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16. Abstract

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The repair of reinforced beams that had been loaded to failure was investigated. Failure modes were flexural and diagonal tension. Sand filler was used with a monomer solution that cured at ambient temperatures. The ratio of repaired beam strength to initial strength ranged from 0.92 to 1.12, with an average of 1.05.

The freeze-thaw durability of repaired non-reinforced slabs was studied to determine the effect of crack width, monomer systems, and surface impregnation and the use of sand fillers. It was found in all cases that the repaired specimens had equal or better freeze-thaw durability than uncracked controls.

Several bridge abutments have been repaired using the techniques developed. A summary of the repairs is given.

17. Key Words

polymer, monomer, repair, concrete, cracks, reinforced concrete, freeze-thaw, durability

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REPAIR OF CONCRETE WITH POLYMERS

by

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Donald R. Paul

Research Report Number 114-3

Polymer-Impregnated Concrete for Highway Applications

Research Project 3-9-71-114

conducted for

The Texas Highway Department

in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

February 1975

PREFACE

This report represents the third on the research on polymer-impregnated concrete for highway application. The authors are indebted to Maurice Ferrari of the Texas Highway Department for suggesting the possibilities of using polymers for repairing damaged or cracked concrete. Previous reports dealt with polymer-impregnated concrete for highway application.

The suggestions and comments of John Nixon, Donald O'Connor and Andy Seely of the Texas Highway Department were particularly helpful.

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January 1975

ABSTRACT

The use of polymers was investigated for repairing cracked or damaged concrete. Several monomer systems, using methyl methacrylate as the primary monomer, were studied. The variables investigated included relative moisture content, crack width, monomer viscosity, concrete temperature, and the use of sand fillers. In many cases the original flexural strength of the plain concrete could be restored by the repair.

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Several bridge abutments have been repaired using the techniques developed. A summary of the repairs is given.

KEY WORDS: polymer, monomer, repair, concrete, cracks, reinforced concrete, freeze-thaw, durability.

SUMMARY

The use of polymers for the repair of cracked or damaged concrete was investigated. For the repair of cracks, a number of variables were studied. They include: monomer systems; relative moisture content; crack width; monomer viscosity; concrete temperature; and the use of sand fillers.

Methyl methacrylate (MMA) was the primary monomer used. Increasing percentages of either isobutyl acrylate or butyl acrylate in combination with MMA were found to result in a flexural strength decrease. Increased moisture in the concrete was found to cause some decrease in flexural strength. Repaired crack widths above 0.2 in. resulted in flexural strengths of less than the original strength. The use of higher monomer viscosity resulted in lower strengths, due to failure in the polymer; lower viscosities resulted in failures in the concrete.

Six reinforced concrete beams that had been loaded to failure were repaired. One beam had failed in diagonal tension; the others failed in flexure (initial yielding of the reinforcement). The strength of the repaired beams ranged from 92% to 112% of the initial strength. The average was 105%. In nearly all cases the failure occurred adjacent to the repaired zone.

Unreinforced slabs were broken and repaired and subjected to freeze-thaw tests. Slabs with 0.5-in. crack widths appeared to exhibit slightly

more volumetric stability than slabs with 0.25-in. crack widths, although both had equal or superior freeze-thaw durability compared to unrepaired, uncracked controls. The use of a 60-40 MMA-IBA solution had little apparent effect on durability as compared to a 100% MMA solution. Repaired surface-impregnated slabs had the best durability of all slabs tested.

Several bridge abutments have been repaired using the techniques previously developed. The crack widths ranged from 0.1 in. to 3 in.

IMPLEMENTATION STATEMENT

The results of this investigation indicate that cracked or spalled concrete can be repaired with polymer-concrete which consists of fine aggregate and monomer which is polymerized. Good bond to concrete and good strength are obtained, and the material cures rapidly. This material appears to have excellent potential for repair of highway structures. Field repairs indicate that the method is simple and effective.

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CHAPTER 1.

Introduction

1.1 Background

Repair of damaged or deteriorated concrete has long been a difficult and perplexing problem in highway structures. Several methods, including the use of epoxies, have been proposed to repair deteriorated and damaged concrete structures. Many of these methods are both inconvenient and expensive. The lack of quantitative data evaluating the performance of each method of repair causes uncertainty in the performance of the repair (1, 2, 3).*

In recent years the use of polymers to improve the durability and strength of concrete has been receiving more attention. Research by Brookhaven National Laboratories and the United States Bureau of Reclamation (4, 5, 6, 7) and studies conducted at the Center for Highway Research at the University of Texas at Austin (8, 9, 10, 11) have confirmed the following improvements: (1) better resistance to abrasion, freeze-thaw, and corrosion due to sulfates and acids; (2) increases in strength of up to 250%;

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*Numbers in parentheses indicate references, as listed following the appendix.

(3) significant decreases in water permeability and water absorption; (4) some improvement in resistance to abrasion; and (5) equal or better skid resistance.

The previous work at the Center for Highway Research has emphasized the development of polymer-impregnated surface treatments for bridge decks. Some research, however, has been directed toward the use of polymers and polymer-concrete for the repair of concrete. A previous report summarized the initial work on the use of polymers to repair cracks in concrete and concluded that it was successful in sealing cracks and in restoring some of the mechanical strength (1). Considerable research has also been conducted at Brookhaven National Laboratory on the repair of deteriorated concrete, and it was published just prior to the publication of this report (12).

1.2 Scope

This report summarizes research studies on the use of polymers to repair concrete. Areas of investigation include (1) monomer systems; (2) effect of relative moisture content, crack width, viscosity, surface temperature, and fillers; (3) repair of reinforced beams; (4) freeze-thaw durability; and (5) field repairs on bridge abutments.

1.3 Definitions

Terms that will be used in this report are defined. The definitions are specific for their use in this study and may not encompass all possible uses of the terms.

1.3.1 Monomer--A monomer is a liquid compound of low-molecular weight that can react to form high molecular weight solids. Three different monomers were used in this study: methyl methacrylate (MMA), isobutyl methacrylate (IBA), and butyl methacrylate (BA).

1.3.2 Polymers--Polymers are high molecular weight solids that are formed from monomers by polymerization.

1.3.3 Copolymers--A copolymer is a polymer made by polymerization of a mixture of two monomers. The relative proportions of the two monomers can be varied to yield copolymers with different characteristics.

1.3.4 Polymerization--Polymerization is the reaction process by which monomer molecules are united to form polymer molecules with high molecular weights. Polymerization can be accomplished by several methods. In this study catalytic polymerization at room temperature was used. An accelerator was used to increase the rate of reaction.

1.3.5 Glass Transition Temperature (Tg)--The glass transition temperature is the temperature at which an amorphous, glassy polymer softens and becomes rubbery-like upon heating.

1.3.6 Cross-linking Agents--Cross-linking agents are used to link linear molecular chains of polymers together. When the molecular chains are cross-linked, the plastic will become stiffer and stronger. In this study the cross-linking agent, used infrequently, was trimethylol-propane trimethacrylate (TMPTMA).

1.3.7 Initiators--Initiators, or catalysts, are used to initiate the polymerization of the monomer. In this study lauroyl peroxide (LP) was used. Because polymerization proceeded at room temperature, an accelerator was used to speed up the reaction. In this study N, N-dimethyl-paratoluidine (DMPT) was used as an accelerator.

1.3.8 Polymer-Concrete (PC)--Polymer-concrete is a mixture of aggregate and monomer that has been polymerized.

1.3.9 Polymer-Impregnated Concrete (PIC)--Polymer-impregnated concrete is a hardened portland cement concrete that is impregnated with a liquid monomer that is subsequently polymerized.

CHAPTER 2.

Monomer Systems

2.1 Previous Research

Previous research (10) at the Center for Highway Research at the University of Texas at Austin investigated the use of polymers for the repair of cracked concrete. Modulus of rupture beams, 3 in. x 3 in. x 14 in., were cracked or broken and repaired with a monomer system of MMA in combination with cross-linking agents, accelerators, and catalysts Polymerization was accomplished at room temperature or at 125° F. After polymerization, the beams were tested by loading at the third points with a span of 12 in. The most promising repairs from the standpoint of strength utilized a solution of MMA, 4% (wt.) catalyst (LP) and 2% (wt.) accelerator (DMPT). It was found that the addition of a cross-linking agent did not significantly improve the flexural strength of the repair.

2.2 Investigation of Other Monomer Systems

Additional studies were conducted using two other monomers, IBA and BA, by themselves and in combination with MMA as comonomers to determine if additional ductility in the repair could be obtained. Both IBA and BA have lower glass transition temperatures and after polymerization are "rubbery" at room temperature.

The test utilized 3 in. x 3 in. x 14 in. modulus of rupture beams. Concrete properties and mix design are summarized in the Appendix. The beams were first oven-dried at 210° F ± 10° F for a period of seven days. After removal from the oven the beams were loaded at third points to failure. The testing was done in general accordance with ASTM C78-64. After failure of each beam, the beam was completely broken into two halves. The two halves were brought together at a specified crack width measured from reference lines on each half marked prior to testing. A sheet metal form was bonded to the sides and bottom of the crack with a silicon adhesive. Using the same adhesive, a shallow dike was formed around the top of the crack to contain the monomer (Fig. 2.1). After the adhesive had hardened, the monomer solution was poured into the crack and replenished as necessary until polymerization occurred at room temperature. After 24 hours the forms were removed and the beams were tested in the original orientation.

2.2.1 Methyl Methacrylate and Isobutyl Acrylate--Beams repaired with MMA and IBA had a crack of 0.05 in. Fig. 2.2 shows the effect of the percentage of MMA and IBA on the strength ratio of the repaired specimen. The strength ratio is the ratio of the ultimate load after repair to the original ultimate load.

The results indicate that when specimens were treated with percentages of IBA of up to 25 to 35%, the use of IBA did not decrease the strength but in some cases increased it. In this range, the failure was in the concrete, which indicated good adhesion of the polymer to the concrete.

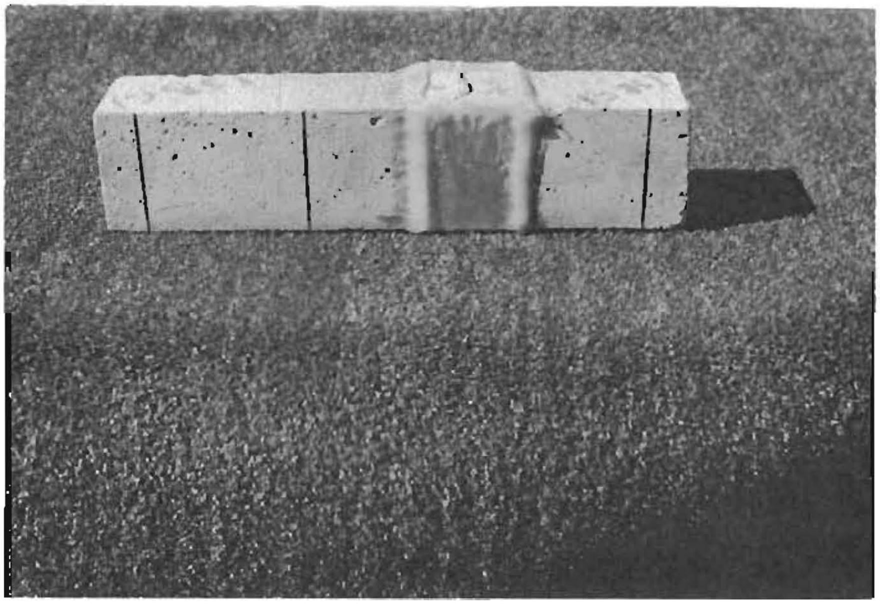


FIG. 2.1 A TYPICAL SPECIMEN WITH METAL FORM

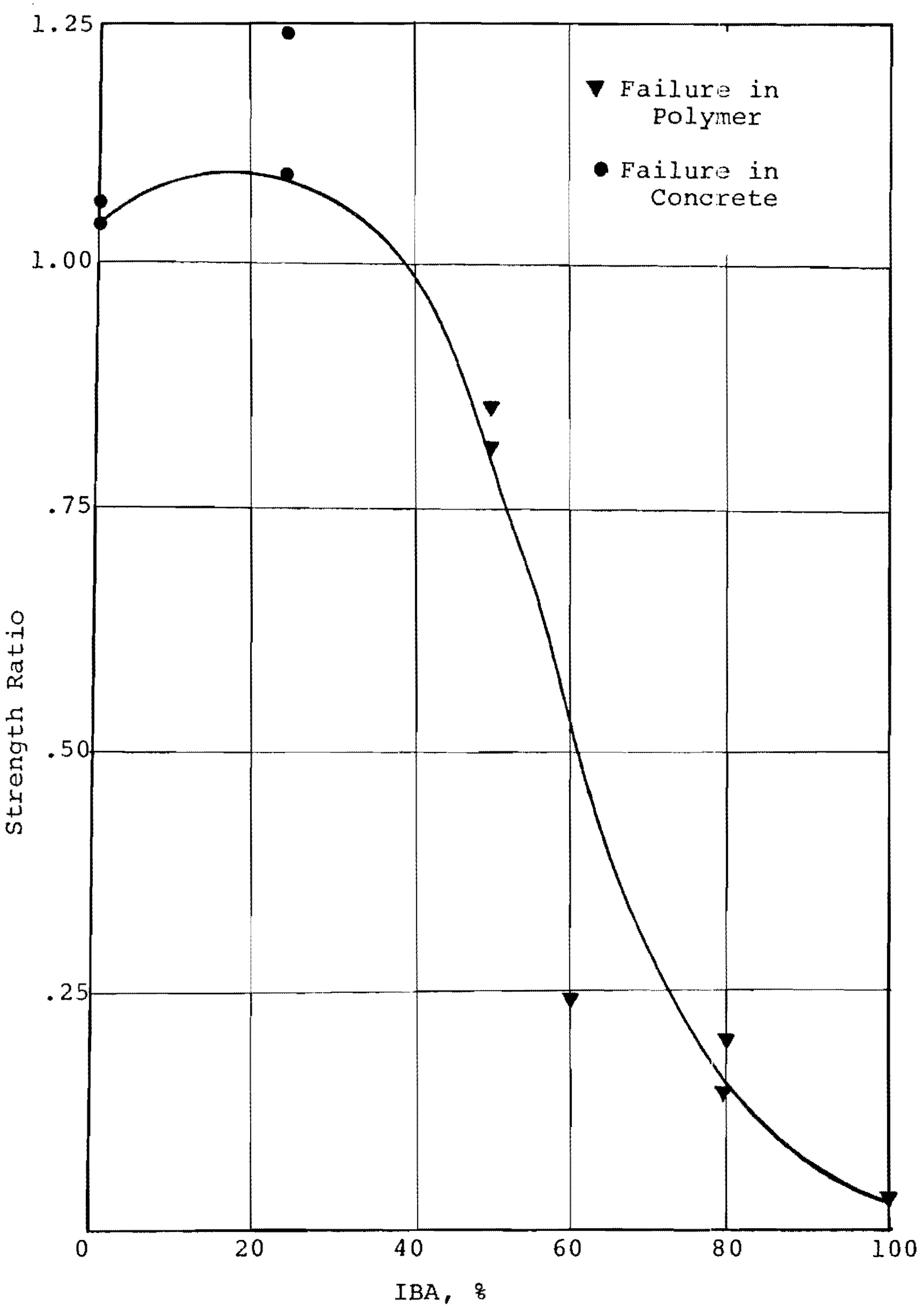


FIG. 2.2 EFFECT ON FLEXURAL STRENGTH OF VARYING PERCENTAGE OF IBA IN MMA SOLUTION

At about 35%, the strength ratio starts to drop rapidly with increasing percentages of IBA until it reaches zero at 100% IBA, when the specimen did not even support its own weight. Although only visual observations were made, the ductility of the repaired zones utilizing IBA was generally more than the specimens with MMA alone. The specimens treated with 60% IBA had a centerline deflection of approximately 1/4 in. at the ultimate load and 1/2 in. when the test was terminated while the specimen still supported about 10% of its original ultimate load. Specimens with treatments using 75% or more of IBA were ductile but the polymer was very sticky and discontinuous and had a very strong smell. In one specimen a cross-linking agent, TMPTMA, was used but only a slight improvement in the strength was obtained.

