyes and face. Respirators may be necessary to prevent inhalation of the vapors.

4.2.5.2 Results

Each of the three specimens was sliced perpendicular to the length of the cracks after the monomer had cured. The depth of penetration of the monomer was then recorded for each specimen. These results are tabulated in Table 4.6. In general, the application of the monomer proved to be more successful when applied to cracks on the underside surfaces than when applied to vertical cracks. The smaller crack width was much more effectively filled (to a 1-in. depth) than the wider crack (to a 1/8-in. depth).

Table 4.6 Results of Monomer Spray Application

Specimen	Crack Width (mm)	Position of Crack	Penetration of Monomer in Crack (in.)
1	2.0	Underneath	1/8
2	0.3	Underneath	1
3	0.5	Vertical	0

The fact that the smaller crack underneath a horizontal surface was more effectively sealed in this test suggests that the monomer acts under the influence of capillary action. Since gravity does not aid the flow of the monomer into cracks on vertical surfaces and the underside of horizontal surfaces, this is the only force available to assist the monomer in penetrating the crack.

Another alternative for application of the monomer into cracks where pouring is impossible is to inject the cracks with the monomer. The crack would have to be sealed as in epoxy injection applications. The monomer could be injected with the airless sprayer.

4.3 Additional Laboratory Tests Using Monomer 1100.

As a result of the success a achieved in the initial test program, additional tests were performed using Monomer 1100 (7). Monomer 1100 was selected since it has a lower modulus than Monomer 200 and 400, and it was theorized that the lower modulus would provide more ductility. Monomer 1300 has an even lower modulus; however, it was more difficult to use because of its "stickiness".

4.3.1 Materials and Preparation

4.3.1.1 Concrete Specimens

Concrete specimens were prepared with wire reinforcing as described in section 4.2.1(1). The concrete mix design,however, was slightly different.

Material	Weight Percent
Cement	14.1
Sand	32.1
3/4-in. coarse aggregate	48.2
Water	5.6

Curing and cracking were performed as described in section 4.2.1(1).

4.3.1.2 Monomer

The only monomer used was Monomer 1100. The initiator and catalyst levels are given in Table 4.1.

4.3.1.3 Application of Monomer

Monomer was brushed onto the surface in the laboratory until the cracks were filled. The monomer was permitted to cure for at least 24 hours before the slabs were recracked.

4.3.2 Effect of Crack Width

4.3.2.1 Test Procedures

The reinforced specimens were cracked to produce crack widths ranging from 0.01 in. (0.2 mm) to 0.08 in. (2.0 mm). The monomer system was then brushed onto the surface.

Four of the specimens were filled outside under a temperature of over 90 degrees F. It had been observed in earlier tests that increasing temperatures would result in a decrease of the monomer curing time. It was thought that this decreased cure time could inhibit the flow of monomer into the finer and deeper cracks, since the penetration potential of the system is limited to the time that it is a low viscosity liquid.

4.3.2.2 Results

After the monomer had cured, the specimens were sawed perpendicular to the length of the cracks. Slices of the cracked cross section permitted the determination of the percentage of crack length filled by the polymer. It was observed that the polymer did not stop abruptly at any specific depth; instead, air pockets formed within the polymer thus creating a discontinous filling along the length of the crack. The percentage of crack length filled was estimated by adding the segment length of the crack filled by the polymer and dividing by the total length of the crack. The crack widths recorded in these tests refer to the widths of the crack at the surface of the slab. Table 4.7 presents the results and Fig. 4.8 provides a graphical representation of the data.

It can be observed that the percentage of crack length filled by the monomer increased with increasing crack widths. Moreover, in most cases, even for the smaller crack widths, a minimum of 80 percent of the crack length was filled. This indicates that, although the penetration potential of the monomer is directly related to the crack the majority of the depth of even very narrow cracks can be filled under dry and clean conditions.

The performance of the monomer seemed to be slightly affected by the hot conditions at the time of application. This effect was more significant in the case of specimens with smaller crack widths. In all the cases, however, a minimum of 85 percent of the crack length was filled.

4.3.3 Recracking Strength

4.3.3.1 Testing Procedure

Specimens were prepared and cracked to produce a range of crack widths. The monomer system was then burshed onto the slabs and allowed to cure. Specimens were then recracked under the same center point loading arrangement used for the initial cracking. The recracking loads were recorded and initial cracking and recracking stresses were calculated for each specimen. Results are presented in Table 4.8 and represented graphically in Fig. 4.9. The specimens were then sliced perpendicular to the crack. These observations are recorded in Table 4.9; typical cracking patterns are shown in Fig. 4.3.

4.3.3.2 Results

Even though the average ratio of recracking stress to initial cracking stress was 0.91, only two of the second cracks were even partially inside the original cracks. The lower recracking stress apparently was due to microcracking caused by the first loading which served as a plane of weakness duing the second loading.

The ratio of the recracking stress to the initial cracking stress for each specimen was plotted against the corresponding crack widths in order to determine if any correlation existed between these values (Fig. 4.10). The plot shows that considerable scatter exists in the data and that no strong conclusion can be drawn. Nearly all the ratios, however, ranged between 75 and 100 percent so it could be safely assumed that in general the ratio of the recracking to the initial cracking stress would fall between these values.

Table 4.7 Percentage of Crack Length Filled by Polymer System Using Monomer 1100

Specimen	Crack Width (mm)	Depth of Crack (in.)	Percent of Crack Depth Full
1	0.60	4.0	98
2*	0.35	3-7/8	85
3	1.40	4-1/8	92
4	0.25	4-5/8	98
5	0.50	4-1/2	85
6	0.40	4-3/8	50
7	1.0	4-1/2	98
8	0.65	4-1/2	98
9	1.80	4-1/2	100
10*	1.0	4.0	90
11*	2.0	5.0	100
12*	0.5	4-1/4	97

* Applied outside under Hot Conditions

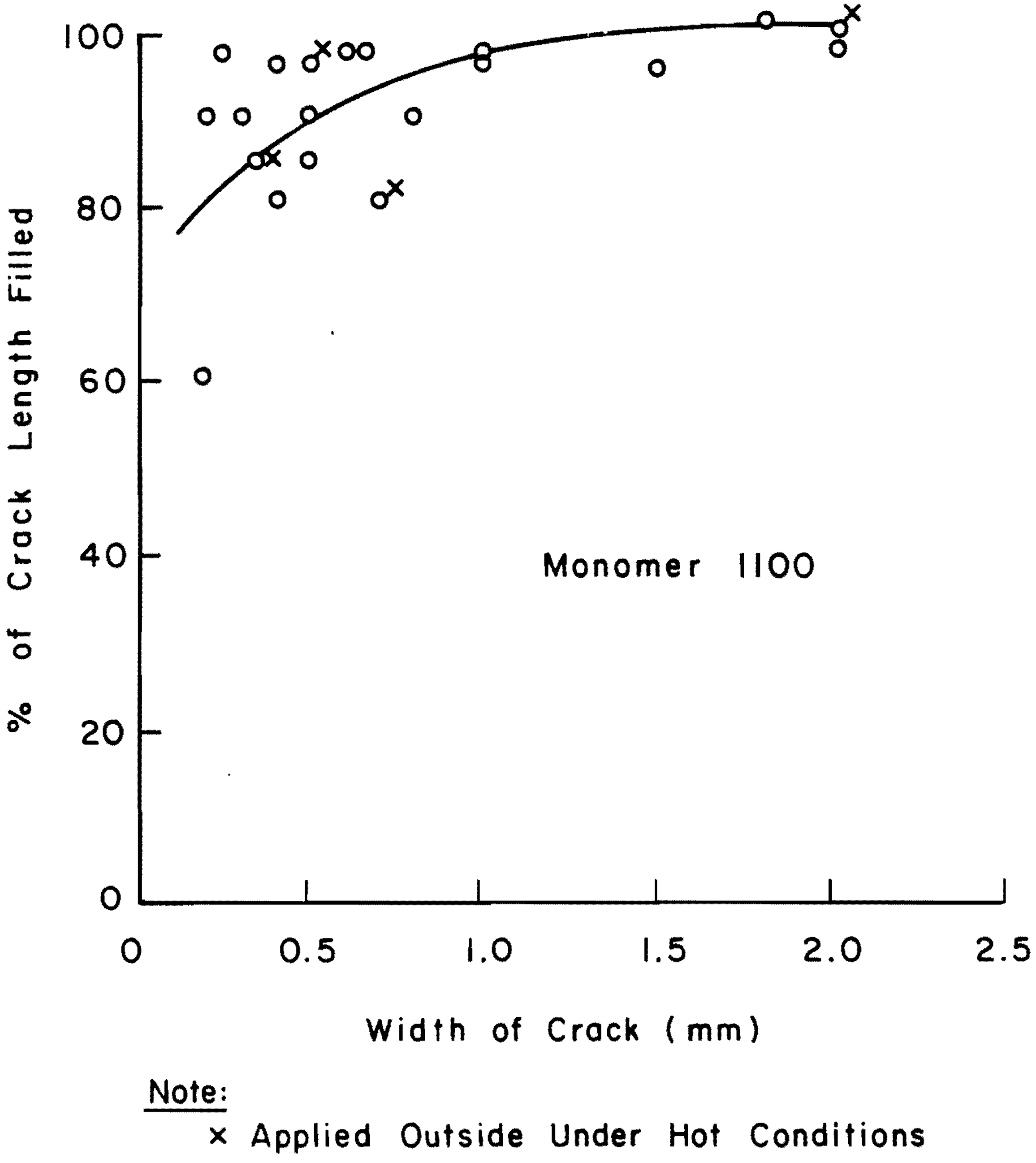


Fig. 4.8 Width of Crack vs. Percentage of Crack Length Filled

Table 4.8 Initial and Recracking Stresses

Specimen	Crack Width (mm)	Percent of Crack Depth Full	Initial Cracking (ksi)	Recracking Stress (ksi)	Recracking Stress / Initial Cracking Stress
1	0.60	98	0.401	0.345	0.86
2*	0.35	85	0.297	0.234	0.79
3	1.40	92	0.277	0.355	1.28
4	0.25	98	0.347	0.341	0.98
5	0.50	85	0.330	0.251	0.76
6	0.40	50	0.287	0.281	0.98
7	1.0	98	0.261	0.261	1.0
8	0.65	98	0.467	0.375	0.80
9*	1.0	90	0.310	0.274	0.89
10*	2.0	100	0.390	0.285	0.73
					Avg. = 0.91

