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METHYL METHACRYLATE POLYMER-CONCRETE FOR BOMB DAMAGE REPAIR

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Methyl methacrylate polymer-concrete was investigated for use in bomb-damage repair. A research program was conducted to develop monomer formulations, determine engineering design properties, develop repair procedures, conduct field tests, conduct analytical studies, and develop an implementation manual. An interim report was published in June 1980. Materials characterization studies have described monomer formulation for a wide range of ambient temperature. Strengths have been determined as a function of time from casting, casting temperature, testing temperature, aggregate moisture levels,		

type and size of aggregate, and amount of coarse aggregate. Aggregate moisture (5 percent) was found to result in up to 80-percent loss in modulus of rupture, or 60 percent when steel fibers were used. Shear strength between polymer concrete and asphalt was found to decrease with increasing temperature. The strength was less than 15 psi at 100°F. Shrinkage of polymer concrete was measured. Fatigue strength, measured in the laboratory using different ratios of minimum to maximum bending stress and different ratios of maximum cyclic stress to static modulus of rupture, was found to be comparable to normal concrete. Small concrete slabs repaired with polymer concrete were tested to determine the fatigue characteristics under simulated aircraft wheel loads.

Repair techniques using both user-formulated and commercially-available polymer are proposed. For spalls, the recommended procedure is to inject the user-formulated monomer system into pre-placed aggregate using an in-line mixing system. Small crater and camouflet repairs can be made using a polymer concrete cap for small areas and precast concrete slabs bonded with polymer concrete for large areas. Large crater repairs can be made using precast concrete slabs with either the user-formulated or commercially-available polymer concrete systems mixed in a portable continuous batching facility. A fire during cleanup of the facility emphasized the flammability of methyl methacrylate and the need for adequate safety measures. Several field tests using the repair methods were conducted at the test facility at Tyndall Air Force Base. The repairs were trafficked with simulated aircraft wheel loads.

Analytical studies were conducted to determine stresses in the repair slabs for different repair locations and varying wheel load locations. A wide range of runway support stiffness was assumed. Design curves are presented which can be used with the simplified design procedure for determining the required thickness of repair.

An implementation manual is included in the Appendix. The implementation manual includes information on the required chemicals, aggregates and other materials; monomer formulations; design procedure; mixing and placing; repair methods; and safety and handling.

PREFACE

This report was prepared by The University of Texas at Austin, Texas 78712, under contract no. F08635-79-C-0103 with the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, Florida 32403.

This report summarizes work done between June 1980 and September 1981. Captain Michael Mcnerney, Major Thomas E. Bretz, Jr., and Captain Daniel J. Pierre were project officers.

This report discusses laboratory and field testing of a contractor-formulated polymer concrete system and various other prepackaged polymer concrete systems for the repair of damaged runways. It does not constitute an endorsement of any of these products by the Air Force, nor can it be used for advertising the product.

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

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

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TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
I	INTRODUCTION	1
	1.0 Background	1
	1.1 Scope of Research	1
	1.2 Nomenclature and Definitions	2
II	MATERIALS CHARACTERIZATION	5
	2.0 Introduction	5
	2.1 Contractor-Formulated Monomer Systems	5
	2.1.1 Formulations for Varying Ambient Temperature	6
	2.1.2 Strength Gain with Time	7
	2.1.3 Effect of Casting and Testing Temperature	12
	2.2 MMA Prepackaged Polymer-Concrete System	12
	2.2.1 Availability	12
	2.2.2 Typical Properties	17
	2.2.3 Effect of Addition of Aggregate	17
	2.3 Aggregate Type and Gradation	20
	2.4 Effect of Wet Aggregate	23
	2.5 Effect of Asphalt on PC	34
	2.5.1 Test Procedure	34
	2.6 Fatigue Strength	39
	2.7 Thickened Contractor-Formulated Systems	44
	2.8 Shrinkage	55
	2.9 Design Properties	58
III	FIELD TESTS OF RAPID REPAIR METHODS	62
	3.0 Introduction	62
	3.1 Field Tests of Spall Repairs	62
	3.2 Field Tests of Crater Repairs	66
	3.3 Performance of the Concrete Mobile [®]	89
IV	EXPERIMENTAL BEHAVIOR	92
	4.0 Introduction	92
	4.1 Mechanical Behavior	92
	4.2 Fatigue Properties of PC Beams	92
	4.3 Fatigue Tests of PC Repairs	93
	4.3.1 Laboratory Test Equipment	94
	4.3.2 Construction of Test Slabs	94
	4.3.3 Laboratory Test Procedure	97
	4.4 Observations and Results	98
	4.4.1 Slab 4(a)	98
	4.4.2 Slab 4(b)	99
	4.4.3 Slab 4(c)	102
	4.4.4 Slab 4(d)	102

TABLE OF CONTENTS (Continued)

<u>Section</u>	<u>Title</u>	<u>Page</u>
	4.4.5 Slab 4(e)	102
4.5	Computer Simulation of Slabs	106
	4.5.1 Program Input	106
	4.5.2 Input	107
4.6	Stress Analysis	109
	4.6.1 Slab 4(a)	109
	4.6.2 Slab 4(b)	109
	4.6.3 Slab 4(c)	115
	4.6.4 Slab 4(d)	115
	4.6.5 Slab 4(e)	115
4.7	Fatigue Characteristics of Repairs	116
4.8	Conclusions	119
V	ANALYTICAL BEHAVIOR OF REPAIRS	120
	5.0 Background	120
	5.1 Modeling Runway Repair Area	120
	5.2 Sensitivity Study of Variables	125
	5.3 Design Charts	131
	5.4 Design Procedure	138
VI	SUMMARY AND CONCLUSIONS	140
	6.0 Summary	140
	6.1 Conclusions	141
	6.1.1 Materials Characterization	141
	6.1.2 Repair Procedures	143
	6.1.3 Experimental Behavior	143
	6.1.4 Analytical Behavior	144
	6.1.5 Implementation Manual (Proposed)	144
	APPENDIX - IMPLEMENTATION MANUAL (Proposed)	145
	1.0 MATERIALS	146
	1.1 Introduction	146
	1.2 Monomer System	146
	1.2.1 Monomer	146
	1.2.2 Cross-Linking Agent	146
	1.2.3 Inhibitors	147
	1.2.4 Promoter	147
	1.2.5 Initiator	147
	1.2.6 Thickening Agent	148
	1.3 Commercially Prepackaged Polymer Concrete Systems	148
	1.4 Steel Fibers	148
	1.5 Mold Release Agents	149
	1.6 Caulking Compounds	149
	1.7 Methylene Chloride	149

TABLE OF CONTENTS (Continued)

<u>Section</u>	<u>Title</u>	<u>Page</u>
1.8	Aggregates	149
1.8.1	Types	149
1.8.2	Gradation	150
1.8.3	Storage and Handling	150
2.0	EQUIPMENT	152
2.1	Introduction	152
2.2	Mixing and Batching Equipment	152
2.2.1	In-Line Mixing Systems	152
2.2.2	Support Equipment	155
2.3	Concrete Mobile Batching Facility	155
3.0	DESIGN PROCEDURE FOR DETERMINING REPAIR DEPTH	157
3.1	Determine Flexural Strength of Polymer Concrete	157
3.2	Correcting for Aggregate Moisture Content	157
3.3	Determine Pavement Thickness	166
4.0	MONOMER SYSTEM	168
4.1	Introduction	168
4.2	Sources and Costs of Chemicals	171
5.0	MIXING OR BATCHING PC	176
5.1	Introduction	176
5.2	In-Line Mixing System	176
5.2.1	Set-Up Instructions	176
5.2.2	Repair Procedure	177
5.2.3	Cleanup	177
5.3	Mobile Concrete Batching Unit (Modified Concrete Mobile®)	178
5.3.1	Setup Instructions	178
5.3.2	Operation of CM	178
5.3.3	Cleanup	179
6.0	REPAIR METHODS	180
6.1	Spall Repairs	180
6.1.1	Alternative Method (Modified Concrete Mobile®)	180
6.2	Crater Repairs	180
6.2.1	Cap Method	180
6.2.2	Precast Method	183

TABLE OF CONTENTS (Continued)

<u>Section</u>	<u>Title</u>	<u>Page</u>
7.0	SAFETY AND HANDLING	185
7.1	Introduction	185
7.2	Physiological Effects and Safety	185
7.3	Flammability and Fire Protection	188
7.4	Storage and Handling	188
ANNEX TO APPENDIX-DETERMINATION OF INHIBITOR CONCENTRATION IN MONOMERS BY THE PEAK EXOTHERM METHOD		194
A.	Introduction	194
B.	Equipment and Reagents	194
C.	Procedure for Preparation of HQ-Free Material	195
D.	Procedure	195
REFERENCES		199

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	Required Levels of BzP and DMT for Curing With All Materials at Ambient Temperature	8
2	Required Levels of BzP and DMT for Curing With Aggregate at Ambient and Monomer at Room Temperature	10
3	Temperature and Compressive Strength Versus Time (0 to 9 Hours)	11
4	Compressive Strength Versus Time (0 to 4 Months)	13
5	Modulus of Rupture for Varying Casting and Testing Temperature	14
6	Compressive Stress Versus Strain as a Function of Casting Temperature	15
7	Compressive Strength as a Function of Loading Rate	16
8	Modulus of Rupture of Silikal [®] R7/Bw as a Function of Casting Temperature and Cure Time	18
9	Effect of Varying Aggregate Content on Modulus of Rupture of Silikal [®] R7/Bw	19
10	Splitting Tensile Strength for Varying Aggregate Size and PC System	21
11	Effect of Moisture on Compressive Strength of PC With Silicious and With Limestone Aggregate	22
12	Effect of Aggregate Moisture on Splitting Tensile Strength of PC With Silicious and With Limestone Aggregate	25
13	Effect of Moisture on Splitting Tensile Strength of Silikal [®] R7/Bw	26

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
14	Effect of Silane Coupling Agent-Coated Aggregate on Splitting Tensile Strength of PC Made With Wet Aggregate	28
15	Effect of Steel Fibers on Compressive Strength of PC Made With Wet Aggregate	29
16	Effect of Steel Fibers on Splitting Tensile Strength of PC Made With Wet Aggregate	30
17	Comparison of Properties of PC Made With and Without Fibers	32
18	Effect of Moisture on Modulus of Rupture of Silikal [®] R7/Bw and Crylcon [®]	33
19	Load-Deflection Response of PC Beams Made With and Without Steel Fibers	35
20	Typical Specimen for Pull-Out Test	37
21	Ultimate Shear Stress Versus Ambient Temperature	38
22	Ultimate Shear Stress of Various Viscosity Formulations	40
23	Log-Log Plot of Stress Versus Number of Cycles Diagram for $f_{min}/f_{max} = 0.25$	45
24	Log-Log Plot of Stress Versus Number of Cycles Diagram for $f_{min}/f_{max} = 0.10$	46
25	Log-Log Plot of Stress Versus Number of Cycles Diagram for $f_{min}/f_{max} = 0.05$	47
26	Comparison of Laboratory Fatigue Tests	48
27	Monomer Content vs Peak Exotherm of PC With MMA 97:TMPTMA 3 (wt %)	50
28	PMMA Content vs Peak Exotherm of PC	51
29	Strength as a Function of Monomer Content	52
30	PMMA Content vs Splitting Tensile Strength of PC	53

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
31	PMMA Content vs Compressive Strength of PC	54
32	Elapsed Time vs Setting Shrinkage of Polymer Concrete	56
33	PMMA Content vs Setting Shrinkage of Polymer Concrete at Peak Exotherm Point and 10 Hours After Cure	57
34	Strength Reduction Factor for PC Made With Wet Aggregate With and Without Steel Fibers	61
35	Typical Spall Repair Sections	63
36	Spalls Before Repair	65
37	In-Line Mixing Gun	67
38	Debris Fill	67
39	Completed Repairs - 4A, 4B, 4C	68
40	Select Fill	68
41	Completed Repairs - 2A, 2B, 2C	69
42	Repair 2B After Traffic	69
43	Repair 5A - No Fines	70
44	Wetted Spall	71
45	Completed Repairs - 5A, 5B, 5C	71
46	Precast Forms	72
47	Quick Release Lift Eye	72
48	Threaded Drage Eye	73
49	Pit No. 2	75
50	Precast Slab Placement	76
51	In-Line Mixing Gun Injecting Monomer Between Precast Slabs	77
52	F-4 Load Cart	77

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
53	C-141 Load Cart	78
54	Profile Measurements	78
55	Pit No. 3	80
56	Concrete Mobile Trailer Unit	81
57	Discharging PC from Concrete Mobile	82
58	Temperature vs Time for PC in Pit No. 3	84
59	Pit No. 1	85
60	Temperature vs Time for 5-in Section of Pit No. 1	86
61	Time Vs Temperature for 8-in Section of Pit No. 1	87
62	Test Slabs Showing Different Repair Configurations	95
63	Fatigue Loading Frame	96
64	Test Slab 4(a)	100
65	Test Slab 4(b)	101
66	Test Slab 4(c)	103
67	Test Slab 4(d)	104
68	Test Slab 4(e)	105
69	Test Slab 4(a) Computer Stress Analysis	110
70	Test Slab 4(b) Computer Stress Analysis	111
71	Test Slab 4(c) Computer Stress Analysis	112
72	Test Slab 4(d) Computer Stress Analysis	113
73	Test Slab 4(e) Computer Stress Analysis, 18 kip Load	114
74	Test Slab 4(e) Computer Stress Analysis, 27 kip Load	117

LIST OF FIGURES (Continued)

<u>Figures</u>	<u>Title</u>	<u>Page</u>
75	Runway Repair	121
76	Aircraft Load and Gear Configurations	123
77	Horizontal Load Position for F-4 and C-141 Aircraft	124
78	C-141 Aircraft Vertical Gear Position	126
79	Stress Versus Runway Support for F-4 Loading 5-x 4.5-Foot Repair and $K_{pc} = 50$ pci	128
80	Maximum Flexural Stress Versus Runway Support for C-141 Loading and 5 x 4.5-Foot Repair	129
81	Maximum Flexural Stress Versus Runway Thickness for 17-x 17-Foot Repair and C-141 Aircraft	130
82	Flexural Stress Versus PC Depth for Edge Loading and $K_{pc} = 300$ pci	132
83	Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Edge Loading	133
84	Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Interior Loading	134
85	Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Edge Loading	135
86	Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Interior Loading	136
2.1	Schematic of Hydraulic Injection System (courtesy of Venus Products, Inc.)	153
2.2	Trailer-Mounted Hydraulic Injection System	154
3.1	Flexural Strength Versus Moisture Content for Example Problem	160

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
3.2	Guidelines for Correcting Flexural Strength for Aggregate Moisture if No Test Data is Available	161
3.3	Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Edge Loading	162
3.4	Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Interior Loading	163
3.5	Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Edge Loading	164
3.6	Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Interior Loading	165
4.1	Required Levels of BzP and DMT for Curing With All Materials at Ambient Temperature	169
6.1	Typical Spall Repair	181
6.2	Typical Cross Section of Small Crater Repair - Cap Method	182
6.3	Precast Repair for Crater	184
A1	Exotherm Versus Time for MMA With 1% BzP	197
A2	Time to Peak Exotherm Versus Inhibitor Concentration for 70°C	198

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
1	Monomer Formulations	3
2	List of Abbreviations and Acronyms	4
3	Modulus of Rupture for 95 percent MMA/5 percent TMPTMA for Curing Temperatures of -20°F and 0°F	9
4	Asphalt Properties and PC Formulations	41
5	Number of Cycles, N, To Failure for Fatigue Beams	42
6	Mechanical Properties for Contractor- Formulated PC Cast and Tested at 77°F	59
4.1	Recommended Levels of DMT and BzP as a Function of Ambient Temperature	168
7.1	Physiological Effects and Protective Measures	186
7.2	Flammability and Precautions	189
7.3	Storage Requirements	191

SECTION I

INTRODUCTION

1.0 Background

Better methods for rapidly repairing runways are continually being investigated by the Air Force Engineering and Services Center (AFESC) at Tyndall Air Force Base (AFB). Current repair procedures¹ are based upon North Atlantic Treaty Organization (NATO) damage criteria which require repairing three 750-pound bomb craters in 1 hour.

New developments in weapons technology alter repair criteria. Currently the threat of many smaller weapons requires that many small and medium-sized craters be repaired in addition to the larger craters.

AFESC is currently engaged in a research and development program to improve the rapid runway repair (RRR) capability. New materials and techniques are being investigated by the Engineering and Services Laboratory at Tyndall AFB. This contract has the objective of developing rapid repair techniques using methyl methacrylate (MMA) polymer concrete (PC).

1.1 Scope of Research

Phase I extended from 1 March 1979 to 30 April 1980 and included the following tasks:

- Task 1: Materials Characterization
- Task 2: Development of Preliminary Repair Concepts
- Task 3: Analytical and Experimental Behavior of MMA
Polymer Concrete

Phase II extended from 1 May 1980 to 30 September 1981 and included the following tasks:

¹ Disaster Preparedness and Base Recovery Planning, AFR 93-2. Washington, D.C.: Department of the Air Force, 1974.

Task 4: Analytical and Experimental Behavior of MMA
Polymer Concrete

Task 5: Finalization of Repair Procedures

Task 6: Field Testing of Repairs

Task 7: Development of Implementation Manual

A report was issued on the research performed in Phase I, which hereafter will be referred to as the Phase I Report².

This report summarizes research in both Phase I and Phase II with emphasis on Phase II. A proposed implementation manual is included in the Appendix.

1.2 Nomenclature and Definitions

Many chemicals can be used in the production of MMA PC. Other monomers can be used to impart desirable properties, such as ductility. Cross-linking agents, which are monomers that possess multiple functionality, can be added to introduce cross linking between polymer chains. In this research cross-linking agents, e.g., trimethylolpropane trimethacrylate (TMPTMA), were used primarily to increase the polymerization (curing) rate. Initiators are used to provide a source of free radicals which are required for polymerization. Benzoyl peroxide (BzP) was the initiator selected for use in this study since it can be accelerated or promoted by the addition of other chemicals referred to as accelerators or promoters, such as dimethyl-para-toluidine.

Table 1 lists the primary monomer formulations used in this research. Table 2 gives the abbreviations for the chemicals. The Phase I Report should be consulted for additional discussion of the chemicals used and the polymerization process.

² Fowler, D.W.; McCullough, B.F.; Meyer, A.H.; and Paul, D.R. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair: Phase I, Report ESL-TR-80-28. Tyndall Air Force Base, Florida: Engineering Services Laboratory, Air Force Engineering and Services Center, June 1980.

TABLE 1. MONOMER FORMULATIONS.

Basic Monomer

MMA

Initiator System

Peroxide Promoter

BP

DMPT

Comonomers

BA AA

EHMA HPMA

IDMA MAA

Cross-Linking Agents

TMPTMA

TTEGDA

Plasticizers

DOP

TABLE 2. LIST OF ABBREVIATIONS AND ACRONYMS.

Monomers

AA	Acrylic Acid
BA	Butyl Acrylate
EHMA	2-Ethylhexyl Methacrylate
HPMA	Hydroxypropyl Methacrylate
IDMA	Isodecyl Methacrylate
MAA	Methacrylic Acid
MMA	Methyl Methacrylate

Initiator Agents

BP (also BPO or BzP)	Benzoyl Peroxide
DMA	Dimethyl Aniline
DMPT (also DMT)	Dimethyl Para Toluidine

Cross-Linking Agents

TMPTMA	Trimethylolpropane Trimethacrylate
TTEGDA	Tetraethylene Glycol Diacrylate

Plasticizers

DOP	Diocetyl Phthalate
TCP	Tricresyl Phosphate

Other Abbreviations and Acronyms

ACC	Asphalt Cement Concrete
AFESC	Air Force Engineering and Services Center
AR	Alkaline-resistant
DCDT	Direct Current Differential Transformer
FAA	Federal Aviation Administration
H.I.S.	Hydraulic Injection System
NATO	North Atlantic Treaty Organization
OSHA	Occupational Safety and Health Administration
PC	Polymer Concrete
PCC	Portland Cement Concrete
PMMA	Polymethyl Methacrylate
RRR	Rapid Runway Repair
SCA	Silane Coupling Agent
UF	User-Formulated
UT	The University of Texas at Austin

SECTION II

MATERIALS CHARACTERIZATION

2.0 Introduction

Task 1 had the objective of developing polymer concrete formulations to satisfy criteria established for rapid runway repair. The primary considerations were to (1) develop monomer formulations that would set in 1 hour or less at temperatures in the range of -25°F to 125°F ; (2) develop monomer formulations that would bond to asphalt and cure in 1 hour or less; (3) determine effects of aggregate types, gradations, moisture content, and temperatures; (4) determine relationship between moisture content of aggregate and strength of the polymer concrete and develop procedures or monomer formulations to permit the use of wet aggregate; and (5) determine flexural strength, modulus of elasticity, and fatigue strength of polymer concrete.

As specified by the contract, only MMA-based PC systems were investigated. Contractor-formulated systems and commercially-available systems were used in the research. The report on Phase I³ presented most of the materials characterization. These results will be summarized in this report, and the Phase I Report should be consulted for more detailed information.

2.1 Contractor-Formulated Monomer Systems

Several comonomers and cross-linking agents were investigated for use with MMA to improve the curing rate and/or ductility⁴. Butyl acrylate (BA) and 2-ethylhexyl methacrylate (EHMA) were monomers added to increase the ductility. TMPTMA and tetraethylene glycol diacrylate (TEGDA) were the cross-linking agents studied to increase the polymerization rate.

³Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair: Phase I.

⁴Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair: Phase I.

However, tests indicated that the benefits of using EHMA or BA with MMA did not warrant the inclusion of an additional monomer. BA provided some increase in ductility, but the noxious odor renders it an undesirable additive. EHMA provided no significant increase in ductility.

The initial tests using the cross-linking agent, TTEGDA, were quite promising. Ductility was about the same for up to 20 percent TTEGDA and actually increased for higher percentages. The addition of TMPTMA resulted in some loss of ductility and tensile strength⁵. However, the use of TTEGDA was ruled out during Phase II because of increasing problems with severe skin irritation caused by direct contact and, in some cases, even with the vapors.

Polymer concrete made with the cross-linking agent TMPTMA has been widely used with good success and it was chosen for further study to develop formulations over a wide temperature range.

2.1.1 Formulations for Varying Ambient Temperature

A formulation of 95 percent MMA/5 percent TMPTMA, including the required levels of BzP and DMT for temperatures between 30°F and 100°F, was presented in the Phase I Report⁶. Additional studies were conducted to determine the proportions of MMA and TMPTMA and the levels of BzP and DMT to provide set times of 1 hour or less at ambient temperatures less than 30°F. Initially, the monomer system was stored at the ambient temperature for 24 hours. Later studies were performed with the monomer maintained at room temperature (~75°F) until just prior to batching.

For polymerization of monomer maintained at ambient temperature, it was necessary to use a monomer system consisting of 10 percent TMPTMA to obtain cure times of one hour or less.

⁵Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair: Phase I.

⁶Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair: Phase I.

The required levels of DMT (promoter) and BzP (initiator) are shown in Figure 1. Up to 15 percent (by weight of the monomer system) of DMT and 5 percent of BzP were required to obtain polymerization.

Additional tests were performed using a 95 percent MMA/5 percent TMPTMA formulation at low temperatures. The monomer was maintained at room temperature; the aggregate was at the ambient temperature. Table 3 indicates the moduli of rupture for various levels of BzP and DMT for temperatures of -20°F and 0°F . For -20°F , the combination of 5 percent BzP and 5 percent DMT produced the fastest set time (30 minutes), but 5 percent BzP and 3 percent DMT produced the highest strength (2035 psi). At 0°F , a combination of 4.5 percent BzP and 2.5 percent DMT resulted in a set time of 47 minutes and a modulus of rupture of 1740 psi. The use of 5.0 percent BzP with 2.5 percent DMT reduced the set time to 26 minutes and the strength to 1650 psi. The 95 percent MMA and 5 percent TMPTMA formula can be used from -20°F to 125°F with only a variation of BzP and DMT. Figure 2 gives the recommended levels of BzP and DMT for this temperature range.

It is recommended that monomer be stored at -75°F to eliminate the need for the high levels of BzP and DMT required to produce polymerization when monomer is at ambient temperatures less than 30°F .

2.1.2 Strength Gain with Time

The effect of strength gain of PC with time after batching was measured for 95 percent MMA/5 percent TMPTMA using 3-in x 6-in cylinders with thermocouples inserted into the PC to measure the temperature. The cylinders were tested in compression within a few minutes after the peak exotherm temperature was reached.

Strength and temperature are shown in Figure 3 as a function of time for the first 9 hours after mixing. The compressive strength was 6000 psi when first tested minutes after peak exotherm. Strength continued to increase for several

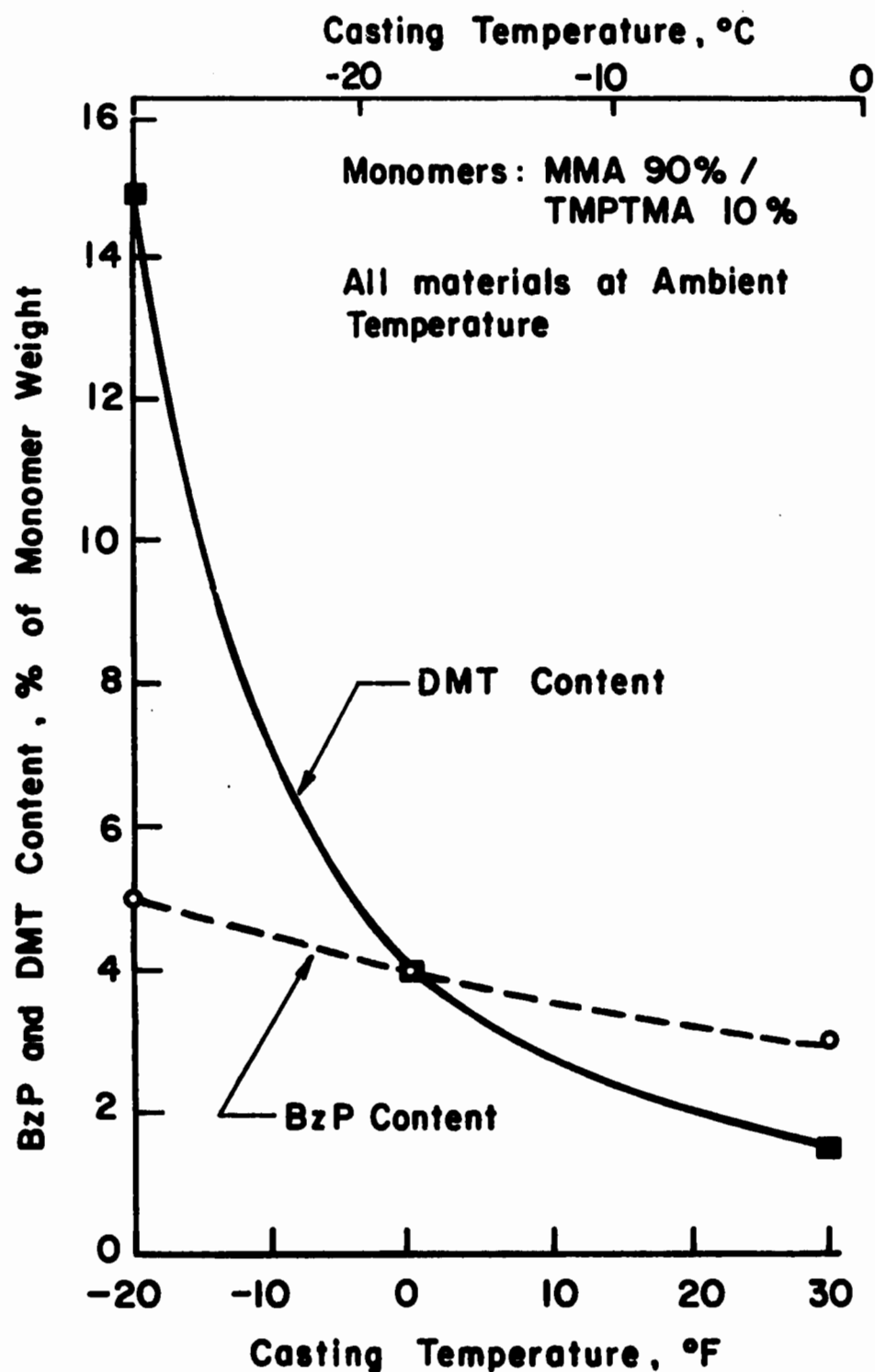


Figure 1. Required Levels of BzP and DMT for Curing With All Materials at Ambient Temperature.