2.2.2 Methyl Methacrylate and Butyl Acrylate--This study employed a crack width of 1/2 in. and clean dry sand to fill the crack. The gradation of the sand is shown in the Appendix. The test results are shown in Fig. 2.3, in which the strength ratio is plotted against the varying percentages of BA. It is of interest to note that the curve had a similar shape as in the IBA study although the strength was less for corresponding percentages of BA. In all cases, the addition of BA resulted in a lower strength. Above 75% of BA the strength ratio was constant at zero since the specimens were unable to sustain their own weight. The specimens with percentages of BA less than 40% developed a failure in the concrete; specimens with 40% or more failed in the polymer.

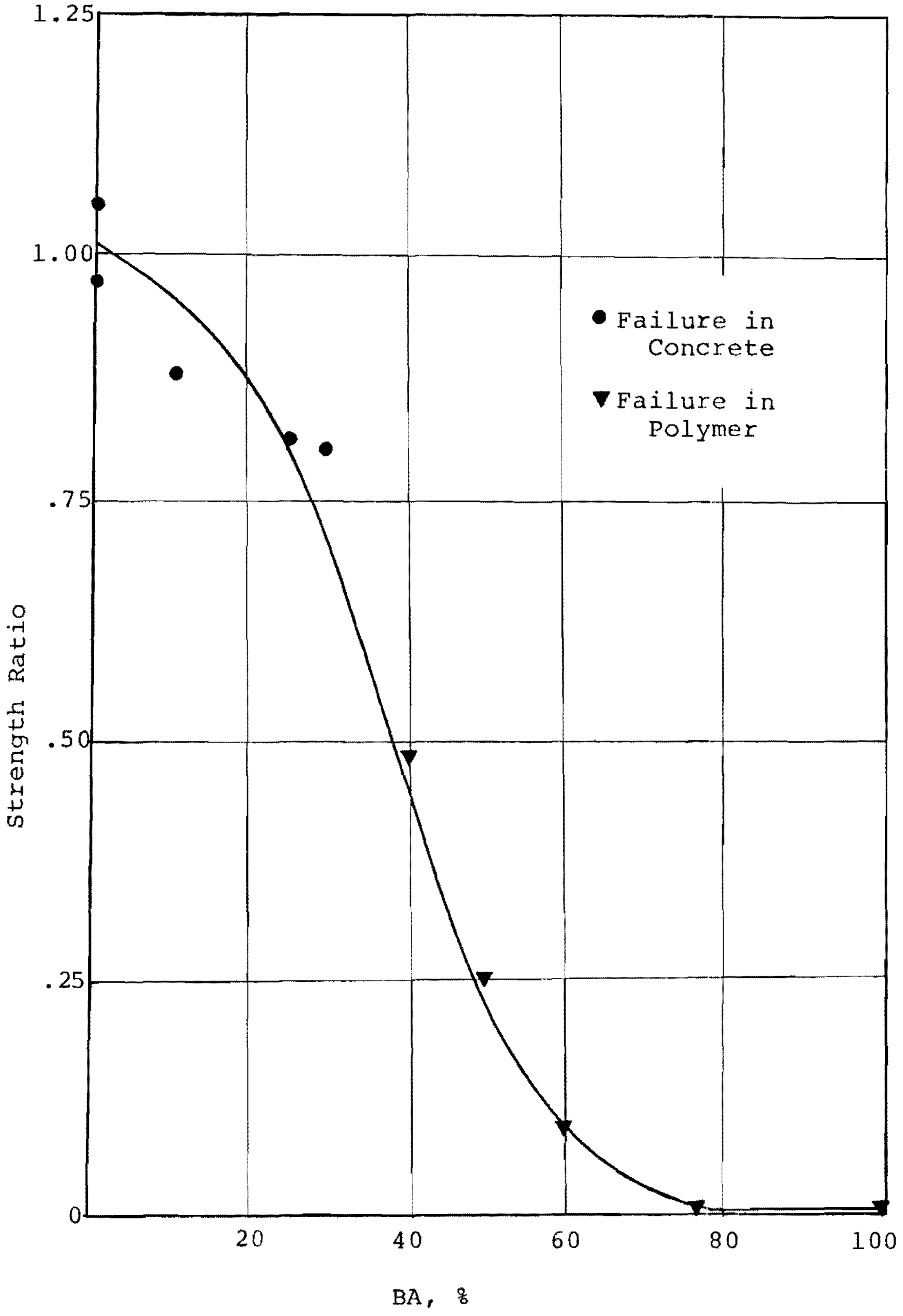


FIG. 2.3 EFFECT ON FLEXURAL STRENGTH OF VARYING PERCENTAGE OF BA IN MMA SOLUTION

The specimens in the range of 40 to 60% BA were very flexible and would return to a horizontal position when unloaded even after the deflection increased without an increase in the load. The specimens with 60% or more BA were also flexible but the monomer was discontinuous and sticky.

CHAPTER 3.

Variables Affecting Crack Repair

3.1 Introduction

Data obtained in earlier studies dealing with the repair of cracked concrete using polymers indicated that there were several variables affecting the strength of the repaired concrete. A series of tests was conducted to evaluate the significance of some parameters on the repair of concrete using polymers. Variables evaluated included relative moisture content, crack width, viscosity, surface temperature, air temperature, and use of fillers. For each study, 3 in. x 3 in. x 14 in. concrete beams were used. The beams were oven dried at 210° F ± 10° F for at least seven days and until no change in weight occurred. All repairs were made with a solution of methyl methacrylate (MMA), 4% (wt.) lauroyl peroxide and 2% (wt.) DMPT, unless otherwise indicated, and the material cured in one or two hours. The test procedure and results of each test are summarized in the following section.

3.2 Relative Moisture Content

Relative moisture content has been found to have a significant influence on surface impregnation of concrete using polymers. The results showed the depth of impregnation of polymer increased as the amount of moisture in concrete decreased (8). This conclusion raised the question of what effect, if any, the moisture content has on crack repair. A series of tests was conducted to determine the effect of moisture in concrete on the strength of the repair.

The beams were weighed to determine the dry weight and then placed under water for a period of one week. After the fully saturated weight had been obtained, the specimens were placed in an oven at 210° F ± 10° F. Subsequently, each specimen was removed at different drying periods to obtain different contents of moisture in each specimen. Each specimen was weighed immediately after removal from the oven and then wrapped in polyethelene to prevent a change in moisture content. The relative moisture content is defined as follows:

$$\text{Relative moisture content} = \frac{\text{Final weight} - \text{Dry weight}}{\text{Fully saturated weight} - \text{Dry weight}} \times 100\%$$

The specimens were tested as previously described in Chapter 2. After the specimens were broken, they were repaired using a monomer solution of 4% (wt.) LP and 2% (wt.) DMPT. A crack width of 0.25 in. was used for all specimens. The crack width was measured from reference lines marked on the specimens before the first testing. The monomer solution was replenished as needed until polymerization started. After approximately 24 hours the specimens were loaded again in the same orientation and using the same procedure until failure. The strength ratio was then calculated as a ratio of the ultimate load for the repaired specimen to the original ultimate load. The test results are illustrated in Fig. 3.1.

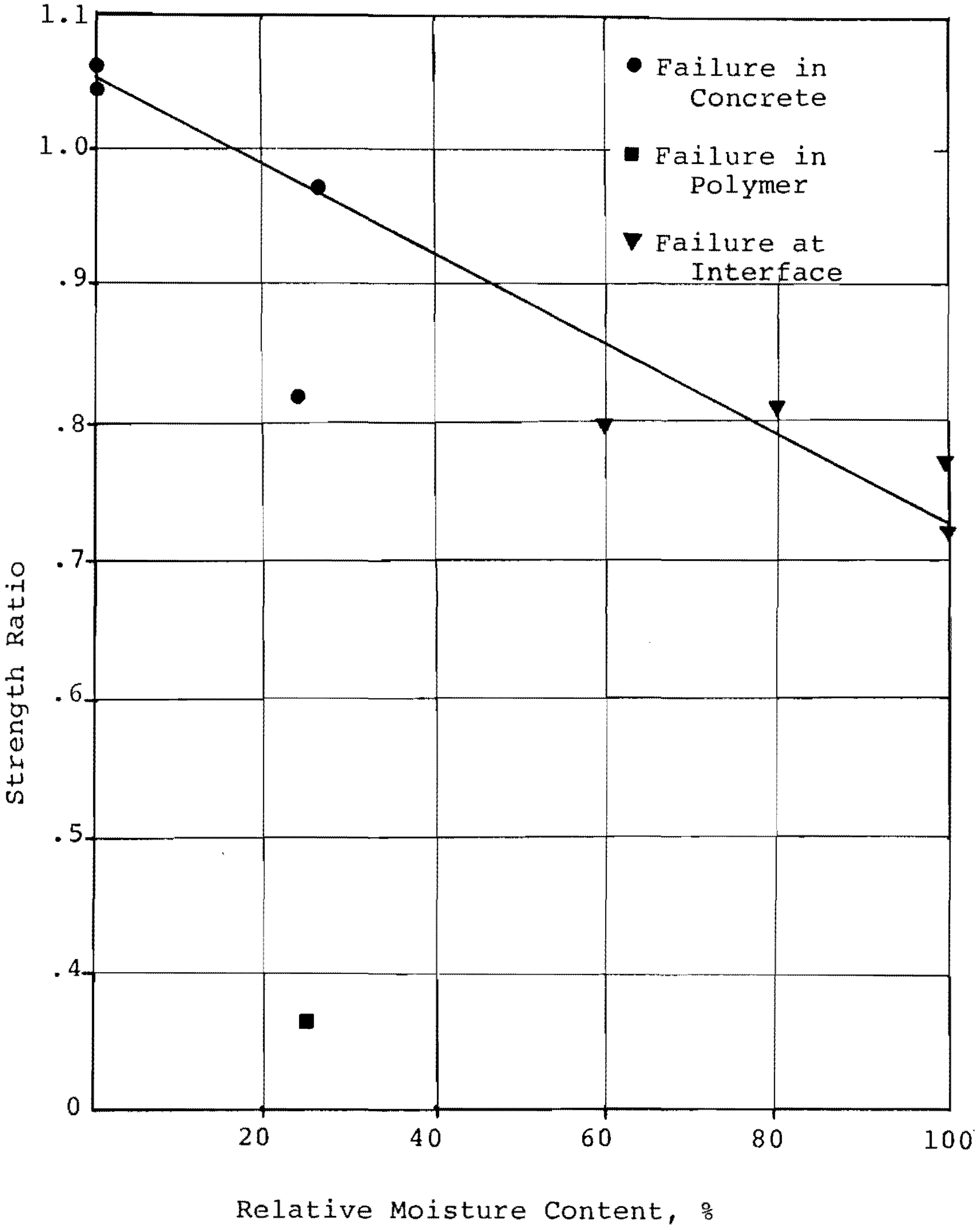


FIG. 3.1 EFFECT OF MOISTURE ON FLEXURAL STRENGTH

The scatter in the results was attributed to the nature of the problem and the difficulty of expressing the ratio of the strength after repair to the original strength since the failure did not always occur in the bond. Only specimens with more than 50% relative moisture content had a failure at the polymer concrete interface. Due to the high strength of the polymer, only one specimen failed in the polymer and this was attributed to incomplete polymerization since a strong smell was detected upon the failure of the specimen.

3.3 Crack Width

After the beams were loaded to failure at the third points, a sheet metal form was fixed to the bottom and sides of the crack using silicon adhesive at the desired crack width measured from reference lines indicated earlier on each beam. A 1/4 in. dike was formed on top of each beam to contain the monomer solution. After the adhesive hardened, the monomer solurion (consisting of MMA as basic monomer, 4% (wt.) LP and 2% (wt.) DMPT) was applied to the crack and replenished as needed until polymerization started. The next day, the forms were removed and the beams loaded in the original orientation using the same test procedure. The strength ratio was calculated for each specimen.

The results of this test are shown in Fig. 3.2. The figure shows that for crack widths between 0.05 in. and 0.20 in. the repaired specimens at least developed their original strength. It also shows that there was a

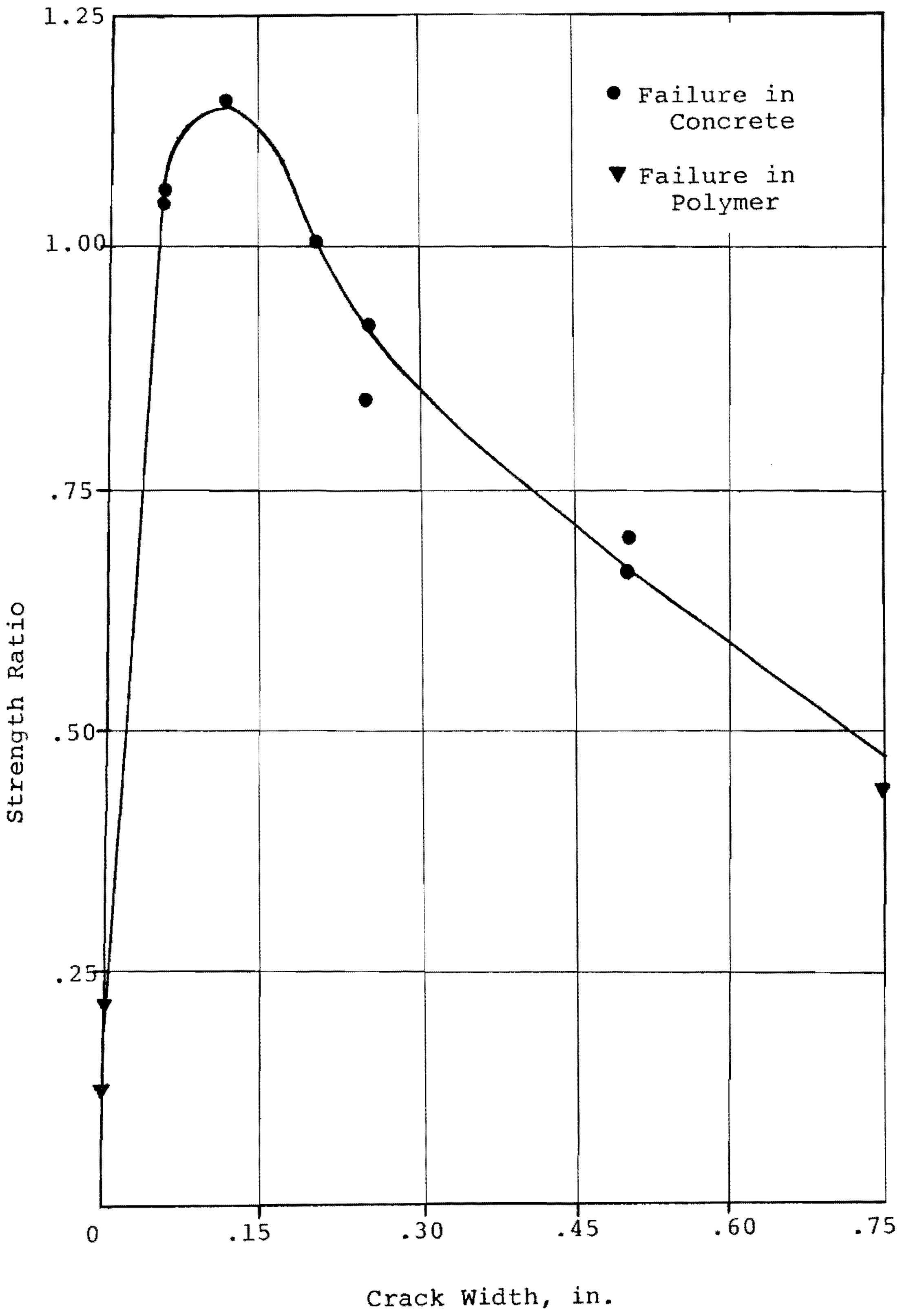


FIG. 3.2 EFFECT OF CRACK WIDTH ON FLEXURAL STRENGTH

significant decrease in strength as the crack widths decreased below 0.05 in. and increased above 0.20 in.