* Applied Under Hot Conditions

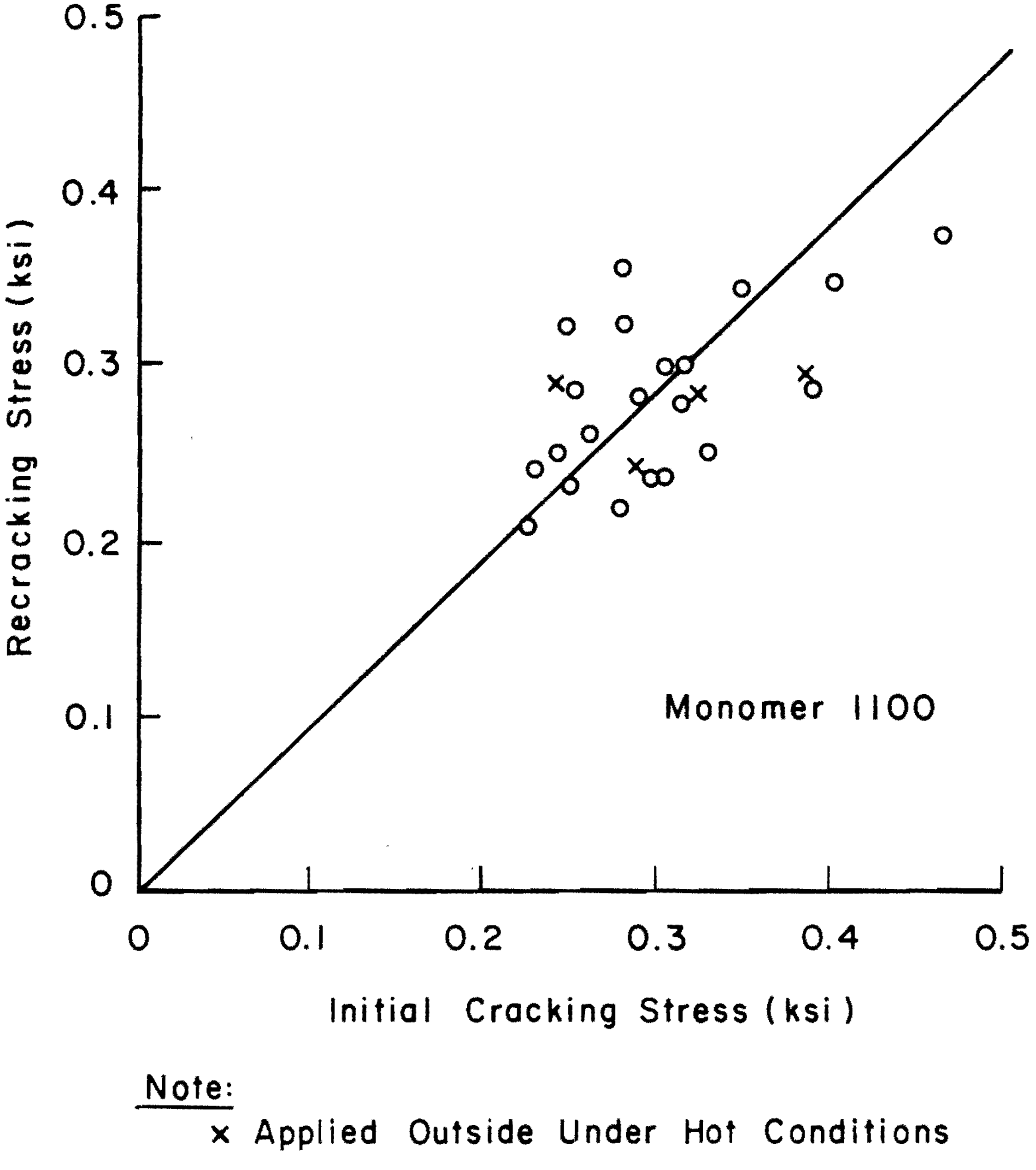


Fig. 4.9 Recracking Stress vs. Initial Cracking Stress

Table 4.9 Location of Recracking Crack

Specimen	Crack Width (mm)	Recracking Stress Initial Cracking Stress	Position of Recracking Crack in Relation to Original Crack *
1	0.60	0.86	Parallel
2	0.35	0.79	Parallel
3	1.40	1.28	Mostly Parallel
4	0.25	0.98	Parallel
5	0.50	0.76	Partially Inside
6	0.40	0.98	Parallel
7	1.0	1.0	Mostly Parallel
8	0.65	0.80	Parallel
9	1.0	0.89	Partially Inside
10	2.0	0.73	Parallel

* Fig. 7 illustrates terms

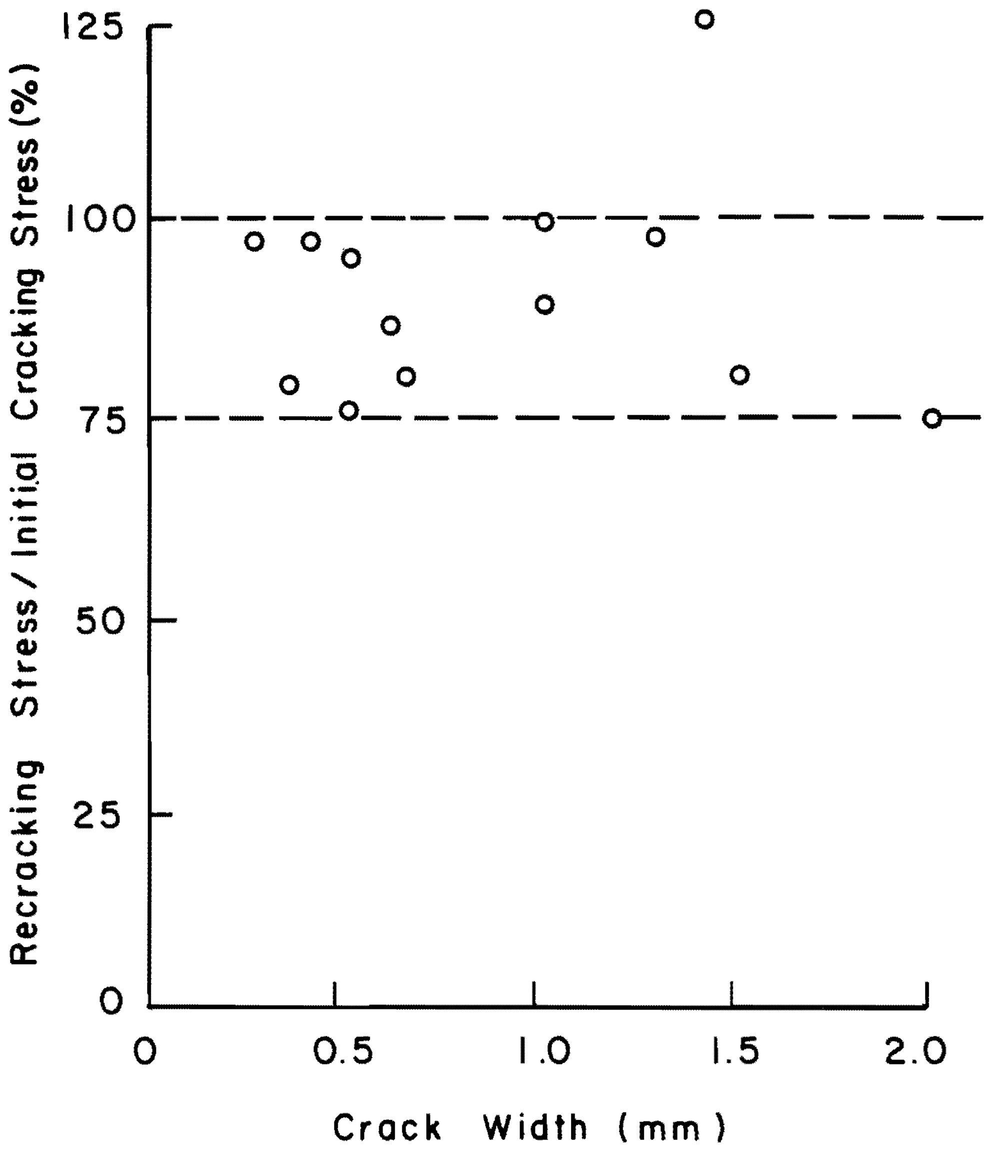


Fig. 4.10 Ratio of Recracking Stress to Initial Cracking Stress vs. Crack Width

Although there is a significant variation in the ratio of recracking stress to initial cracking stress, it is evident from the results of this test that the monomer system significantly restored structural integrity and strength to the cracked slabs.

4.3.4 Effect of Moisture

In the initial test program it was found that moisture in the concrete significantly affected the ability of the monomer to fill the crack completely (section 4.2.4). Additional slabs were cracked, saturated, and permitted to dry varying lengths of time before monomer application.

4.3.4.1 Test Procedure

Five reinforced slabs were prepared and cracked as described in 4.3.1. The specimens were placed in a moist chamber for approximately a month. The slabs were taken immediately outside and permitted to dry in direct sunlight. The temperature ranged from the mid-70s at night to the high 90s during the day. Relative humidity ranged from 50 to 75 percent.

In order to examine the effects of varying size of cracks, each specimen contained a different crack width, ranging from small (0.25 mm) to large (1.3 mm) cracks. The specimens were brought inside and brushed with monomer after drying times of 4 hours, 6 hours, 12 hours, 1 day, and 1-1/2 days. After curing for at least 24 hours, the specimens were sawed into thin sections to permit the percentage of crack length filled to be determined.

4.3.4.2 Results

Table 4.10 gives the results of the percentage of the crack length filled. The results were surprisingly good. Even after only 4 hours of drying, the specimen with a crack width of 0.45 mm was filled to 85 percent of its crack length. The specimen with the smallest crack width, 0.25 mm, was 94 percent filled after only 12 hours drying. To eliminate the effect of crack width so that the effect drying time could be determined, the percent filled values for the wet slabs were divided by the percent filled values for the same crack width for dry slabs (Fig. 4.8). The results are shown in Table 4.10 and Fig. 4.11.

Table 4.10 Results of Drying Tests

Crack Width (mm)	Expected Percented Full (from Table 7.1)	Actual Percent Full	Drying Time (days)	$\frac{\text{Actual Percent Full}}{\text{Expected Percent Full}}$
0.25	98	94	1/2	96
0.35	85	80	1/4	94
0.45	85	85	1/6	100
0.65	98	94	1-1/2	96
1.30	95	94	1	99