TABLE 3. MODULUS OF RUPTURE FOR 95 percent MMA/5 percent TMPTMA
FOR CURING TEMPERATURES OF -20°F AND 0°F^a.

Ambient Curing Temperature (°F)	BzP (%)	DMT (%)	Peak Exotherm		Modulus of Rupture (psi)	
			Average Time (min.)	Average Temperature (°F)	Individual Specimen	Average
-20	3	3	106	68	1563	1645
					1677	
					1702	
	5	5	30	106	1640	1715
					1664	
					1846	
0	5	3	46	94	2057	2035
					2011	
					2039	
	4.5	2.5	47	103	1960	1740
					1647	
					1620	
	5.0	2.5	26	117	1454	1650
					1709	
					1781	

^a Aggregate maintained at ambient temperature and monomer at room temperature

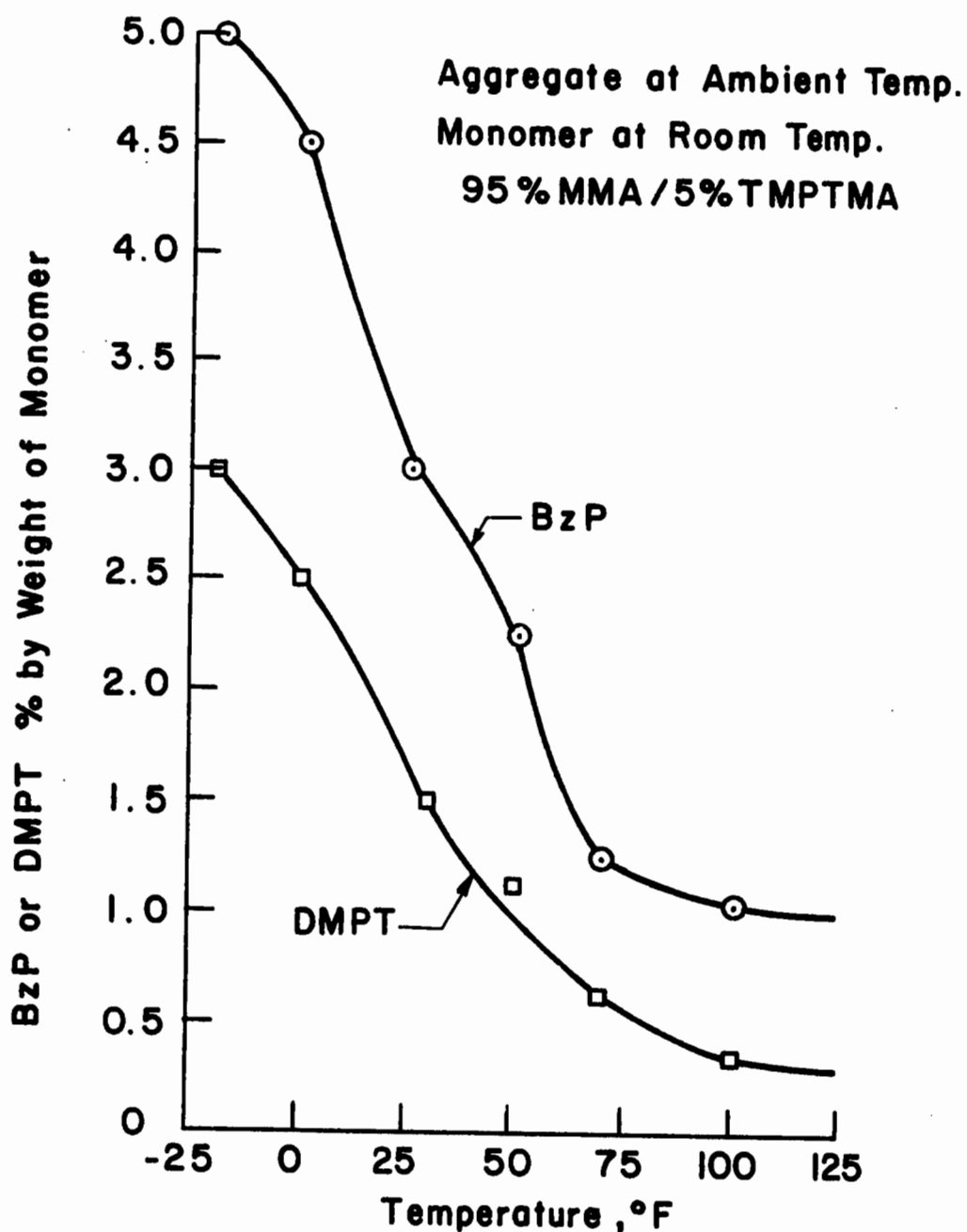


Figure 2. Required Levels of BzP and DMT for Curing With Aggregate at Ambient and Monomer at Room Temperature.

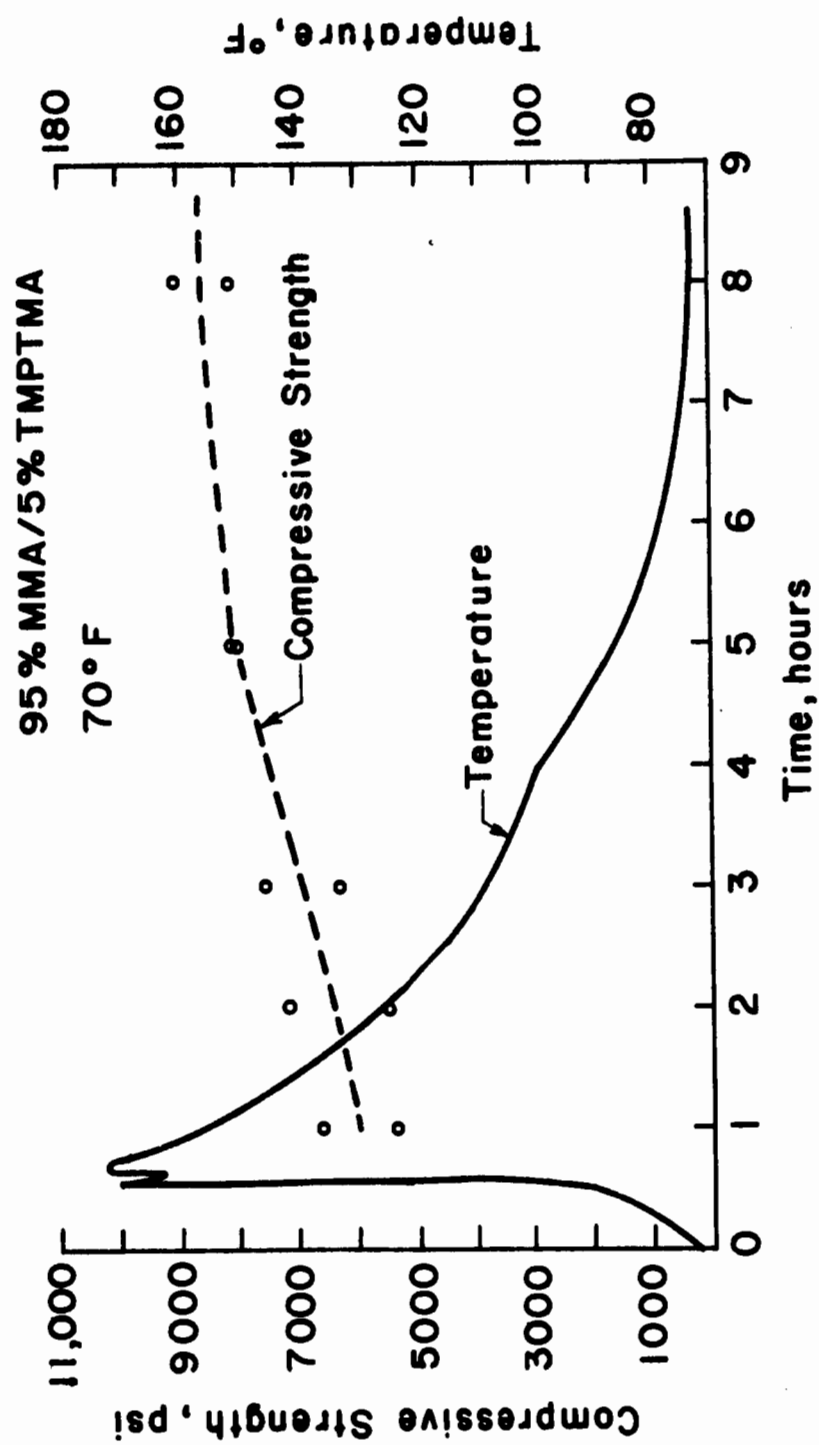


Figure 3. Temperature and Compressive Strength Versus Time
(0 to 9 Hours).

hours. Figure 4 shows the strength gain from 1 hour to 4 months. Approximately 65 percent of the maximum strength was reached after 1 hour, 68 percent after 2 hours, 75 percent after 3 hours, 87 percent after 5 hours, and 95 percent after 8 hours.

2.1.3 Effect of Casting and Testing Temperature

The effect of casting and testing temperatures on the strength of polymer concrete was described in Reference 2. Figure 5 summarizes modulus of rupture values for PC cast and tested at different temperatures. PC specimens cast at various temperatures and tested at room temperature indicated some loss in strength for specimens cast at low temperatures. Specimens cast at room temperature developed lower strength with increasing test temperatures. But for both cases, the modulus of rupture was in excess of 2000 psi over the range of temperatures tested. Figure 6 shows compression stress-strain curves for PC cast at 30^o, 70^o, and 100^oF. Some loss of ductility was observed for 30^oF, although the strength was highest at that temperature.

A comparison of compression stress-strain curves for two loading rates, 23.58 psi/sec and 47.16 psi/sec, indicated little difference in strength or ductility (Figure 7).

2.2 MMA Prepackaged Polymer-Concrete System

2.2.1 Availability

There are several prepackaged MMA-based polymer concrete systems currently marketed in the U.S. and abroad. Silikal[®] is one of the most widely known PC systems, having been developed in West Germany in the early 1960s. It is currently sold in the U.S. under its own trade name and marketed under several other trade names by companies licensed to market the product. A special version, Silikal[®] R7/Bw, is made specially for the German army for bomb damage repair and is stockpiled at German bases. DuPont is currently marketing a PC system, Crylcon[®], in the U.S.

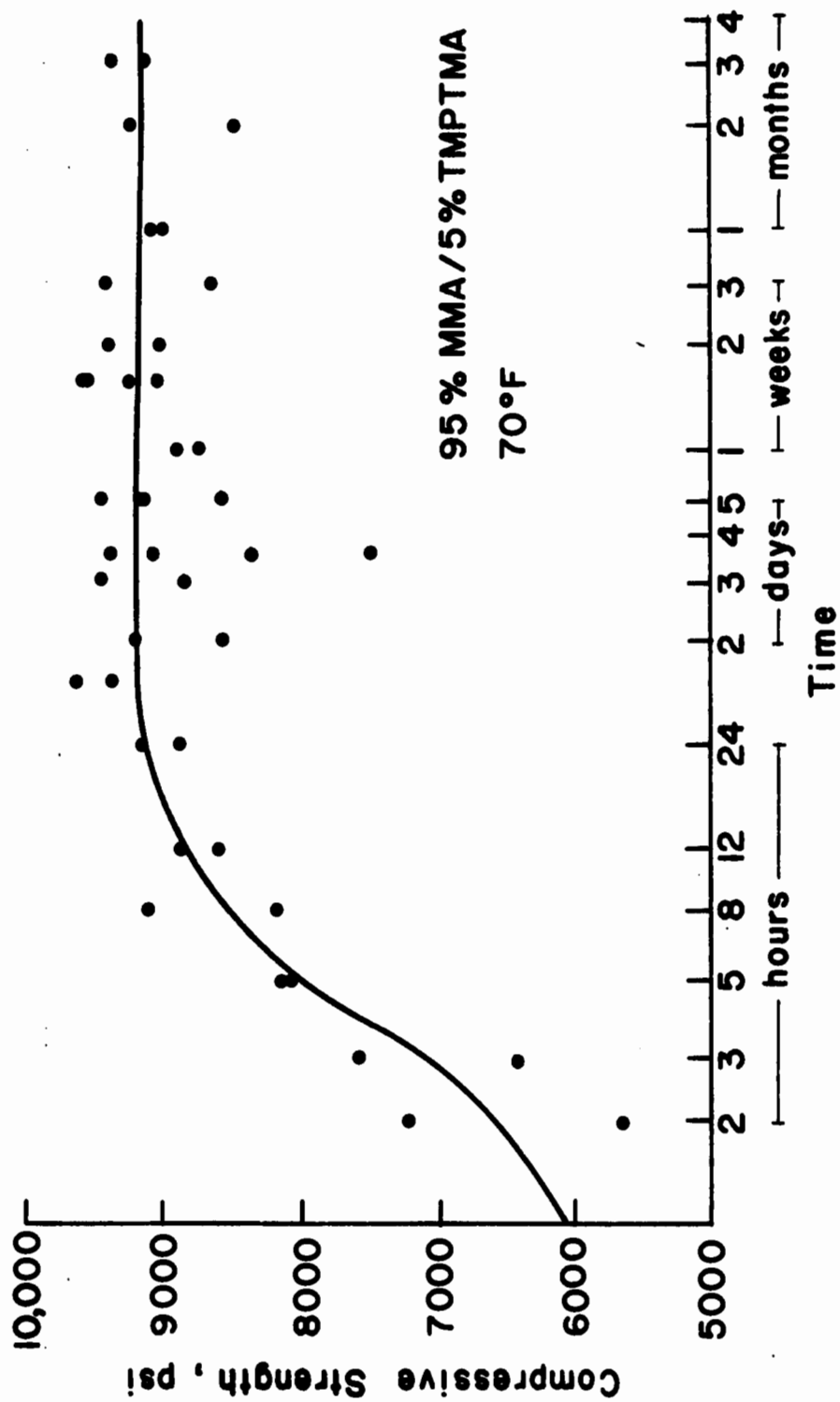


Figure 4. Compressive Strength Versus Time (0 to 4 Months).

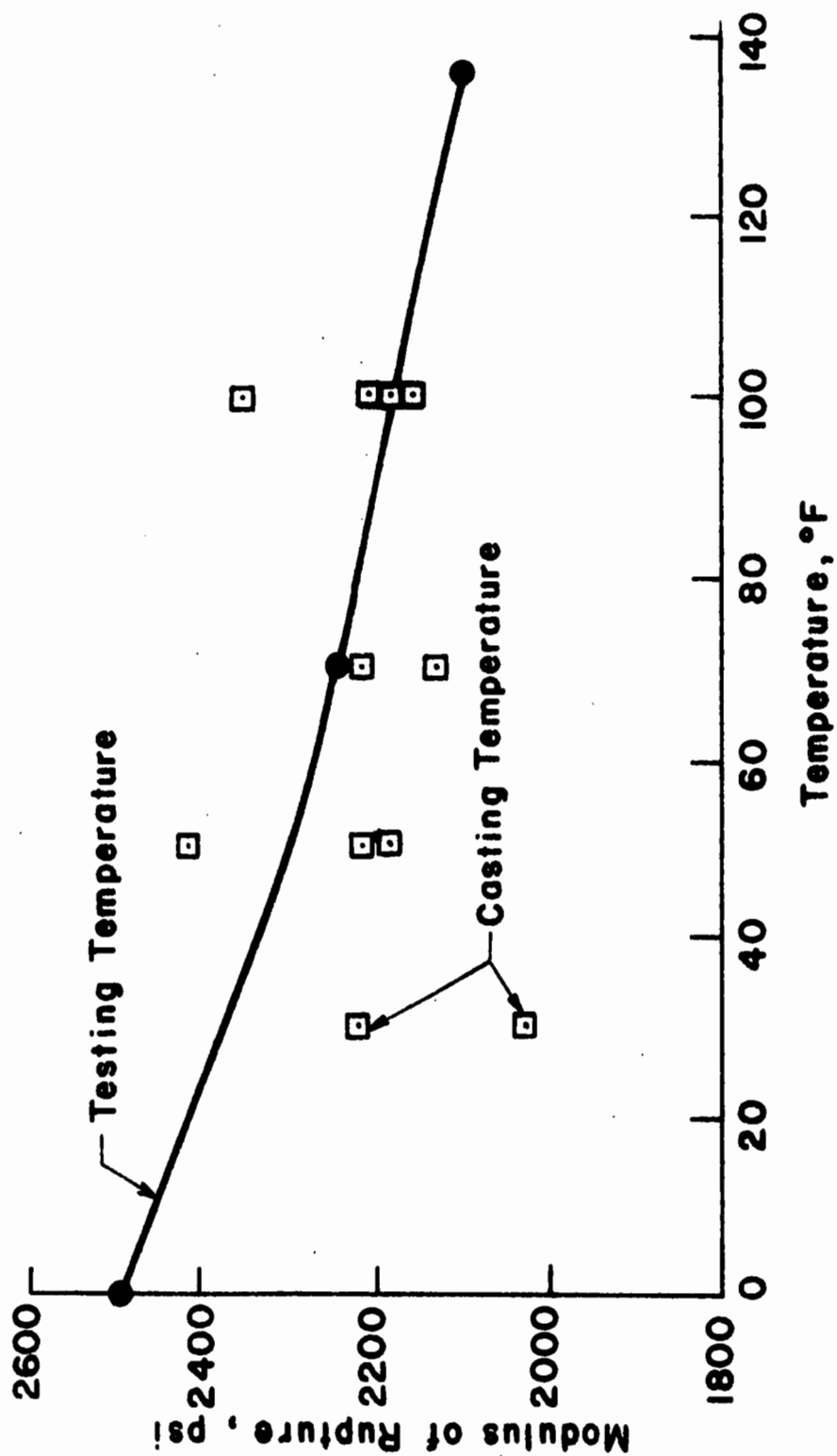


Figure 5. Modulus of Rupture for Varying Casting and Testing Temperature.

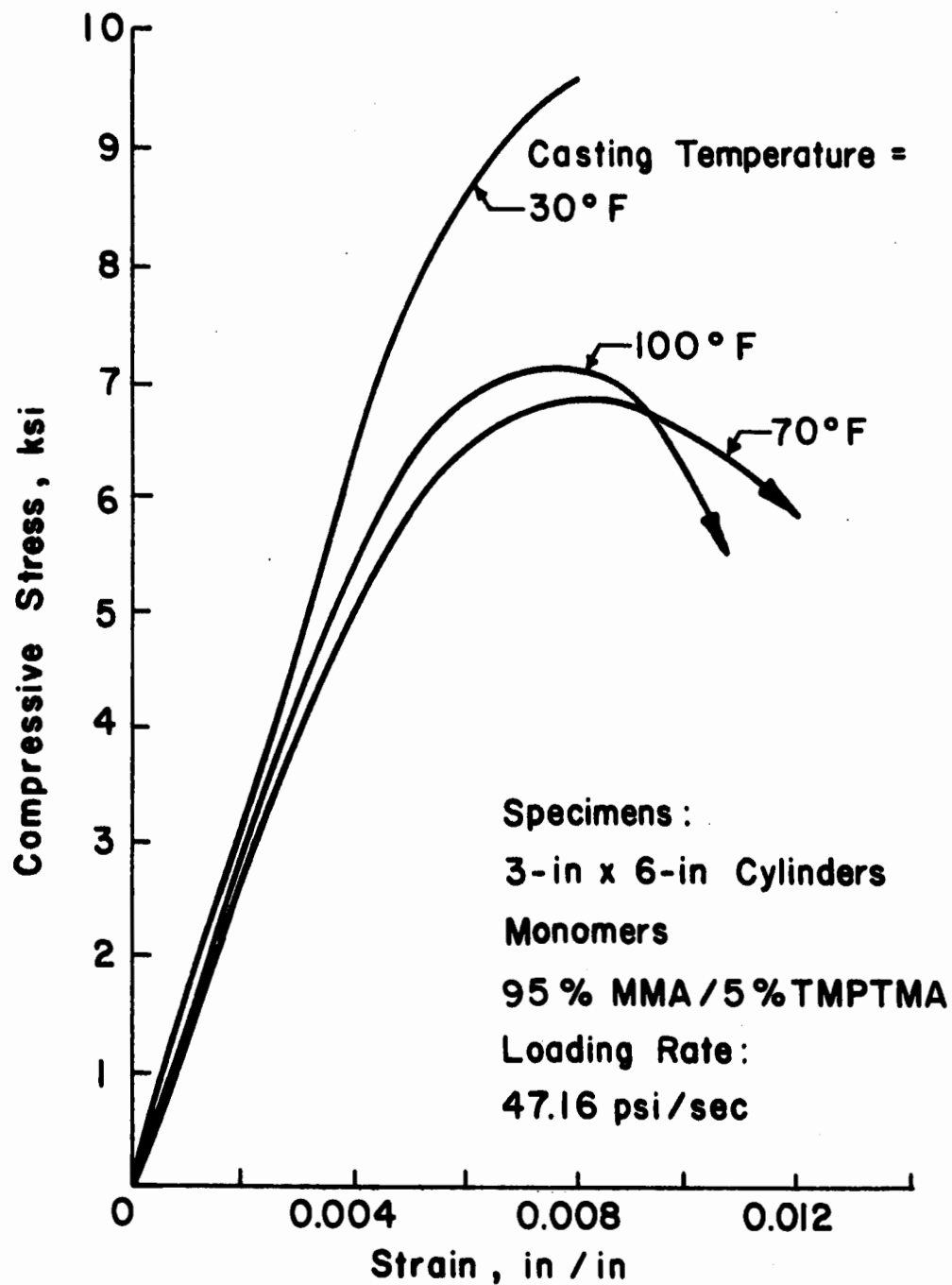


Figure 6. Compressive Stress Versus Strain As A Function of Casting Temperature.

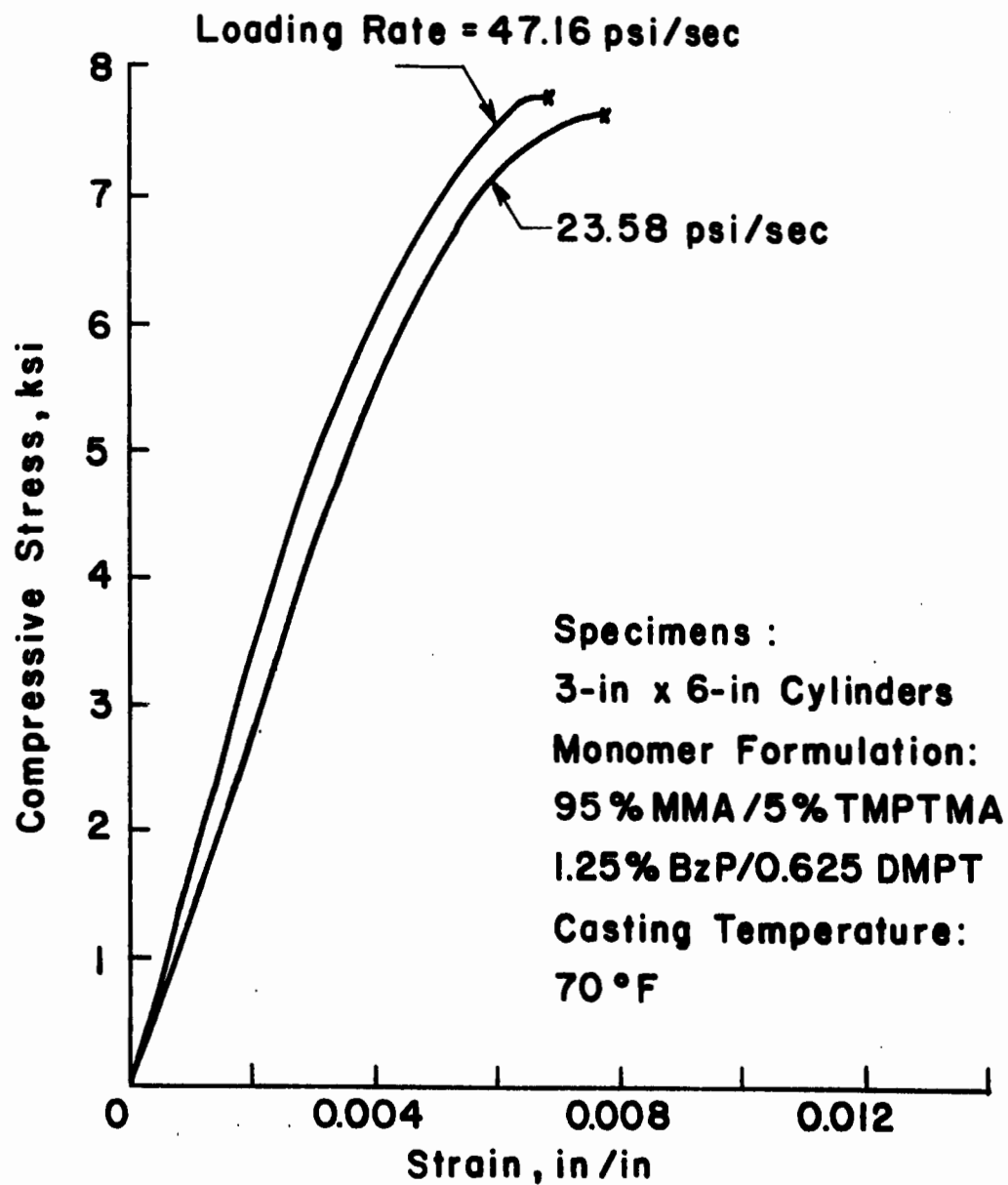


Figure 7. Compressive Strength as a Function of Loading Rate.

MMA prepackaged systems consist of a liquid component which contains primarily MMA and a powder component which apparently contains fine aggregate, colorants, initiators, and other additives designed to improve the workability and reduce the evaporation. The liquid and powder components can be mixed in plastic bags provided by the manufacturer. The manufacturers also recommend that the PC can be extended by the addition of aggregate.

2.2.2 Typical Properties

Properties of most of the polymer concrete systems have been reported by the manufacturers for room temperature applications. However, little information is available for low temperature applications.

Silikal[®] R7/Bw was tested for low temperature applications. Additional accelerator is supplied separately with the liquid component to reduce the set time at low temperatures. A series of 3-in x 3-in x 12-in flexural beams was cast at temperatures of 0°, 25°, and 35°F using Silikal[®] with and without the accelerator. The mortar was extended with an equal weight of 3/8-in silicious aggregate. The results of the tests are shown in Figure 8 as a function of the elapsed time from casting until testing. The accelerator did result in faster setting time which permitted faster testing. Some increase in strength was observed for specimens made under the same conditions with longer set times before testing. The strengths for all specimens ranged from 1620 psi to 2750 psi.