3.4 Viscosity

It was anticipated that some repairs, such as wide deep cracks, may necessitate the use of more viscous monomer systems to prevent the loss of the monomer. A study to investigate the effect of the viscosity of the monomer system on the strength of repaired concrete was initiated. The test procedure employed was the same as in Section 2.2.4. The width of the crack was a constant 0.05 in. for all test beams. The monomer system used consisted of MMA with different percentages of Rohm and Haas Acryloid 6906-XP polymer as a basic monomer, 4% (wt.) LP, and 2% (wt.) DMPT. Rohm and Haas Acryloid 6906-XP polymer was initially in pellet form and was used to increase the viscosity of the monomer.

The test results are shown in Fig. 3.3. Although there was significant scatter in the results, it showed that the strength ratio decreased as the percent of polymer (and viscosity) increased. Failure usually occurred in concrete for percentages of polymer up to 25% and in polymer for percentages of 50% and above. Visual observations indicated that there was a decrease in ductility as the percentage of polymer increased.

3.5 Surface Temperature

It was observed, during the treatment of some specimens just removed from the oven, that polymerization occurred in a shorter time than

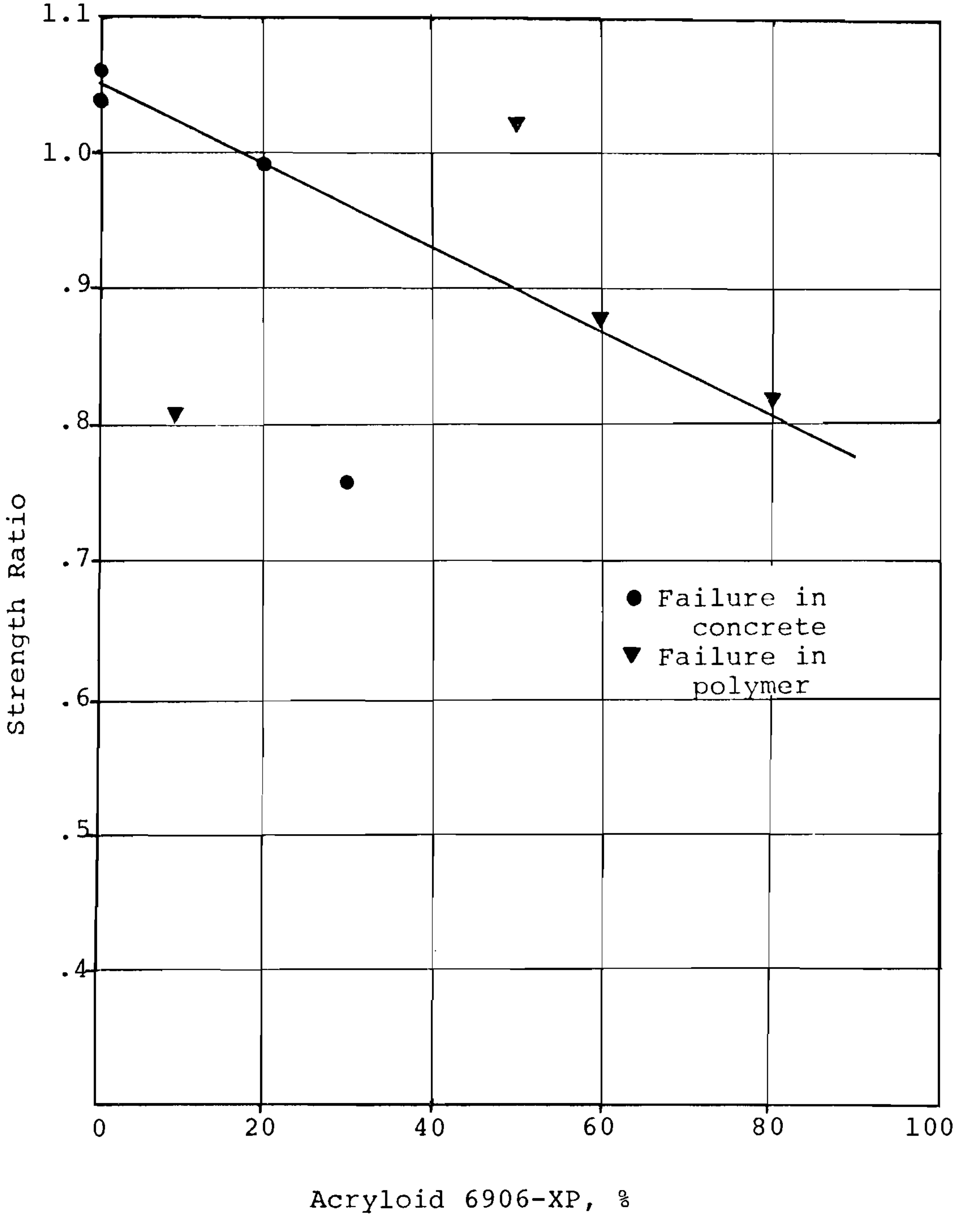


FIG. 3.3 EFFECT ON FLEXURAL STRENGTH OF VARYING PERCENTAGE OF ACRYLOID 6906-XP IN MMA

usual. That observation lead to the question of what influence the surface temperature has on the time to polymerization of the monomer and the strength of the repaired concrete.

A series of beams was tested to evaluate the repair of beams with varying surface temperatures. The crack width was fixed at 0.5 in. for all specimens tested. Temperature readings were taken by a potentiometer connected to a thermocouple fixed at mid-depth in the crack. The specimens were placed in an oven at 350° F ± 10° F until the surface temperature at the level of the thermocouple had reached the desired temperature. Next, the specimens were removed from the oven and the standard monomer solution was immediately applied. Temperature readings were taken at one minute intervals.

Fig. 3.4 shows that the time required to reach maximum temperature, which is a measure of the rate of polymerization, decreased as the initial surface temperature increased. Fig. 3.5 shows the relationship between the initial surface temperature and the maximum temperature. The results indicate that the maximum temperature increased as the initial surface temperature increased. When sand was used as a filler, the strength tests showed that there was no change in strength as the surface temperature was varied since generally all specimens were restored to their original strength. For specimens in which no sand filler was used, boiling of the monomer always occurred during polymerization. The amount of boiling increased with increased surface temperatures and the monomer was porous

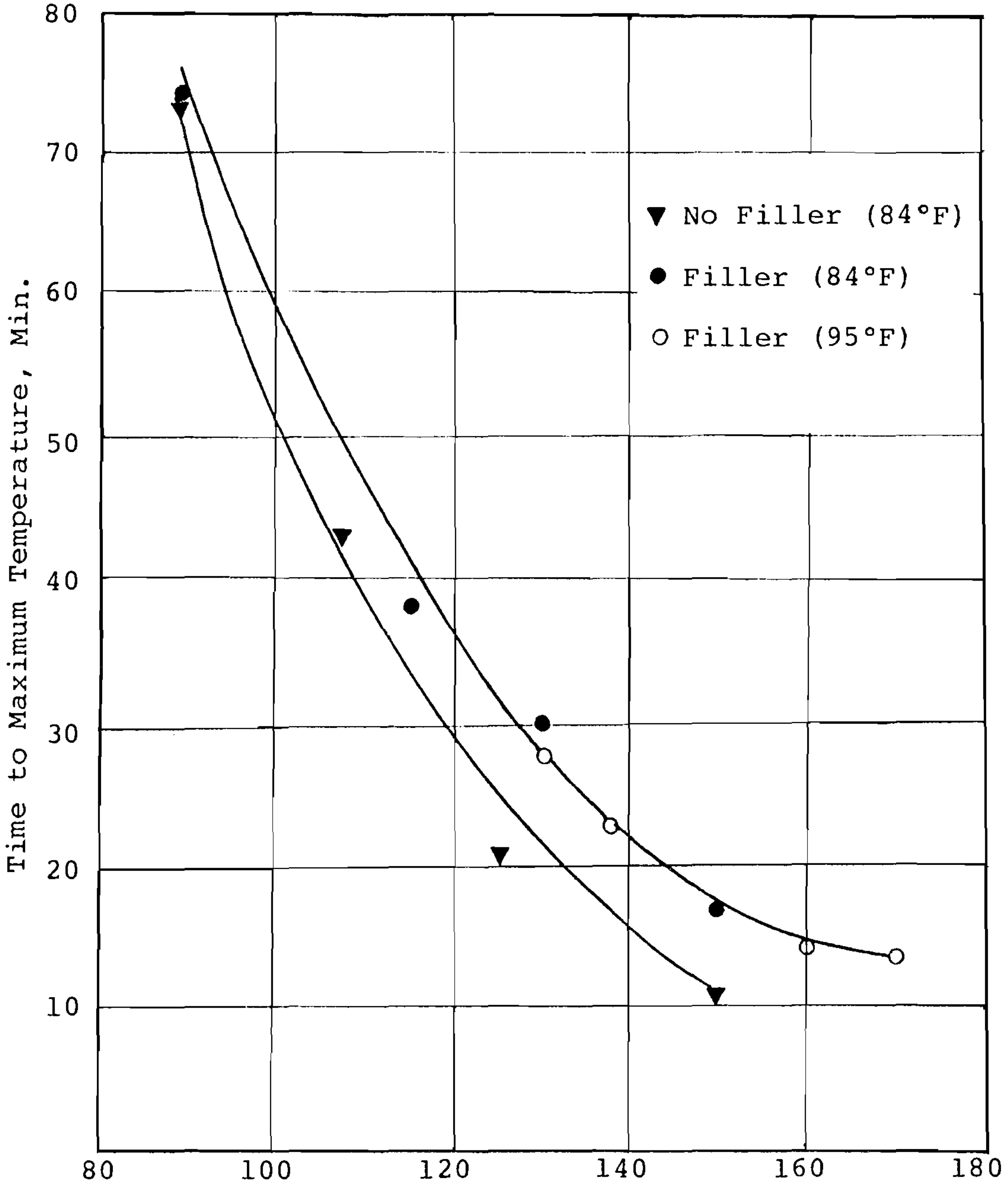


FIG. 3.4 EFFECT OF INITIAL SURFACE TEMPERATURE ON TIME TO MAXIMUM TEMPERATURE

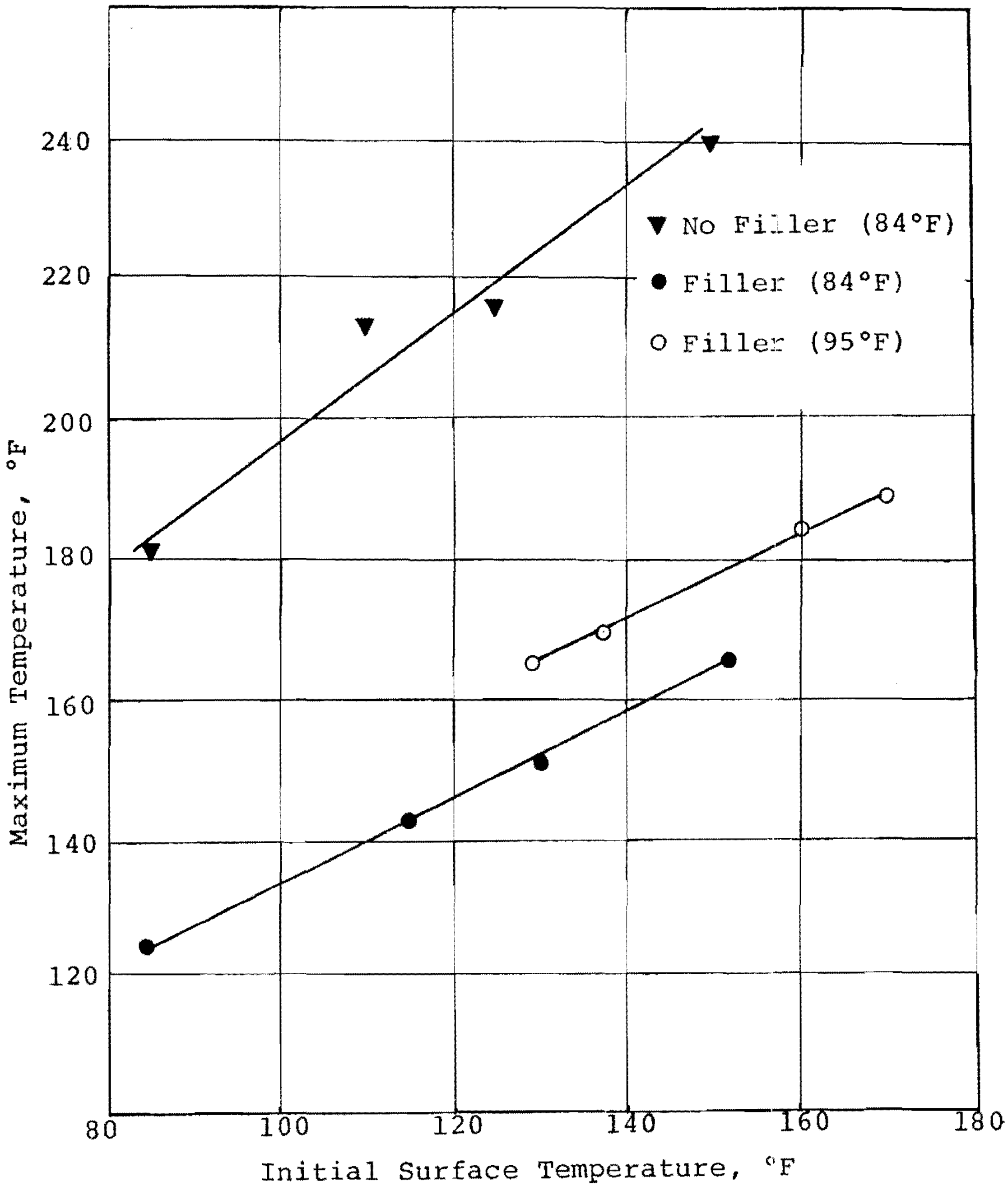


FIG. 3.5 EFFECT OF SURFACE TEMPERATURE ON MAXIMUM TEMPERATURE

and therefore had less strength. It was observed that the strength decreased as the surface temperature increased.

Fig. 3.4 and Fig. 3.5 also indicate that slight changes in air temperature had very little effect on the time to maximum temperature at the range of surface temperatures investigated. The effect of air temperature was more significant with respect to the maximum temperature reached. An 11° F difference in air temperature produced an average of 13° F difference in maximum temperature reached.

3.6 Fillers

To minimize the cost of the repair, attempts have been made to reduce the amount of monomer used. Oven-dried sand has been used in several of the studies. It was found that sand did not reduce the strength of the repair and sometimes resulted in better treatments since it resulted in a reduced monomer mass and provided a heat sink which prevented boiling of the monomer. Fig. 3.4 indicates that the use of sand results in slightly longer times to polymerization as expressed by time to maximum temperature. Fig. 3.5 shows that the use of sand as a filler resulted in a 55° F or more reduction in maximum temperature.

In this study sand was the only filler used. A monomer loading of 25% was required using a regular run Colorado River washed sand. A study (7) has shown that high strength polymer-concrete, which is a mixture of aggregate and monomer that has been polymerized, can be prepared with a polymer loading of less than 6% (wt.) using properly graded aggregate. However, it should be noted that for crack repair some monomer will impregnate the concrete, and, therefore, loadings of more than 6% (wt.) based on the weight of the sand in the repair should be expected, even for optimum gradations of sand.

CHAPTER 4.

Repair of Reinforced Beams

4.1 Introduction

In addition to the factors associated with the repair of cracks in concrete, the repair of damaged reinforced concrete beams was studied. The possibility of modification of the load-deflection characteristics after the repair because of the difference in properties of the polymer-concrete and concrete made it essential to compare the load-deflection response of reinforced concrete members before and after repair. A series of tests on reinforced concrete beams was performed to investigate the behavior of repaired reinforced concrete beams. In this study, six beams were used.