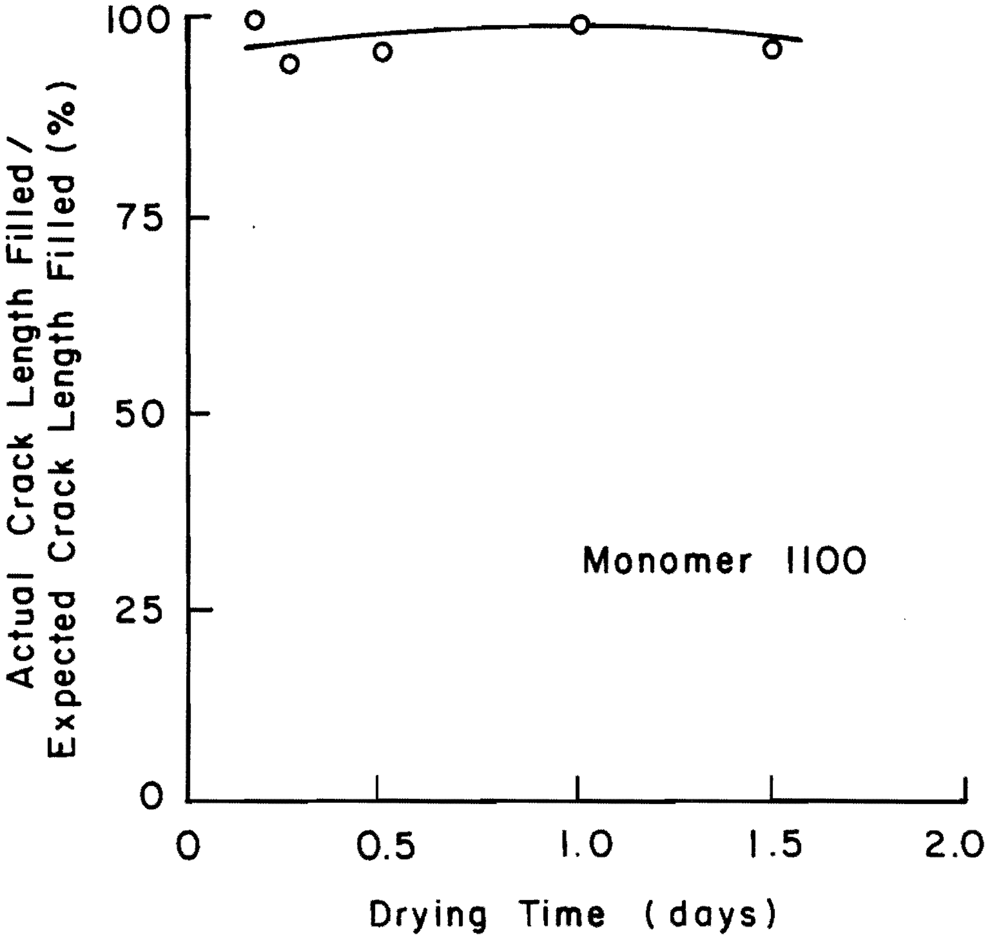


Fig. 4.11 Ratio of Actual Crack Length Filled to Expected Crack Length Filled vs. Drying Time for Small to Medium Size Cracks.

Figure 4.11 indicates that the drying time was less significant than for the slabs tested in the initial study (Fig. 4.7). It does appear that a drying time of 24 to 48 hours would be adequate to achieve good crack sealing.

4.3.5 Spray Application

Four additional cracked slabs were sprayed as described in section 4.2.5. Two slabs were positioned in a vertical orientation and two in a horizontal orientation with the crack on the underside. The crack widths varied from 0.35 mm to 1.0 mm. The results (Table 4.11) were very similar to those given in section 4.2.5. No penetration was observed in the vertical slabs. The greatest penetration (0.75 in.) was found for the slab with the smallest crack width when sprayed overhead. The precautions given in section 4.2.5.1 should be observed.

4.4 Summary of Laboratory Study

Several important findings resulted from the laboratory study:

1. Cracks in dry concrete as narrow as 0.2 mm can be successfully filled to 80 percent or more of their depth.
2. Cracks in wet concrete slabs which has dried for 24 hours can be filled to 50 percent or more of their depth.
3. Excellent bond to the concrete is obtained. The recracked specimens nearly always fail outside the repaired zone.

Chapter 5
Crack-Repair Field Studies

5.1 Introduction

The previous chapters describe laboratory evaluations of polymer repair methods and materials. This chapter describes field tests performed in several areas of the state tests (6, 7).

5.2 Repair Procedures

This chapter is primarily concerned with field applications of high molecualr weight methacrylate (HMWM). Polymer concrete (PC) crack repairs are discussed in Chapter 2. It was noted that field work was not done as part of this research study, but, since the method has been found to be successful for repairing cracks in pavements, the repair procedures, performance and cost are discussed in Chapter 2.

Epoxy injection laboratory studies were performed, but only limited field tests were conducted since (1) the procedures are well understood, having been in use for many years and (2) the HMWM proved to be preferable due to its much greater simplicity of application and lower cost.

5.3 Field Tests

5.3.1 McLean, Texas Field Study

5.3.1.1 Introduction

This crack repair field study was performed on April 11, 1984, on the eastbound bridge on I-40 in McLean. The bridge deck, which had not been opened to traffic, had exhibited plastic shrinkage cracking. The resulting cracks ranged in size from 1/32 in. (0.8 mm) to 1/16 in. (1.6 mm) in width and from 1.5 ft (.5 m) to 6.1 ft (2 m) in length (Fig. 5.1). Two methods of crack filling were tested. The Monomer 400 system was applied to three areas of the bridge. Two other cracks were filled by epoxy injection. It should be noted that it had rained lightly on the previous day and the cracks were still noticeably moist at the time of the study.

5.3.1.2 Monomer Application

An attempt was made to dry out one of three sections to which Monomer 400 was applied by means of a butane burner (Fig. 5.2). However, the high winds present made it very difficult to keep the flame directly over the cracks. Therefore, this drying method did not prove to be very effective. Two applications of monomer were made to one of the remaining two sections and only one coat was applied to the other section.

Monomer 400 was mixed with benzoyl peroxide and cobalt napthanate at the site and then poured directly onto the surface. It was then spread over the surface with a squeegee (Fig. 5.3) and further pushed into the cracks with a paint brush.

The cracks appeared to remain saturated with the monomer. This was very different than what was usually experienced with laboratory specimens, in which the surface level of the monomer in the crack recessed over a period of time. This lowering of the surface level suggests continuing penetration of the monomer into the finer portions of the cracks. Since the cracks on the bridge deck remained full of monomer, a second application of monomer appeared to have no effect on the amount of penetration of the monomer.

5.3.1.3 Results of Monomer Application

Cores were taken from each of the three test areas. These cores were sliced perpendicular to the length of the crack and examined through the use of a binocular microscope and then under ultraviolet light. Examination of the slices revealed that a great deal of silt had accumulated in the crack just beneath the surface of the slab. This moist silt apparently blocked the penetration of the monomer into the crack. No polymer could be seen by the naked eye below this line of silt. However, under the microscope, polymer could be seen coating the walls of the crack periodically along its depth. These traces of polymer were highlighted when the slices were placed under ultraviolet light.

Cores from the three different test sections did not exhibit significant differences in amount of penetration of the monomer.

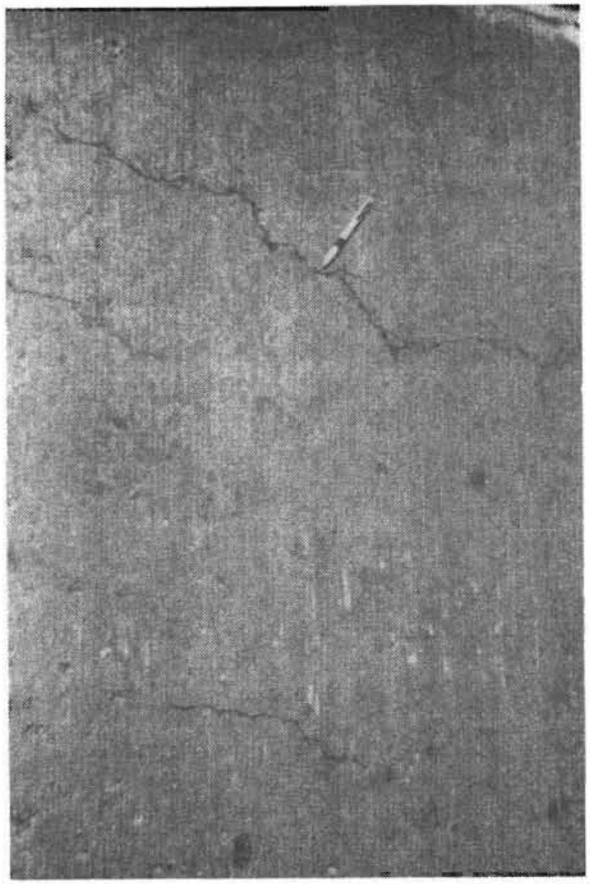


Fig. 5.1 Typical Cracks

Fig. 5.2 Drying The Cracks

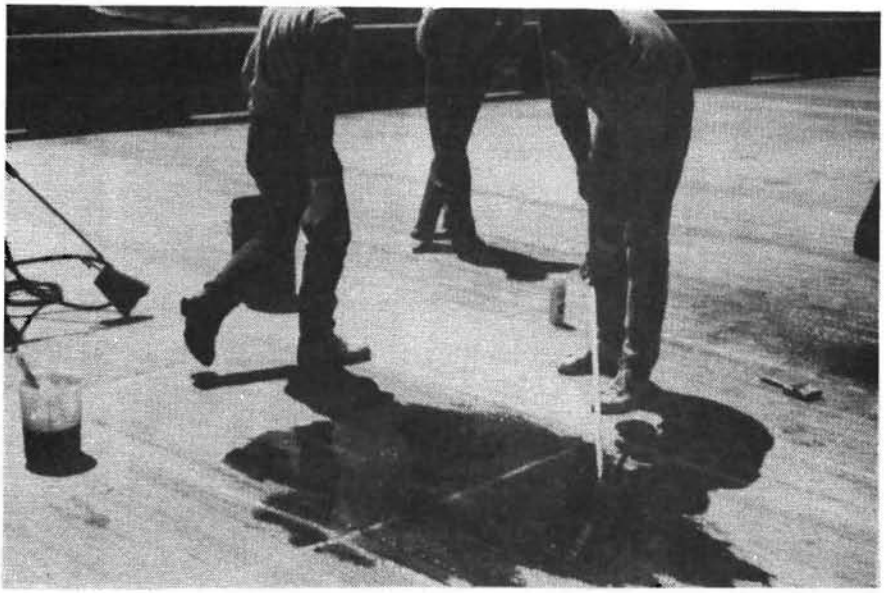


Fig. 5.3 Monomer Application

5.3.1.4 Epoxy Injection

Epoxy injection was performed on two of the longer cracks in the bridge deck. Due to the large number and the typically short length of the cracks, epoxy injection did not appear to be the optimum method for sealing the bridge since each crack would have to be injected individually. However, these two cracks were sealed by epoxy injection in order to investigate the injection procedure and to see how much of the crack depth the epoxy would fill.

Holes were drilled, 1/2 in. (1 cm) in diameter, at each end of one of the cracks (Fig. 5.4). Injection ports, as shown in Fig. 5.5, were to be placed in the holes for the injection process. However, since it is necessary to vacuum out the concrete dust from the holes in order to successfully perform this type of injection, and no vacuum was available on the job site, an alternate, less preferred, method of injection was used.

This procedure involved the use of surface ports instead of drilled ports. These ports were placed directly on top of the crack and held in place by lightly hammering a nail through the port into the surface at each end of the crack (Fig. 5.6). A putty material was then prepared and applied over the tabs which extended from the bottom of the ports. This material was also applied to the surface of the crack between the ports (Fig. 5.7). When cured, the putty became very hard and held the ports in place and also prevented the epoxy from escaping from the top of the crack during the injection process.

The epoxy used was a two-component epoxy supplied by Rocky Mountain Chemical Company (now known as Rescon). The application machine, supplied by the same company, mixed the two-component system in the correct proportion and then injected it under pressure provided by an air compressor.

The cracks prepared for injection are shown in Fig. 5.8 . In order to fill a crack by epoxy injection, a tube extending from the application machine was placed over one of the two surface ports. The epoxy was then injected into the crack under a recommended pressure of 25 psi until the epoxy began to flow out of the second port (Fig. 5.9). At this point, the portion of the crack between the two ports was full. These particular cracks required 30 minutes of injection at each port to fill.