2.2.3 Effect of Addition of Aggregate

The prepackaged PC systems can be extended by the addition of coarse aggregate. A study was conducted to determine the modulus of rupture for different weight ratios of aggregate to mortar. Ratios ranging from 0 to 1.0 were used, and the modulus of rupture beams were tested at either 2 or 24 hours after casting. The PC was made with Silikal[®] using 3/4-in coarse aggregate. The results are shown in Figure 9. The flexural strength reduced significantly as up to 33-weight percent

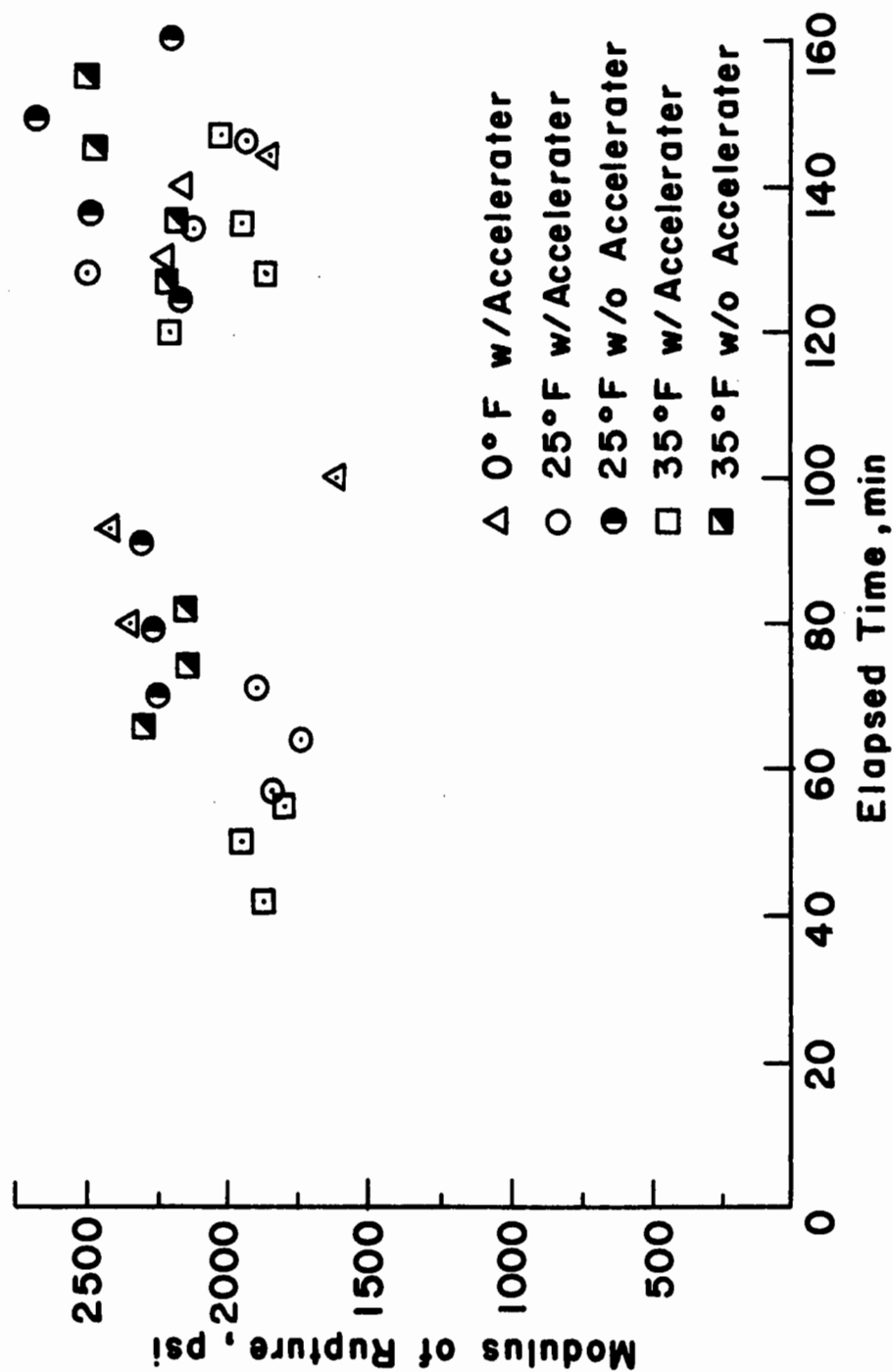


Figure 8. Modulus of Rupture of Silikal® R7/Bw As a Function of Casting Temperature and Cure Time.

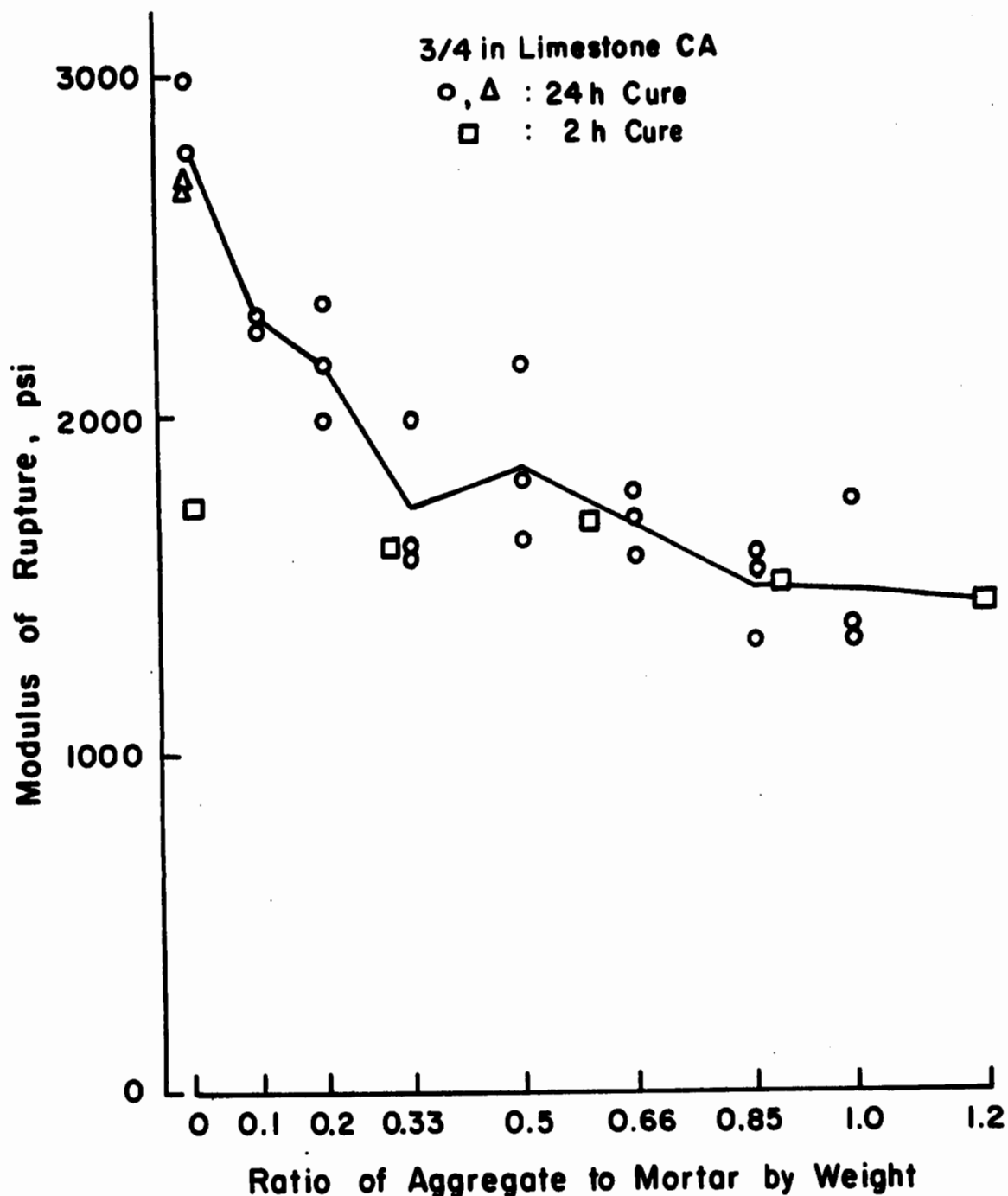


Figure 9. Effect of Varying Aggregate Content on Modulus of Rupture of Silikal® R7/Bw.

aggregate, based on the mortar weight, was used. The reduction was not very significant as the aggregate was increased from 33 percent to 120 percent.

2.3 Aggregate Type and Gradation

Phase I Report contains results of research on aggregate type and gradation. Four types of aggregate were used: silicious sand and 3/8 in coarse aggregate; sand and 3/8 in trap rock; sand and dolomite; and sand and granite. Using the compressive strength of the PC made with silicious sand and coarse aggregate as the reference value, the trap rock PC developed 2.4 percent higher strength, dolomite only 91 percent of the strength, and the granite 85 percent of the strength. In general, the aggregate should be suitable for making portland cement concrete. Weak aggregate will provide a weakened plane which will result in lower PC strengths.

Aggregate gradation should be such as to minimize the volume of monomer required. For contractor-formulated PC, a well-graded concrete sand coarse aggregate should be used for repairs. Ideally, the gradation should be selected to yield minimum voids and to provide good workability. However, even single gradation sand passing a No. 30, 50, or 100 sieve was shown in Reference 2 to yield compressive strength of 6000 psi or higher⁷. However, the monomer loading, including the monomer absorbed by the aggregate, ranged from 44.6 to 47.9 percent. The higher monomer volume has several disadvantages - higher cost, higher exotherms, greater shrinkage, and, in some cases, poorer wear, strength, and durability.

The use of large aggregate with site-mixed and prepacked PC was investigated by means of splitting tensile strength tests on 6-in x 12-in cylinders. A comparison of PC made with 2 to 3 in and with 1/2 to 3/4 in aggregate is shown in Figure 10. The larger aggregate yielded slightly higher strengths for the site-mixed PC and slightly lower for Silikal[®]. It should be

⁷Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair, Phase I.

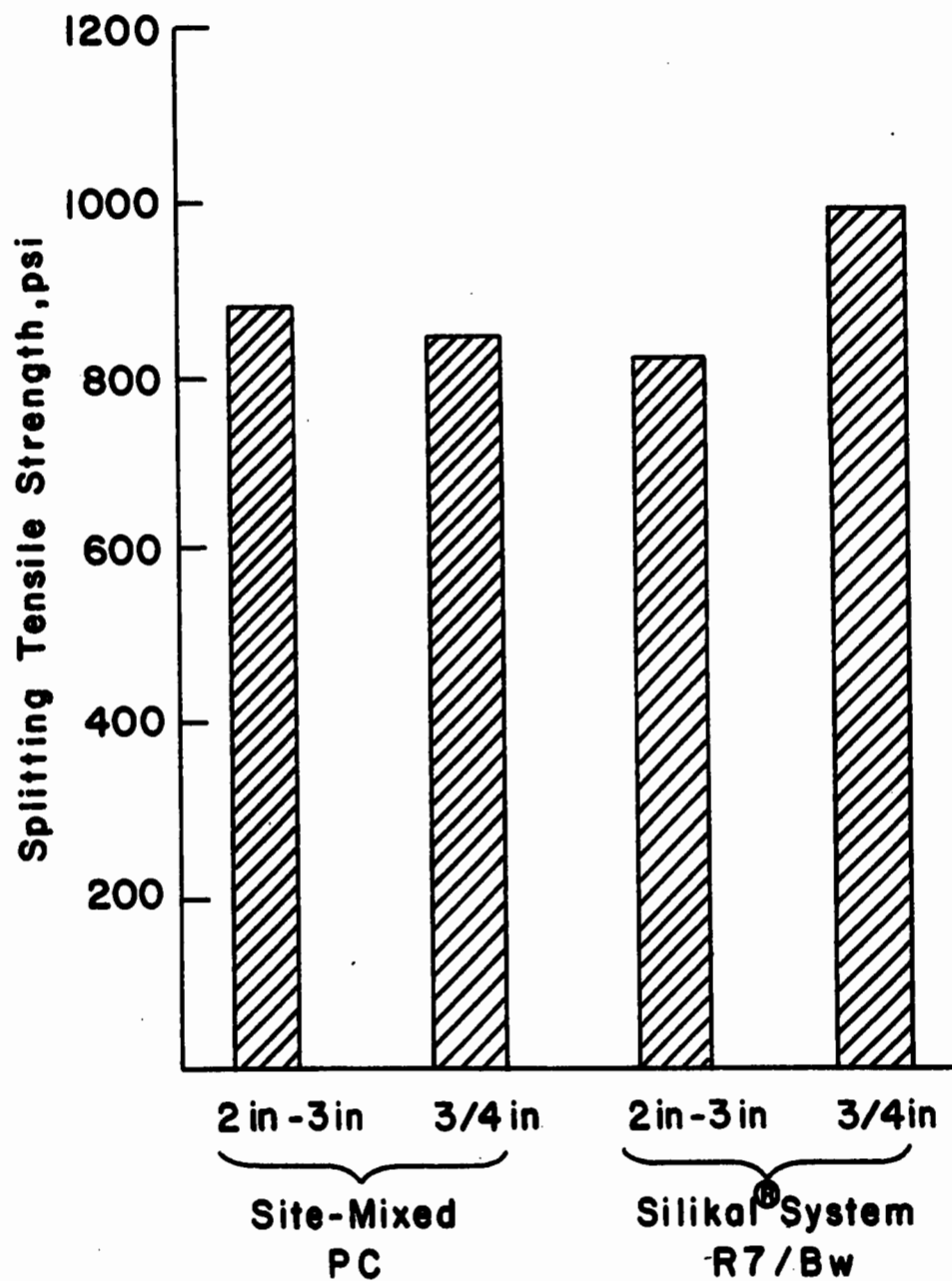


Figure 10. Splitting Tensile Strength for Varying Aggregate Size and PC System.

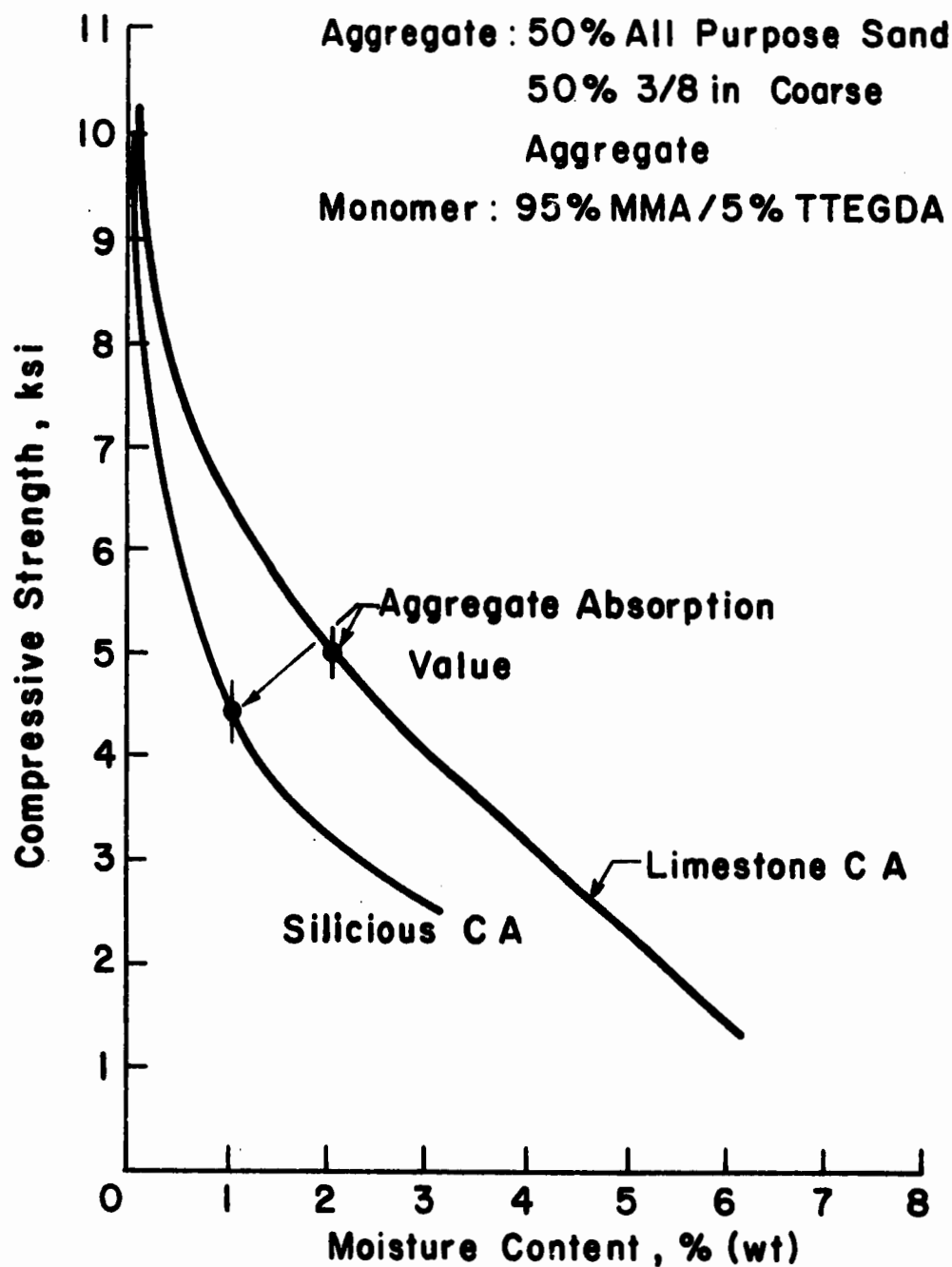


Figure 11. Effect of Moisture on Compressive Strength of PC With Silicious and With Limestone Aggregate.

noted that the site-mixed PC had equal weight parts of sand and coarse aggregate and the Silikal[®] had equal weight parts of mortar and coarse aggregate. These results indicate that size of the large aggregate can be varied without significantly affecting the properties of the PC. However, large aggregate will affect the workability, and, for this reason, a maximum size of 3/4 to 1 in is recommended.

2.4 Effect of Wet Aggregate

It is well known that the presence of excess water in the aggregate reduces the mechanical strength of MMA polymer concrete. The maximum amount of water permitted by specifications for MMA PC has generally been in the range of 0.5 to 1.0 percent by weight. The maximum moisture content appears to be dependent upon several variables, including aggregate porosity and gradation. It would be expected that aggregate with a relatively high porosity would tolerate a higher moisture content since more water would be absorbed by the aggregate, which would reduce the free water in the pores. Similarly, for gradations containing a relatively high percentage of fines, the higher surface-to-void ratio should permit more water to be absorbed by the aggregate.

To determine the effect of moisture in aggregate on the properties, compressive and split tensile tests were performed on 3-in x 6-in cylinders made of PC using 50 weight percent all-purpose sand and 50-weight percent 3/8-in coarse aggregate. Both silicious and limestone coarse aggregates were used. The gradations and properties of the aggregates are given in the Phase I Report⁸. Aggregates used in all moisture tests were dried at ~250°F and cooled, and the aggregate was then soaked in water for 24 hours. The monomer formulation was 95 percent MMA, 5 percent TTEGDA, 1.33 percent BzP, and 0.70 percent DMPT. The results of the compressive strength tests for silicious and limestone coarse aggregate are shown in Figure 11. The silicious

⁸Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair, Phase I.

aggregate had a relatively low absorption value, and the strength was reduced very rapidly with increasing moisture content. The limestone aggregate has a higher absorption value than the silicious aggregate, which enables the PC to tolerate a higher moisture content. For moisture contents in excess of 3 percent, it was difficult to remove the cylinders from the molds. Figure 12 gives splitting tension results for silicious and limestone coarse aggregates.

Tests were also performed on Silikal[®] P7/Bw, the special version for the German army, to determine the effect of moisture content. The PC was extended at the volume ratio of one part Silikal[®] to one part 1/2- to 1-in coarse aggregate. Figure 13 indicates the splitting tensile strength for silicious and limestone aggregate. The moisture content was a function of the coarse aggregate. It should be noted that since the Silikal[®]-to-aggregate weight ratio was .0.1:1, the moisture contents based on total weight would have been less than those values shown in Figure 13.

Several methods were investigated to minimize the effects of moisture in aggregate: chemical additives in the monomer, aggregate treatment, and addition of fibers to the mix. The results of this investigation are discussed in the Phase I Report⁹.

Chemical additives would represent a very desirable solution to the wet aggregate problem. Considerable effort was made to identify and test additives, but none of the additives resulted in significant increases in strength.

Several aggregate treatments were investigated. One approach was to use moisture absorptive additives including cement, gypsum, and lime. Little increase in strength was found when the PC was tested after 3 hours; some increase occurred after 3 days, apparently due to hydration.

Another approach in the use of aggregate treatments was to coat the aggregate in an attempt to provide increased bond

⁹Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair, Phase I.

**Aggregate : 50 % All Purpose Sand
50 % 3/8 in Coarse
Aggregate**

Monomer : 95 % MMA / 5 % TTEGDA

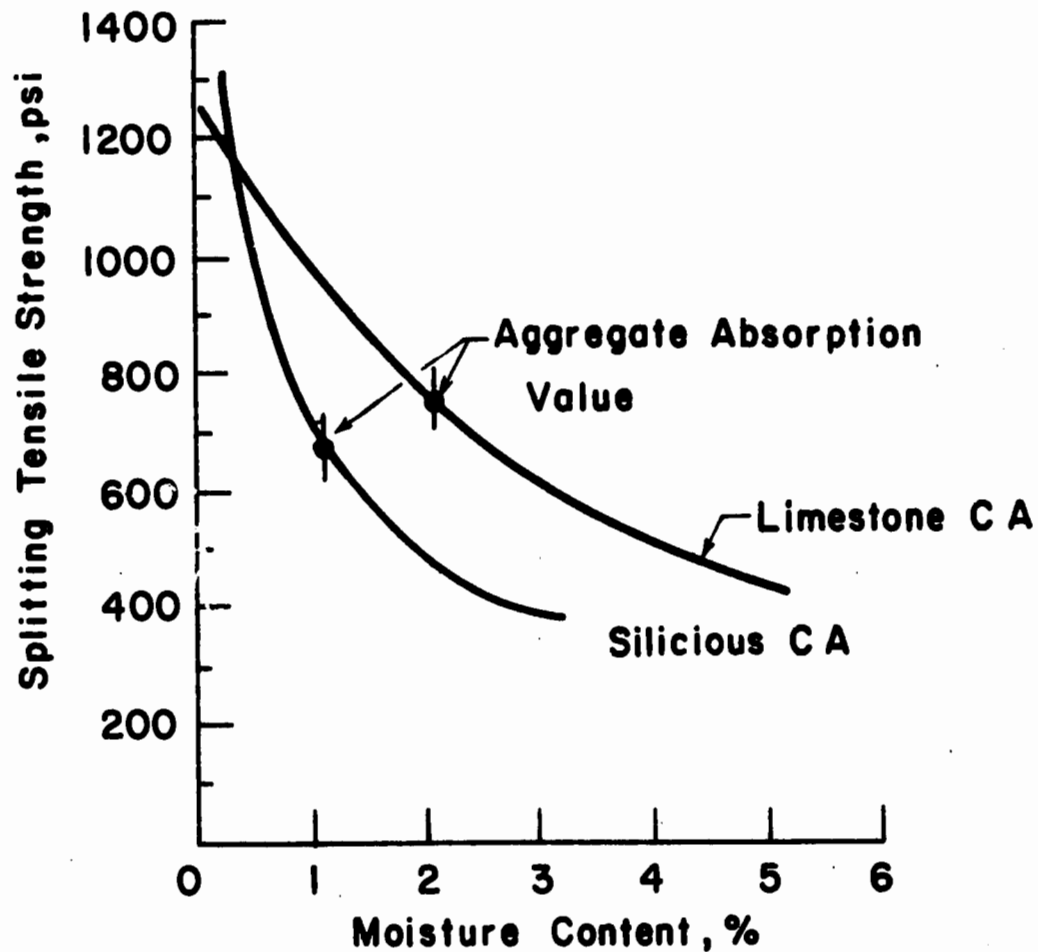


Figure 12. Effect of Aggregate Moisture on Splitting Tensile Strength of PC With Silicious and With Limestone Aggregate.

Mix : 1 Vol Part Silikal®
1 Vol Part Aggregate
Aggregate : 1/2 in. - 1 in

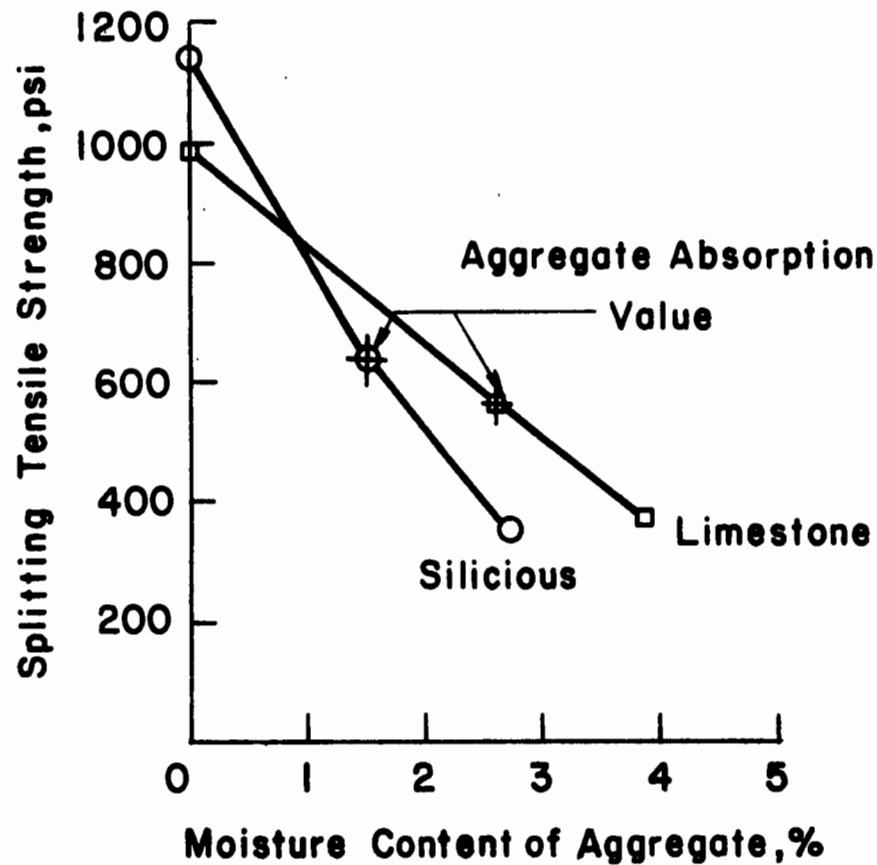


Figure 13. Effect of Moisture on Splitting Tensile Strength of Silikal® R7/Bw

between the polymer and aggregate. Polymethyl methacrylate was tried without success. However, silane coupling agent-coated aggregate did show considerable promise. Figure 14 shows the improvement in splitting tensile strength when aggregate was soaked for 10 minutes and for 1 hour. The process for coating the aggregates, described in the Phase I Report, will require further development to make it feasible for treating large quantities of aggregate. The cost of silane coupling agent is also quite high (approximately \$100 per gallon in small quantities). For these reasons, the use of silane coupling agent-coated aggregate was not considered to be a viable solution to the wet aggregate problem.

The use of fibers in the PC mix was investigated to improve the strength when moisture is present. Fibers are available in glass, polymer, and steel, and steel fibers are available in several types and sizes.

A screening study was conducted to evaluate the fibers in PC in the Phase I Report. Both 3-in x 6-in and 6-in x 12-in cylinders were made. Fibers used were steel (Bekaert), alkaline-resistant (AR) glass, polyethylene, and polypropylene. Percentages of fibers by weight of aggregate varied. Based on the initial tests, the Bekaert ZL 30/50 fibers (0.5 mm x 30 mm), which had the highest strength of 1838 psi, were selected for further use in PC made with wet aggregate. The aggregate, which consisted of 50 percent all-purpose sand and 50 percent 3/8-in crushed limestone, was first dried at 250°F, cooled to room temperature, wetted to provide the desired moisture content, and permitted to soak for at least 24 hours. The steel fibers were added as a percentage of the dry aggregate weight and thoroughly mixed. The monomer (95 percent MMA and 5 percent TTEGDA) was added and mixed into the aggregate. The PC specimens were then cast into molds.