4.2 Test Procedure

In this test 4 in. x 5-1/2 in. x 60 in. reinforced concrete beams were used. The beams were made of normal weight concrete and reinforced with one No. 5 grade 50 or 60 deformed steel bar at the bottom of the beam. The mix design and properties of concrete are shown in the Appendix. After casting, the beams were moist cured for one week and then air cured until tested. Beams were at least 28 days old before testing. The details of the beams are shown in Fig. 4.1, and the test setup is shown in Fig. 4.2. Beams were first tested to failure and load, and midspan deflection readings

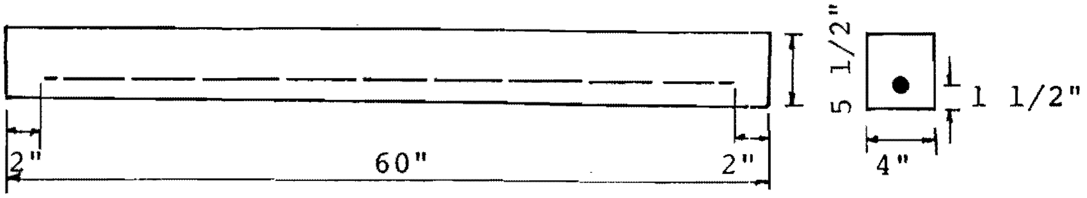


FIG. 4.1 BEAM DETAILS

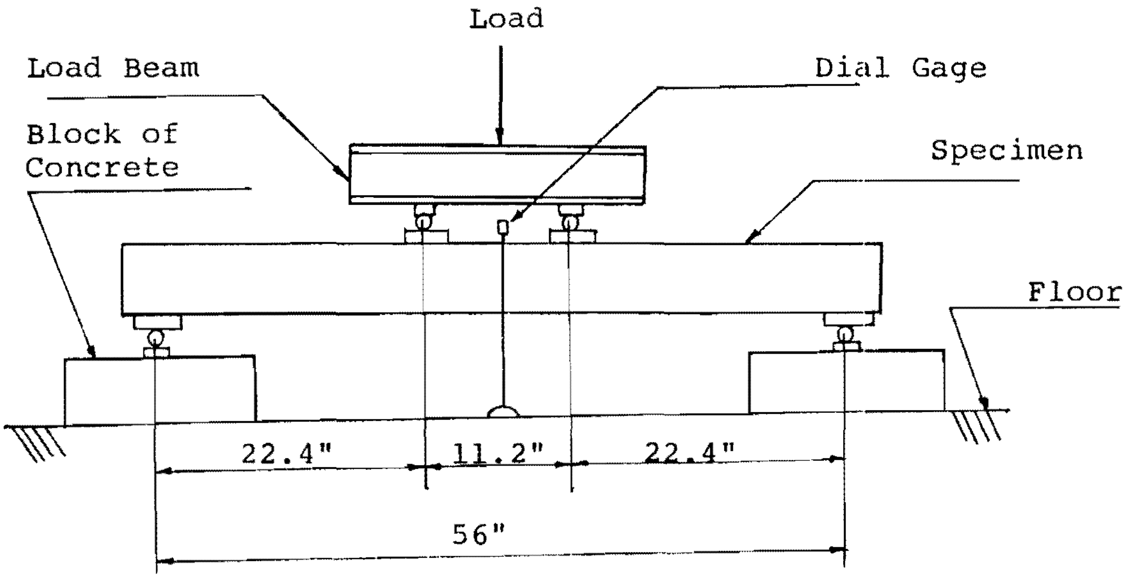


FIG. 4.2 TEST SETUP

were taken. The dial gages used to measure deflections were removed prior to failure so the load-deflection response all the way to failure was not obtained.

After the beam was removed from the testing machine, loads were placed on each end of the beam to keep it straight during treatment. Next, a sheet metal form was fixed around the bottom and sides of the spalled zone (Fig. 4.3). Silicon adhesive had hardened, the cracks and the crushed zone were filled with clean oven-dry sand. Next the monomer was applied to the crack and replenished as necessary until polymerization started. Polymerization was essentially completed in a few hours. After about 24 hours, the loads were removed and the sheet metal form was stripped (Fig. 4.4). The specimen was loaded in the same manner and orientation as in the first test.

4.3 Test Results

The results of the tests are summarized in Table 4.1. The following sections discuss the results of each test in some detail.

4.3.1 Beam 3RC-2--Beam 3RC-2 had an initial primary failure caused by yielding of the reinforcing steel and a secondary failure caused by the crushing of the concrete in compression. This type of failure will be subsequently referred to as a flexural failure. The failure mode of the repaired beam was diagonal tension and end anchorage. The strength ratio of the beam was 0.92, which was the lowest value obtained. The load deflection-curves before and after the repair are shown in Fig. 4.5, and the failure of the

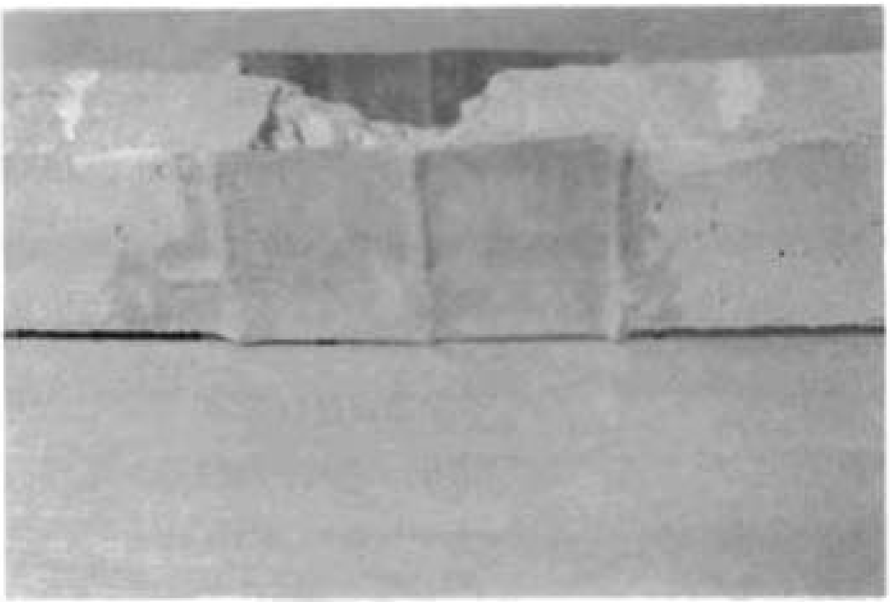


FIG. 4.3 TYPICAL BEAM WITH FORM

FIG. 4.4 TYPICAL BEAM AFTER REPAIR

TABLE 4.1

RESULTS OF REINFORCED BEAM TESTS

Beam No.	Average Steel Yield Stress, psi	Original Ultimate Load, lb.	Original Failure Mode	Ultimate Load After Repair, lb.	Failure Mode of Repaired Beam	Strength Ratio
1RC-4	52,800	5630	flexural	6310	diagonal tension	1.12
1RC-7	52,800	5270	flexural	5800	flexural	1.10
1RC-14	52,800	4500	flexural	4720	flexural	1.05
2RC-23	68,700	6450	diagonal tension	6380	diagonal tension --anchorage	0.99
3RC-2	52,100	5000	flexural	4580	diagonal tension --anchorage	0.92
3RC-4	52,100	5400	flexural	5890	diagonal tension	1.09
					Average	1.05

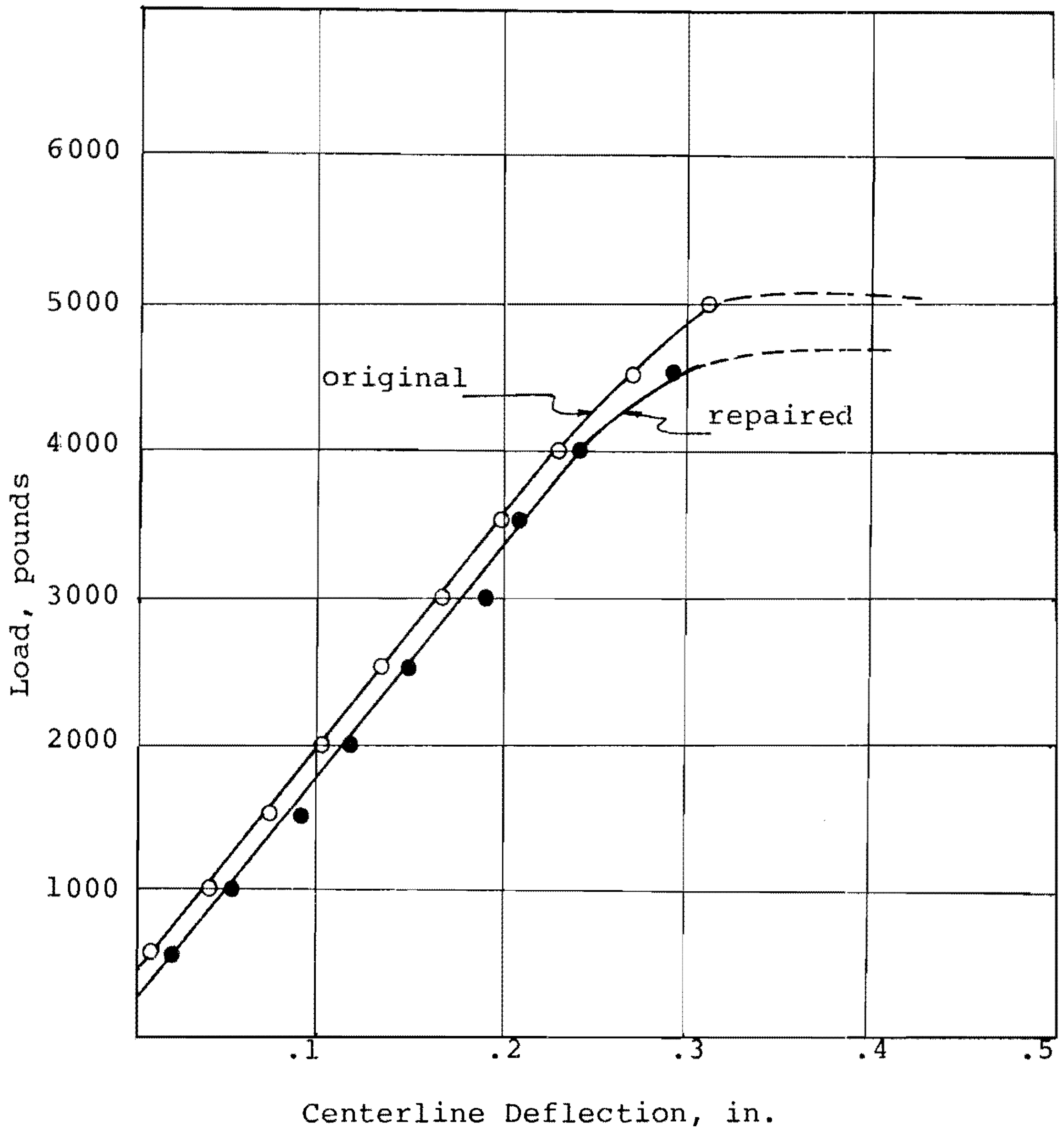


FIG. 4.5 LOAD-DEFLECTION RESPONSE OF BEAM 3RC-2

repaired beam is shown in Fig. 4.6. The repaired beam had larger centerline deflections than the original beam at the same load level because of the slightly lower load at which the deflection readings were started. It is significant to note that (1) the slopes of the two curves are almost identical, which indicates that the initial or elastic stiffness was not significantly changed by the polymer-concrete repair, and (2) the failure occurred outside the repaired zone.

4.3.2 Beam 1RC-7--Beam 1RC-7 was first tested in cyclic loading in the range of 200 lb. to 1360 lb. and had sustained 2,029,477 cycles of loading before being subjected to static loading which resulted in a flexural failure. The failure after the repair was similar to the original failure but at a different location, as in Fig. 4.7. The strength ratio was 1.10. This significant increase in strength may be partly attributed to fatigue recovery since the first static test was made soon after the cyclic testing was completed whereas the repair was made several months later. The load-deflection response of both the original and the repaired beams is shown in Fig. 4.8. As concluded in the discussion of beam 3RC-2, the deflections for the repaired beam are usually larger than the original beam yet the stiffness, as indicated by the slopes of the curves, has not been altered.

4.3.3 Beam 1RC-4--Beam 1RC-4 had a flexural failure in the original loading. In the loading after the repair, the beam developed a flexural failure at a different location than the original failure. Fig. 4.9 shows the original and the repaired beam failure modes. The strength ratio for this beam