Fig. 5.4 Drilling for Epoxy Injection

Fig. 5.5 Drilled Injection Ports

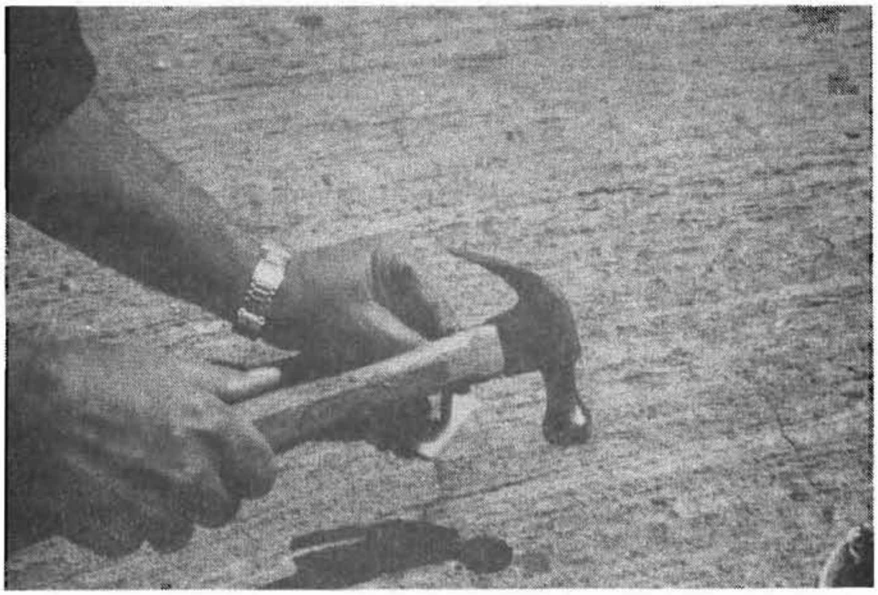


Fig. 5.6 Securing the Surface Port

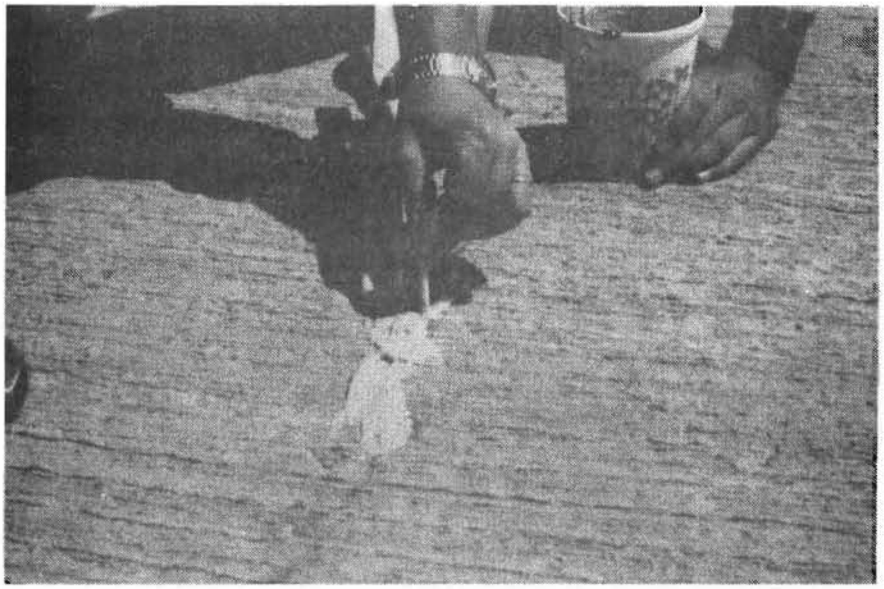


Fig. 5.7 Applying Putty to the Port and Cracks's Surface

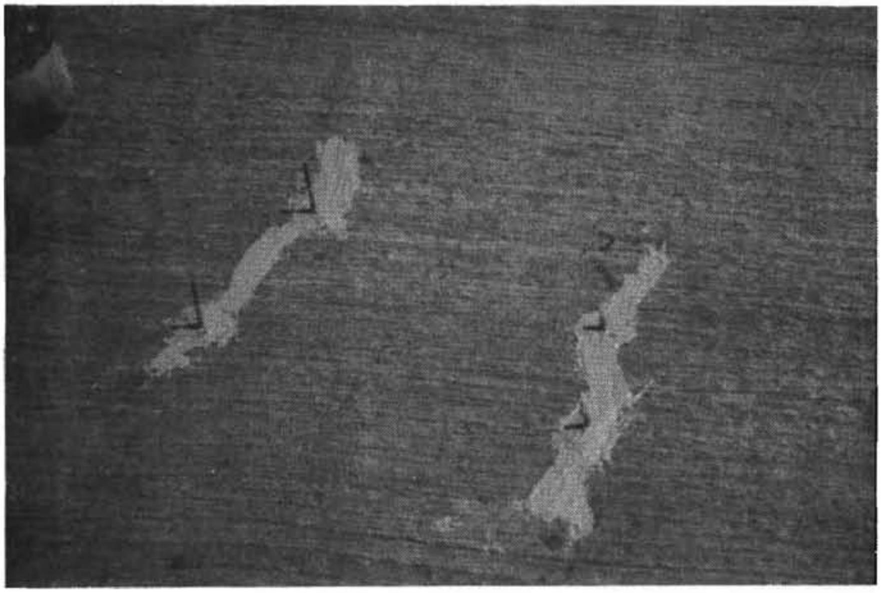


Fig. 5.8 Cracks Prepared for Epoxy Injection

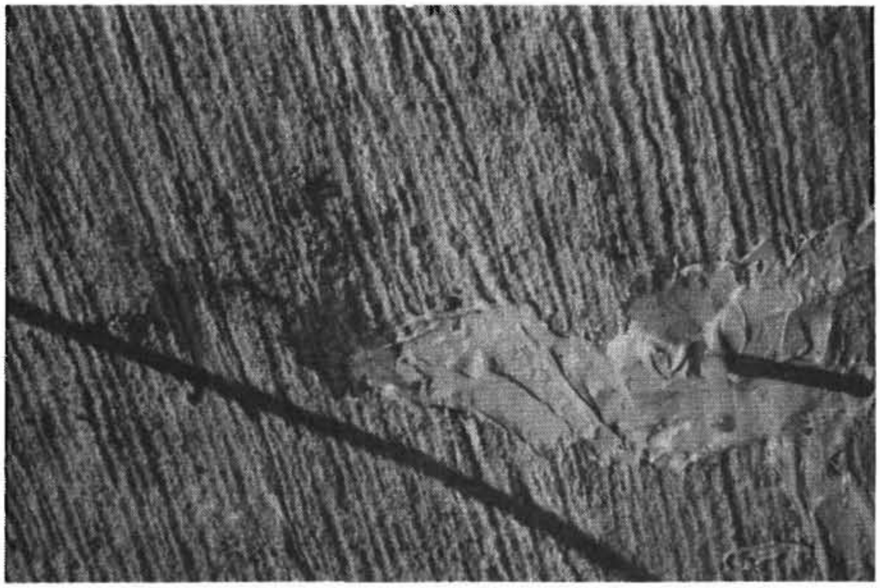


Fig. 5.9 Epoxy Flowing From Full Crack

5.3.1.5 Epoxy Results

One core was taken immediately after the injection and pulled apart at the crack before the epoxy had set. The epoxy appeared to have penetrated the entire 4-in. (10-cm) depth of the crack. Other cores were later taken. Slices were made from these cores and examined as previously described for those treated with the monomer. These slices showed a very small amount of void space in the epoxy. It had apparently penetrated the entire depth of the core.

5.3.1.6 Conclusions

The poor performance of the monomer system could probably be attributed to the damp silt in the crack. Although the results of the epoxy injection were very favorable, it would have taken an enormous amount of time to fill the number of cracks on the bridge using this process.

5.3.2 Fort Worth, Texas Field Study

5.3.2.1 Introduction

This field test was performed on the deck of the I-20 overpass bridge, over I-30, west of Fort Worth in Parker County. The concrete slab, which was supported by continuous steel plate girders, experienced random cracking due to plastic shrinkage of the concrete. This study was performed on June 20, 1984. Several days of dry weather preceded the day on which the study was performed. However, to ensure that the cracks were dry at the time of filler application, tape had been placed over the cracks several days before the study. The tape also served to keep dirt and debris out of the cracks. Both epoxy injection and monomer application were performed on these cracks.

5.3.2.2 Monomer Application

The Monomer 200 system was used to fill two of the cracks. It was poured into one and injected into the second. The Monomer 200 system was prepared at the site and then poured into the first crack. A broom was then used to sweep the excess material toward the crack in order to keep it full as the monomer penetrated into the crack.

The monomer was also injected into a second crack. The crack preparation procedure used was similar to the one used for the epoxy injection in the McLean, Texas, field study described in section 5.3.1.4. Two 1/8-in. (0.3-cm) ID plastic injection ports were set over the crack at a spacing of about 8 in. (20 cm). Polyester putty was then applied to the ports and over the crack extending between the ports. An airless, electric sprayer (Fig. 5.10) was used to inject the monomer under a pressure of 25 psi. The monomer flowed from the sprayer through a tube, fitted over the injection ports, directly into the crack (Fig. 5.11). Only three to five seconds were required for the monomer to flow out of the adjacent port.

5.3.2.3 Epoxy Injection

Epoxy injection was performed on a third crack. This crack was prepared in the same manner as the crack described for the monomer injection. As in the McLean, Texas, field study, a two-component epoxy supplied by Rocky Mountain Chemical Company was used. The injection machine, also supplied by Rocky Mountain Chemical Company, is shown in Fig. 5.12. The two components of the epoxy were mixed in the proper proportions in the tube through which it was injected. As can be seen in Fig. 5.13 the injection was accomplished by simply placing the tube containing the mixed epoxy over the injection ports. As with the monomer injection, the epoxy was injected under a pressure of 25 psi.

The epoxy was injected through the port until the material flowed out of the adjacent port. The epoxy injection process also took only three to five seconds.