Compressive strength is shown in Figure 15 for PC (3-in x 6-in cylinders) made with a moisture content of 3.7 percent. For five and seven percent fibers, significant strength increases resulted. Splitting tensile strength is shown in Figure 16 for 3.7 percent moisture. One data point is shown for

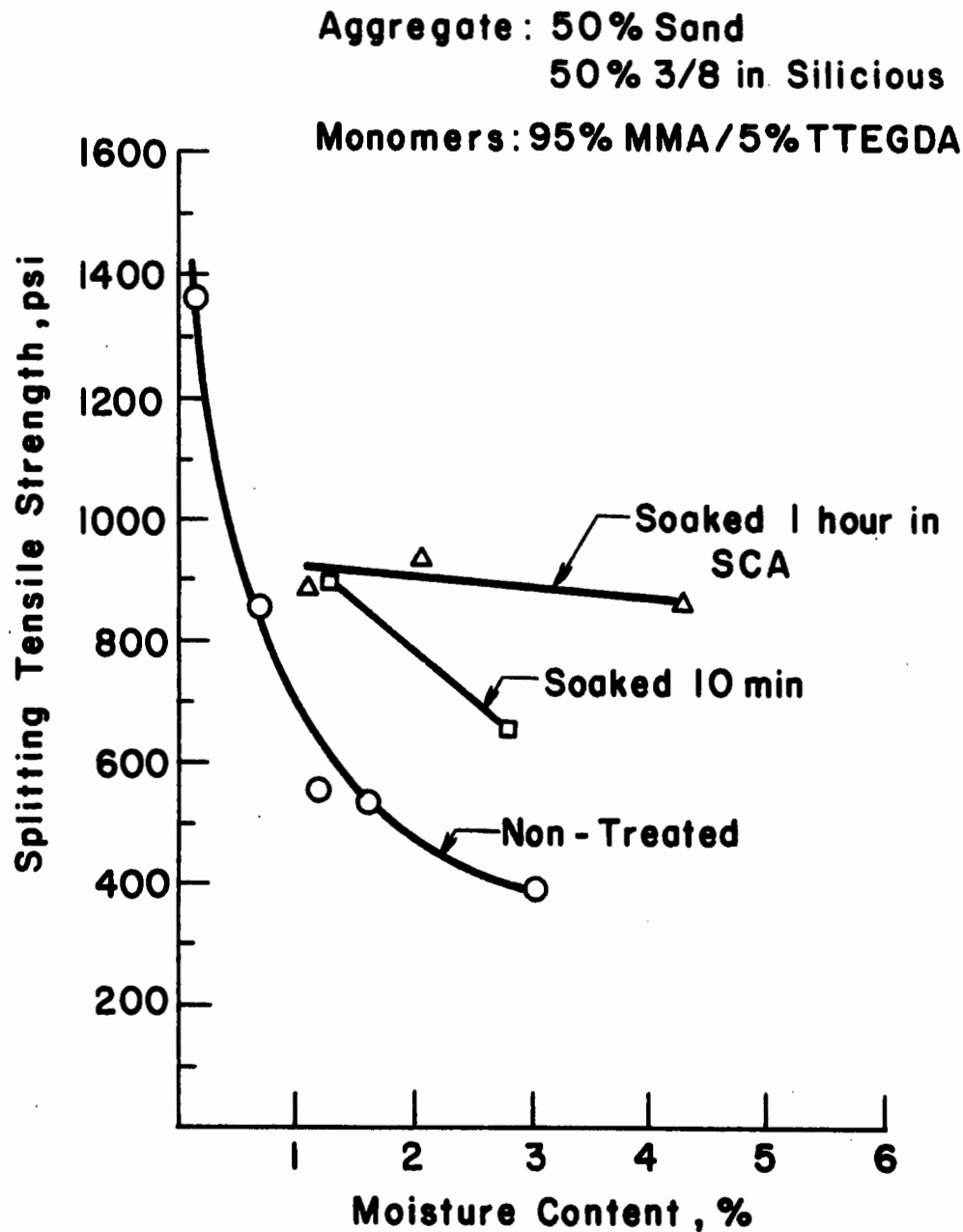


Figure 14. Effect of Silane Coupling Agent-Coated Aggregate on Splitting Tensile Strength of PC Made With Wet Aggregate.

Aggregate : 50% Sand (A P)
50% Crushed Limestone (3/8 in)
Monomers: 95 % MMA / 5% TTEGDA
Fibers: 0.5 x 30mm, Hooked
MC : 3.7 %

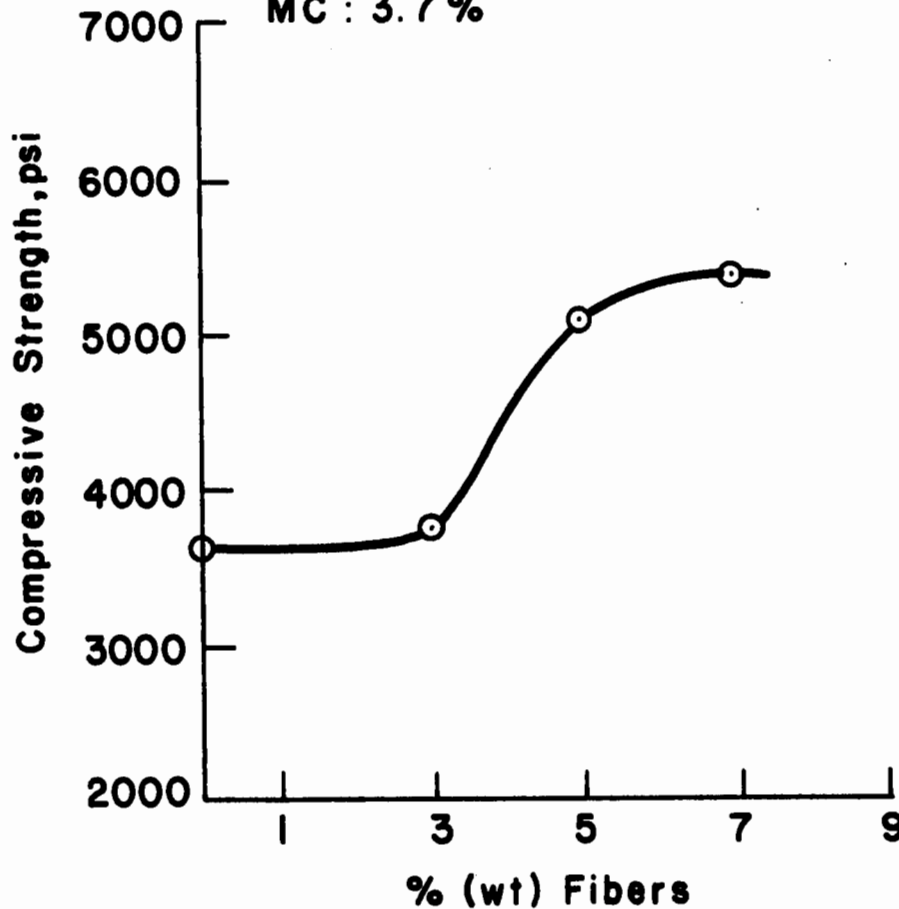


Figure 15. Effect of Steel Fibers on Compressive Strength of PC Made With Wet Aggregate.

Aggregate : 50 % Sand (A P)
50 % Crushed Limestone (3/8 in)
Monomers: 95% MMA / 5% TTEGDA
Fibers: 0.3 x 50mm , Hooked
MC : ○ 3.7 % MC
△ 5.0 % MC

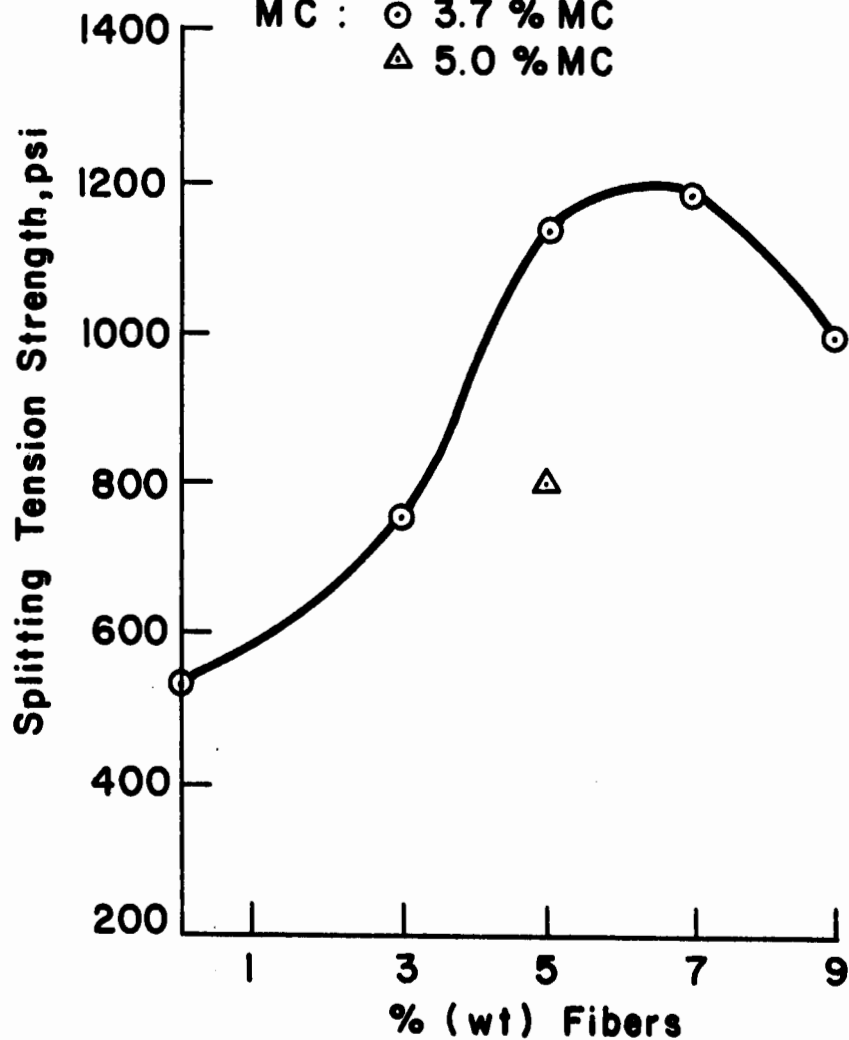


Figure 16. Effect of Steel Fibers on Splitting Tensile Strength of PC Made With Wet Aggregate.

5 percent fibers and 5 percent moisture, which indicates that strength is increased more than 100 percent for 5 and 7 percent fibers for 3.7 percent moisture and by nearly 50 percent for 5 percent moisture.

Based upon workability and increase in strength, a value of 5 percent of fibers by weight of aggregate was selected for further research. Figure 17 shows a comparison in strengths with and without fibers for 2.5 and 5.0 percent moisture. Modest increases in strength were observed for splitting tensile strength and compression strength for 2.5 percent moisture when fibers were present. Very significant increases in strength were found for modulus of rupture with 2.5 percent moisture and for all strength tests when 5.0 percent moisture was present. The modulus of rupture (810 psi) for 5.0 percent moisture is well above the minimum goal of 400 psi for rapid runway repair.

The use of Type 3 cement with fibers was investigated. Splitting tensile strength 4 hours after casting increased about 18 percent with 7 percent cement. 5 percent fibers and 5 percent moisture content were used in making the PC.

A series of tests was performed using SCA on PC made with 5 percent fibers and 5 percent moisture content. Compared to strength without the use of SCA, the following increases in strength were obtained: SCA-treated aggregate, 12.5 percent; SCA-treated fibers, 14.25 percent; and SCA-treated fibers and aggregate, 27.0 percent. A series of 3-in x 3-in x 12-in beams with a 9 in span was tested using 5 percent moisture content and 5 percent fibers. Using SCA-treated fibers and aggregate, an increase of 48.1 percent in modulus of rupture was obtained; an increase of 18.1 percent was found for nontreated aggregates and fibers.

Two prepackaged systems, Crylcon[®] and Silikal[®] were tested using wet aggregate and steel fibers. Silikal[®] was extended with an equal volume of limestone aggregate and Crylcon[®] was extended with an equal weight of silicious aggregate. Results are shown in Figure 18 for PC with and without steel fibers for moisture

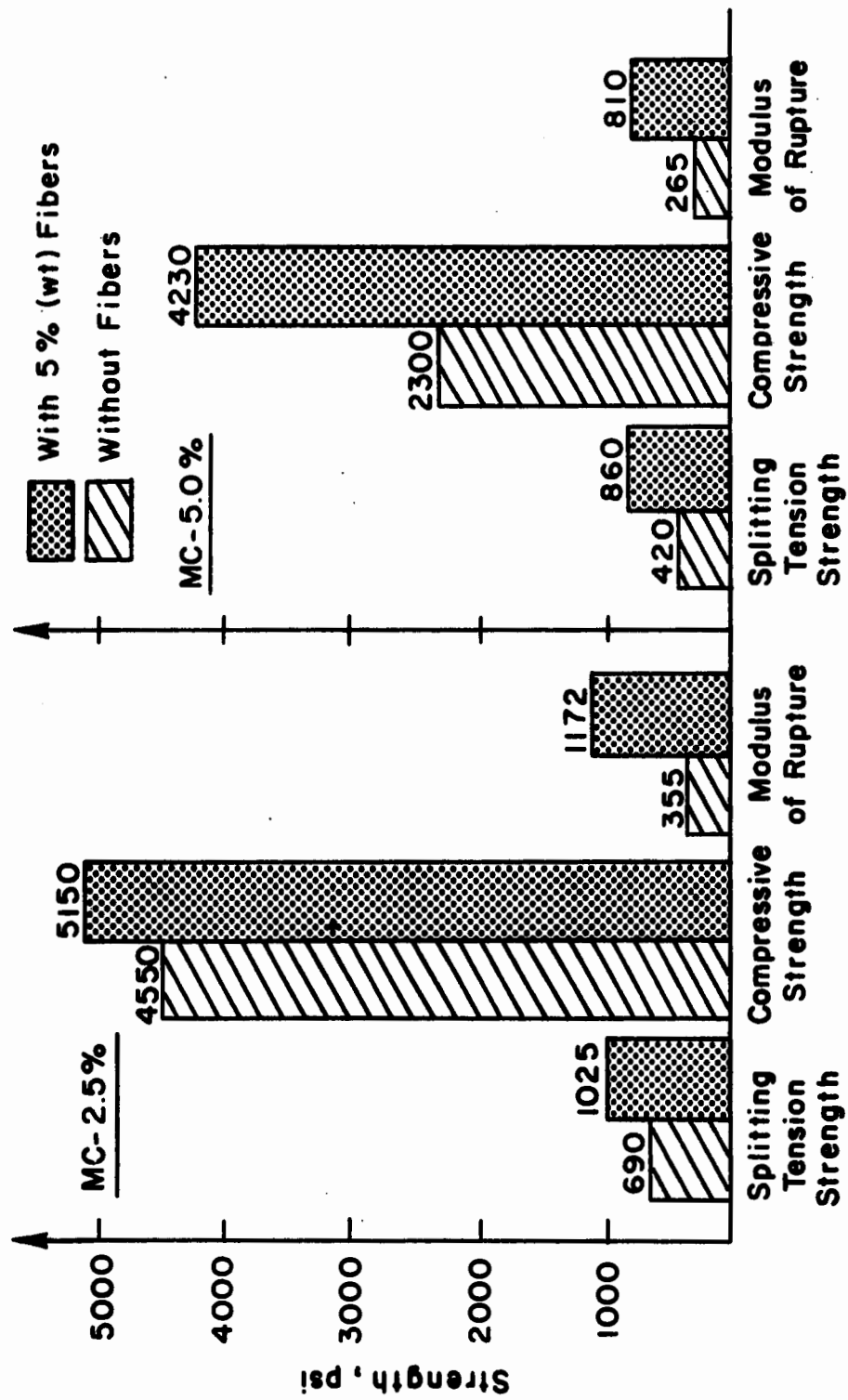


Figure 17. Comparison of Properties of PC Made With and Without Fibers.

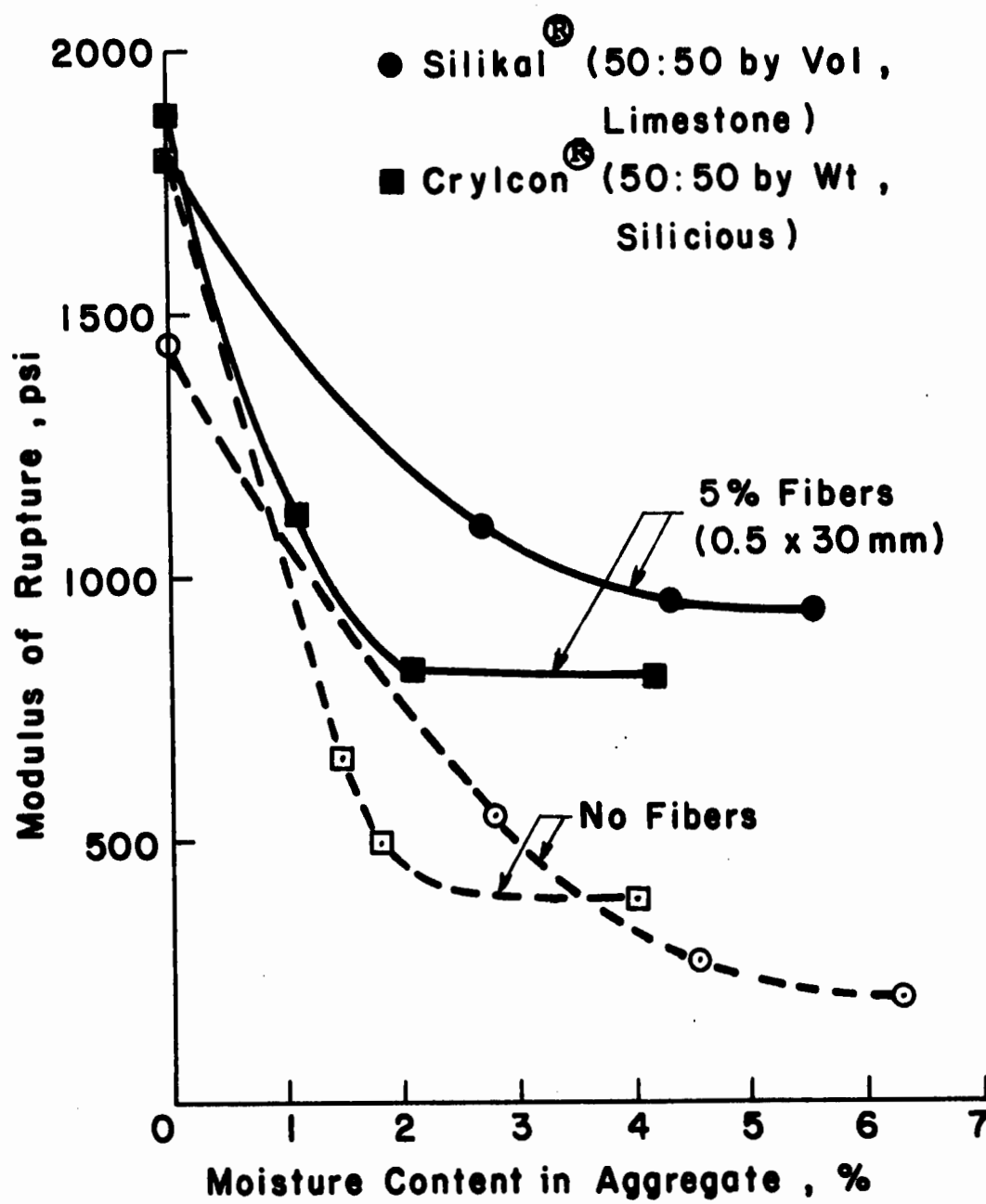


Figure 18. Effect of Moisture on Modulus of Rupture of Silikal[®] R7/Bw and Crylcon[®]

contents up to 6 percent in the aggregate. It should be noted that the moisture content in the total batch would be approximately one-half the moisture content in the aggregate.

The use of steel fibers appears highly promising to minimize the effect of wet aggregate. Fiber-reinforced PC also has the added advantage of producing flexural members with considerable more toughness as evidenced by the load-deflection response shown in Figure 19 for a 3-in x 3-in x 12-in beam with 5 percent fibers and no moisture. The greater toughness and ductility has great potential for insuring longer life for bomb damage repair applications.

2.5 Effect of Asphalt on PC

In many bomb-damaged runway repairs, the polymer concrete will be in direct contact with surrounding asphalt overlays. In some repairs, the spall will not extend through the asphalt; in others, the repair will extend through the asphalt and into or through the concrete.

It has been found that the monomer acts as a solvent on the asphalt and that the presence of asphalt serves to inhibit polymerization. Studies were conducted to determine the effect of asphalt on the curing time and strength of the polymer concrete.

2.5.1 Test Procedure

After several preliminary tests were investigated¹⁰, a pull-out test was developed to measure the bond stress. To achieve more consistent results in the test data, asphaltic concrete specimens were made in the laboratory using the criteria for mix design specified by the Federal Aviation Administration (FAA). Each HVEEM stabilometer specimen was cast with a 2-in diameter by 1-in long steel plug at its center. Upon removal of the plug the specimen was cooled in a freezer for 5 minutes at -30°F to harden the asphalt and the hole was brushed with a wire

¹⁰ Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair, Phase I.

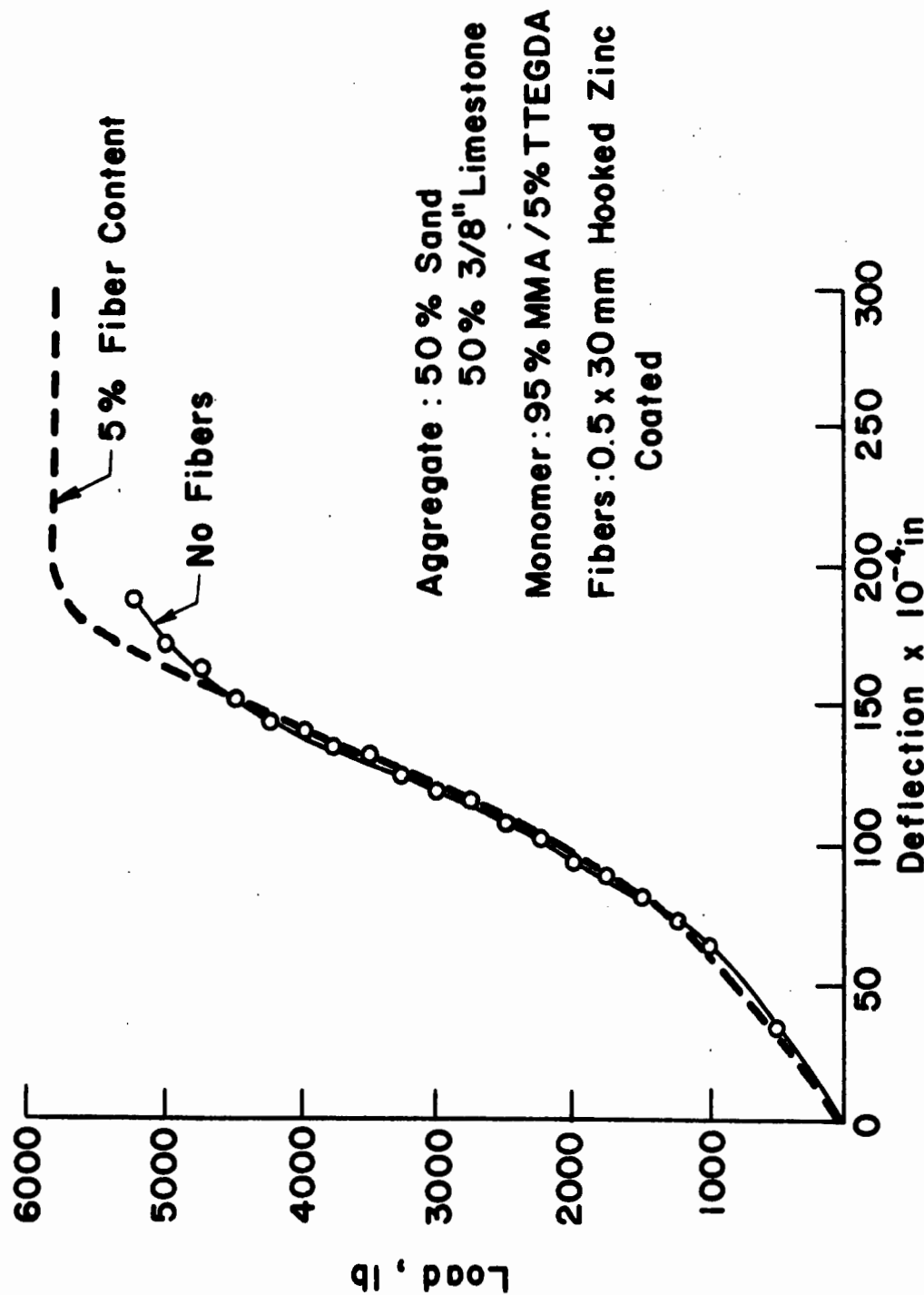


Figure 19. Load-Deflection Response of PC Beams Made With and Without Steel Fibers.

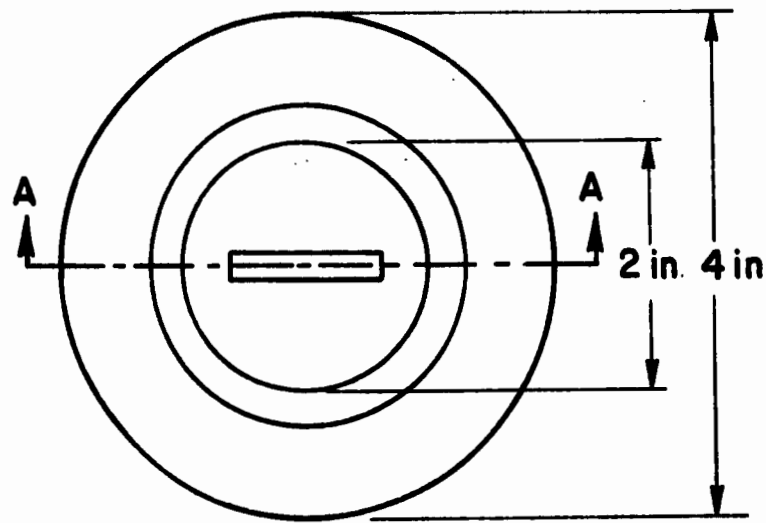
brush to expose the aggregate. A thin disk of aluminum foil was then placed in the bottom of the hole to eliminate any tensile forces generated during pull out of the PC plug. The hole was then filled with PC, and a steel U-bolt was embedded as an attachment point for the testing machine (Figure 20). Three PC formulations were utilized in this test procedure.

When preparing the PC formulations using the monomer (MMA), the hole in the HVEEM stabilometer specimen was filled with sand, and the monomer was poured over it until saturation occurred. A thermocouple was inserted at the interface to measure peak exotherm. Due to the small volume of the hole, coarse aggregate was not used.