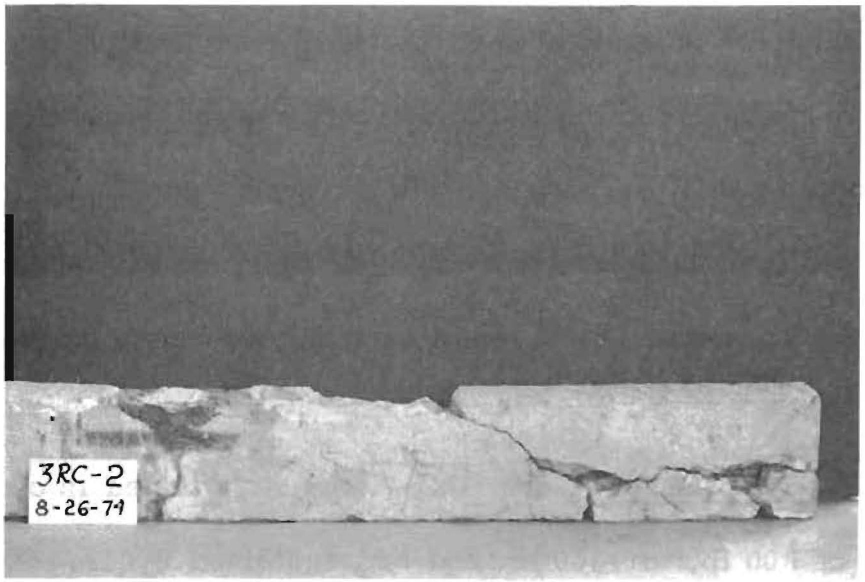


FIG. 4.6 FAILURE MODE OF BEAM 3RC-2

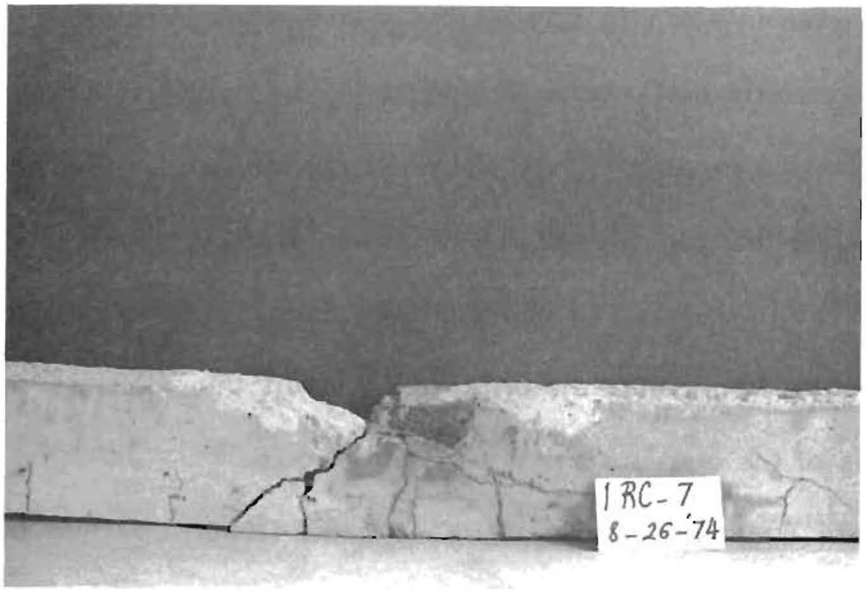


FIG. 4.7 FAILURE MODE OF REPAIRED BEAM 1RC-7

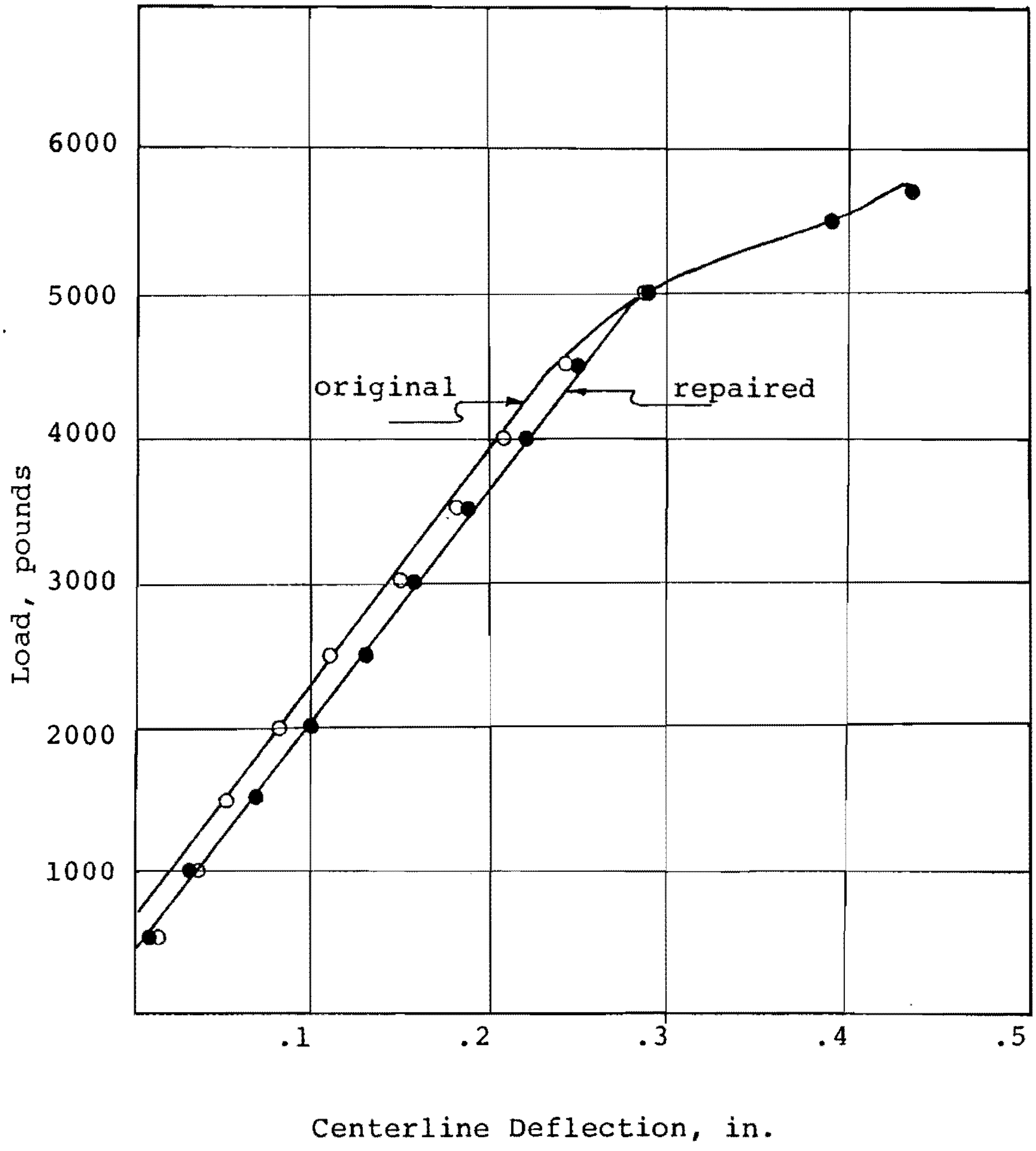
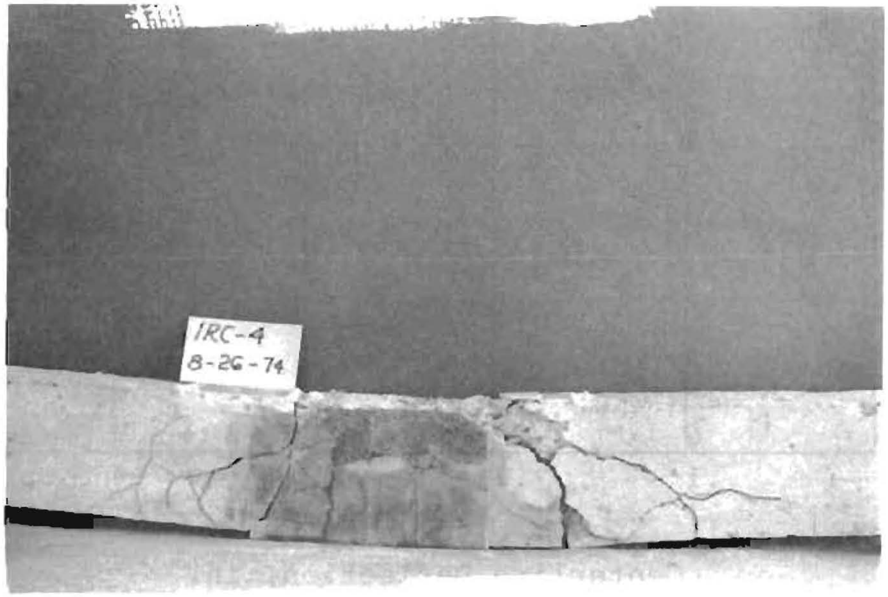


FIG. 4.8 LOAD-DEFLECTION RESPONSE OF BEAM 1RC-7

a) Original Failure



b) Failure After Repair

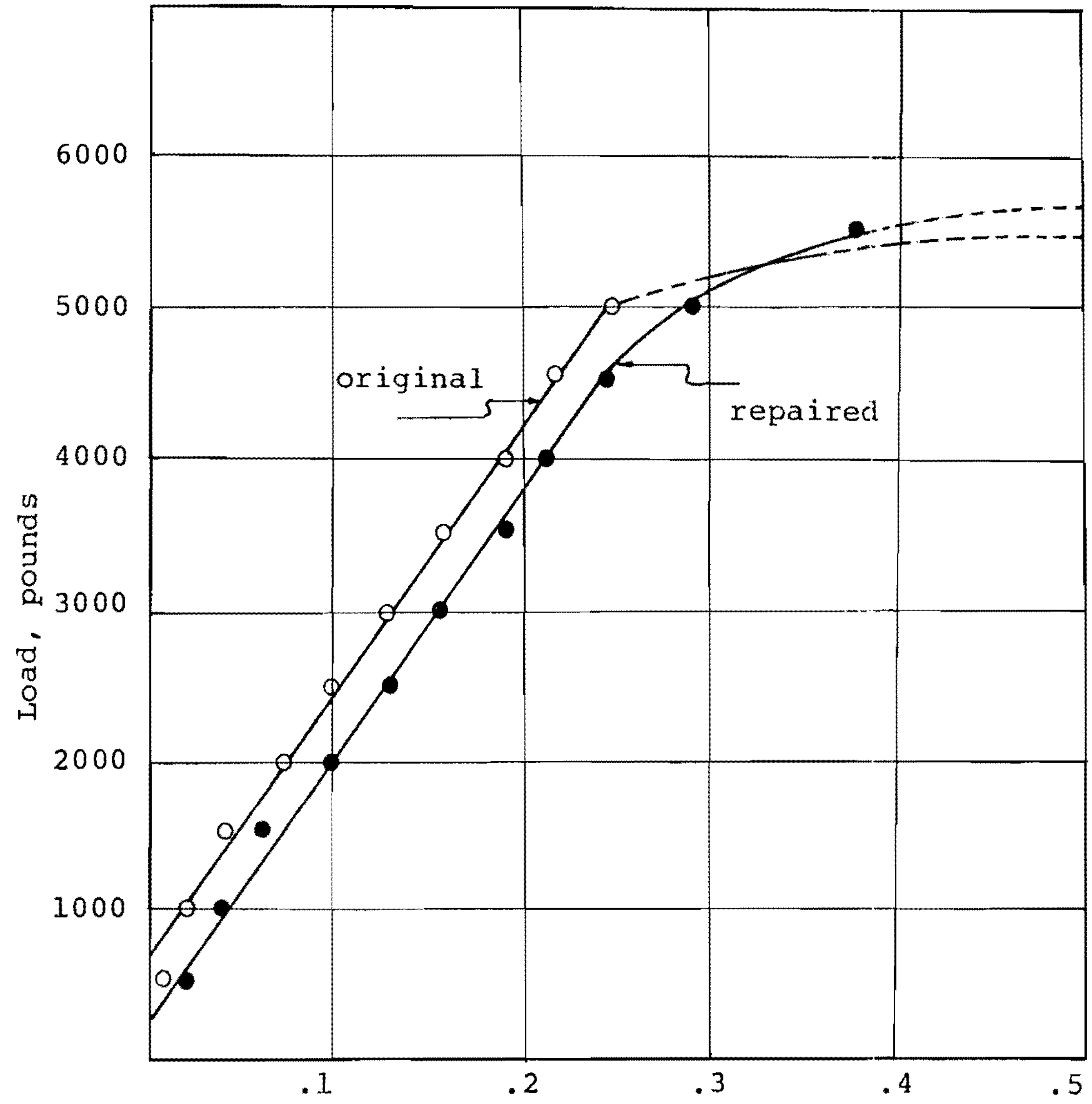
FIG. 4.9 BEAM 1RC-4

was 1.12. As evidenced by the similar load-deflection curves of the original and the repaired beam, there was no change in the flexural stiffness (Fig. 4.10).

4.3.4 Beam 2RC-23--This beam had a diagonal tension and end anchorage failure in the original loading and a diagonal tension failure, adjacent to the old failure, after the repair. Fig. 4.11 shows the two failure modes. Fig. 4.12 shows the load-deflection response for the beam originally and after repair. There was a slight change in the stiffness of the beam but it was not of a significant magnitude. The strength ratio of this beam was approximately unity.

4.3.5 Beam 3RC-4--Beam 3RC-4 had a flexural failure in the original loading and a similar failure after repair but at different locations. Fig. 4.13 shows that the stiffnesses of the two beams were nearly the same. The strength ratio of the beam was 1.09. Fig. 4.14 indicates that the failure occurred adjacent to the repaired zone.

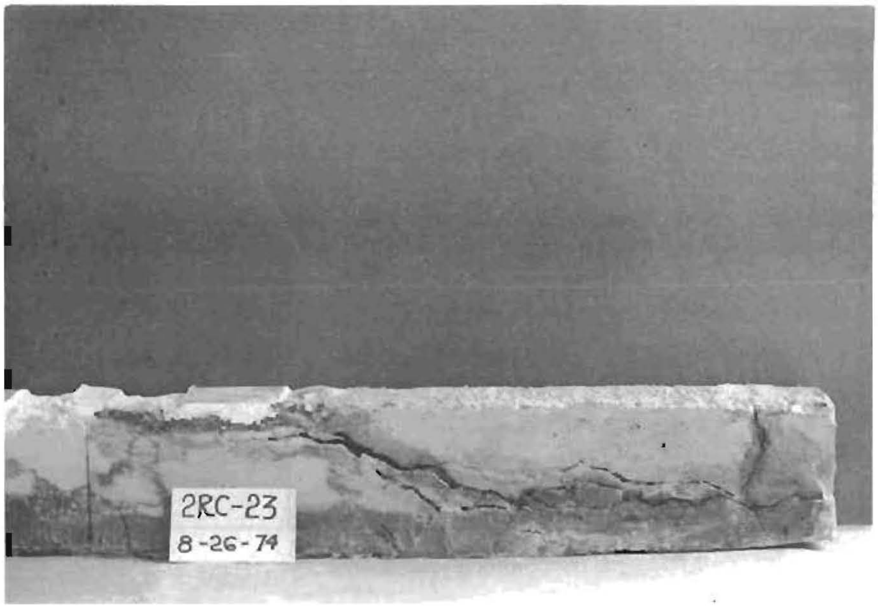
4.3.6 Beam 1RC-14--This beam had a flexural failure in the first loading. The failure mode after the repair was similar to the first but at a different location. Fig. 4.15 shows repaired beam 1RC-14 after failure. The strength ratio was 1.05. The load-deflection response is shown in Fig. 4.16 accompanied with the load-deflection response of beam 1RC-7 for purposes of comparison. There probably was a slight reduction in stiffness since the accompanying beam was made from the same concrete batch as 1RC-7, yet the difference in slopes is insignificant, as concluded from Fig. 4.16.



Centerline Deflection, in.