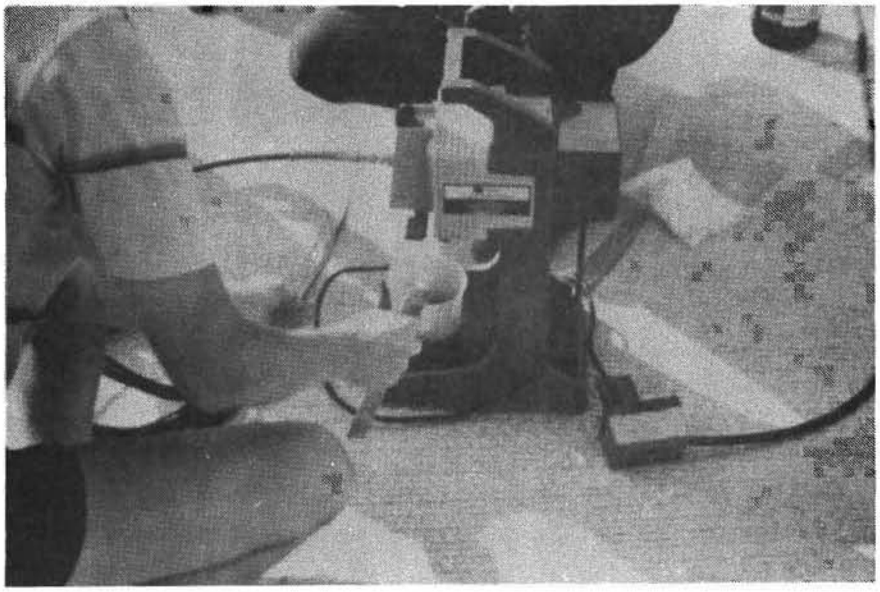


Fig. 5.10 Sprayer Used for Monomer Injection

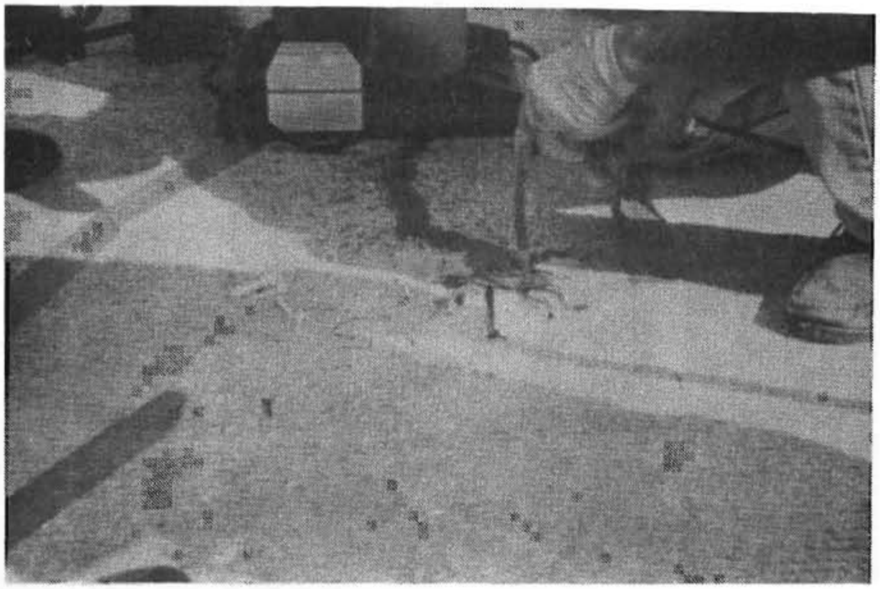


Fig. 5.11 Monomer Injection

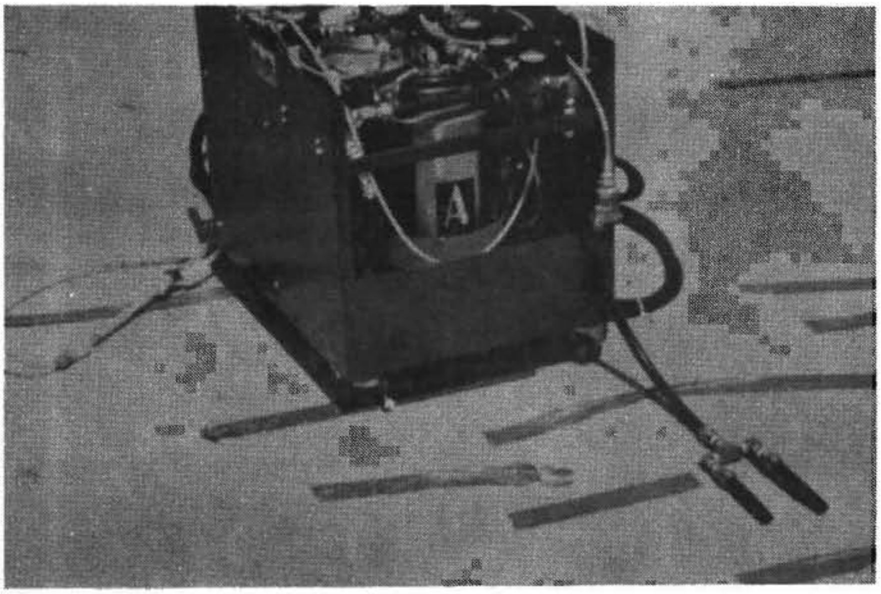


Fig. 5.12 Apparatus for Epoxy Injection

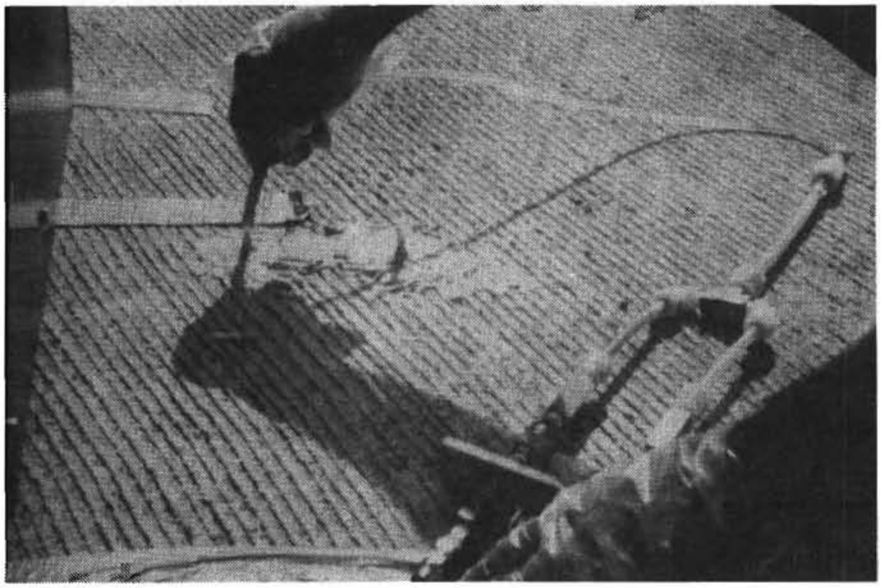


Fig. 5.13 Epoxy Injection

5.3.2.4 Results

Two days after the cracks were filled, several cores were taken, including one core from each of the three cracks filled by the various methods. These cores were sliced perpendicular to the direction of the crack in order to approximate the percentage of the crack full and the depth of penetration of the sealants into the crack.

The width of the cracks in the cores, measured at the slab surface, ranged from 0.04 to 0.05 in. (0.95 to 1.3 mm). Compared to the typical crack widths experienced in the field studies, these widths could be considered average to large. The depth of the cracks ranged from 5-1/8 to 8-1/4 in. (13 to 21 cm). On the average, 95 percent of the crack volume was filled and from 90 to 97 percent of its depth was filled. These observations are summarized in Table 5.1.

It was observed that in the core injected with the epoxy, the portion of the crack which was not filled was located at the bottom of the crack. Also, toward the center of the core, voids existed in the epoxy. The crack into which the monomer was poured and filled all the way to the bottom except for a couple of air pockets in the lower half of the cores. The core containing the crack which was injected with monomer had a void space at the very top of the crack, directly underneath the putty. The bottom portion of the crack was completely filled. However, in some areas near the top of the cores, the polymer just coated the walls of the crack. Cross-sections of these three cores are shown in Figs. 5.14, 5.15, and 5.16.

5.3.2.5 Conclusions

Both the monomer and epoxy effectively sealed the cracks, thereby preventing the intrusion of water. In each case almost the entire depth of the crack was completely filled, except for a few isolated areas. The success of each application could probably by attributed to the cleanness and dryness of the cracks. The monomer pour method was selected for treating the entire bridge due to its simplicity and low cost. Only the cracks were treated.

Table 5.1 Fort Worth Results

Core No.	1	2	3
Sealant	Epoxy	Monomer 200	Monomer 200
Type of Application	Injection	Pour	Injection
Crack Width at Top (mm)	1.30	0.95	1.10
Depth of Crack (in.)	6-1/2	8-1/4	5-1/8
Percent of Crack Filled	95	95	95
Percent of Depth Filled	90	92	97

Fig. 5.14 Epoxy Injection Core

Fig. 5.15 Monomer Pour Core

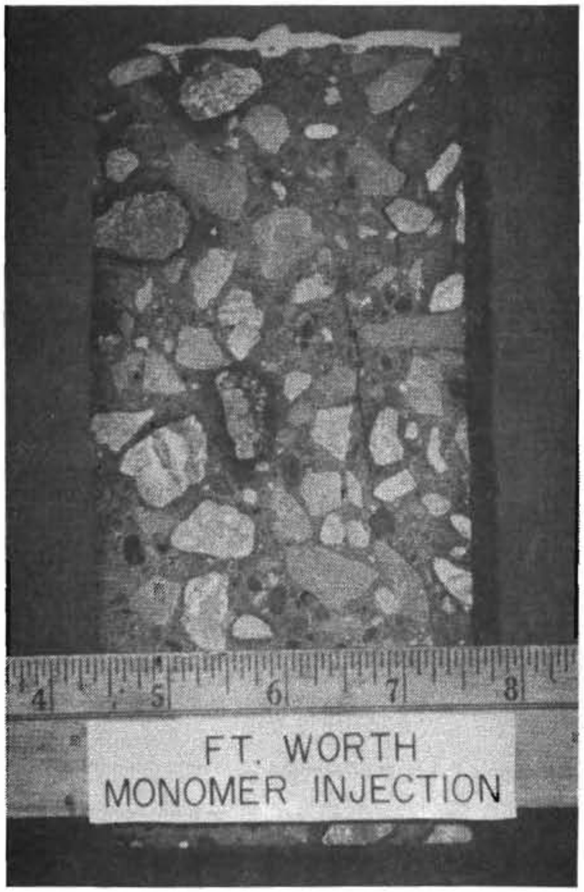


Fig. 5.16 Monomer Injection Core

5.3.3 Corpus Christi, Texas Field Study

5.3.3.1 Introduction

This field study was performed on the deck of the Corpus Christi Harbor Bridge (US 181). The lightweight aggregate concrete bridge deck had developed random cracking and spalling, thought to have been caused by the screeding procedure used at the time of concrete placement. The study was performed on July 26, 1984. Three different HMWM systems were applied to test sections: Monomer 200, Monomer 1100, and Monomer 1300. The widths of the cracks were noticeably larger than the widths encountered in previous field studies (Fig. 5.17). These cracks ranged in width from 0.08 to 0.2 in. (2 to 6 mm). It was thought that the larger widths would facilitate the pouring method of monomer application. Therefore, this was the only application method used.

5.3.3.2 Monomer Application

Each of the three monomer systems was mixed on the site and then poured directly onto the slab. A broom was then used to sweep the excess material towards the cracks in order to keep them full. One of the sections was sandblasted before it was filled.

A pot hole was also repaired by placing layers of sand in the hole and saturating each layer of the sand with Monomer 200, thereby forming polymer concrete.

5.3.3.3 Results

The day after the study was performed, six cores were taken from the various areas of monomer application. A core was also taken at the edge of the treated pothole patch.

This bridge was built more than 25 years ago. Cracking, reportedly, had occurred soon after its slab was poured. As could be expected, over the years a large amount of debris, including salt, had accumulated in the crack. The penetration of debris into the cracks was facilitated by the large width of the cracks at the slab surface. Examination of the sliced cores revealed debris in large amounts near the slab surface.