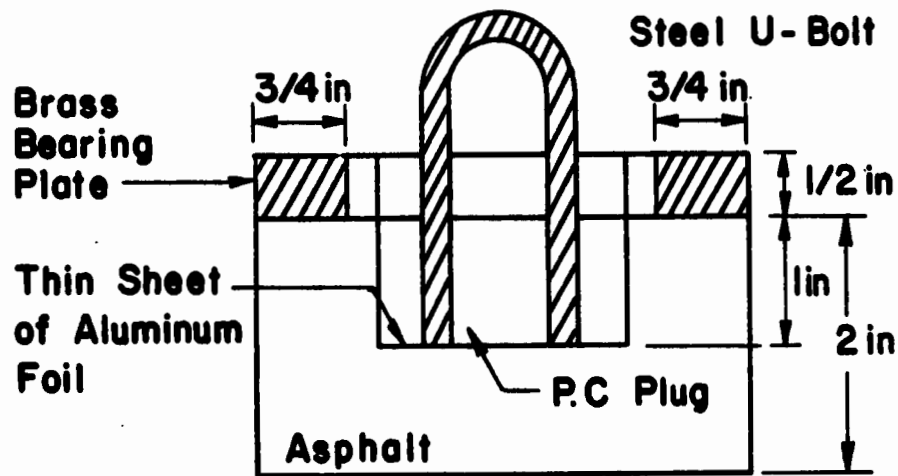
In the first batch of specimens the mix design of the asphaltic concrete was varied to determine which mix gave the optimum bond strength. The FAA has stipulated a specific mix design for runways subjected to heavy aircraft. This design is based on ASTM D3515 and ranges from Type 4A to 6A. The optimum bond strength was achieved by using a Type C mix with 6 percent asphaltic content¹¹. All subsequent specimens were made with this mix.

The effect of temperature was found to be very important. A comparison of the shear stress for asphaltic concrete, Silikal[®] and the user-formulated system (95 percent MMA/5 percent TMPTMA) was made. The UT formulation reached peak exotherm at 18 minutes for 100°F ambient temperature and 80 minutes for 0°F. The Silikal[®] PC reached peak exotherm at 11 minutes for 100°F and 85 minutes for 0°F. The PC specimens were tested 2 hours after casting. The ultimate shear strengths versus ambient temperatures are shown in Figure 21. The shear strengths were dramatically reduced with increasing temperatures. The user-formulated system had lower strengths; this can be attributed to the less viscous monomer which softened the AC to a greater depth than in the Silikal[®] system. At the higher temperatures, the user-formulated system

¹¹ Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair, Phase I.



Plan View



Section A-A

Figure 20. Typical Specimen for Pull-Out Test.

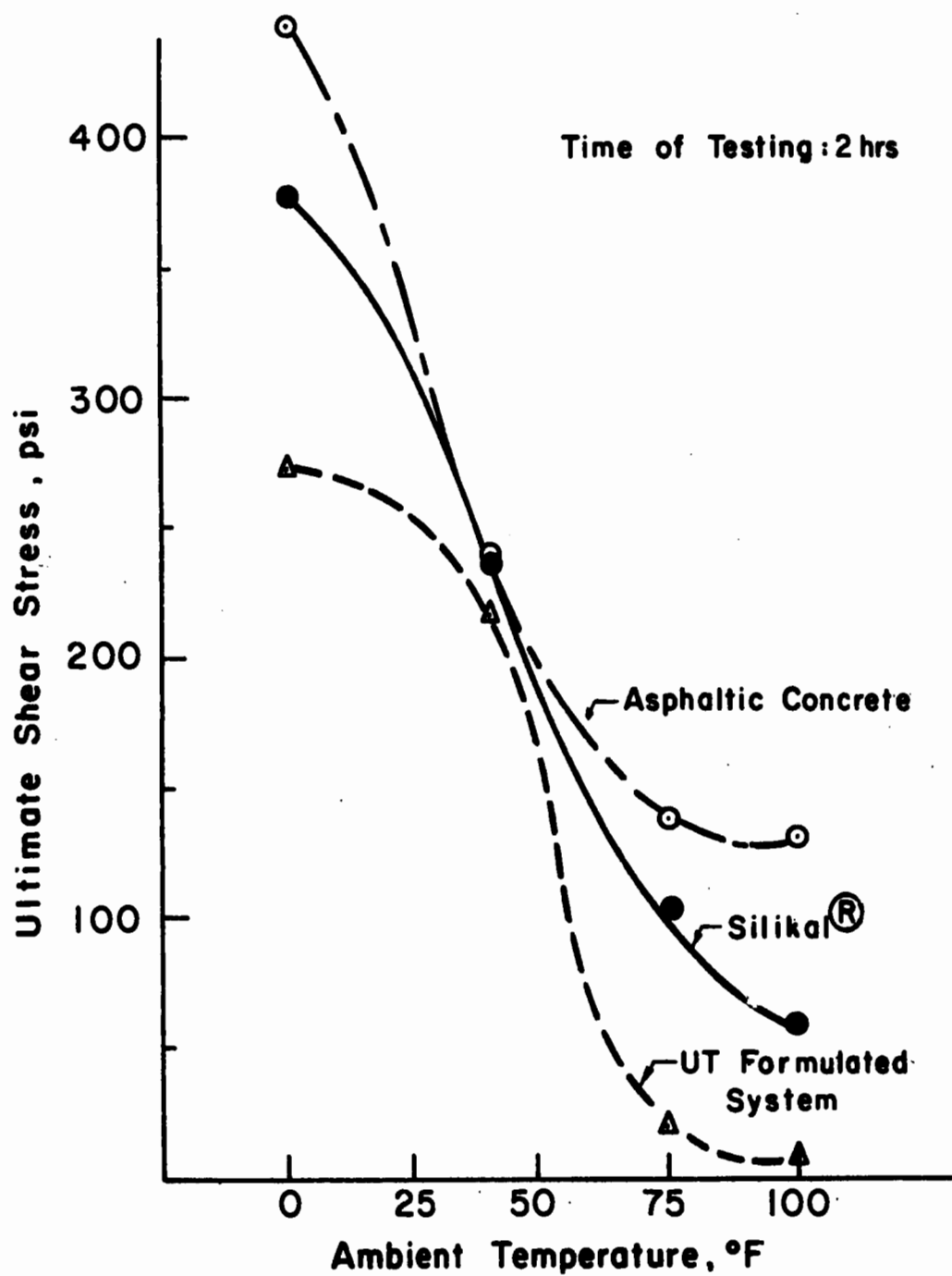


Figure 11. Ultimate Shear Stress Versus Ambient Temperature.

developed little or no adhesion to the AC.

A summary of shear strengths for several materials with and without primer tested at room temperature is shown in Figure 22. The user-formulated mixes No. 1 and No. 2 and the batch mix are described in Table 4. The use of primer increased the shear strength of each material with which it was used.

The shear stress at the AC to PC interface will, in all probability, be low since the asphalt is supported by the concrete to which the PC will be bonded and both the concrete and PC are supported on fill material. The shear strength between the PC should be adequate with the possible exception of high temperature uses when the shear strength is quite low. But, repairs made on AC pavements and on bridge decks with AC overlays have shown that there is no short term or long term problem with AC to PC bond even in hot weather.

2.6 Fatigue Strength

The fatigue strength of polymer concrete beams was investigated to determine the number of cycles of loading that could be achieved for various stress levels in the beams. Variables included stress level and stress range.

All beams were 6 in x 6 in x 36 in with a 30 in span. Loads were applied at third points at a loading frequency of 5 cycles per second. The monomer formulation was 95 percent MMA, 5 percent TTEGDA, 1.25 percent BzP, and 0.62 percent DMT. Aggregate consisted of equal weights of all-purpose sand and 3/8 in silicious pea gravel.

Three stress ranges were used: $f_{\min}/f_{\max} = 0.25, 0.10,$ and 0.05 , where $f_{\min}$ and $f_{\max}$ are the minimum and maximum stresses, respectively. The maximum stress was selected as a percentage of the static flexural strength, f_r . Table 5 summarizes the results of the fatigue tests. For a stress range of 0.25 , considerable variation in number of cycles was found at a maximum stress of $0.80 f_r$, with two specimens withstanding over 100,000 cycles; however, three specimens failed at less than 6000 cycles. Four of five beams went more than 450,000 cycles at a maximum of 0.70

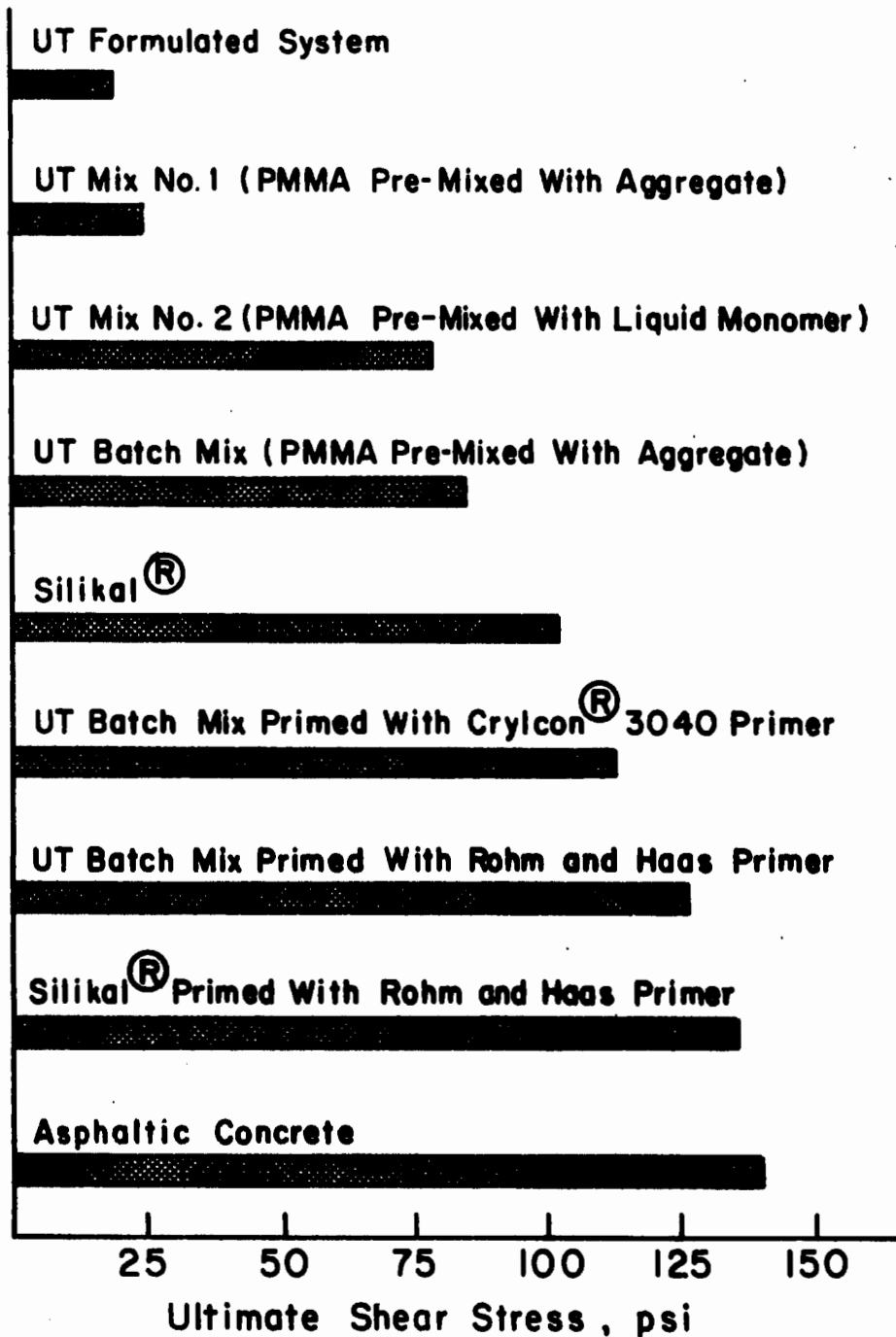


Figure 22. Ultimate Shear Stress of Various Viscosity Formulations.

TABLE 4. ASPHALT PROPERTIES AND PC FORMULATIONS.

Asphaltic Concrete

Asphalt: Type - AC 20; Penetration at 77°F, 64;
and Specific Gravity at 77°F, 1.003

Crushed Limestone Gradation

Percent by Weight Retained

Sieve Size	Type D	Type DC	Type C
5/8"			5
3/8"	5	5	40
#4	35	50	20
#10	25	20	10
#40	10	10	10
#80	10	5	5
+200	10	5	5
-200	5	5	5

Polymer Concrete Formulations

All UT formulations used 95 percent MMA, 5 percent TMPTMA,
1.25 percent BzP and 0.625 percent DMT

Aggregate was all-purpose sand

PMMA was Crylcon® EP 4160

UT Mix No. 1: PMMA powder was mixed with sand and placed
in repair area. Monomer was poured over
sand.

UT Mix No. 2: PMMA was mixed with monomer and poured into
repair area. Sand was poured on top of
monomer.

UT Batch Mix: PMMA was mixed with sand and then mixed
with monomer. Monomer and aggregate were
placed into repair area.

TABLE 5. NUMBER OF CYCLES, N, TO FAILURE FOR FATIGUE BEAMS.

a. $f_{\min}/f_{\max} = 0.25$

$f_{\max}$						
$0.35 f_r$	$0.50 f_r$	$0.60 f_r$	$0.65 f_r$	$0.70 f_r$	$0.8 f_r$	$0.9 f_r$
2×10^{6a}	2×10^{6a}	2×10^{6a}	1,619,910	41,300	27,280	8,630
		2×10^{6a}	2×10^{6a}	1,251,360	15,110	10
			2×10^{6a}	1,801,450	1,120	10
				453,820	5,830	
				641,240	2,960	
					111,104	
					367,040	
					41,700	
^a Test was terminated after 2×10^6 cycles						

b. $f_{\min}/f_{\max} = 0.10$

$f_{\max}$				
$0.60 f_r$	$0.65 f_r$	$0.70 f_r$	$0.80 f_r$	$0.90 f_r$
99,290	2×10^6	43,300	50	80
	253,170	5,530	33,580	
	1,966,230	646,780	26,510	
		104,650	63,680	
		439,150	28,350	

TABLE 5. NUMBER OF CYCLES, N, TO FAILURE FOR FATIGUE BEAMS.
(Concluded)

c. $f_{\min}/f_{\max} = 0.05$

$f_{\max}$			
$0.6 f_r$	$0.65 f_r$	$0.70 f_r$	$0.80 f_r$
2×10^6	1,617,560	150,230	10
2×10^6	1,106,880	1	10
947,620	1,437,840	248,000	10,270
4,281,390		5,590	9,170
10×10^6		668,880	13,640
		352,230	10,710
		145,370	10,130
		268,840	

f_r . But at $0.65 f_r$, all three beams went more than 1.6×10^6 cycles.

Similar behavior was found for $f_{min}/f_{max} = 0.10$ and 0.05 . At a maximum stress of $0.65 f_r$ all but one specimen withstood more than 1×10^6 cycles; however, considerable variation was found for $0.70 f_r$ or higher stresses.

$\log N_{max}$ versus $\log f_{max}$ for the three stress ratios are shown in Figures 23, 24, and 25. The best fit line through the data points is shown. The line which represents a probability of failure = 0.1 is also shown.

A comparison of fatigue behavior for Silikal[®] and for user-formulated PC is shown in Figure 26. The Silikal[®] data are based upon unpublished research performed at Marquette University by Professor Gerald Woefel. As a comparison, the Portland Cement Association design curve and the fatigue response for portland cement concrete (PCC) are shown in Figure 26. Even though portland cement will sustain a larger number of cycles for $f_{max} \approx 0.8 f_r$, it should be noted that f_r is much lower for PCC than for PC.

2.7 Thickened Contractor-Formulated Systems

The use of polymethyl methacrylate (PMMA) in polymer concrete provides two benefits: (1) the PMMA serves as thickening agent which makes the freshly mixed PC more cohesive, similar to the commercially available systems, and (2) the PMMA results in a skin forming on the surface soon after placement, which reduces evaporation and minimizes danger of fire.

The use of PMMA in the contractor-formulated system would be desirable if the Concrete Mobile[®] is to be used. The PMMA helps to prevent the separation of monomer and aggregate, which is important in a continuous mixing process.

A study was performed to determine the effect of various variables on the setting time and strength of PC with PMMA. The variables were: amount of TMPTMA; amount of PMMA; and amount of monomer in the batch. The amount of monomer varied from 7 to 10 percent of the weight of the aggregate. The amount of TMPTMA

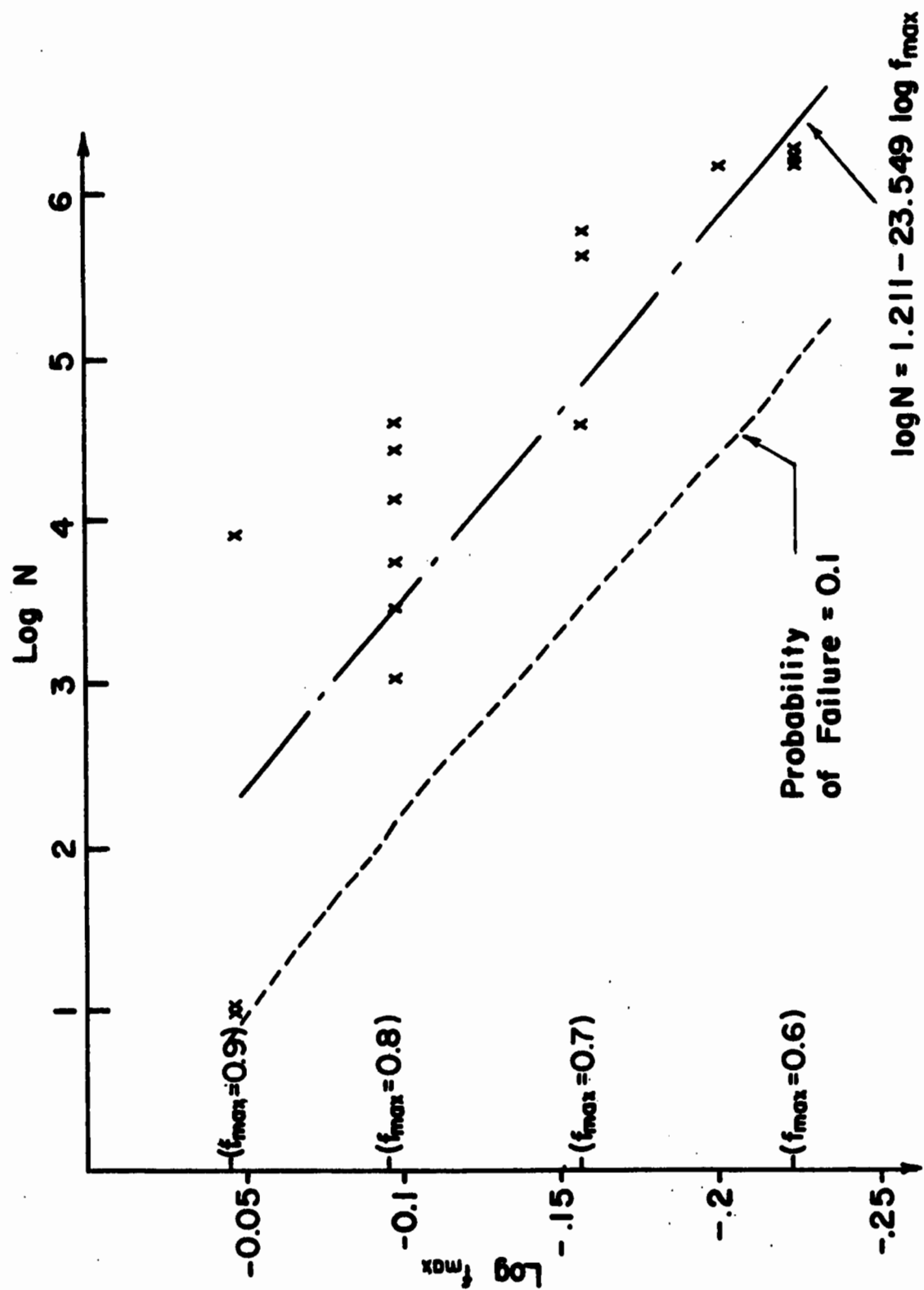


Figure 23. Log-Log Plot of Stress Versus Number of Cycles Diagram for $f_{min}/f_{max} = 0.25$.

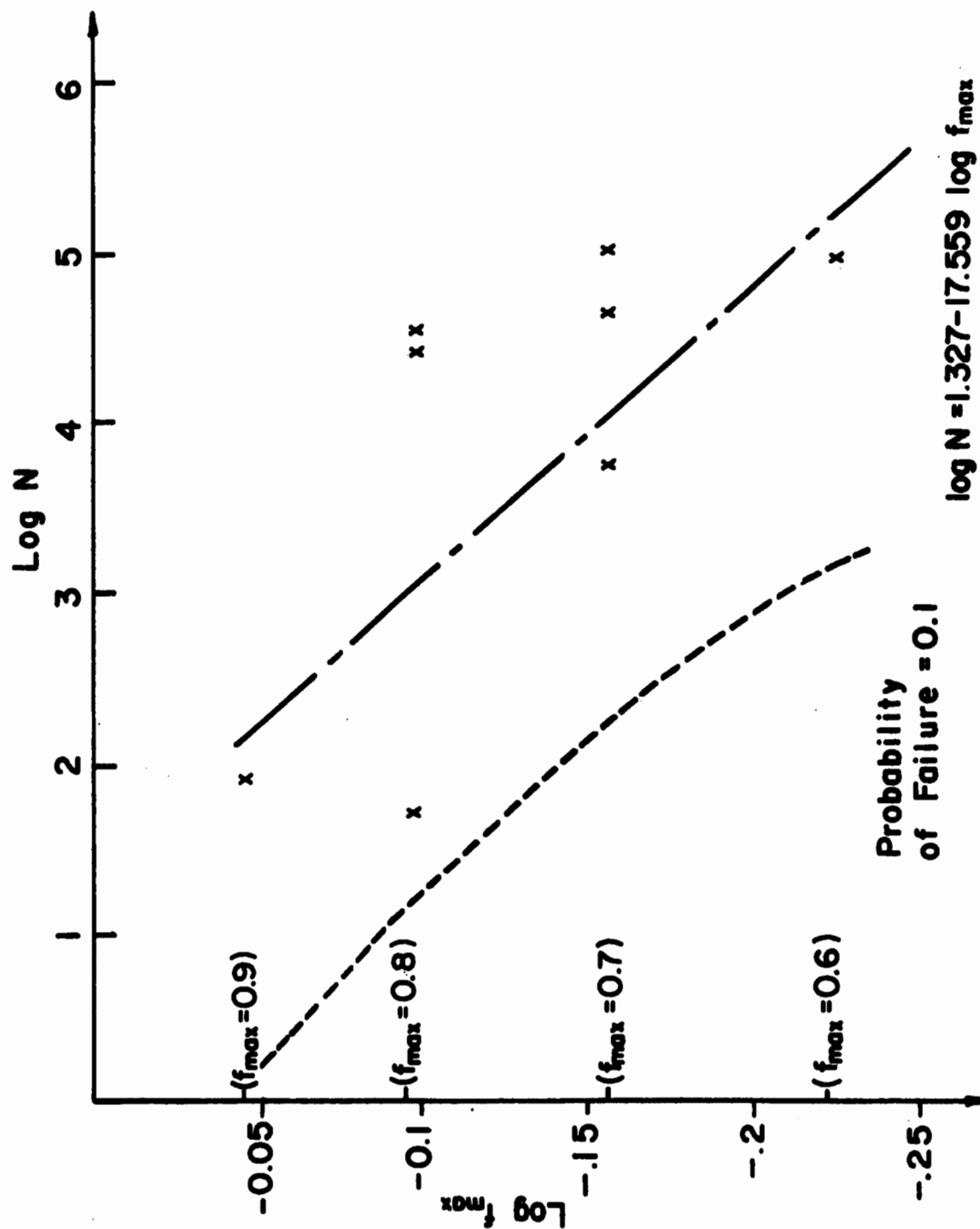


Figure 24. Log-Log Plot of Stress Versus Number of Cycles Diagram for $f_{\min}/f_{\max} = 0.10$.

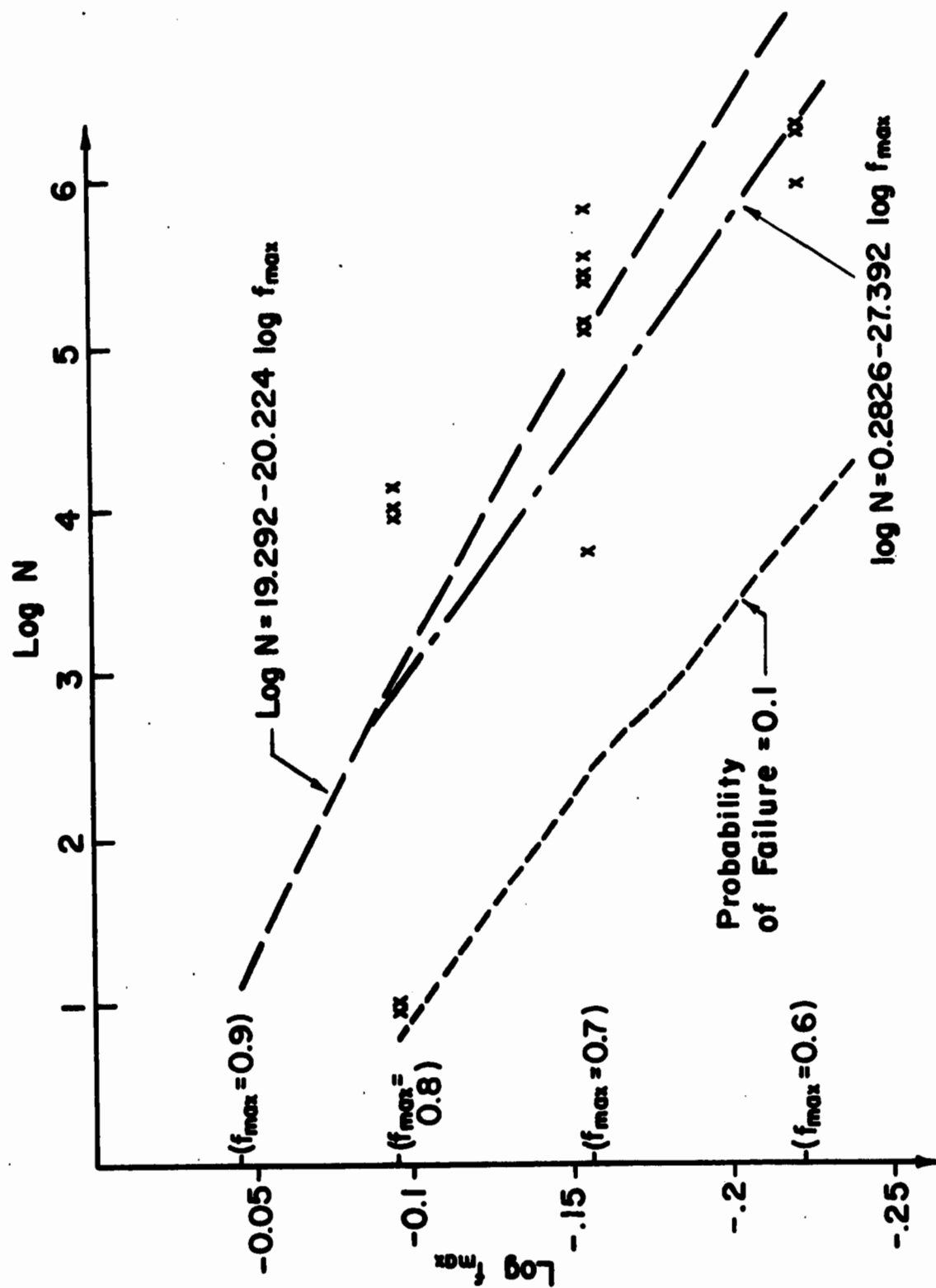


Figure 25. Log-Log Plot of Stress Versus Number of Cycles Diagram for $f_{min}/f_{max} = 0.05$.