FIG. 4.10 LOAD-DEFLECTION RESPONSE OF BEAM 1RC-4

a) Original Failure Mode



b) Failure Mode After Repair

FIG. 4.11 BEAM 2RC-23

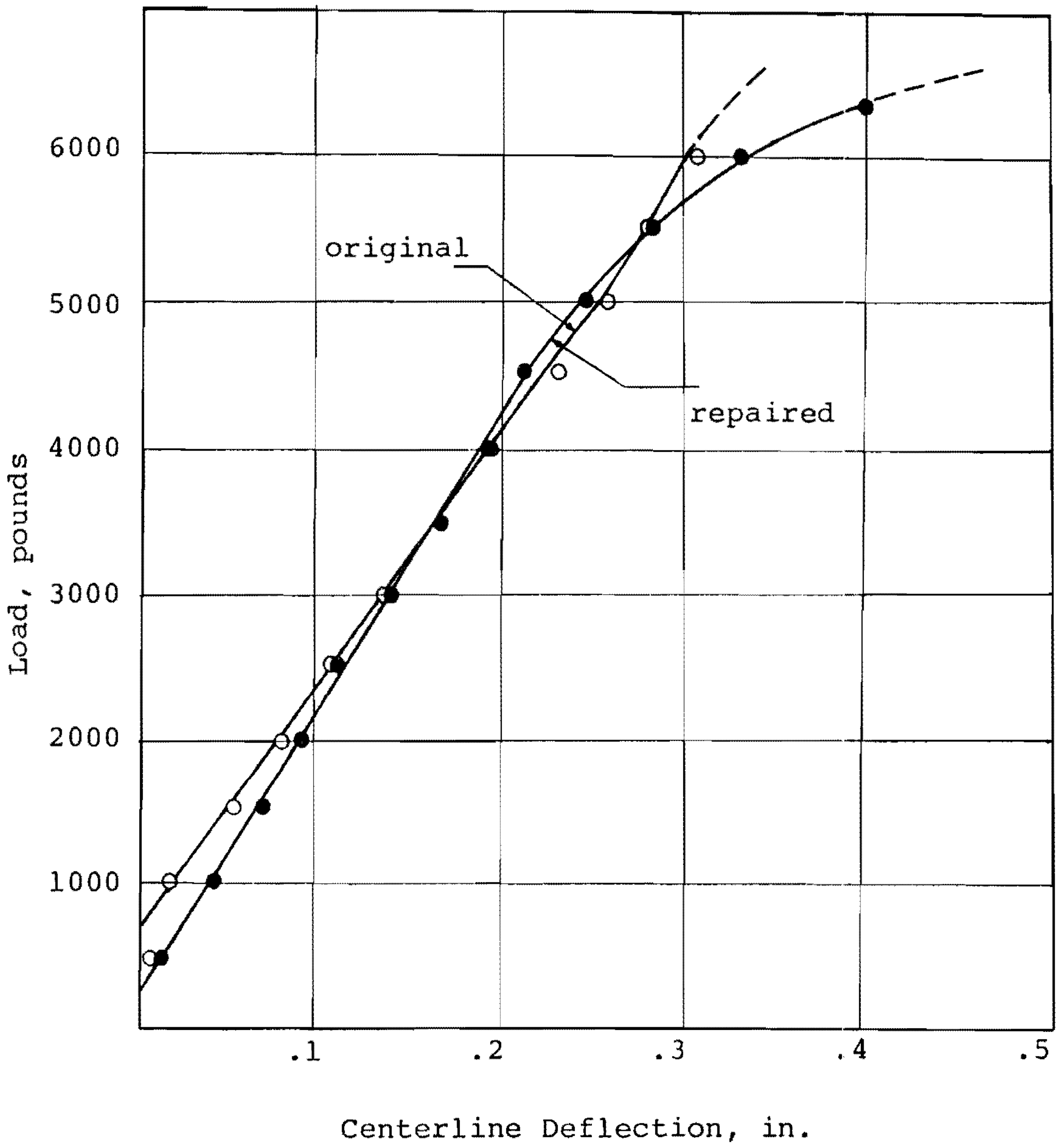


FIG. 4.12 LOAD-DEFLECTION RESPONSE OF BEAM 2RC-23

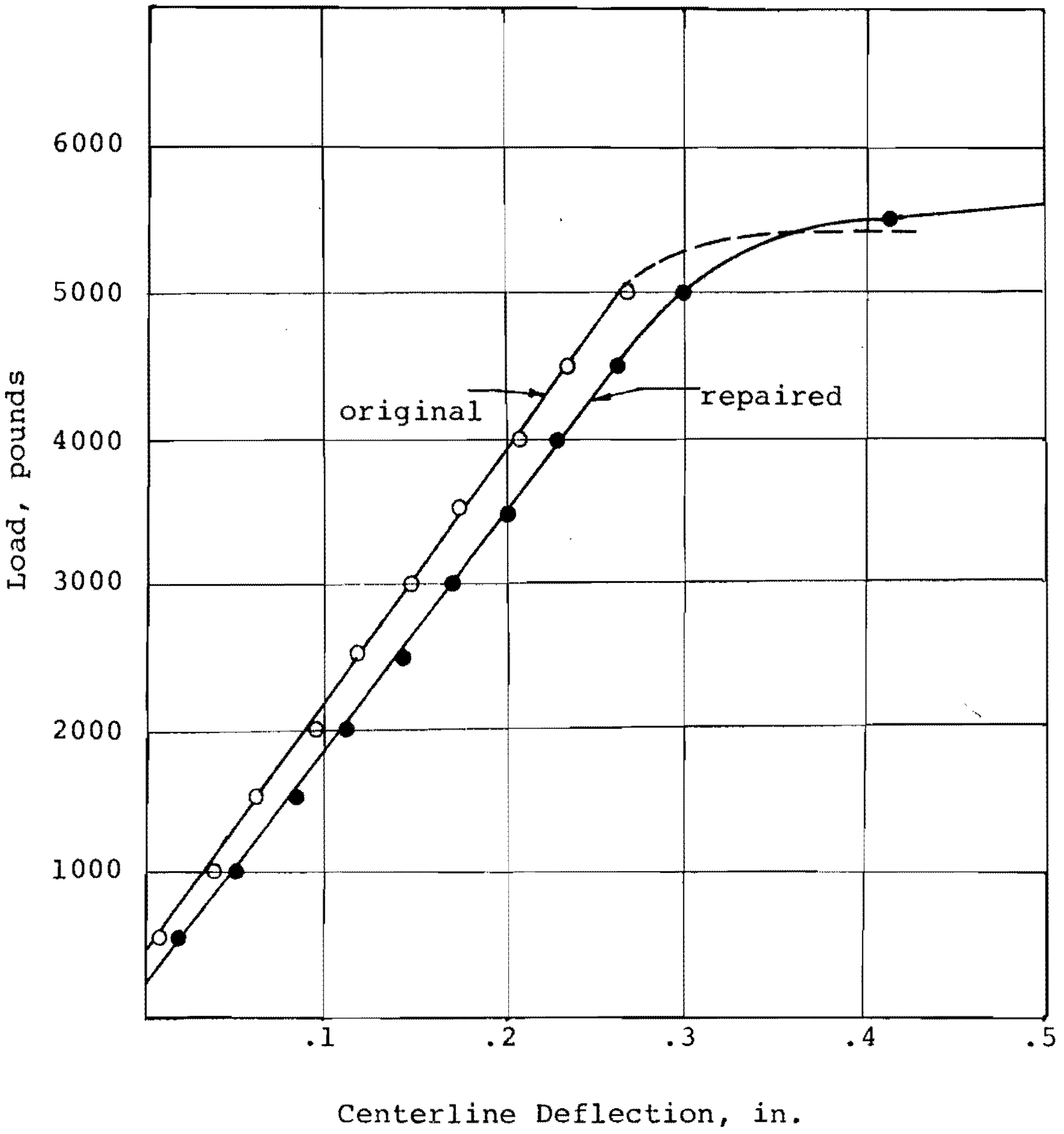


FIG. 4.13 LOAD-DEFLECTION RESPONSE OF BEAM 3RC-4

FIG. 4.14 FAILURE MODE OF REPAIRED BEAM 3RC-4

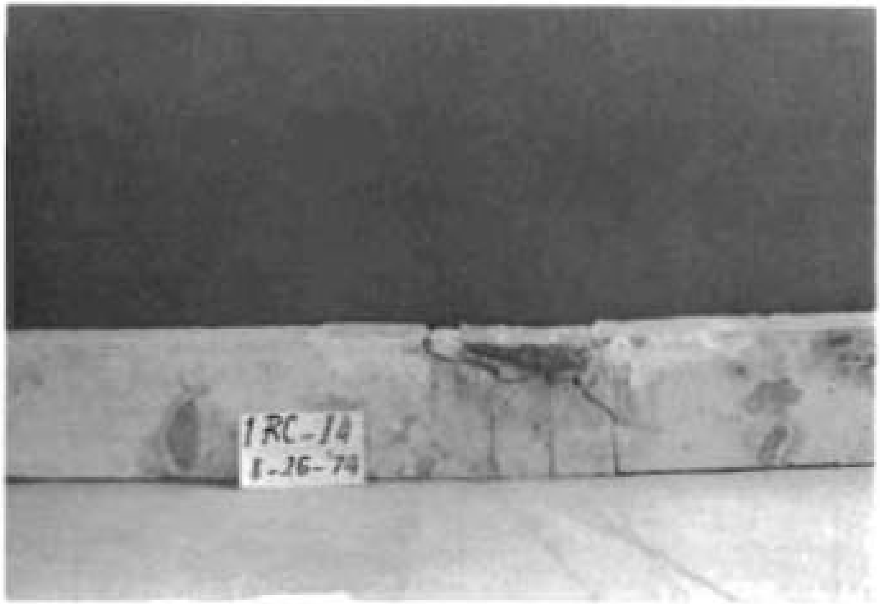


FIG. 4.15 FAILURE MODE OF REPAIRED
BEAM IRC-14

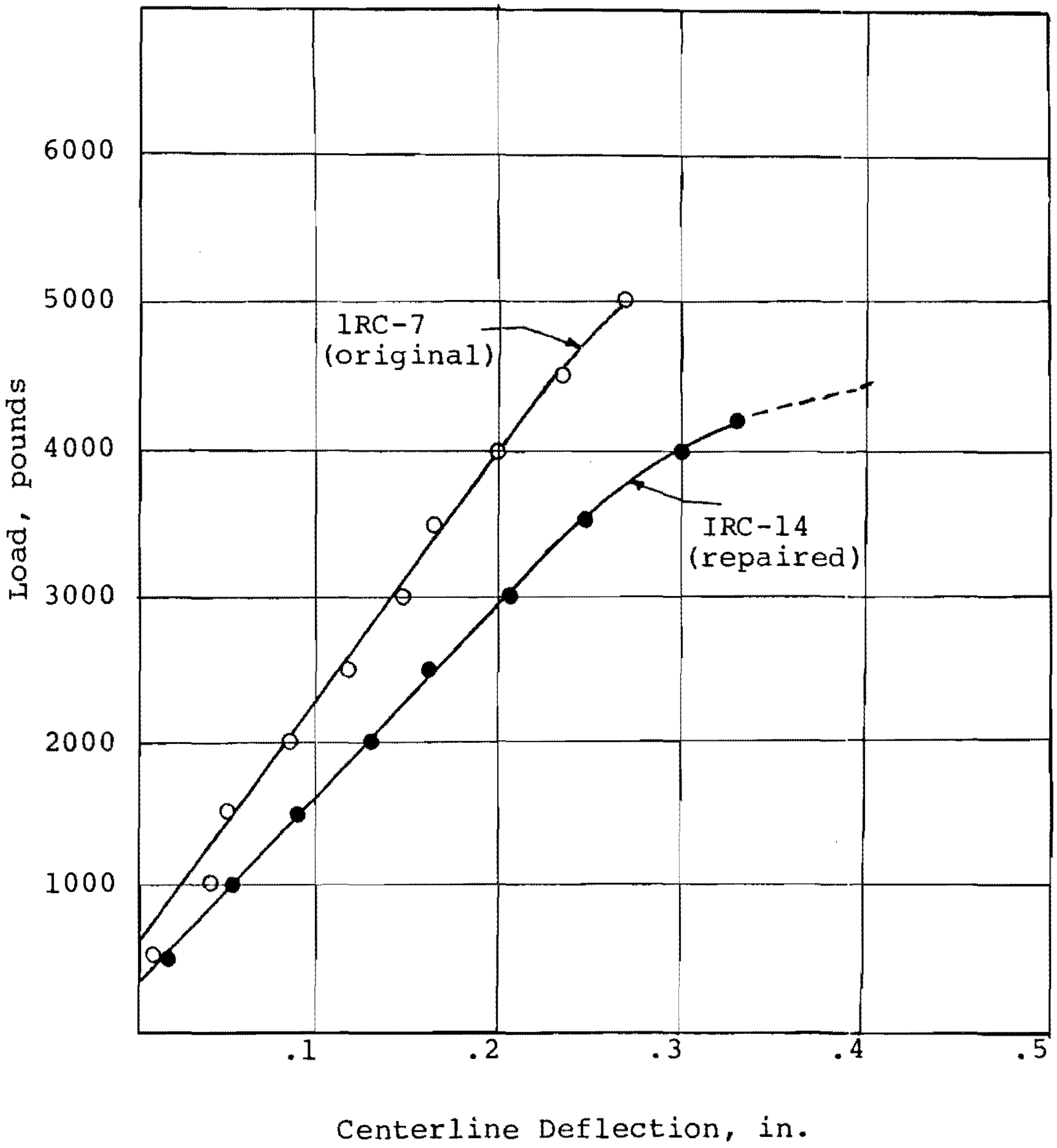


FIG. 4.16 LOAD-DEFLECTION RESPONSE OF BEAM 1RC-14

4.4 Summary of the Beam Tests

Although this study did not investigate all of the variables involved in beam repair, some general conclusions can be drawn from it:

(1) The flexural stiffness was not significantly affected by the repair as evidences by deflections;

(2) The levels of deflections are approximately the same before and after the repair; and

(3) There was a 5% average increase in strength, which might be attributed to the higher strength polymer-concrete that usually reinforced the weakest zone in the beam which permitted the beam to support more load.

CHAPTER 5.

Freeze-Thaw Durability

5.1 Introduction

Several series of freeze-thaw tests have been conducted to investigate the durability and behavior of repaired concrete. Factors that showed significance in the strength studies, mentioned in Chapter 3, were investigated here. The tests were performed on 6 in. x 10 in. x 10 in. slabs of normal weight concrete. Three specimens were used to investigate each parameter. A summary of the concrete mix design and strengths is found in the Appendix.

5.2 Test Procedure

All slabs used in freeze-thaw testing were oven dried at 210° F ± 10° F for a period of approximately seven days. After drying, the slabs were removed from the oven and broken in half, and the two halves were separated by the desired crack width using references previously inscribed on each slab. A sheet metal form was then placed around the bottom and sides of the crack using silicon adhesive. The monomer was applied and replenished whenever necessary. A summary of the treatments used in the freeze-thaw specimens is shown in Table 5.1.

TABLE 5.1

TREATMENTS OF FREEZE-THAW SPECIMENS

Specimen No.	Crack Width	Crack Treatment	Surface Treatment	Crack Filler
PC-41-C1 control	None	None	None	None
PC-41-C2				
PC-41-C3				
PC-41-F1	1/2 in.	MMA + 4% LP + 2% DMPT	None	Sand
PC-41-F2				
PC-41-F3				
PC-41-CW1	1/4 in.	MMA + 4% LP + 2% DMPT	None	None
PC-41-CW2				
PC-41-CW3				
PC-41-CW4	1/2 in.	MMA + 4% LP + 2% DMPT	None	None
PC-41-CW5				
PC-41-CW5				

TABLE 5.1 (Cont'd)

Specimen No.	Crack Width	Crack Treatment	Surface Treatment	Crack Filler
PC-41-IBA1 PC-41-IBA2 PC-41-IBA3	1/4 in.	60 MMA + 40% IBA + 4% LP + 2% DMPT	None	None
PC-41-ST1 PC-41-ST2 PC-41-ST3	1/4 in.	MMA + 4% LP + 2% DMPT	MMA + 1% BP + 10% TMPTMA (steam cured)	(Sand for cover)

After the monomer had polymerized, the forms were removed and the vertical surfaces of the slabs were coated with epoxy to prevent moisture intrusion from the sides to simulate the interior of a large slab. After the epoxy cured, an 8-in. diameter metal ring was bonded to the top surface of each slab with silicon adhesive. At this time four stainless steel reference tabs were bonded to the repaired side of the slab in pairs, 1/2 in. below the top surface and 1/2 in. above the bottom surface, with a gauge length of 8 in. Next, the specimens were cured for 24 hours at 76° F ± 3° F, after which initial horizontal length measurements were taken by use of an 8-in. Berri gauge (10).

Each freeze-thaw cycle consisted of overnight freezing at -15° F ± 5° F followed by an 8-hour thaw. Prior to each freeze cycle, tap water was added as needed to maintain a depth of 1/4 in. within the metal rings throughout the test period. The first freeze-thaw cycle was conducted with each specimen in the dry condition after which the testing was continued with ponded water. In order to provide numerical as well as visual data concerning the condition of the test specimens during freeze-thaw exposure, strain readings were made periodically.

5.3 Test Results

Test results have revealed three possible failure mechanisms. The first mechanism is the inability of the polymer filling the crack to hold water due to an initial poor treatment. The second mechanism is the cracking of the concrete at the interface of the polymer and the concrete. The third mechanism is the cracking of the concrete in the sides and bottom of the slab. The second and third mechanisms are shown in Fig. 5.1. Visual observations have revealed that the cracking of the concrete was generally more severe on the sides along the repaired crack than on the sides perpendicular to the crack. The specific results of each test on each parameter investigated are summarized in the following discussion.

5.3.1 Effect of crack width--Two crack widths, 0.5 in. and 0.25 in., were investigated. Two of the specimens with the 0.5-in. crack width without filler failed to hold water after 15 cycles of freeze-thaw, possibly due to the boiling that occurred during the treatment, which provided a very porous polymer repair. The other specimen with the 0.5-in. crack was able to sustain 27 cycles of freeze-thaw after which it started losing water through a crack in the interface of the concrete and polymer. Cracks started to form on top of the concrete and propagated along the surface and the sides of concrete until failure occurred.

The specimens with the 0.25-in. cracks were able to hold water until failure of concrete occurred, at 31 cycles of freeze-thaw. Cracks in the concrete started to propagate after 22 cycles of freeze-thaw. The cracks occurred on all sides along which the crack was treated.

Fig. 5.2 compares the top strains of the specimens with the 0.25-in. and 0.5-in. cracks to those of the control specimens. It can be observed that the repaired slabs exhibited more volumetric stability than the

a) Cracking at Interface (Side View)

b) Severe Cracking of Freeze-thaw Specimens (Side View)

FIG. 5.1 FAILURE MECHANISMS IN FREEZE-THAW SPECIMENS

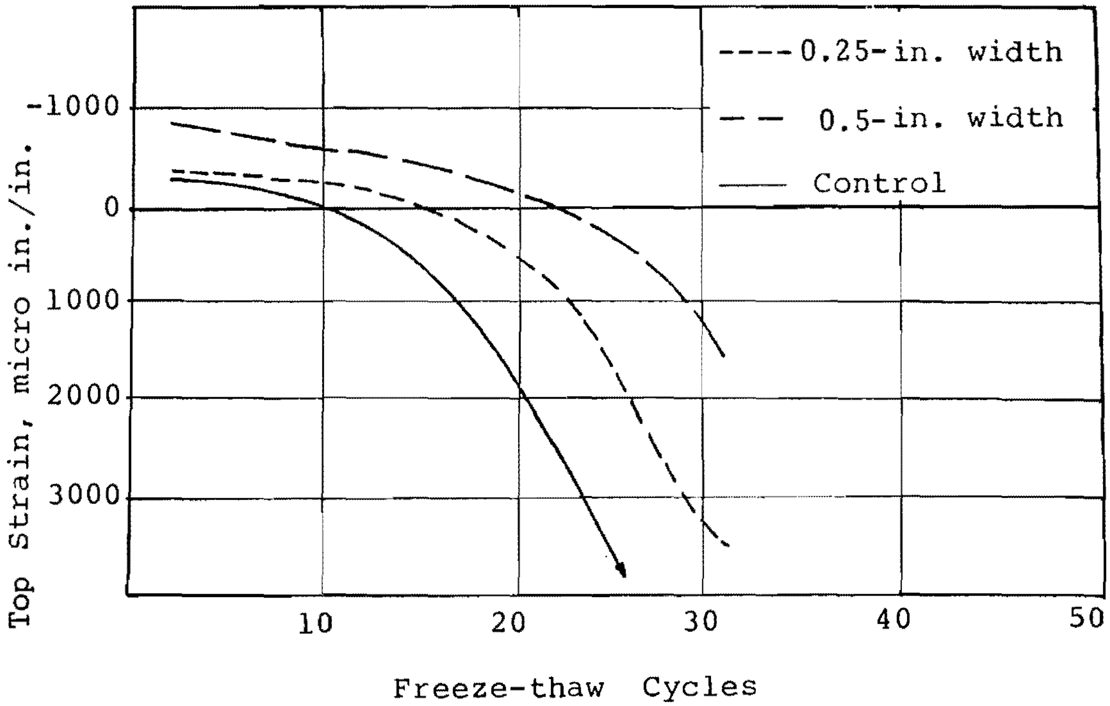


FIG. 5.2 EFFECT OF CRACK WIDTH ON FREEZE-THAW VOLUMETRIC STABILITY

control slabs, although it appears that the specimens with the 0.5-in. crack width exhibited more stability than slabs with the 0.25-in. crack as failure of concrete approached.