Fig. 5.17 Typical Cracks

Examination of the cross-sections of these cores also reveled the surprising fact that the depths of the cracks were sometimes smaller than their widths at the surface. The width of the cracks decreased very rapidly from the top to the bottom of the crack (Figs. 5.18 and 5.19). Obsevations of the cores filled with the three different monomer systems are recorded in Tables 5.2 and 5.3. The core taken from the pothole which was patched displayed good bond between the existing concrete and the new polymer concrete. Also, as shown in Fig. 5.20, some of the monomer flowed through the sand and into the crack extending below the spall, thereby sealing the crack.

5.3.3.4 Conclusions

The monomer did not penetrate the entire depth of the crack. This appeared to be due to the debris in the crack and the small width of many of the cracks below the surface. Therefore, the monomer did not restore complete structural integrity to the slab. It did, however, seal the cracks at the slab surface.

5.3.4 Monahans, Texas Field Study

5.3.4.1 Introduction

A crack repair field study was performed on the Westbound I-20 overpass bridge deck over Texas Park Road 41, five miles east of Monahans.

The four-year-old bridge deck carries the two westbound lanes. The bridge is 160 ft. long with three prestressed concrete girder spans (40 ft-80 ft., and 40 ft.) and a 7.5-in.-thick deck slab. The girders are simply supported and the slab is continuous over the interior bents. The overall width of the bridge is 44 ft and the clear roadway width is 42 ft. Internally sealed concrete was used in the construction of the bridge deck. Internally sealed concrete is a portland cement concrete in which a small portion of the aggregate is repalced with an equal amount of small spherical particles of wax. After the concrete has hardened, the deck is heated to a temperature of approximately 185 degree F, which causes the wax to melt and flow into the pores and capillaries of the concrete. Upon removal of the heat, the wax solidifies and the capillary network becomes a discontinuous, closed system that effectively blocks the penetration of water and chlorides.

Fig. 5.18 Top View of Core

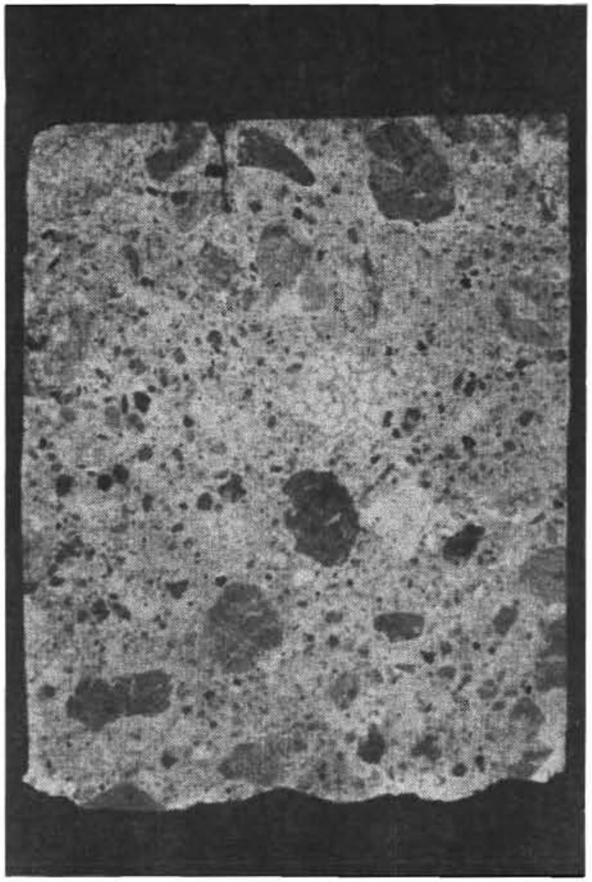


Fig. 5.19 Cross Section of Core

Table 5.2 Corpus Christi Core Descriptions

Core No.	1	2	3	4	5	6
Monomer	1300	1300	1100	1100	200	200
Special Preparation	None	None	None	None	Sand-blasted	None
Width of Crack Surface (mm)	2.0	3.0	2.0	2.0	6.0	4.0
Depth of Crack (cm)	3.8	12.5	13.0	13.0	2.9	4.0

Table 5.3 Corpus Christi Results

Core No.	1	2	3	4	5	6
Depth of Crack Completely Filled (cm)	0.9	1.6	0.6	1.9	2.5	1.9
Percent of Depth Completely Filled	23.7	12.8	60.0	14.6	86.2	47.5
Depth to Which Traces of Monomer Could Be Seen (cm)	2.5	3.2	0.6	1.9	2.5	2.4
Percent of Depth That Traces of Monomer Could Be Seen	65.8	28.0	60.0	14.6	86.2	60.0
Width of Crack at Bottom of Completely Filled Segment of Crack (mm)	0.2	0.4	Hairline	0.6	Hairline	0.2

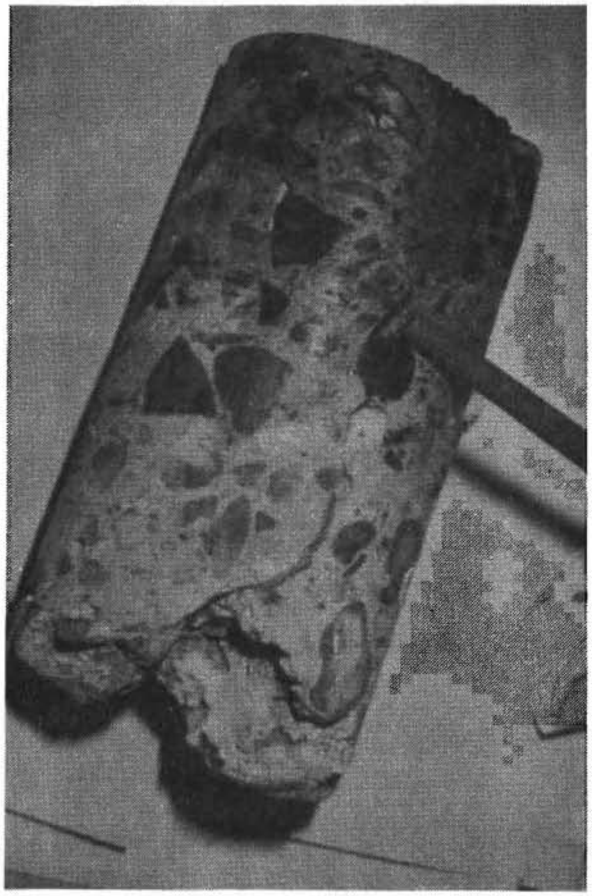


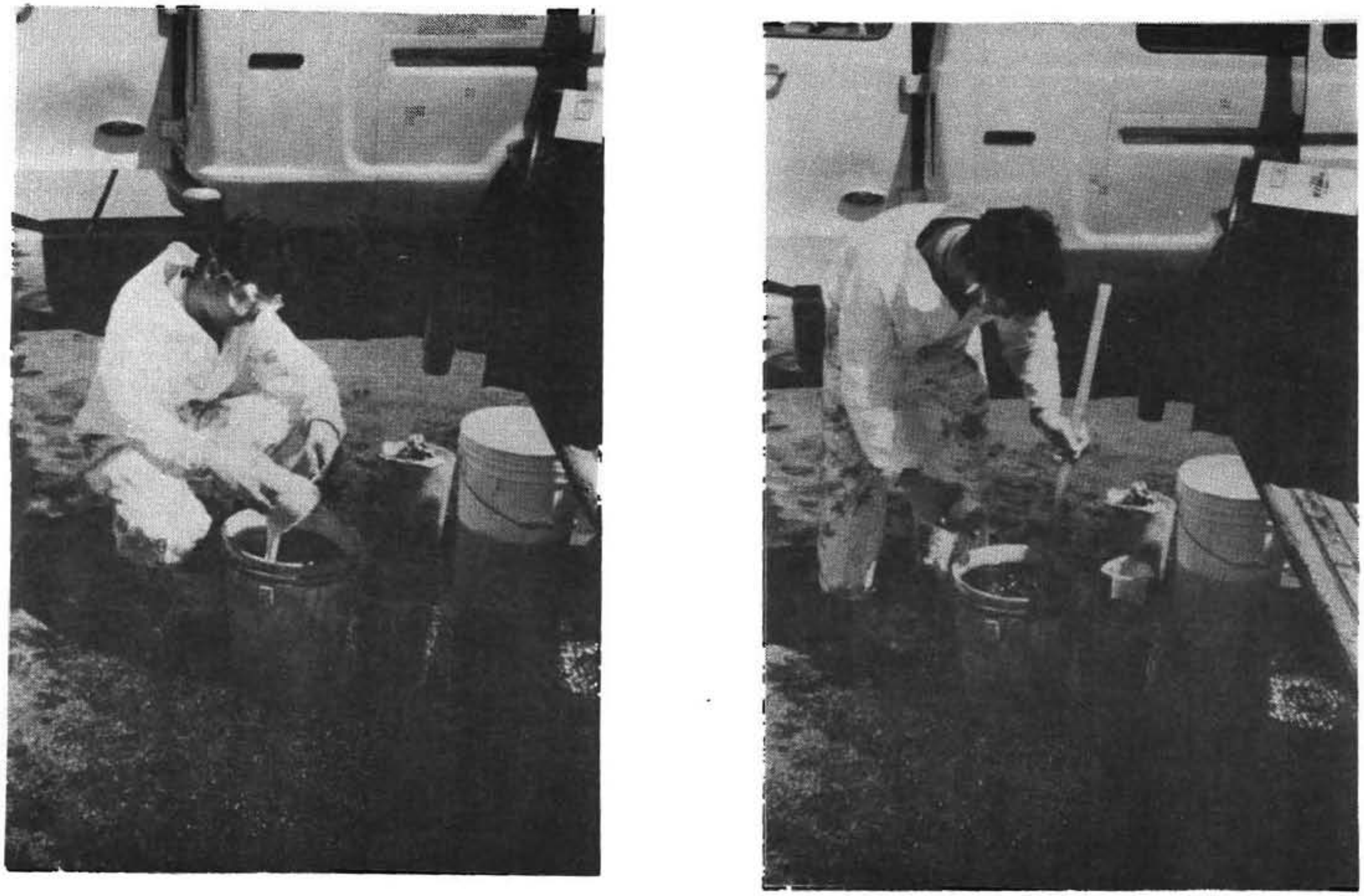
Fig. 5.20 Core from Repaired Pot Hole

The internally sealed, normal weight concrete bridge deck experienced random cracking, probably caused by the high temperature used to melt the wax. District personnel reported that water leaked through the deck during rainy weather, and a visual inspection of the underside of the deck indicated extensive cracking through which water had penetrated. The following sections describe the technique and materials used to treat and seal the entire deck and summarize the results obtained.