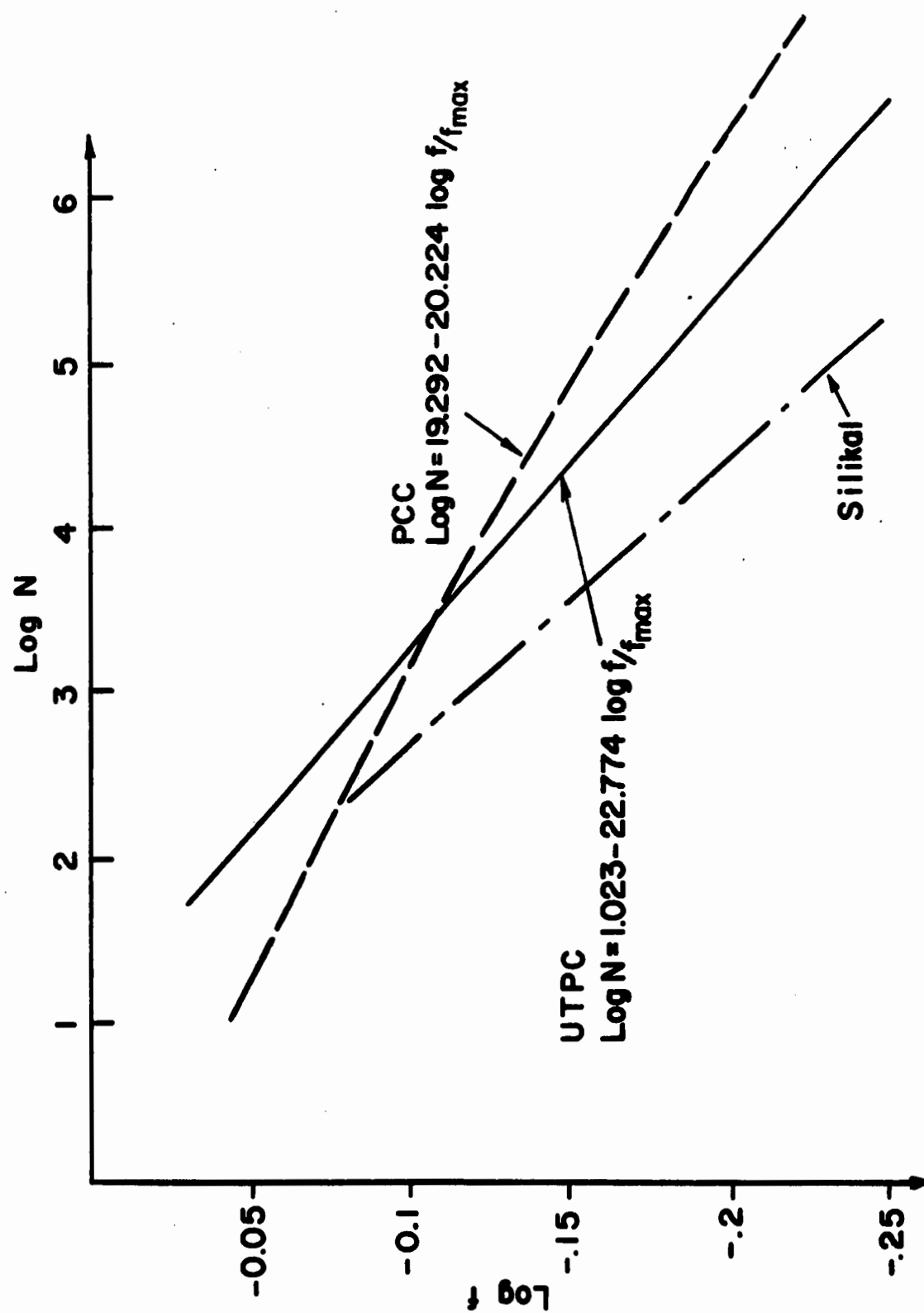


Figure 26. Comparison of Laboratory Fatigue Tests.

varied from 0 to 5 percent of the total monomer (MMA and TMPTMA). The PMMA varied from 0. to 5 percent of the total aggregate weight. The promoter and initiator were 0.6 percent DMT and 1.2 percent BzP, respectively.

The aggregate and the PMMA were premixed, and the aggregates, PMMA and monomer system were mixed together before the PC was placed in the cylinders. A temperature probe was inserted into the PC during polymerization to monitor the exotherm temperature.

The peak exotherm time and temperature versus monomer content are shown in Figure 27. It can be observed that the time to peak exotherm ranged from 35 to 40 minutes and was essentially independent of monomer content. The peak exotherm temperature increased with increasing monomer content.

Figure 28 gives the peak exotherm time and temperature as a function of PMMA content and amount of TMPTMA. It can be observed that the time to peak exotherm decreases with increasing PMMA content and with increasing TMPTMA content.

Figure 29 shows the relationship for splitting tensile strength and compression strength as a function of monomer content for a monomer system of 97 percent MMA and 3 percent TMPTMA with 3 percent PMMA. The strength increased as monomer content was increased to 9 percent. The lower strengths for the lower monomer contents apparently reflect the fact that insufficient monomer was present to fill the voids in the aggregate.

Figure 30 gives the relationship for splitting tensile strength as a function of PMMA content and amount of TMPTMA. Tensile strength increases significantly with increasing PMMA and to some extent with decreasing levels of TMPTMA. Figure 31 shows compressive strength as a function of PMMA content and TMPTMA level. Compressive strength is influenced only slightly by changes in these variables.

Based on these results, the use of 3-percent weight PMMA based upon total aggregate weight is recommended with a monomer system of 97 percent MMA and 3 percent TMPTMA. This combination provides optimum setting time and strength.

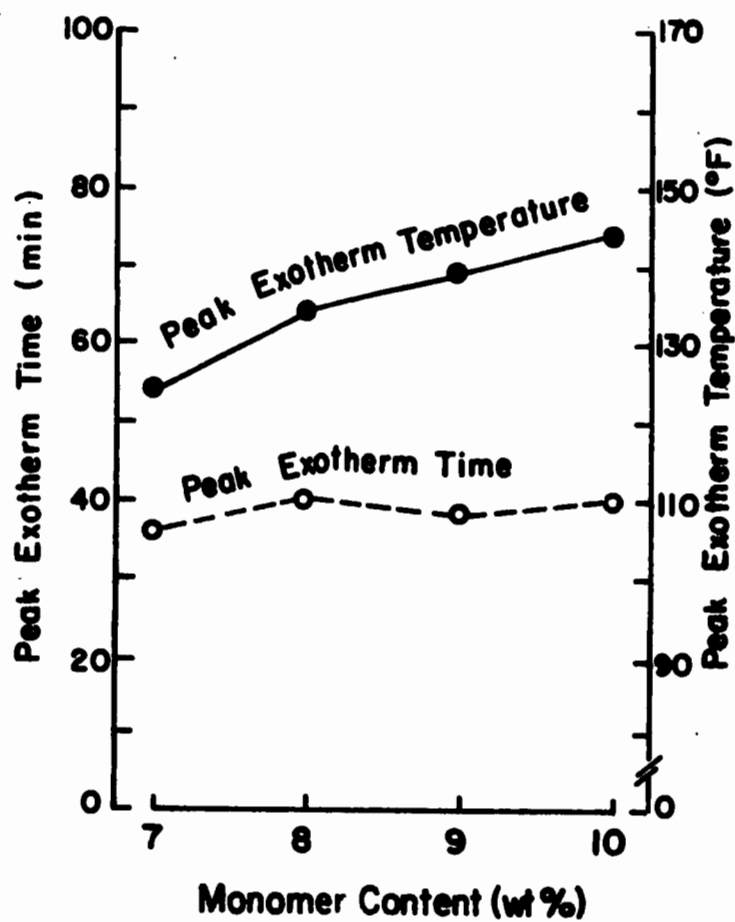


Figure 27. Monomer Content vs. Peak Exotherm of PC with MMA 97: TMPTMA 3 (wt %).

Legend:

MMA: TMPTMA

▲ △ 95:5

● ○ 93:3

■ □ 100:0

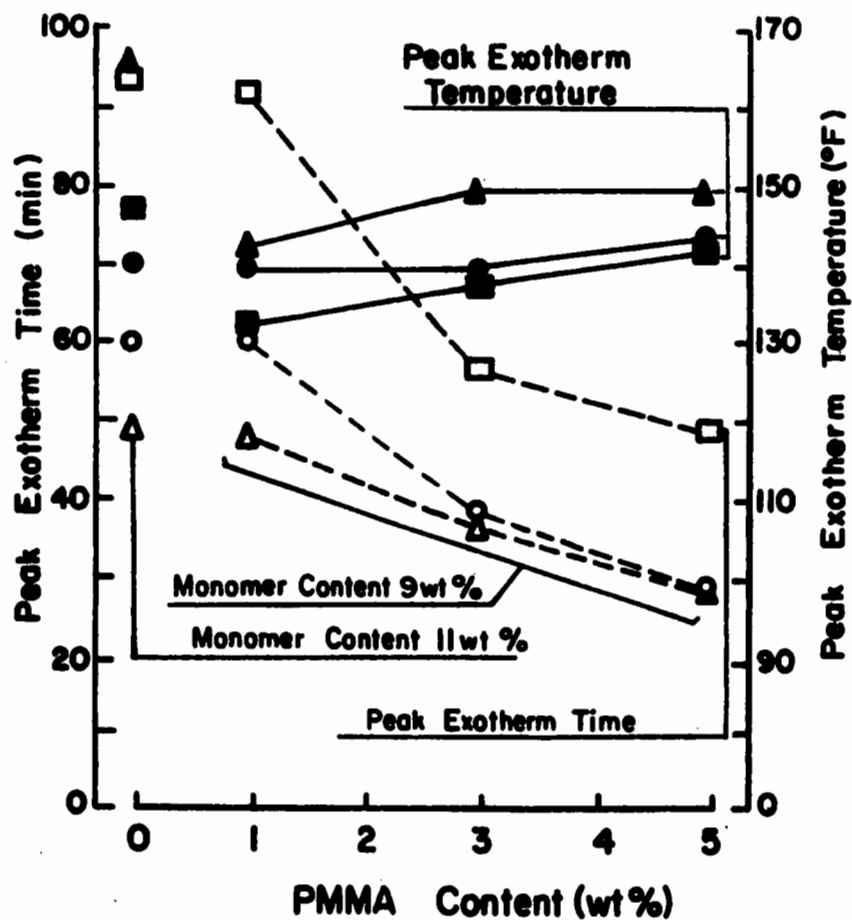


Figure 28. PMMA Content vs. Peak Exotherm of PC.

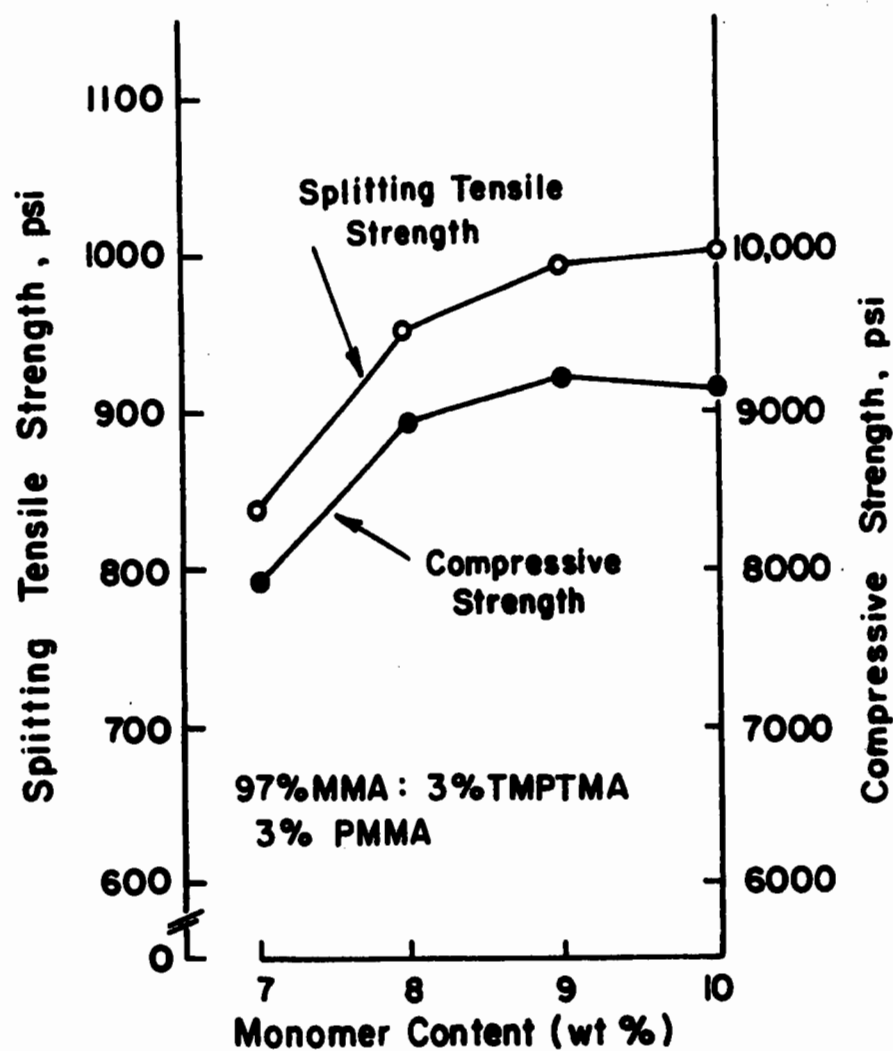


Figure 29. Strength As A Function of Monomer Content.

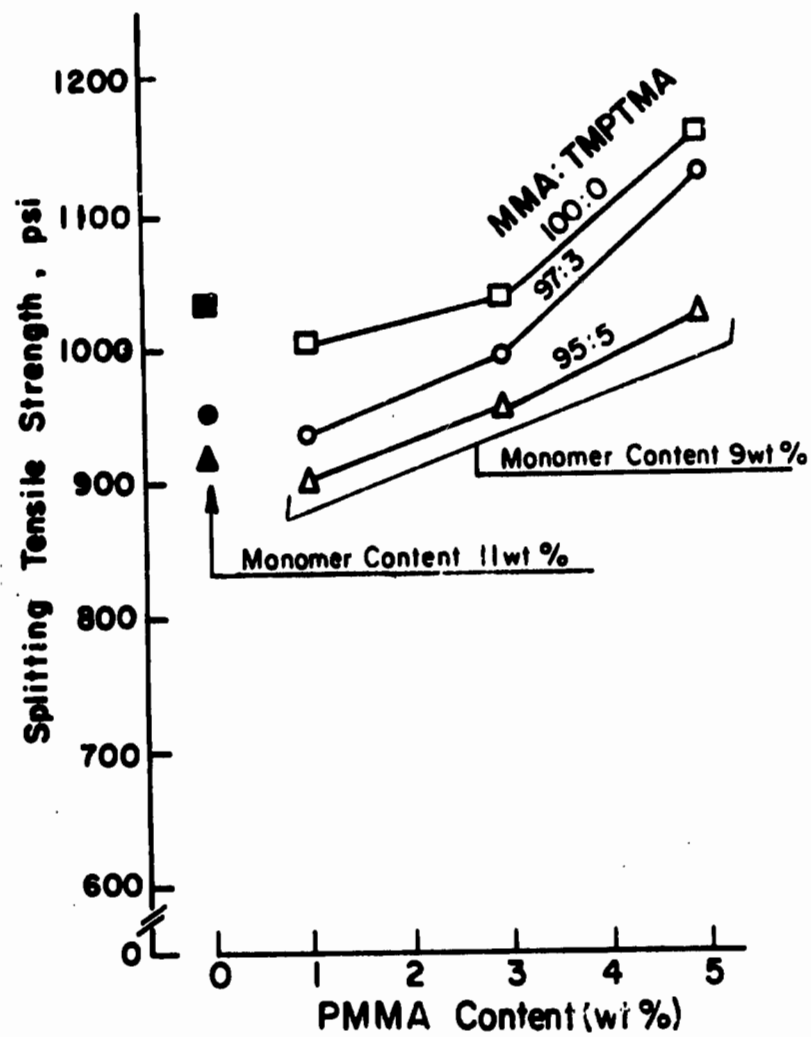


Figure 30. PMMA Content vs Splitting Tensile Strength of PC.

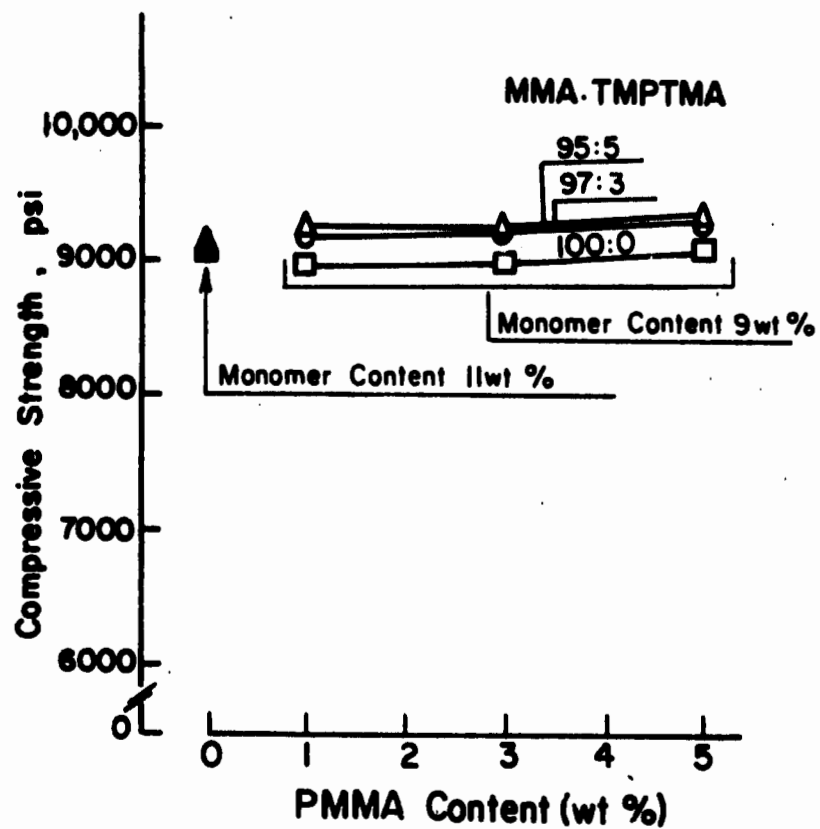


Figure 31. PMMA Content vs Compressive Strength of PC.

2.8 Shrinkage.

Tests were performed to determine shrinkage of polymer concrete using an apparatus developed by Ohama and Demura¹². The test specimens are 1-1/2 in x 1-1/2 in x 6 in. A direct current differential transformer (DCDT) is used at each end to measure the contraction of the specimen during polymerization.

The specimens were made using equal weight parts of concrete sand and 3/8 in. silicious pea gravel. The variable was the amount of polymethyl methacrylate (PMMA) powder added to the mix. With the PMMA powder, a monomer system consisting of 97 percent MMA, 3 percent TMPTMA, 0.6 percent DMT, and 1.2 percent BzP has been found to set in less than 1 hour at room temperature.

The specimens were made by premixing the dry aggregate and PMMA powder. The PMMA powder was used in the amounts of 0, 1, 3, and 5 weight percent of the aggregate weight. The mixed aggregate and PMMA were placed in the molds in three approximately equal depth layers. Each layer was saturated with the monomer system. The DCDTs were then placed in contact with steel discs at each end of the mold. As the specimens contracted during shrinkage, the spring-loaded plungers forced the steel discs to maintain contact with the PC. The output from the DCDTs was converted to deformation.

Figure 32 gives the relationship between shrinkage strains and time for the different amounts of PMMA powder. The shrinkage was found to decrease with increasing PMMA. The shrinkage for 5 percent PMMA was about 1450×10^{-6} in per in as compared to about 2200×10^{-6} in /in for specimens containing no PMMA, a reduction of 34 percent.

Figure 33 gives the shrinkage at the time of peak exotherm and after 10 hours. For PC without PMMA, the 10-hour shrinkage is about twice the shrinkage at peak exotherm, but for PC with 5

¹² Ohama, Y.; Demura, K.; and Masahi, K. Length Change of Polyester Resin Concrete. Department of Architecture, College of Engineering, Nihon University, Koriyama, Fukushima 963, Japan.

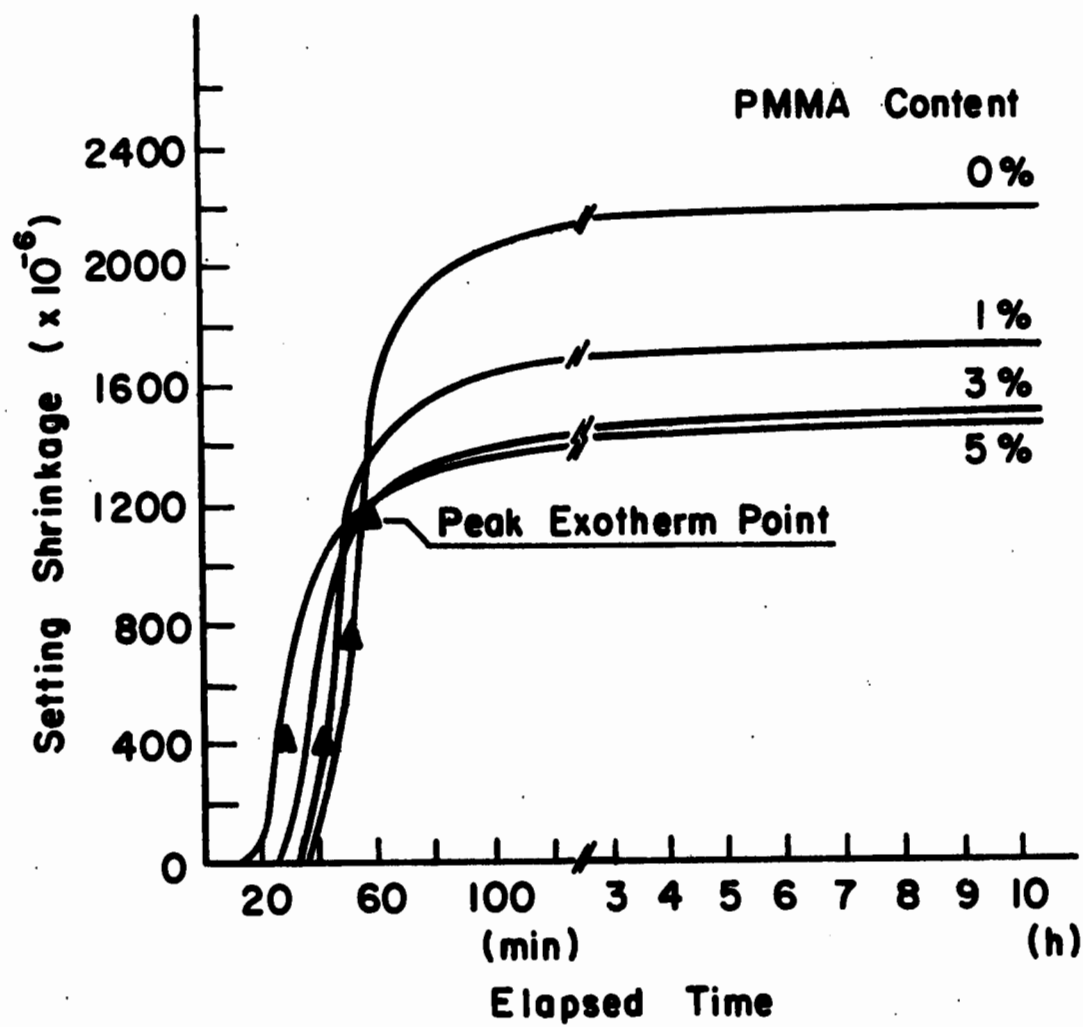


Figure 32. Elapsed Time vs Setting Shrinkage of Polymer Concrete.

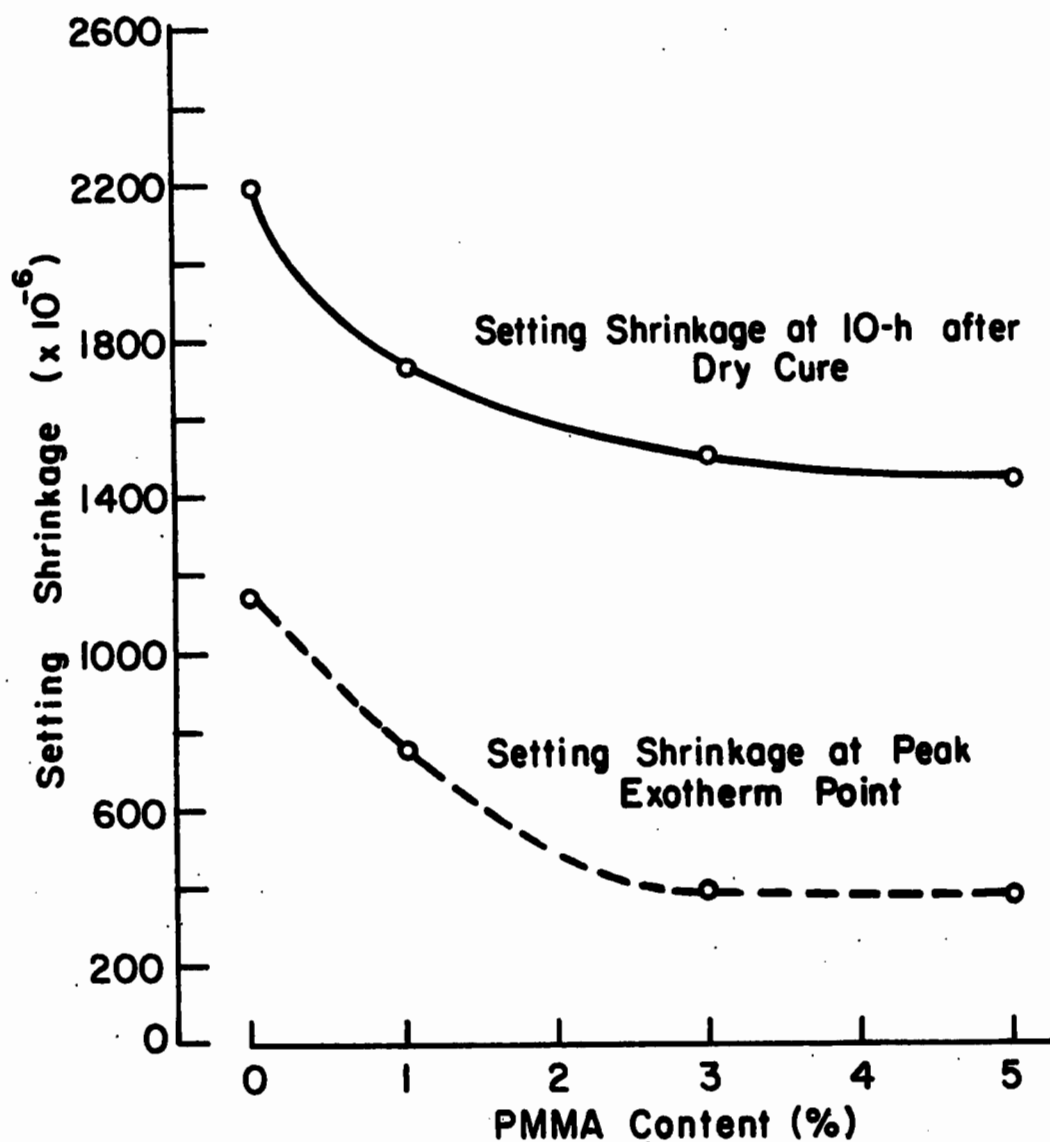


Figure 33. PMMA Content vs Setting Shrinkage of Polymer Concrete at Peak Exotherm Point and 10 Hours After Cure.

percent PMMA, the 10-hour shrinkage is nearly 4 times greater than the shrinkage at peak exotherm.

2.9 Design Properties

A summary of material properties is shown in Table 6. Since a range of values was obtained for each property during the investigation, the 95-percent confidence value is given for compressive strength, splitting tensile strength, and modulus of rupture (flexural strength). The 95-percent confidence value represents the strength that 95 percent of the specimens should equal or exceed.