5.3.2 Effect of isobutyl acrylate--Failure of the specimens treated with a combination of MMA (60%) and IBA (40%) occurred at 31 cycles of freeze-thaw as did the specimens treated with MMA alone. The failure of these specimens occurred in concrete, following the same mechanism as in the specimens treated with MMA with the same crack width. Fig. 5.3 shows that specimens treated with IBA-MMA had volumetric stability similar to that of those treated with MMA alone.

5.3.3 Effect of fillers--Specimens treated using a sand filler with MMA failed at 31 cycles as did the control specimens. Failure of those specimens occurred in concrete, following the same mechanism as the control specimens. Fig. 5.4 shows that the specimens repaired using clean dry sand as a filler and MMA were less stable than those treated with MMA alone but more stable than the control specimens. The initial strains both top and bottom were smaller than in the MMA treated specimen yet larger than in the control specimens.

5.3.4 Effect of a surface treatment--The specimens used in this study had 0.25-in. cracks repaired with MMA, 4% (wt.) LP, and 2% (wt.) DMPT. After the specimens were repaired, they were oven dried at 220° F ± 10° F for a period of one week. Next, the top surfaces of the specimens were partially impregnated with a monomer solution consisting of MMA,

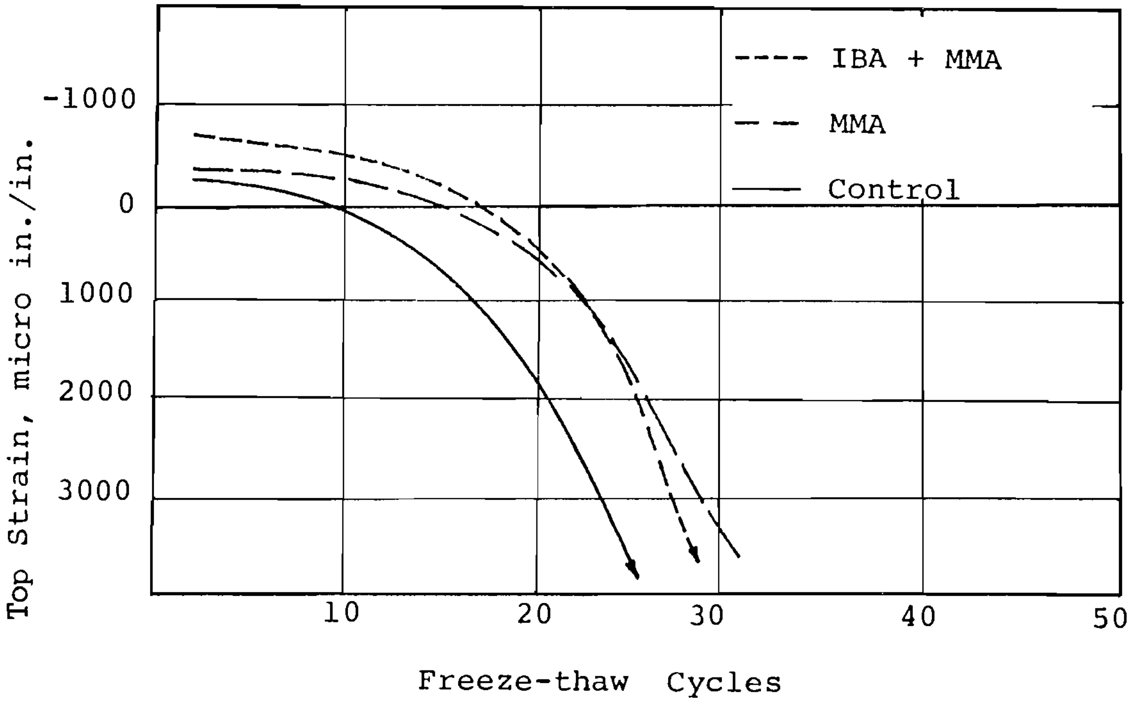


FIG. 5.3 EFFECT OF IBA ON FREEZE-THAW VOLUMETRIC STABILITY

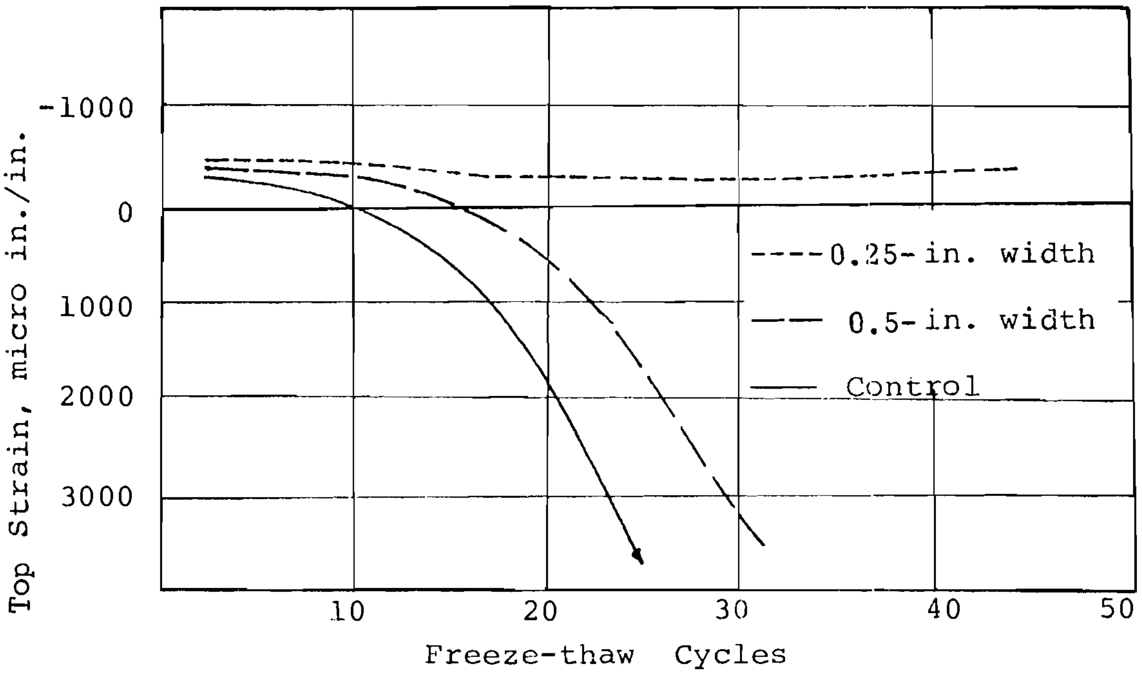


FIG. 5.4 EFFECT OF SURFACE TREATMENT ON FREEZE-THAW VOLUMETRIC STABILITY

1% (wt.) benzoyl peroxide, and 10% TMPTMA. The soaking period lasted for about ten hours, after which the specimens were steam cured for 80 minutes.

Slabs with treated 0.25-in. cracks and MMA surface treatment showed more stability than all the other treatments. The specimens have sustained 50 cycles of freeze-thaw without failure. Fig. 5.5 compares the top and bottom strains versus the number of cycles. The figure shows that the top initial strain was slightly higher for the surface treated slabs than for the control and for the specimens with the same crack width. The initial bottom strain was almost equal to the strain in the control specimens and in the non-impregnated slabs with the same crack width.

5.3.5 Summary of differential strains--Fig. 5.6 shows the difference between the top and bottom strains of each test versus the number of cycles of freeze-thaw. The strain difference is assumed positive if the top strain is larger than the bottom strain. From the figure it is apparent that the specimens with the highest positive strain differential were the slabs with the surface treatment. It also appears that the specimens with the highest negative strain differential were the slabs treated with IBA and MMA. The slabs with the surface treatment showed less change in strain differential than all the others. It might be of interest to note that the maximum strain differential usually occurred between 22 and 30 cycles of freeze-thaw, excluding the surface treated slabs. Other than the surface-treated slabs, slabs treated with MMA alone, with both 0.5-in. and 0.25-in. cracks, had the

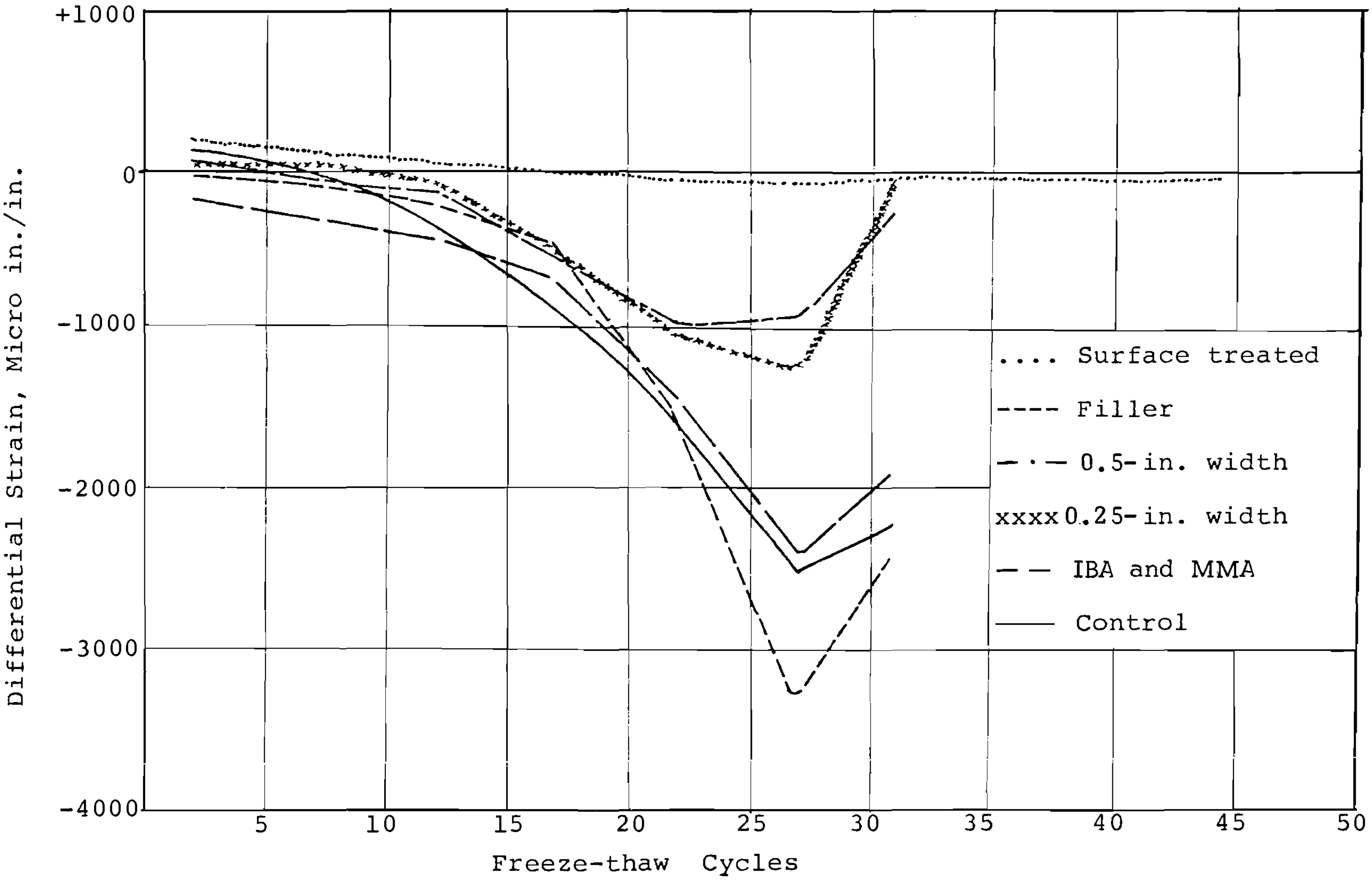


FIG. 5.6 COMPARISON OF DIFFERENTIAL STRAIN

smallest maximum strain differential. Specimens with the MMA and sand filler had the largest maximum strain differential, which was more than three times as great as for the slabs with the same crack width but without filler.

CHAPTER 6.

Crack Repairs on Actual Structures

6.1 Introduction

To evaluate the laboratory results under field conditions, some field treatments have been performed. The treatments included two bridge abutments with various sizes of cracks. The details of each treatment along with descriptions of each abutment are summarized in this chapter. All bridges treated are located in southeast Austin.

6.2 Bridge S36-T72

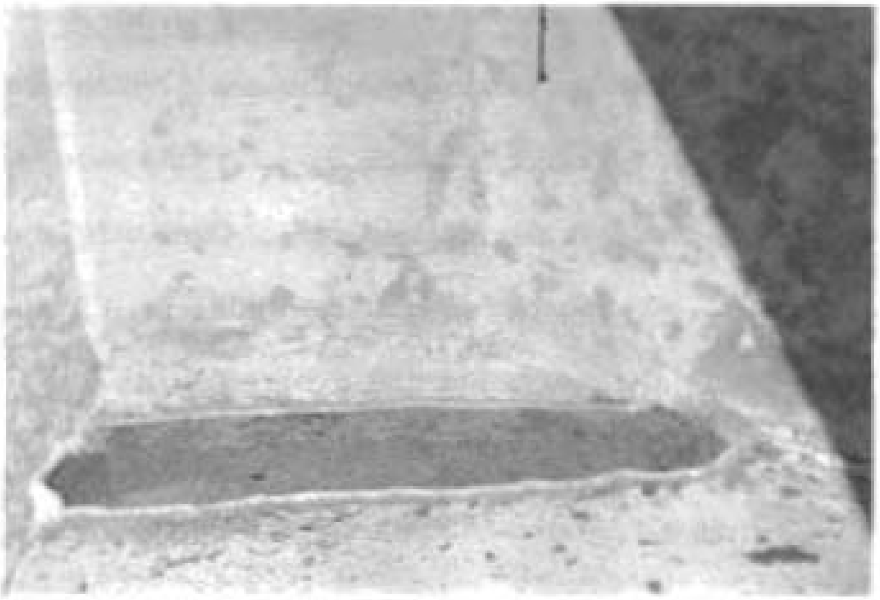
Both abutments of the bridge were cracked on both ends, apparently due to the differential settlement of the wing walls and abutments. The drilled shafts supporting the wing walls are not as deep as those supporting the abutments. The west side of the abutment had a single crack (Fig. 6.1), which varied in width between 1/2 in. and 2-1/2 in. and apparently continued all the way to the bottom of the abutment. One steel reinforcing bar could be seen about 2-1/2 in. from the top of the abutment. The east side of the abutment had several cracks of lesser width (Fig. 6.2). Some of the cracks continued down but some stopped at about 5 in. from the top. The crack was repaired in December 1973.