5.3.4.2 Application of Material

This field study was performed on July 7, 1985. Several days of hot, dry weather preceded the day on which the study was performed. The Monomer 1100 system was used to fill the cracks. The formulation used is described in Table 4.1. The three materials were mixed at the site (Figs. 5.21 and 5.22) and then poured directly onto the slab (Fig. 5.23). Before application of the sealant, the deck was swept with brooms. The entire deck as well as the east approach slab was sealed. The materials were mixed and poured onto the deck. Push brooms and squeeges were then used to sweep the excess material towards the cracks in order to keep them filled (Fig. 5.24). At the beginning of the application the temperature on the surface of the deck was about 100 degrees F. Because of the high temperature the material at first cured very quickly, thus giving little time to work it into the cracks. Fourteen-and-a-half batches of 5 gallons each, a total of 72.5 gallons, were used to seal both the deck and the approach slab. The coverage rate for the bridge deck and approach slab was about 106 sq. ft/ gal. At current prices, the cost of the monomer system would be about $0.35/ sq. ft.

In order to provide more time to work with the material, an extender was added to the mix. This extender, provided by Rohm and Haas personnel, decreased the curing rate of the monomer system. The extender was used from the fifth batch on. Unfortunately, the temperature of the deck kept increasing (up to about 120 degree F within an hour after the application was begun), which in turn accelerated the rate of curing of the material. Thus, even with the added extender, not much time was available to work with the material. In slight depressions, the material ponded and set very quickly, creating slick spots on the deck. In order to prevent this, sand was poured on these areas, right after the monomer was poured, to restore the surface skid



Figures 5.21and 5.22 Mixing of Materials at the Site.

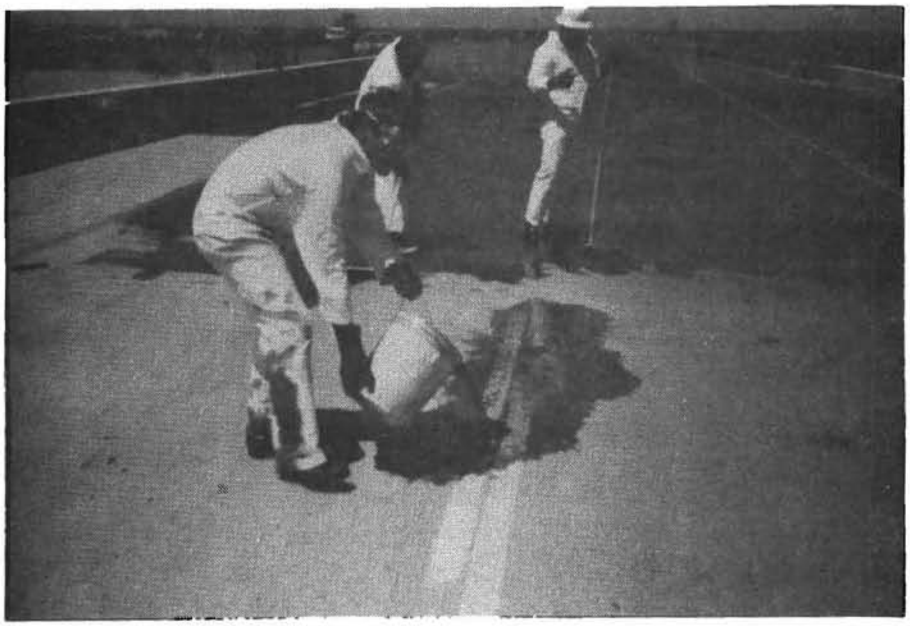


Fig. 5.23 Pouring Sealant Directly Onto the Slab.

Fig. 5.24 Sweeping Excess Material Towards the Cracks.

resistance of the concrete topping (Fig. 5.25). The work was performed between 10:30 a.m. and 1:30 p.m. Three people were involved in sealing the first half of the deck, while five people sealed the second half.

5.3.4.3 Results

A few days after the deck was sealed, two cores were taken from different sections of the deck. Figures 5.26 and 5.27 show the tops of the cores sealed by the monomer system. A large amount of debris was found in the cracks. The penetration of debris in the cracks was facilitated by the fact that the cracks were very wide at the top of the slab, ranging from 1.0 to 5.0 mm.

The two cores containing the filled cracks were sliced perpendicular to the direction of the crack in order to determine the amount and depth of the penetration of the polymer into the cracks (Fig. 5.28). In one of the cores the crack extended to a depth of 3 in., while in the other the cracks extended to the entire depth of the core. The cross-sections of the cores revealed that even though the cracks were very wide at the top of the slab, the widths of the cracks decreased very rapidly from the top to the bottom of the crack. In fact, in both cores the crack width was reduced to about 0.1 mm or less (hairline) in less than one inch of depth. The cross-sections also showed that in both cores the cracks extended into the deformed reinforcing bars and then continued underneath the rebar. In one of the cores the depth of penetration of the polymer into the cracks was 3 in., while in the other it was about one in. In the first core, penetration was stopped by the presence of the rebar in the deck; in the second core, penetration seemed to have been hindered by the presence of debris in the crack. The bridge deck surface appeared to be very slick about two hours after the monomer application was completed. However, the surface did not feel very slick. The bridge was opened to traffic by 4 p.m., and no problems were encountered with skid resistance.

Fig. 5.25 Pouring Sand Onto the Slab in order to Restore the Surface Skid Resistance of the Concrete Topping.

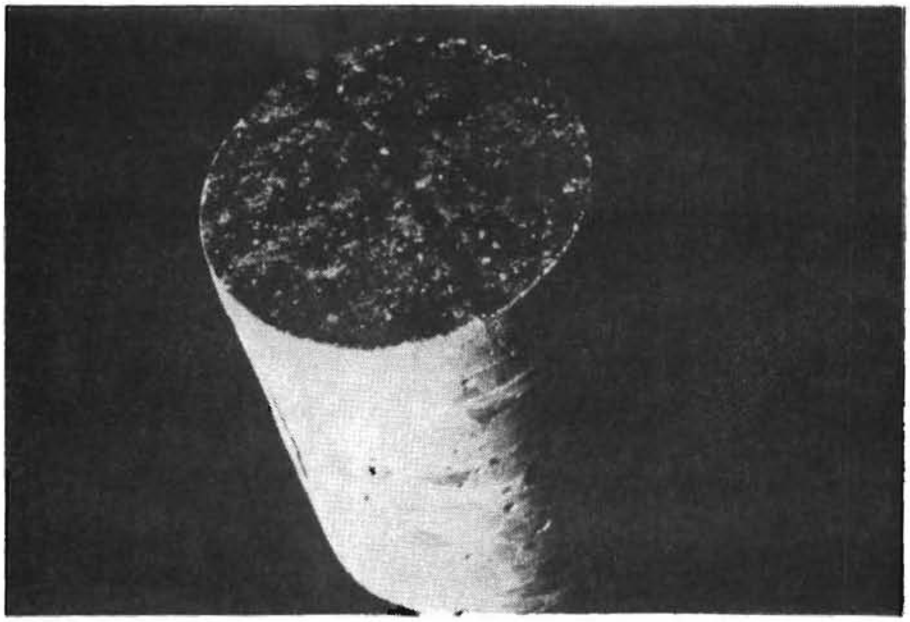


Fig. 5.26 Top of Core 1.

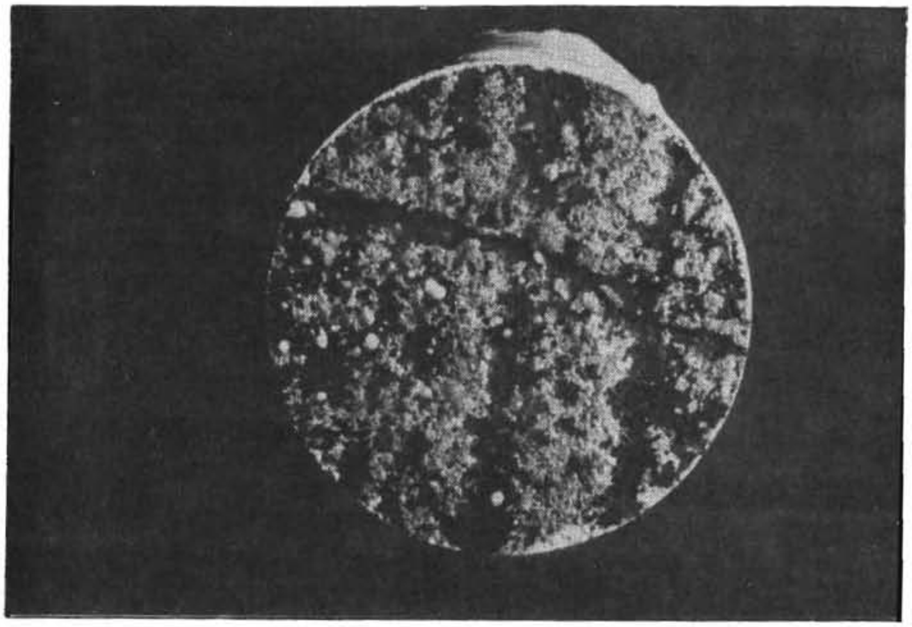


Fig. 5.27 Top of Core 2

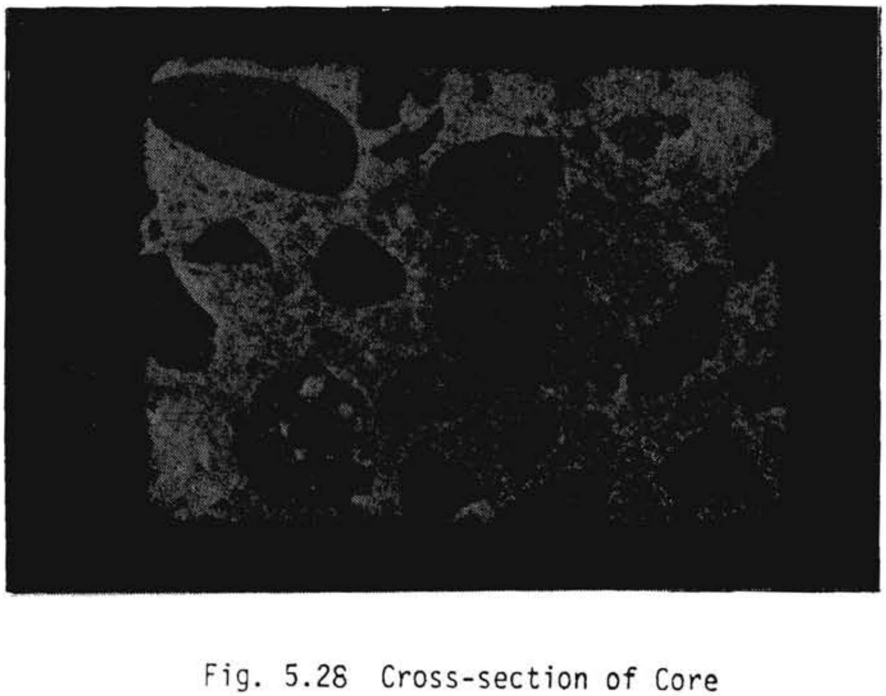


Fig. 5.28 Cross-section of Core

5.3.4.4 Conclusions

The monomer penetrated one in. in one core and 3 in. in the second core. Penetration did not extend to the full depth of the cracks, apparently due to (1) the presence of either debris in the cracks or reinforcement running through the cracks; (2) the small widths of the cracks below the surface; and/ or (3) the high temperature of the deck surface, which led to rapid curing of the material and thus a decrease in the available time for penetration. The monomer did, however, seal the cracks, which will prevent the intrusion of water.