The 95-percent confidence value is obtained by the following procedure:

$$f_{95} = \bar{f}_{avg} - 1.65\sigma$$

where: f_{95} = 95-percent confidence value
 $\bar{f}_{avg}$ = average, or mean, value
 σ = standard deviation.

The standard deviation is obtained by:

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (f_i - \bar{f}_{avg})^2}{N-1}}$$

where: f_i = strength of test specimen i
 N = number of test specimens.

The average value is used for modulus of elasticity since the modulus is used to calculate deflections, which are not critical from the standpoint of strength. It is important, however, to know that the strength properties are conservative and that few samples would have lower values.

Environmental effects must also be considered. The effect of casting and testing temperature was shown in Figure 5 to have relatively minor effects on modulus of rupture values. However, initiator and promoter concentrations require variations to maintain consistency in set time. Casting at temperatures less than

TABLE 6. MECHANICAL PROPERTIES FOR CONTRACTOR-FORMULATED
PC CAST AND TESTED AT 77°F.

	Range	Standard Deviation, psi	95% Confidence Value
Compressive strength (psi) ^a	7640-10,800	1134	6980
Splitting tensile strength (psi) ^a	1043-1460	118	1130
Modulus of rupture (psi) ^b	1830-2300	157	1790
Compressive modulus of elasticity (psi) ^a	2.1-2.5 x 10 ⁶		2.3 x 10 ⁶ (Avg)
Flexural modulus of elasticity (psi) ^a	2.1-3.5 x 10 ⁶		2.7 x 10 ⁶ (Avg)

^aBased on 3 in x 6 in cylinders.

^bBased on 6 in x 6 in x 36 in beams.

room temperature, at which most test specimens are made, causes a slight reduction in strength. Testing at lower temperatures results in higher strengths. It is probably not necessary to modify the strength for either low or high temperature uses.

The effect of moisture is more serious. Figure 34 gives the reduction of strength for both user-formulated (UT formulation) PC and commercially available PC (Silikal[®] and Crylcon[®]) with and without fibers. If at all possible, moisture content in the aggregate should be kept at less than 1 percent. However, if the moisture content is greater than 2 or 2.5 percent, the use of 5-percent (wt) hooked steel fibers should be used with a reduction in modulus of rupture of about 60 percent. Without fibers, the reduction is about 80 percent.

The moisture contents shown in Figure 34 represent the total moisture in the fine and coarse aggregate for user-formulated and moisture in the coarse aggregate used to extend the commercially-available PC. The data points are for both silicious and limestone aggregate and each point represents the average of several test values. Approximately equal weights of aggregate were used with the mortar for the commercially available PC specimens.

It is recommended that test data be taken at each site for the aggregates to be used. Moisture contents should be varied to determine the strength reduction with increasing the moisture contents.

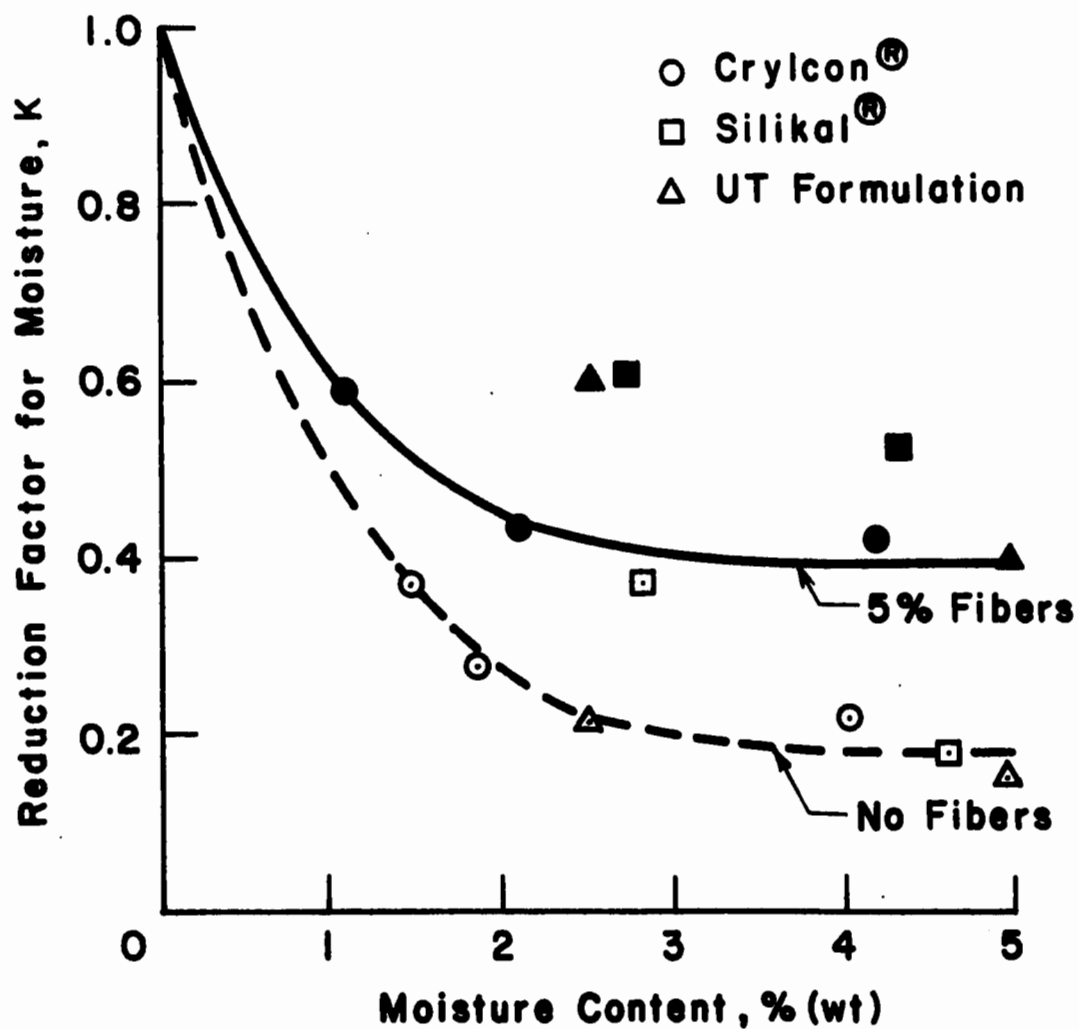


Figure 34.. Strength Reduction Factor for PC Made With Wet Aggregate With and Without Steel Fibers.

SECTION III

FIELD TESTS OF RAPID REPAIR METHODS

3.0 Introduction

The Phase I report described several methods of rapid repair for four types of bomb damage. In selecting the methods, emphasis was on simple procedures that would minimize personnel and equipment requirements. Each method was used in a simulated field test and trafficked with load carts at Tyndall Air Force Base in Florida.

A detailed description of the various types of bomb damage and the various methods of repair is presented in Section III of the Phase I Report¹³.

3.1 Field Tests of Spall Repairs

A series of fifteen simulated spalls was made in the Tyndall research pavement. The section of pavement consisted of a clay subgrade covered by 12 in of portland cement concrete (PCC), overlaid with 4 in of asphalt cement concrete (ACC). This pavement cross-section is similar to that which exists at several Air Force bases.

The test series included five sets of three spalls each, with each set having a small, medium and large spall. Type "A" spalls were small, type "B" were medium and type "C" were large (Figure 35). Three sets were repaired using the user-formulated system and the in-line mixing gun.

The spalls were filled with aggregate and the in-line mixing gun was injected into the aggregate. The user-formulated monomer system consisted of 90 percent MMA and 10 percent TMPTMA. The promoter was 0.6 percent DMT and the initiator 1.2 percent BzP based upon the weight of the monomer. The BzP was a 40-percent

¹³Fowler, D.W., et al. Methyl Methacrylate Polymer Concrete for Bomb Damage Repair: Phase I.

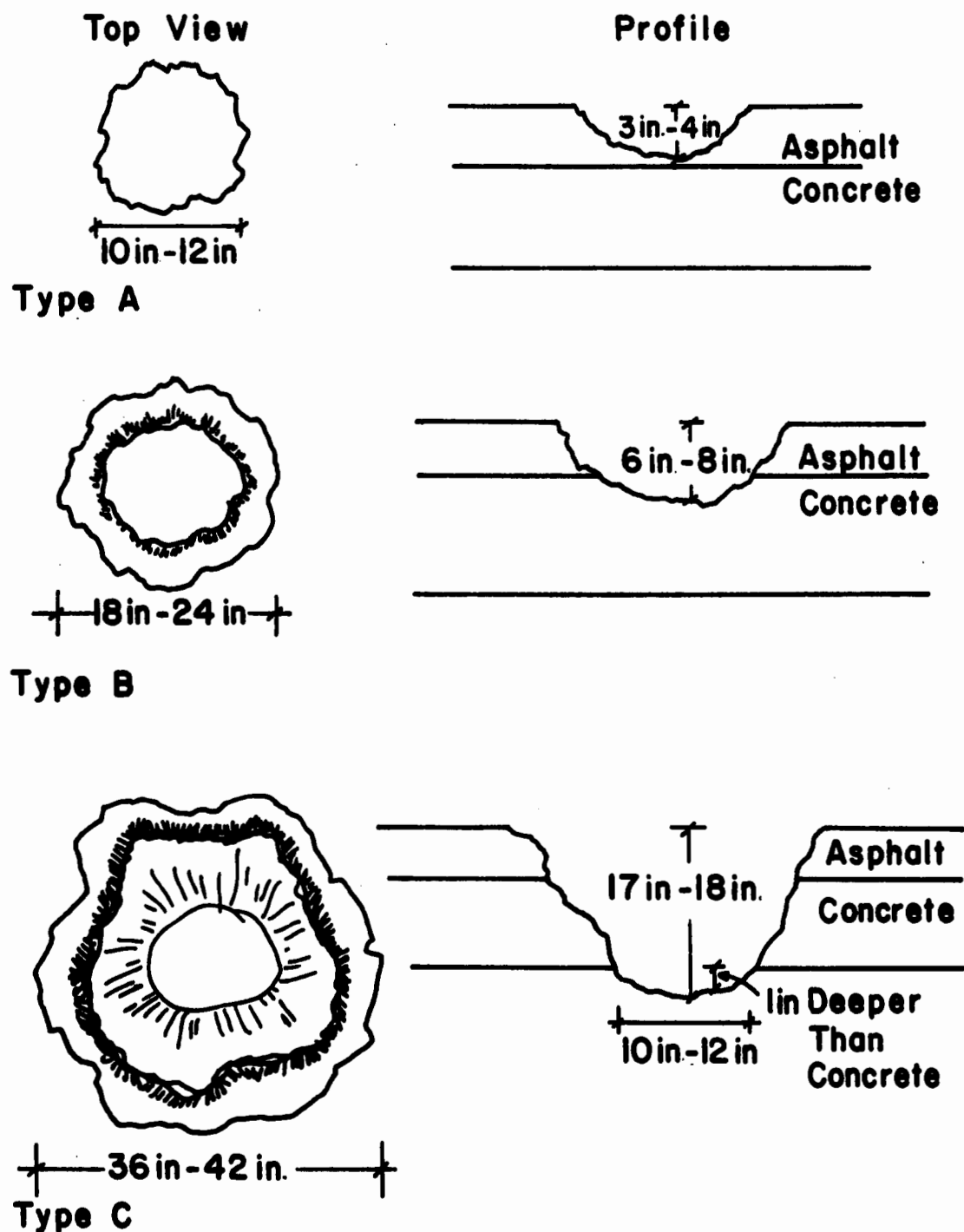


Figure 35. Typical Spall Repair Sections.

dispersion which could more easily be used in the in-line mixing gun.

Set 2 was repaired using selected dry aggregates. A 3/4 in coarse aggregate was mixed with concrete sand in an approximate 50:50 ratio. Spall 2B failed on one side of the repair early in the load cart tests. From visual inspection, the failure was due to a pocket of unpolymerized material. Spalls 2A and 2C performed satisfactorily under the load cart tests.

Set 4 was repaired using debris as the aggregate. Select dry sand was used to finish the surface. The tip broke off the in-line mixing gun while making the second repair and the balance of the repairs were made using only the handle of the gun, which by itself did not provide adequate mixing of the initiator and the monomer. No difficulties were encountered using the debris and the repairs performed satisfactorily under the load cart tests.

Set 5 was designed to evaluate wet conditions during repairs. The sides of the spalls were wetted, and water was left standing in the bottom (Figure 36). Repair 5A was made using dry coarse aggregate only so that without the fine aggregate, the wicking action of the water would be minimized. The repair performed satisfactorily. For repairs 5B and 5C, a more viscous initiator was used than had previously been used with the in-line mixing gun. In these two repairs, coarse aggregate was placed in the spall to a depth of about 2 in above the water, and then the remainder of the repair was filled with the same 50:50 mix used in Set 2. Repairs 5B and 5C failed on the first pass of the load cart. From visual inspection, it was obvious that no polymerization had taken place. The lack of polymerization could be attributed to the different initiator, to the broken gun or a combination of both.

After this series of tests, the mixing chamber and tip of the in-line mixing gun was redesigned and made stronger.

From this series of tests, the in-line mixing gun was proven to be effective for applying monomer. It allows the chemicals to be mixed at the point of application and it minimizes exposure



Figure 36. Spalls Before Repair.

of personnel to the chemicals. The tests also verified that debris can be used for at least part, if not all, of the aggregates required, provided some select material is available for finishing. It should be noted that large pieces of debris were not used, nor did the debris contain a significant amount of asphaltic materials.

The repairs of Sets 1 and 3 were made with Silikal[®] and were not a part of this study. Figures 37 through 45 illustrate the spall repairs.

3.2 Field Tests of Crater Repairs

Three methods of crater repair were tested at the pavement research facility at Tyndall Air Force Base. Three 20 ft x 20 ft test pits were prepared using clay as the base material. All coarse aggregate used in these tests was 3/4 in crushed limestone.

The first two crater repairs (Pit No. 2 and Pit No. 3) were made using precast slabs. The precast slabs were prepared from normal portland cement concrete. The slabs were nominally 6 ft x 6 ft square and of two thicknesses, 12 in and 8 in. All slabs had concave keyways on all sides. All slabs were cast with quick release lifting eyes and threaded drag eyes. Concrete was placed in the wooden forms, consolidated, and allowed to cure more than 28 days prior to use.

The 6-ft x 6-ft size was selected to match the 20-ft x 20-ft pit to be repaired. By using 9 slabs in the repair area, there was an approximate 6 in gap between slabs and edges for the PC bonding material. Also, the 12-in thick slabs weighed about 5200 pounds each and the 8-in thick slabs weighed about 3500 pounds. Both of these weights are well within the handling capabilities of the front end loaders, small cranes, and fork lifts usually available at most bases.

Figures 46 through 48 illustrate the preparation of the precast slabs. Pit No. 2 was repaired using the precast slabs flush with the surrounding pavement. The base of the pit was a clay layer some 21 in below the grade surface. A 6-in



Figure 37. In-Line Mixing Gun.

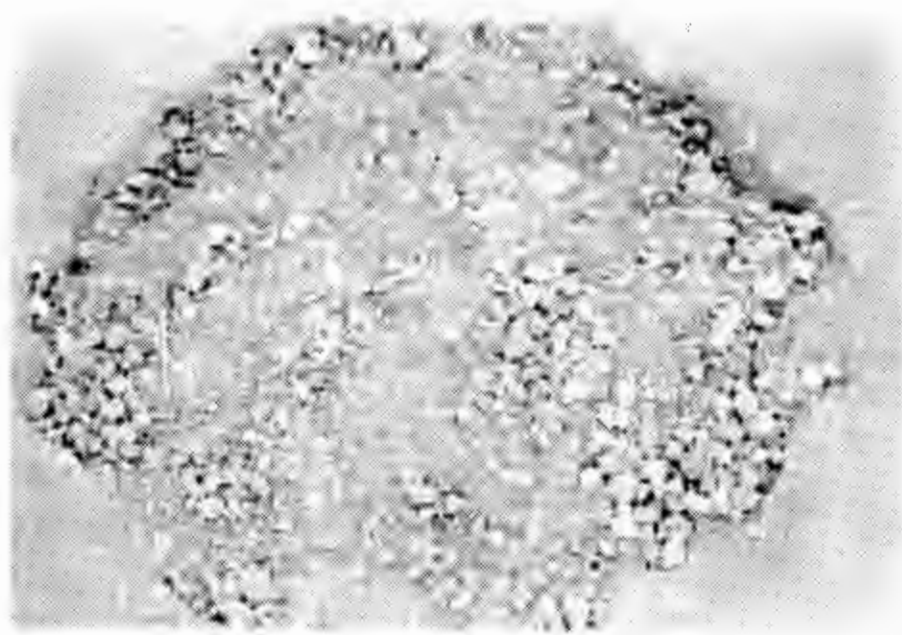


Figure 38. Debris Fill.



Figure 39. Completed Repairs - 4A, 4B, 4C.

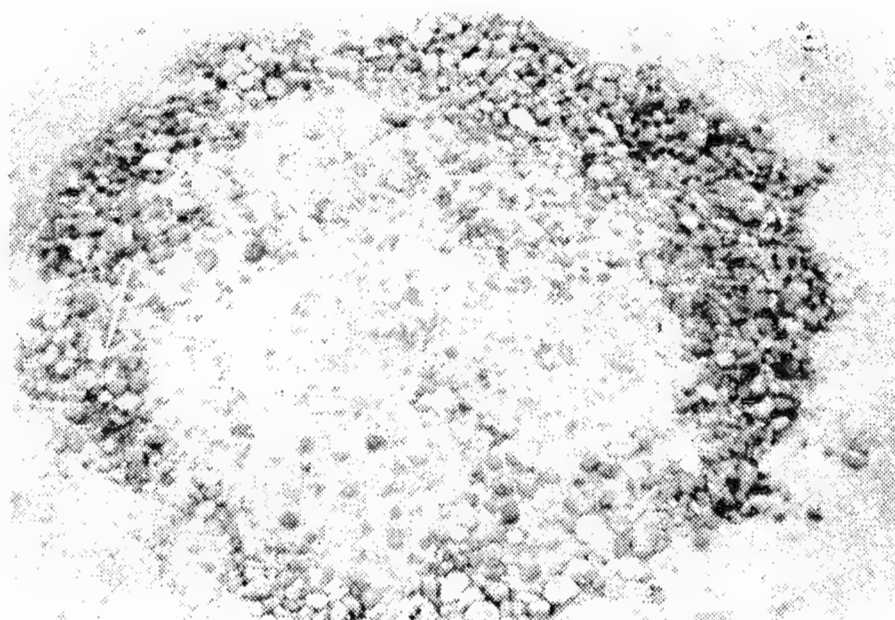


Figure 40. Select Fill.

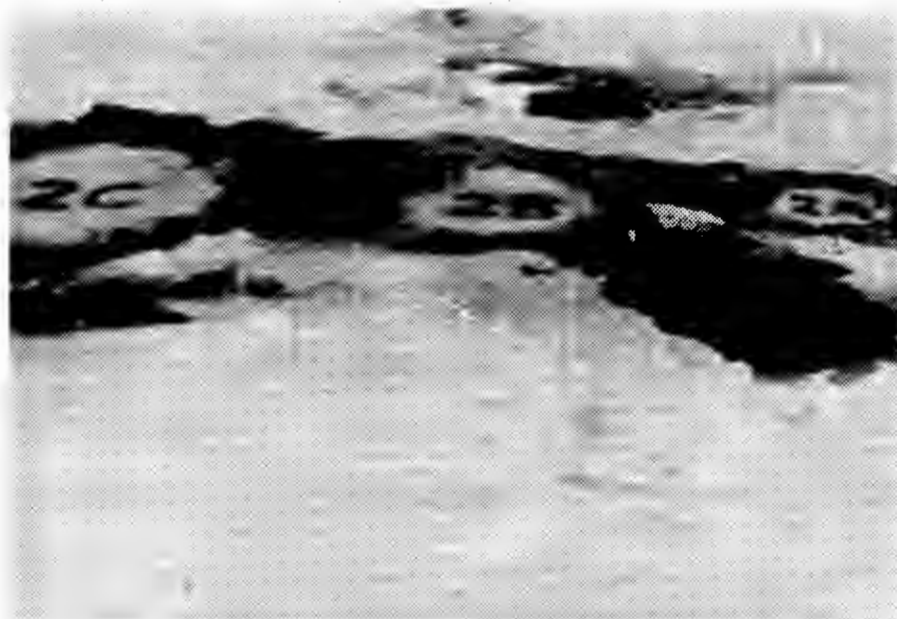


Figure 41. Completed Repairs - 2A, 2B, 2C.



Figure 42. Repair 2B After Traffic.



Figure 43. Repair 5A - No Fines.

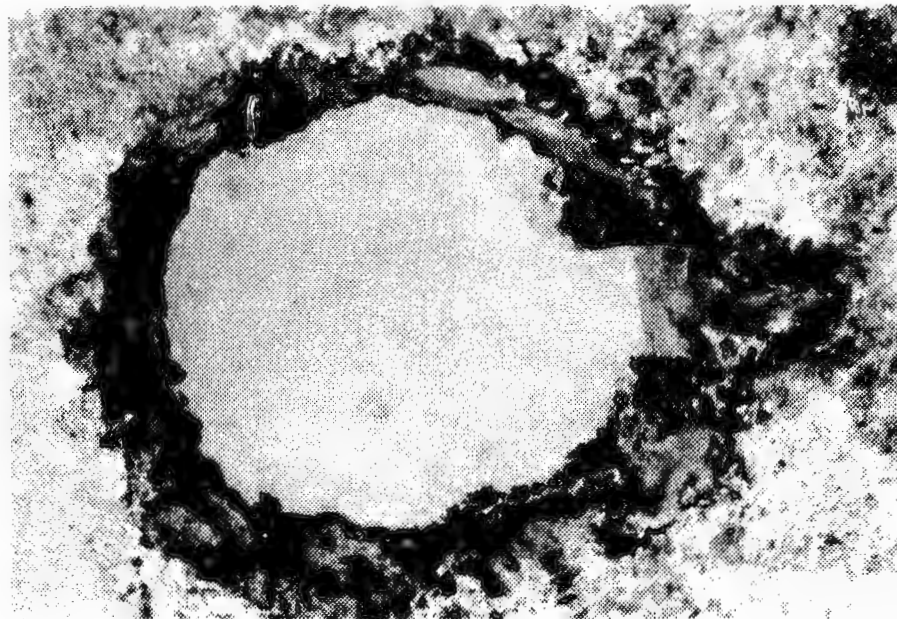


Figure 44. Wetted Spall.

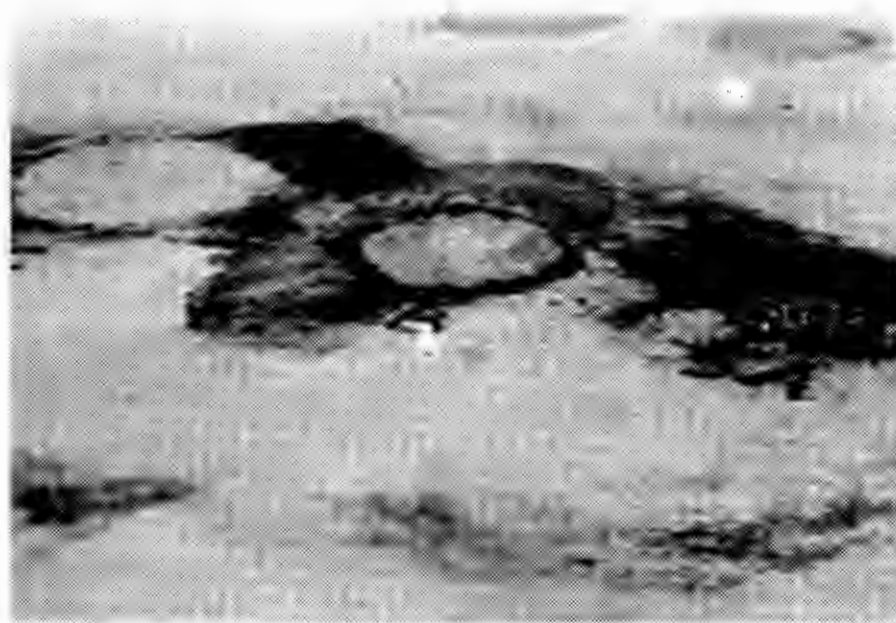


Figure 45. Completed Repairs - 5A, 5B, 5C.



Figure 46. Precast Forms.



Figure 47. Quick Release Lift Eye.

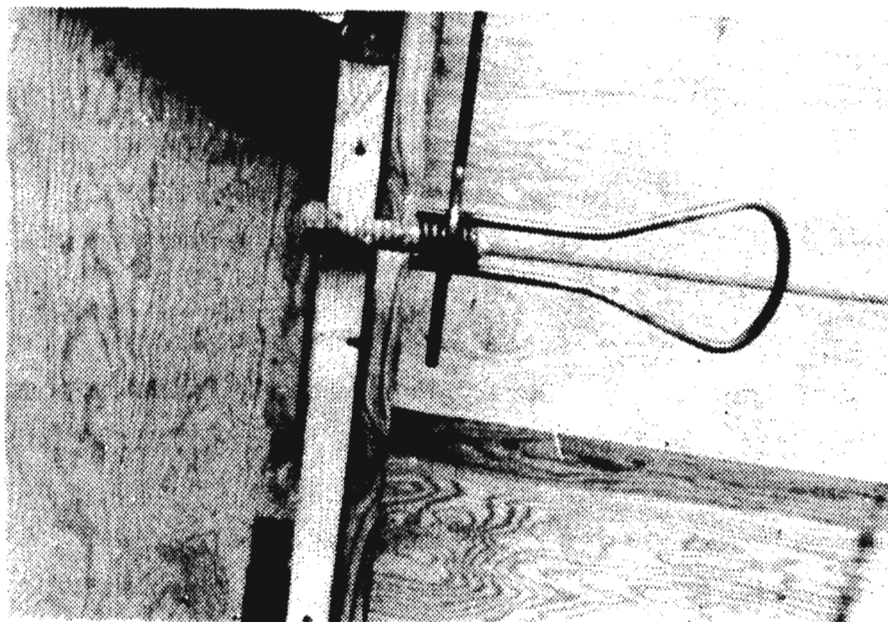


Figure 48. Threaded Drag Eye.

layer of crushed limestone was compacted over the clay and a 3 in sand leveling course was placed over the crushed limestone. Figure 49 illustrates a plan view and a cross-section of Pit No. 2.

The 12-in thick precast slabs were lifted into place using a front end loader with a lifting arm attachment. A cable sling was attached to the slabs using quick release lifting eyes (Figure 50).

A polyethylene film was placed with the sand layer to prevent leakage of the monomer when placing the PC. After leveling the slabs, a 50:50 mixture of air-dried sand and gravel was shoveled into the voids around each slab (Figure 49).

The monomer formulation used for test Pit No. 2 consisted of 95 percent MMA/5 percent TMPTMA. The promoter was 1 percent DMT and the initiator was 1.6 percent BzP.

The monomer was injected into the aggregates with an in-line mixing gun (Figure 51). During the repair, the monomer was discharged too fast, and the aggregates, particularly the fines, tended to wash out of the mix in the area of the gun. This problem can be reduced through redesign of the nozzle. Also, a problem with the air compressor developed due to the high humidity of the air. Periodically the water filters would fill and allow water into the air lines. This problem can be reduced by using larger capacity water filters. After the aggregates were saturated, the PC was trowelled to a fine textured finish.

Pit No. 2 was then load cart tested with 150 coverages of the F-4 load cart and 70 coverages of the C-141 load cart. The repair showed no visible signs of deterioration. The profile of the repair remained virtually unchanged from the beginning to the end of load cart testing. Also, from the profile data, the riding quality was excellent since there was very little change in elevation across the slab (Figures 52 to 54).