FIG. 6.1 CRACKING ON THE WEST SIDE OF ABUTMENT OF BRIDGE S36-T72

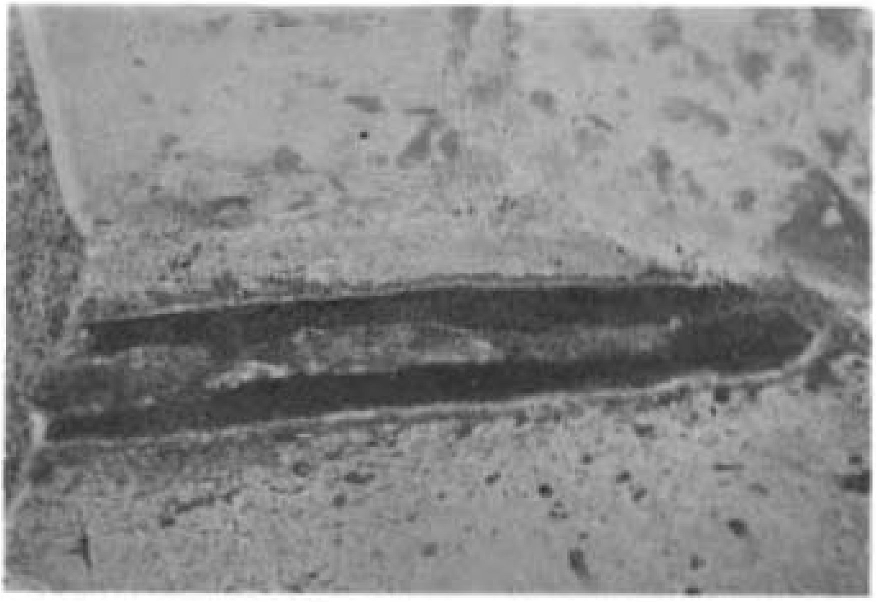
FIG. 6.2 CRACKING ON THE EAST SIDE OF ABUTMENT OF BRIDGE S36-T72

6.2.1 Repair procedure--First the surfaces of the cracks were brushed with a wire brush and then the cracks were washed several times with water. Next, the vertical surfaces where the cracks intersected were sealed with silicon adhesive to prevent the monomer from leaking. Using the same adhesive, a shallow dike was formed around the crack to contain the monomer (Fig. 6.3a). The crack was covered with polyethelene and left for two days, for the adhesive to harden. Two days later, the major crack was filled with clean oven-dried sand to minimize the amount of monomer to be used. The monomer solution was applied to the crack and replenished as necessary. The monomer solution consisted of MMA mixed with a polymer, Rohm and Haas Acryloid B-44, in the approximate proportion of one gram of polymer to 3 ml. of MMA. The polymer was used to increase the viscosity of the monomer, which reduced the amount of monomer wasted through leakage and evaporation. The monomer-polymer solution was mixed with 4% (wt.) LP and 2% (wt.) DMPT. Approximately 25 minutes later, the solution started to react, accompanied by boiling on the surface (Fig. 6.3b). The reaction was complete about 15 minutes later. The repair of the large crack used up about 1500 ml. of the solution. The air temperature during the treatment was about 65° F and it was windy and partly cloudy.

6.2.2 Observations--Three months later it was observed that the polymer concrete in the large crack in the west side of the abutment was starting to develop a hair-line surface crack. It was also observed that the area of concrete near the crack was starting to develop new cracks. The



a) West Side With Sand and Adhesive Dike Around the Crack



b) West Side After Treatment

FIG. 6.3 REPAIR OF BRIDGE S36-T72

cracks were continuous and were about 5 to 6 in. from the edge of the original crack. There were no cracks in the polymer on the east end.

Observations made nine months after the repair indicated that the cracks on the surface of the major crack on the west side were increasing and apparently going deeper in the repaired zone. There was no change in the concrete cracks which occurred after the treatment. In the east side, the top layer of polymer was starting to develop very fine superficial cracks.

One year after the repair was made the repair appeared to be stabilized. The crack width on the west side (Fig. 6.4) was one mm or less; on the east side the crack width was less than one mm.

6.3 Bridge SS44-T50

Both abutments of this bridge were cracked in a manner similar to bridge S36-T72 and apparently due to the same cause. One abutment of this bridge was treated on both sides. The west side of the abutment had one crack varying in width between 0.1 in. and 3 in. In the same side of the abutment, there was another crack with a 0.25-in. width that joined with the major crack (Fig. 6.5a). Apparently all the cracks continued all the way down to the bottom of the abutment. The cracks in the east side of the abutment are shown in Fig. 6.5b. The repairs were made in August 1974.

6.3.1 Repair procedure--The cracks were first cleaned with an air compressor, and then clean dry sand was used to fill the cracks. Next, the

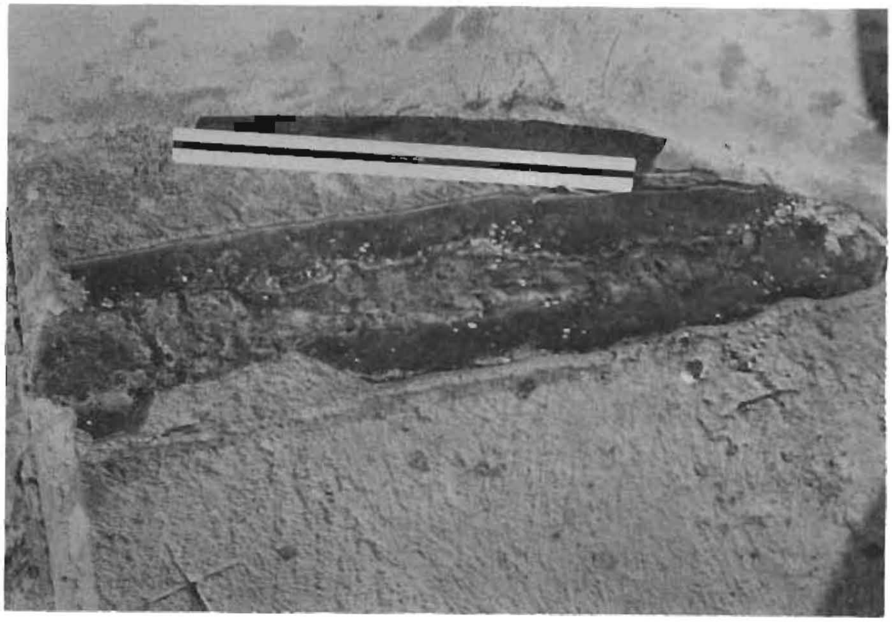


FIG. 6.4 BRIDGE S36-T72 ONE YEAR AFTER REPAIR

a) Cracking on the West Side

b) Cracking on the East Side

FIG. 6.5 ABUTMENT OF BRIDGE S44-T50

cracks were sealed with silicon adhesive in the same manner as for the first bridge abutment. Ten days later, the monomer solution was applied to the crack (Fig. 6.6). For the west side of the abutment, the monomer solution used contained 40% (wt.) MMA and 60% (wt.) IBA as the monomer and 4% (wt.) LP and 2% (wt.) DMPT. The IBA was used, based on the results summarized in Chapter 2, to increase the ductility of the polymer. For the east side of the abutment the monomer system contained MMA, 4% (wt.) LP and 2% (wt.) DMPT. Neither treatment contained any polymer, due to its lack of ductility. The west side of the abutment used up about 4500 ml. of monomer. The air temperature was about 85° F with sunny and calm conditions. A photograph of the west side of the abutment after treatment is shown in Fig. 6.7.

It was observed in this case that the flow of monomer was much faster than in the previous field study. It was also observed that the quantity of monomer used was more than the previous study for similar size cracks. These observations indicate that a more viscous monomer might result in more savings in the quantity of monomer used.

6.3.2 Observations--Observations in January 1975 indicated no visible cracks in the repair on the west side. On the east side, very fine cracks (<< 1 mm) were observed (Fig. 6.8).

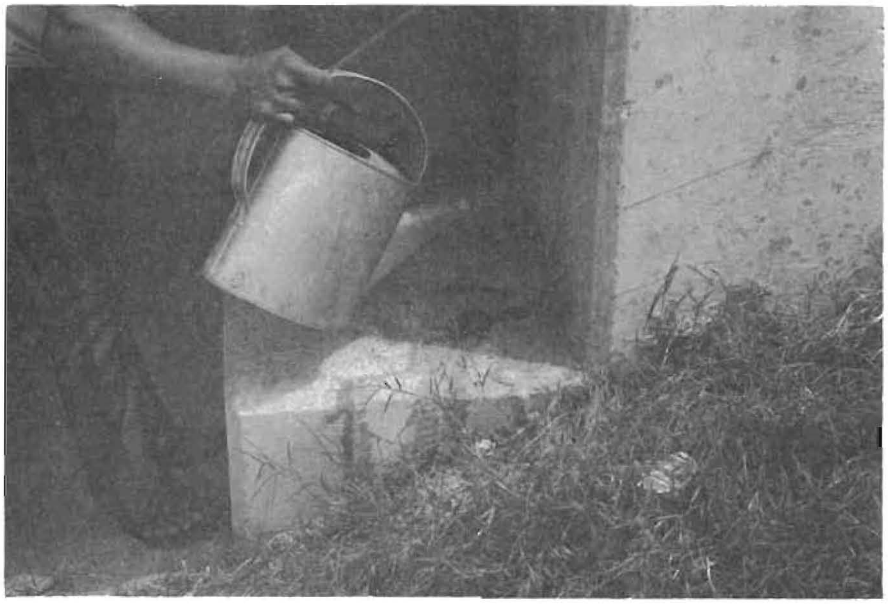


FIG. 6.6 APPLICATION OF THE MONOMER

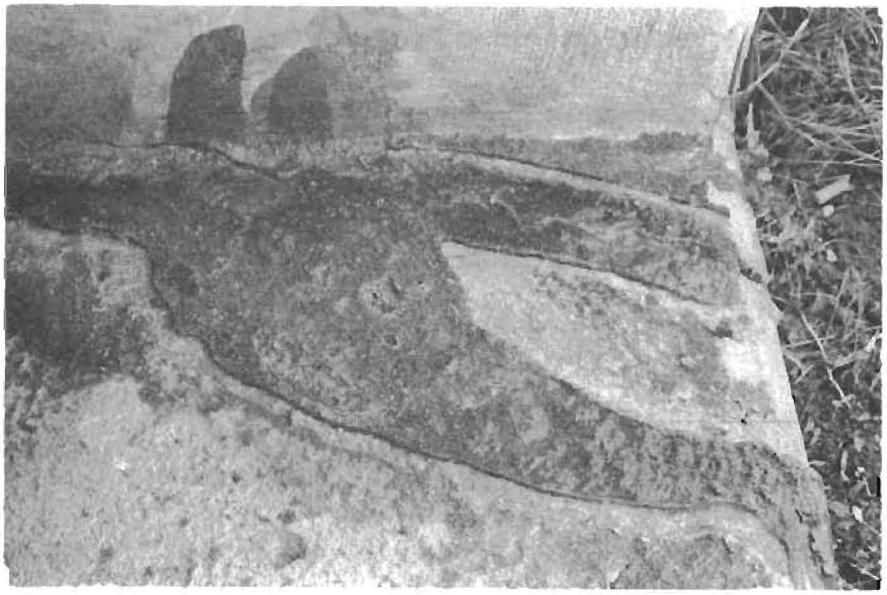


FIG. 6.7 THE WEST ABUTMENT OF BRIDGE S44-T50
AFTER TREATMENT

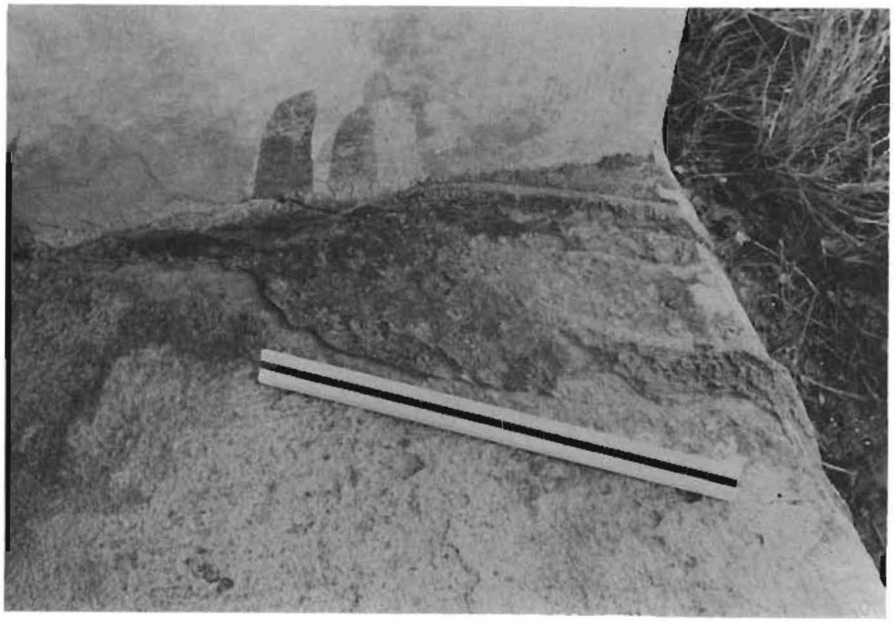


FIG. 6.8 WEST END REPAIR OF BRIDGE S44-T50 AFTER FIVE MONTHS

CHAPTER 7.

Conclusions and Recommendations

7.1 Conclusions

The repair of cracks in concrete has been investigated using catalyzed monomer systems that are subsequently polymerized. Several conclusions may be drawn from the study.

(1) A limited study of monomer systems indicated that MMA or MMA and IBA with 4% (wt.) catalyst (LP) and 2% (wt.) accelerator (DMPT) can restore the flexural strength to a plain concrete beam. Large percentages of IBA and small percentages of BA result in reduced strength.

(2) For relative moisture contents of 60% or higher in the concrete, the flexural failure occurred at the interface between polymer and concrete.

(3) For crack widths in the range of 0.05 to 0.20 in., the original flexural strength of the concrete could usually be achieved. For larger crack widths, the strength reduced linearily with increasing width.

(4) Sand fillers were found to reduce the maximum exothernic temperature and increase the time for polymerization to occur. Sand fillers did not reduce the strength of the repair.

(5) Ordinary reinforced concrete beams which had been load tested to failure and repaired with monomer and sand were found to develop slightly higher loads after the repair than initially. The second failure nearly always occurred outside the repaired zone. The flexural stiffness was not found to be reduced.

(6) Freeze-thaw tests of repaired, unreinforced slab specimens indicate that the repaired specimens are at least as durable as control specimens. Repaired surface-impregnated slabs were found to be much more durable for a crack width of 0.25 in. and slightly more durable for a crack width of 0.5 in.

(7) Several cracks in bridge abutments have been repaired. The repairs have proven successful thus far.

7.2 Recommendations

The use of polymers and polymer-concrete appears to provide a very promising repair technique. Additional research is desirable to investigate other aspects of repair procedures. The following studies are recommended:

(1) Determination of the optimum gradation of aggregate to minimize the repair cost.

(2) Investigation of fatigue strength and long-term deflection of repaired beams.

(3) Investigation of repairs on the tension side of beams.

(4) Development of repair techniques for deteriorated or damaged bridge decks.

APPENDIX

TABLE A.1

CONCRETE MIX DESIGN

Concrete Mix No.	Cement[a] %	Water %	Fine Aggregate %	Aggregate %	Coarse Air %	Cement Factor sk/yd^3	Water Cement Ratio gal/sk	Slump in.
21	10.3	18.7	34.0	35.5	1.5	6.9	6.5	6
30	8	17.8	34.8	37.9	1.5	4.5	8	1 3/8-2
38	8.3	18.5	34.3	37.4	1.5	4.7	8	4 1/2-5 1/2
41	8.3	18.5	34.3	37.0	1.5	4.7	8	8

[a] Type I

TABLE A.2

28-DAY TEST RESULTS

Concrete Mix No.	Compressive Strength		Split Tensile Strength	
	3 in. x 6 in. cylinders, psi	6 in. x 12 in. cylinders, psi	3 in. x 6 in. cylinders, psi	6 in. x 12 in. cylinders, psi
PC-21	--	6340	--	560
PC-30	6400	4180	520	420
PC-38	4240	3810	500	470
PC-41	4150	--	570	--
PC-45		3740		470

TABLE A.3

AGGREGATE PROPERTIES

Source: Colorado River, Austin, Texas

Type: Primarily rounded, siliceous river aggregate

SSD Bulk Specific Gravity:

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

Absorption:

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

Sieve Analysis (by ASTM C 136):

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

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