Inspection after 15 months showed skid resistance to be good. The glazed appearance has worn off, and no water is coming through the deck. However some new cracking has developed and it is assumed that the cracking was caused by contractions and/ or flexural stresses since the old crracks have been rebonded.

5.3.5 Sweetwater, Texas Field Study

5.3.5.1 Introduction

A field study in sealing a cracked concrete bridge deck overlay with HMWM was conducted on the U. S. 70 bridge over Sweetwater Creek in Nolan County just south of Sweetwater, Texas. The bridge is 40 ft. x 221 ft. (8840 square feet), a two lane traffic surface with adjacent 8-ft. shoulders. The structure was overlaid in April 1985 with a 2-in. overlay of portland cement concrete. As significant cracking in the overlay became apparent a surface treatment for sealing the entire deck with HMWM was scheduled for August. Additionally the surface was reported as smooth so it was expected that the monomer treatment with sand would improve the friction on the deck. It should also be noted that the deck was accidentally sealed with the typical linseed oil treatment prior to the monomer treatment. The methods of application and materials involved are described in the following section.

5.3.5.2 Application of Material

After several days of dry weather the entire deck was sanblasted to remove any road film from the deck surface. The following morning, August 12, 1986, the treatment began.

The monomer system used is a new one, with reduced toxicity, which is manufactured by the Rohm and Haas Company under the name of PCR 1500 and is similar to Monomer 200. PCR 1500 is a new monomer that exhibits low toxicity. PCR 1500 uses the same formulation as Monomer 200 (Table 4.1), which allows 40 minutes working time on the deck surface (20 minutes in bulk) at an ambient temperature of 95 degrees F. The deck temperature ranged from approximately 100 degrees F at 9:30 a.m. to 110 degrees F by 1:30 p.m.

The deck was closed on one side of the centerline to allow the sealing operations to proceed, and traffic used the other half of the bridge. After the first application cured (in approximately two hours) the traffic was switched to the other side to permit sealing the second half of the deck.

The treatment consisted of hand-mixing the monomer and the catalyst and initiator in a five-gal. open top can and pouring the mixture onto the deck. Because of the quantity of cracking and because of the need to permanently seal the deck while healing the cracks, the material was moved with push brooms and squeegees. The monomer system was broomed back and forth across the cracks at short intervals to insure that the cracks were filled and that, as monomer slowly seeped deeper into the cracks, the crack would remain filled.

The squeegees helped to make sure that only a thin coating of monomer was applied to the entire deck. This was done not only to get a good application rate but to avoid ponded areas of monomer in slight surface depressions and irregularities, since ponded monomer will cure to a glossy surface with poor skid resistance. However, a good sealing job with HMWM will cure to a textured sheen which gives the false appearance of poor skid resistance. This has been noted on many bridges throughout the U. S. Although unponded monomer treatments have resulted in good skid properties, the best skid numbers are insured by broadcasting a light application of dry sandblast sand (typically 10 to 20 seive size) at a rate of 0.2 lb per sq. yd. (about 4500 sq. ft. per 100 lb). This sand application was made on this bridge deck. However, the first section began to harden before the sand was spread so that one-sixth of the surface area had very little sand texturing.

While the monomer application rate typically ranges from 80 to 120 sq. ft./ gal., the actual rate on this deck was 160 sq. ft./ gal. This unusually high application rate was due to the fact that the deck had inadvertantly been treated with linseed oil one month earlier by personnel who were unaware of the scheduled monomer treatment. The linseed oil treatment is part of the routine general bridge maintenance procedures.

5.3.5.3 Results

Even as the traffic was turned onto the sealed bridge the slightly glazed appearance caused doubts about proper skid resistance on the deck. Two weeks after the monomer application, a skid trailer was run over the bridge. The six skid readings ranged from 37 to 45 with an average of 42, a very acceptable skid number for the SDHPT.

No cores have been obtained for evaluation of the crack filling.

5.3.5.4 Conclusions

At this time, until the cores are evaluated for depth of monomer penetration, the only conclusion to be drawn is that the monomer treatment provided a good skid-resistant coating on the deck.

After a year or two it will be easier to determine longer term sealing properties. However, at this point the SDHPT personnel are pleased with the treatment.

* Cores will be evaluated in time for the final report.

5.4 Cost

The cost of the HMWM monomer has varied over the time the field studies were conducted. The cost as of November 1987 is approximately $37/ gal. The application rate in generally in the range of 80 to 120 sq. ft./ gal which results in a monomer cost of $.31 to $.46/ sq. ft. Labor costs can vary considerably depending upon many variables: area to be treatd, method of application, weather conditions, condition of deck, and traffic conditions. The Monahans bridge deck required about 15 manhours of labor (including the person mixing the monomer) or a rate of approximately 500 sq. ft./ manhour. This rate includes monomer application only; mobilization, travel, clean up, and traffic control are not included. If the effective rate were 100 sq. ft./ manhour at an average rate of $10/ hour, the labor cost would only be $0.10/ sq. ft., resulting in a cost considerably less than $1.00/ sq. ft.

One of the attractive features of the HMWM is that it can be applied by maintenance personnel, eliminating the need for outside contractor. Some training of personnel in the use of the materials would be required, but it would not require extensive time or unusual skills. Special equipment would not be required unless very large areas are treated. Spray bars are available from one of the manufacturers (the Rohm and Haas Company).

5.5 Safety

Some of the HMWM monomers used in this study have been forced to be toxic. The use of those materials requires protective clothing and minimal skin contact. However new monomers have been developed that exhibit low toxicity. One of these, PCR 1500, very similar to Monomer 200, was used in the Sweetwater bridge treatment. The new low toxicity monomer will be furnished in the future. However, the manufacturer's instructions concerning safety and handling should be carefully followed.

The initiator and catalyst (Table 4.2) should never be mixed together in concentrated form since a violent reaction will occur.

Chapter 6
Conclusions and Recommendations

6.1 Conclusions

Three methods were investigated for repairing cracks in concrete: (1) enlarging cracks with a crack cutter and filling with polymer; (2) epoxy injection; and (3) high molecular weight methacrylate monomer treatment. All three methods were found to be effective for some conditions.

The following specific conclusions can be drawn:

1. Relatively wide cracks in concrete pavements can be enlarged to a one-in. width and a depth of one to two in. and then filled with polymer concrete consisting of sand saturated with a low viscosity monomer system. The polymer concrete bonds well to the concrete. Many miles of cracks have been repaired successfully on I 610 since 1980.

2. Laboratory tests on epoxy injection indicated that 85 to 90 percent of cracks in concrete test specimens could consistently be filled. However, temperatures of 40 degrees F were found to significantly increase the cure time and to reduce the recracking strength of the repaired crack. Field tests indicated that debris-filled cracks can be successfully filled, but considerable time is required.

3. The use of high molecular weight methacrylate monomer system to repair cracks proved very beneficial for most applications. Laboratory tests showed that concrete with crack widths as small as 0.2 mm can be filled to 95 percent or more of their depth by mopping the monomer system on to the surface. For saturated concrete, small cracks (0.2 to 0.6 mm) can be filled to about 50 percent of their depth after 24 hours of drying; wider cracks can be filled even more.

The monomer treatment can provide a bond stronger than the concrete. Many specimens, upon recracking, form cracks outside the repair zone.

Many field tests were performed, primarily on bridge decks. The treatments were generally successful in sealing the cracks unless the cracks were filled with silt or debris. The application rate ranged from 80 to 160 sq. ft./ gal., and 2000 to 3000 sq. ft./ hr. of bridge deck can be treated without the use of mechanical equipment. The monomer cures in one to two hours to a glazed finish which has an adequate skid resistance, particularly if a light application of sand is broadcast on the surface.

The current cost of the monomer is approximately $37/ gal. For application rates of 80 to 120 sq. ft./ gal, the cost of monomer will range from $.31 to $.46/ sq. ft.

6.2 Recommendations

6.2.1 Polymer Concrete Crack Repairs

Polymer concrete can be used to seal cracks and restore some structural integrity to the concrete. The crack must be sufficiently wide for the polymer concrete to be placed. The following procedures are recommended:

1. Enlarge the crack (unless the width is at least 0.5 in.) with a crack cutter or router to a width of one in. and a depth of 2 in. Water should not be used in the cutting operation since it will fill the crack below the enlarged zone, preventing the monomer from penetrating the crack.
2. Blow out the crack with compressed air.
3. Fill the enlarged crack with clean, dry, well-graded concrete sand.
4. Saturate the sand with a methyl methacrylate (MMA) monomer system, described in Reference 4. The monomer can be mixed and poured over the sand by means of a sprinkler can. The sand should be rewetted with monomer every few minutes to replace the monomer which has evaporated and/ or penetrated into the narrow crack below. Polyethylene membrane can be placed over the crack to minimize evaporation. In lieu of MMA, a high molecular weight monomer system, described in Chapter 4, can be used. The repaired surface can generally be turned back to traffic within one to two hours.

6.2.2 Epoxy Injection

Epoxy injection can be effectively used where one or more of the following conditions exist; (1) structural integrity must be fully restored; (2) cracks are deep and narrow; and (3) cracks contain debris and/ or moisture.

Most epoxy injection is performed by professional applicators, and detailed recommendation on procedures will not be made since they are dependent upon the existing conditions, type of injection equipment, and type of epoxy used.

6.2.3 High Molecular Weight Monomer Application

The use of high molecular wieght methacrylate monomer system has been shown to provide good crack sealing and bonding for concrete bridges and pavements. The recommended procedures are as follows:

1. The concrete should be dry after a rain; a minimum of at least one day and preferably two should elapse prior to monomer application. It is also desirable to have the surface relatively cool to ensure open cracks and to prevent prenative polymerization of the monomer.
2. The surface should be clean. If the surface has been exposed to traffic, a light sandblast should be applied.
3. One of the monomer systems, preferably Monomer 1100 or the equivalent, should be mixed in accordance with the formulation given in Table 4.2. Precaution should be taken not to directly mix the initiator and catalyst together since a violent raction will occur. If the monomer is to be applied by hand, four to five galllon batches should be mixed and poured over the deck. Workers dressed in protective clothing should spread the monomer with push brooms or squeegees. The monomer should be pushed back and forth over the cracks to provide an adequate supply of monomer to keep the cracks full. Excess monomer should be pushed onto untreated portions of the deck before it begins to gel. Monomer should not be permitted to pond in depressions; if ponding cannot be prevented, clean dry sand should be sprinkled over the ponded areas.
4. For large areas, monomer spray bars are available from one of the monomer manufacturers (the Rohm and Haas Company). The spray bar can be pulled behind a tow vehicle at one to three miles

per hour. The monomer, initiator, and catalyst can mixed mechanically in correct proportions.

5. After the monomer has been applied and before it has cured, a light application of sand at the rate of 0.25 to 0.30 lb/ sq. yd. should be made.
6. Cleaning of brooms, tools, and containers can be done with plain soap and water while the monomer is still liquid. After the monomer polymerizes it can often be cleaned up with acetone, methyl ethyl ketone, or chlorinated hydrocarbon solvents like methylene chloride, or trichloroethylene.

The monomer manufacturer should be consulted for specific recommendations concerning safety and handling of the monomer.

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