Pit No. 3 was repaired using a combination of precast slabs and cap methods of repair. The base of the pit was a clay layer (CBR = 4) which was covered with 6 in of compacted, crushed limestone. The 8-in precast slabs were then placed on the

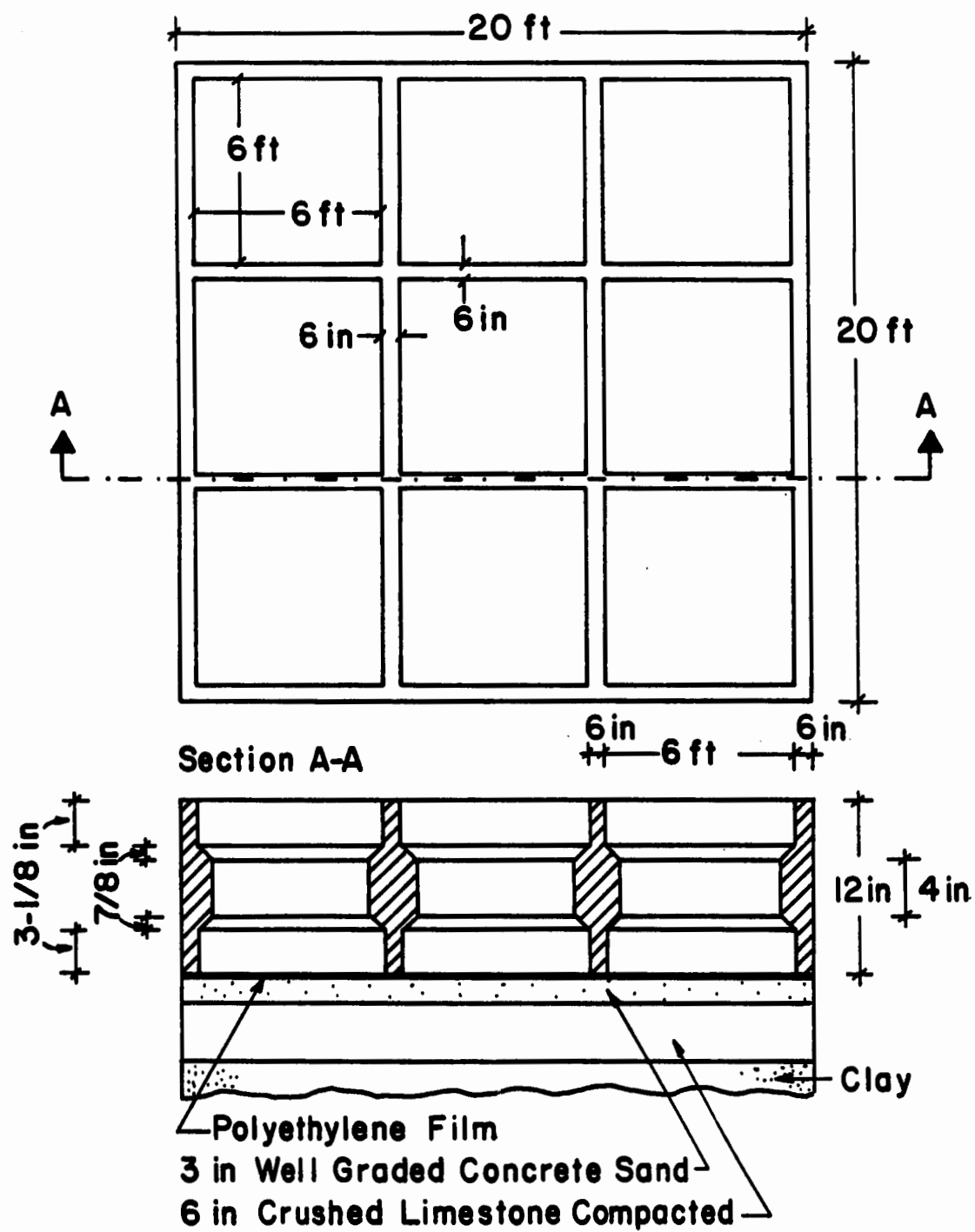


Figure 49. Pit No. 2.

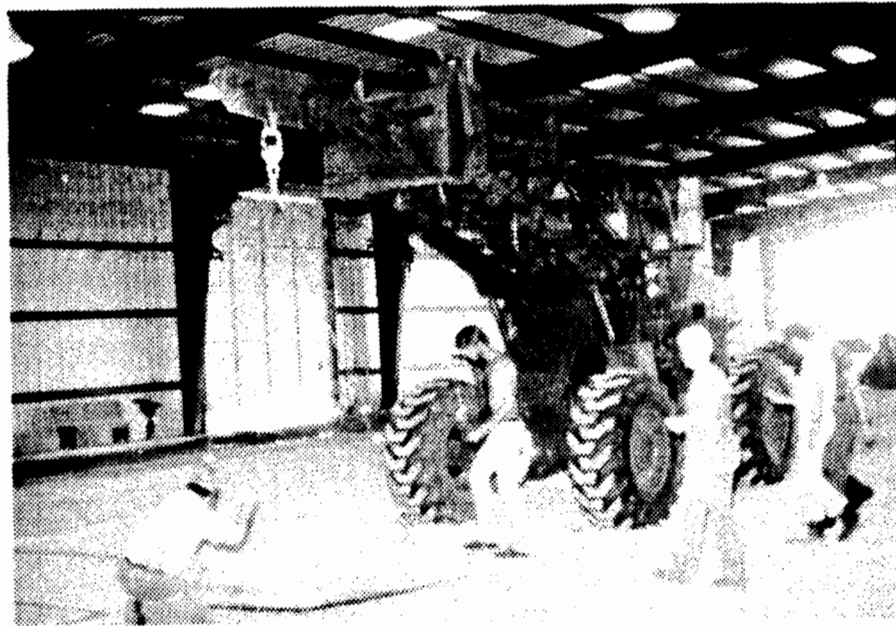


Figure 50. Precast Slab Placement.



Figure 51. In-Line Mixing Gun Injecting Monomer Between Precast Slabs.

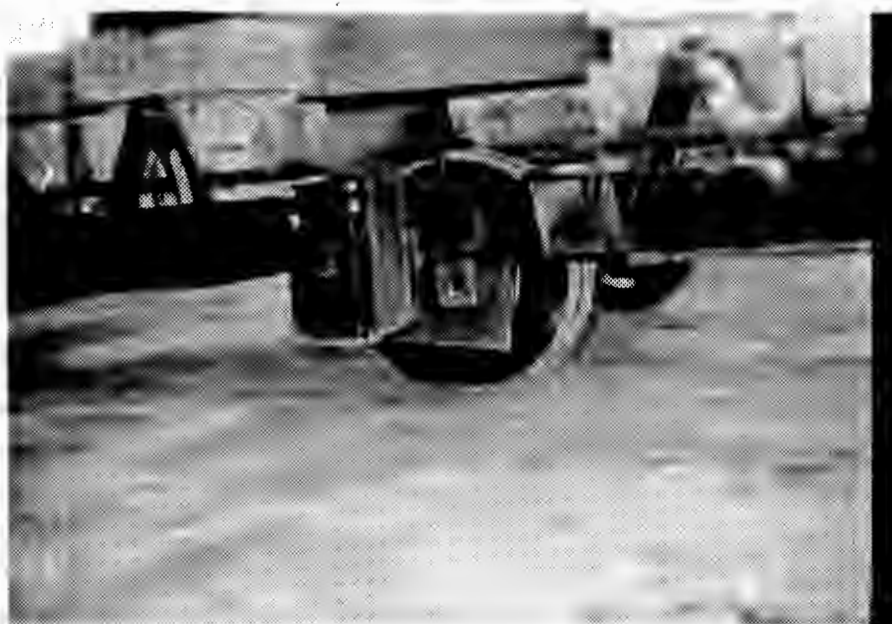


Figure 52. F-4 Load Cart.

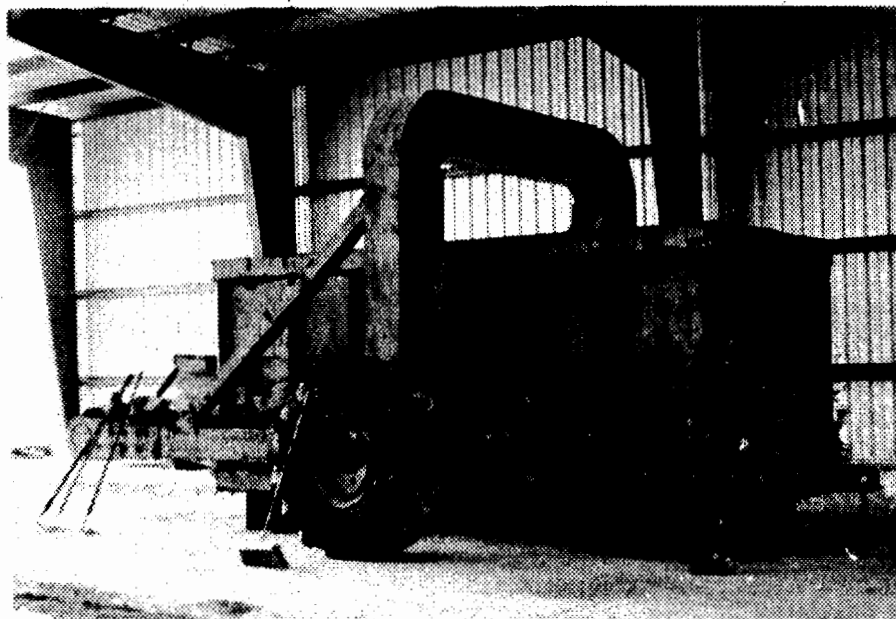


Figure 53. C-141 Load Cart.

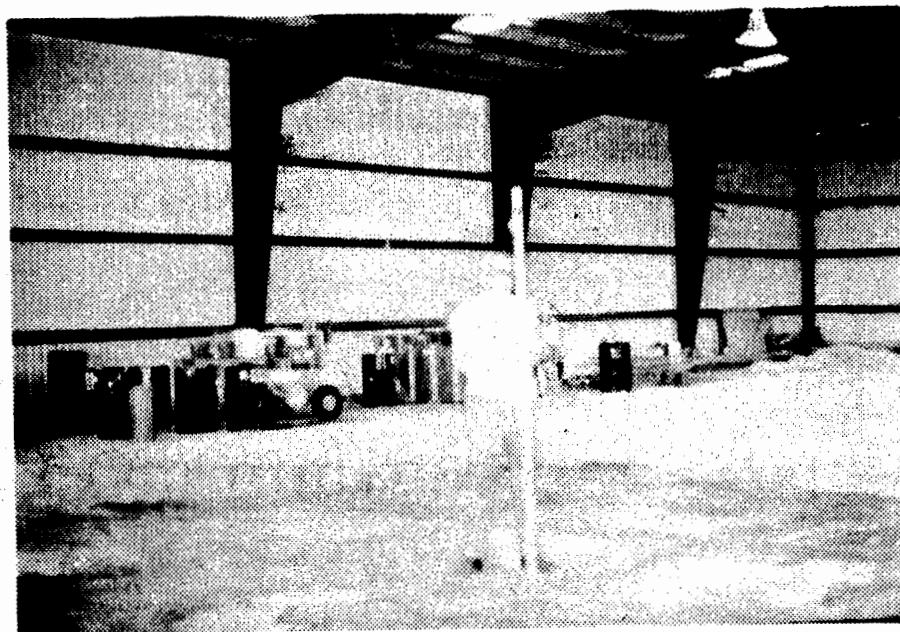


Figure 54. Profile Measurements.

crushed limestone. Polymer concrete was placed around and over the slabs to bring the repair to grade. The PC cap over the slab was nominally 2 in thick (Figure 55).

Three polymer concretes were used. Crylcon[®], Silikal[®], and University of Texas user-formulated (UF) system were all placed using the Modified Concrete Mobile[®] furnished by AFESC. The output capacity of this model of the Concrete Mobile[®] is 60 cubic yards per hour. The Concrete Mobile[®] uses internal storage of materials and an auger mixer which allows the mixing of the materials as needed (Figures 56 and 57).

The Crylcon[®] and Silikal[®] were each extended with an equal amount of coarse aggregate. The liquid and powder components and aggregate were stored in separate compartments. The mixing of the materials proved to be satisfactory.

The user-formulated (UF) system required that concrete sand, coarse aggregate, monomer (MMA, TMPTMA, and DMT) and BzP be stored in separate compartments. The ratio of sand to coarse aggregate and 50:50 by weight. The monomer system used with the Concrete Mobile[®] for both Test Pit No. 3 and Test Pit No. 1 consisted of 95 percent MMA and 5 percent TMPTMA. The DMT varied from 0.8 percent to 1.2 percent and the BzP varied from 3 percent to 4 percent. However, the liquid admixture system on the Concrete Mobile[®] did not have adequate capacity for the BzP dispersion, and, the BzP was added in dry powder form through the cement bin. The Concrete Mobile[®] could be easily modified to accommodate a complete liquid system and thus improve performance for the UF PC system. Additionally, for these tests, powered MMA (PMMA) was mixed with the sand. The amount used was 6.25 percent of the weight of the sand. The PMMA dissolved during the mixing process to produce a more viscous mix to facilitate placement with the Concrete Mobile[®].

The Crylcon[®] section was placed first, screeded, and finished; the Silikal[®] sections were placed second, screeded, and finished; and finally, the UF material was placed, screeded, and finished.

Six thermocouples were placed in the PC to measure temperature and time to peak exotherm. Thermocouple No. 2 placed at

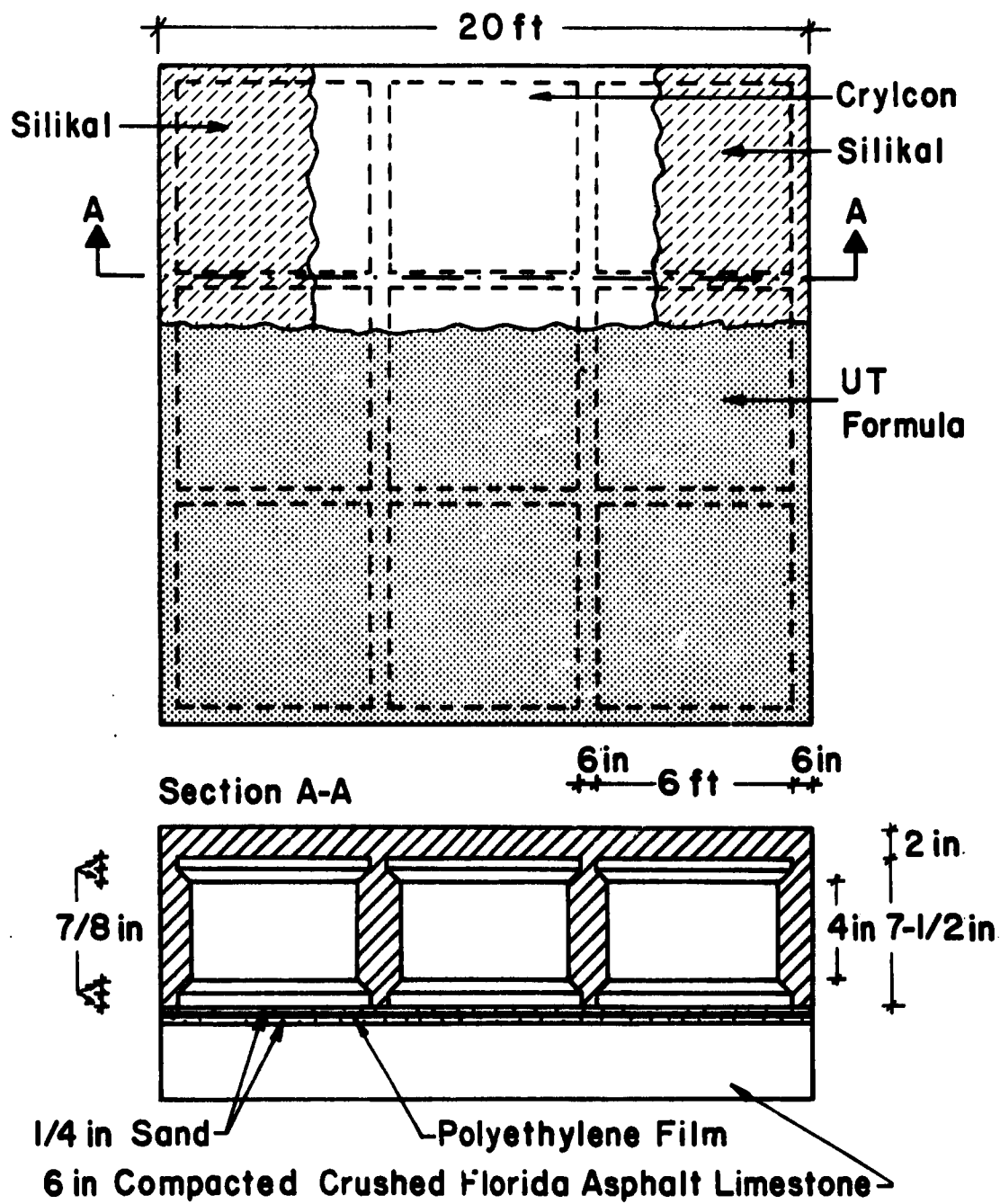


Figure 55. Pit No. 3.

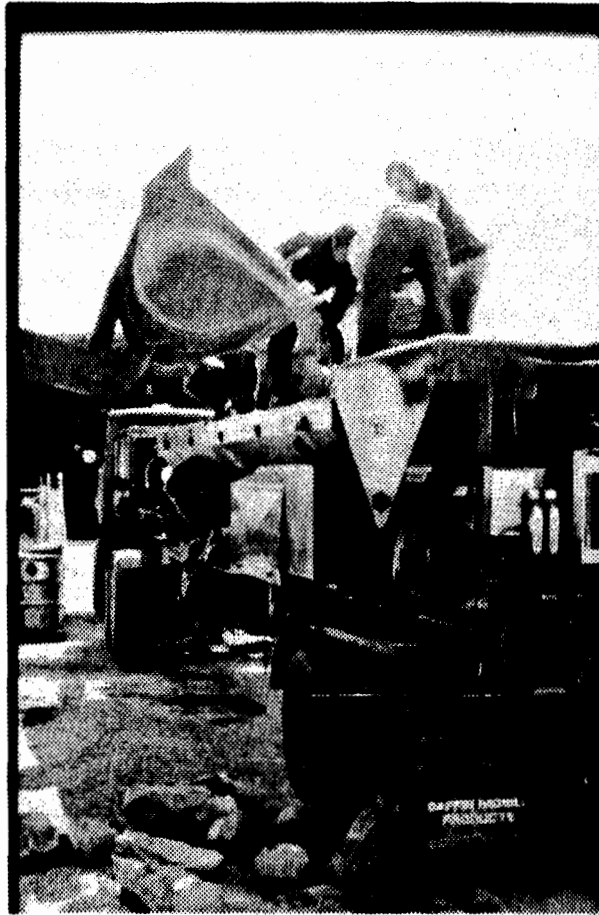


Figure 56. Concrete Mobile[®] Trailer Unit.



Figure 57. Discharging PC from Concrete Mobile[®].

the edge of the pit did not function properly and indicated only a temperature rise. The other thermocouples were reasonably uniform in measuring a peak temperature of 75°C to 82°C and a time to peak exotherm of 22 to 33 minutes. All values were in the range expected for PC (Figure 58).

Though the flexural beams made from Crylcon® failed to cure, the material placed in the repair seemed to cure adequately.

Pit No. 3 was tested with the load carts and analysis of the profile data revealed essentially no change in profile from beginning to end of the tests. The profile data also illustrated excellent riding quality in that the maximum change along any profile line was 0.09 ft (1.08 in) in 20 ft.

This method of repair offers some distinct advantages:

1. Most of the surface layer (top 12 in) of the repair is constructed of materials of known and controlled quality (the precast slabs);
2. The precast units do not have to be aligned as required with repairs which used slabs flush with the pavement;
3. The method reduces the volume of PC required which reduces the amount of chemicals which must be stored and mixed.

Pit No. 1, which had a clay base, was repaired using UF PC. The repair consisted of half of the PC cap being nominally 8 in. thick and half of the repair being nominally 5 in thick (actual average thickness was 4.53 inches). Figure 59 shows a cross-section of Pit No. 1. The clay under the 8-in. section had a CBR of six and the clay under the 5-in. section had a CBR of three.

The UF PC was placed in Pit No. 1 using the Concrete Mobile® as in Pit No. 3. After placement, the PC was screeded and finished. Thermocouple data from both the 5-in and 8-in thick sections revealed expected values for both peak temperature (approximately 80 to 90°C) and time to peak exotherm (approximately 30 to 35 minutes) (Figures 60 and 61).

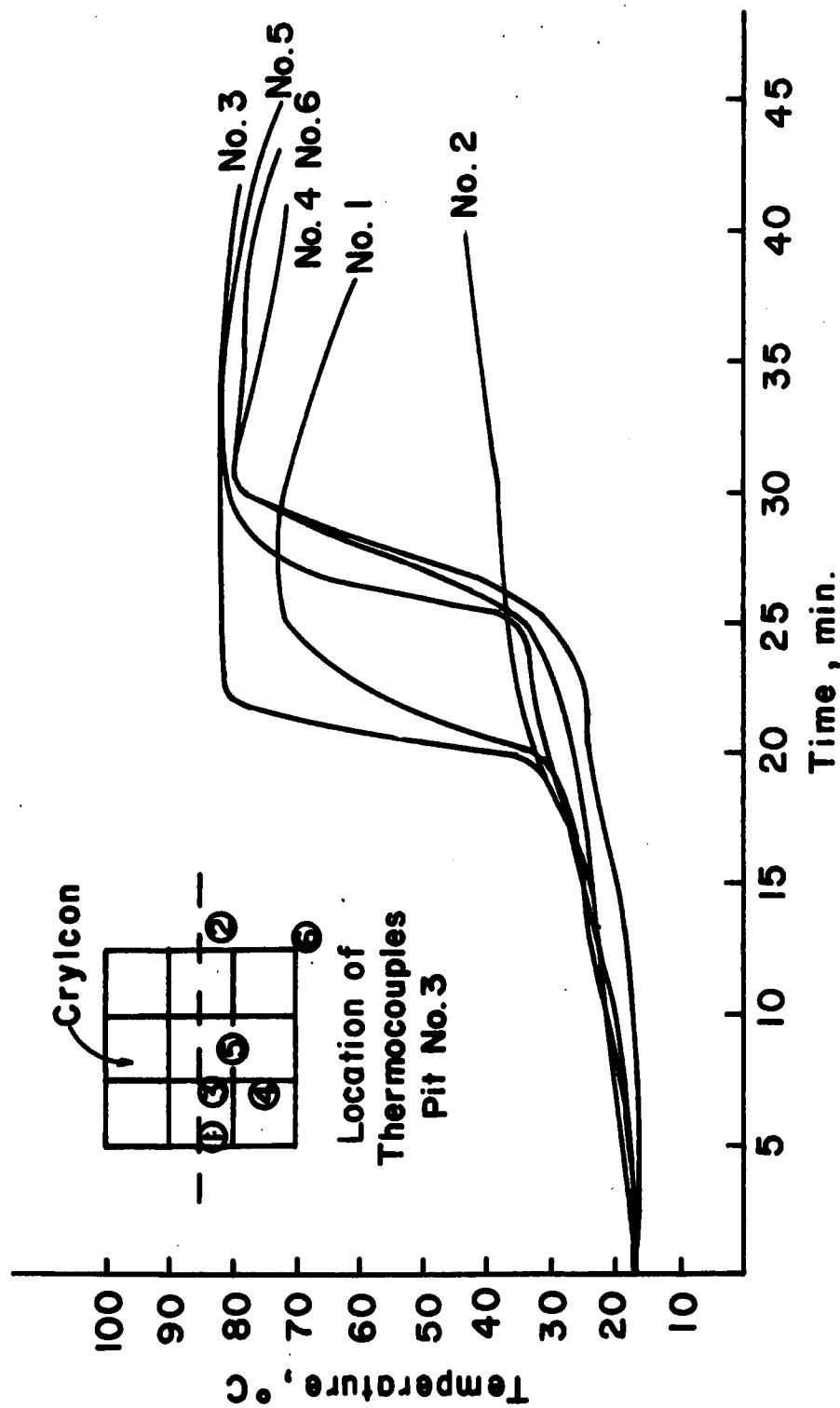
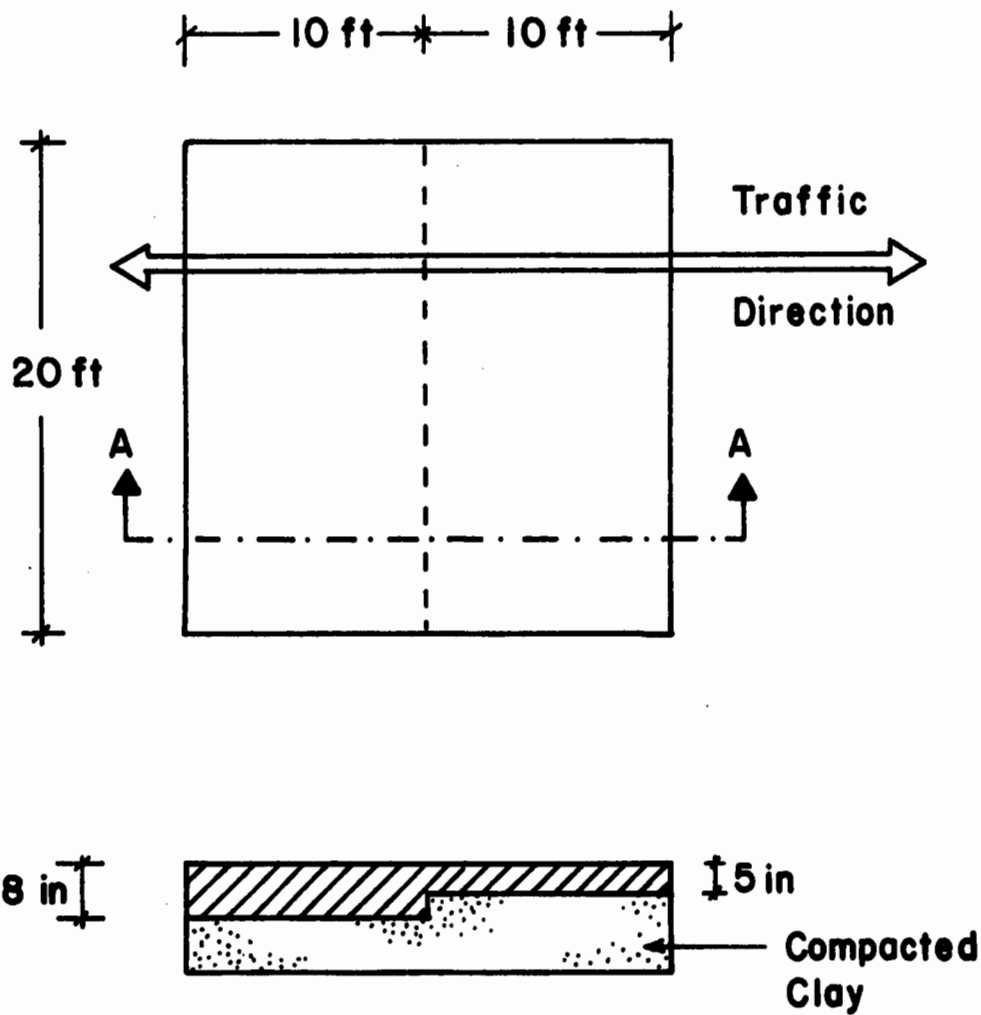


Figure 58. Temperature vs Time for PC in Pit No. 3.



**Section A-A
(Not to Scale)**

Figure 59. Pit No. 1.

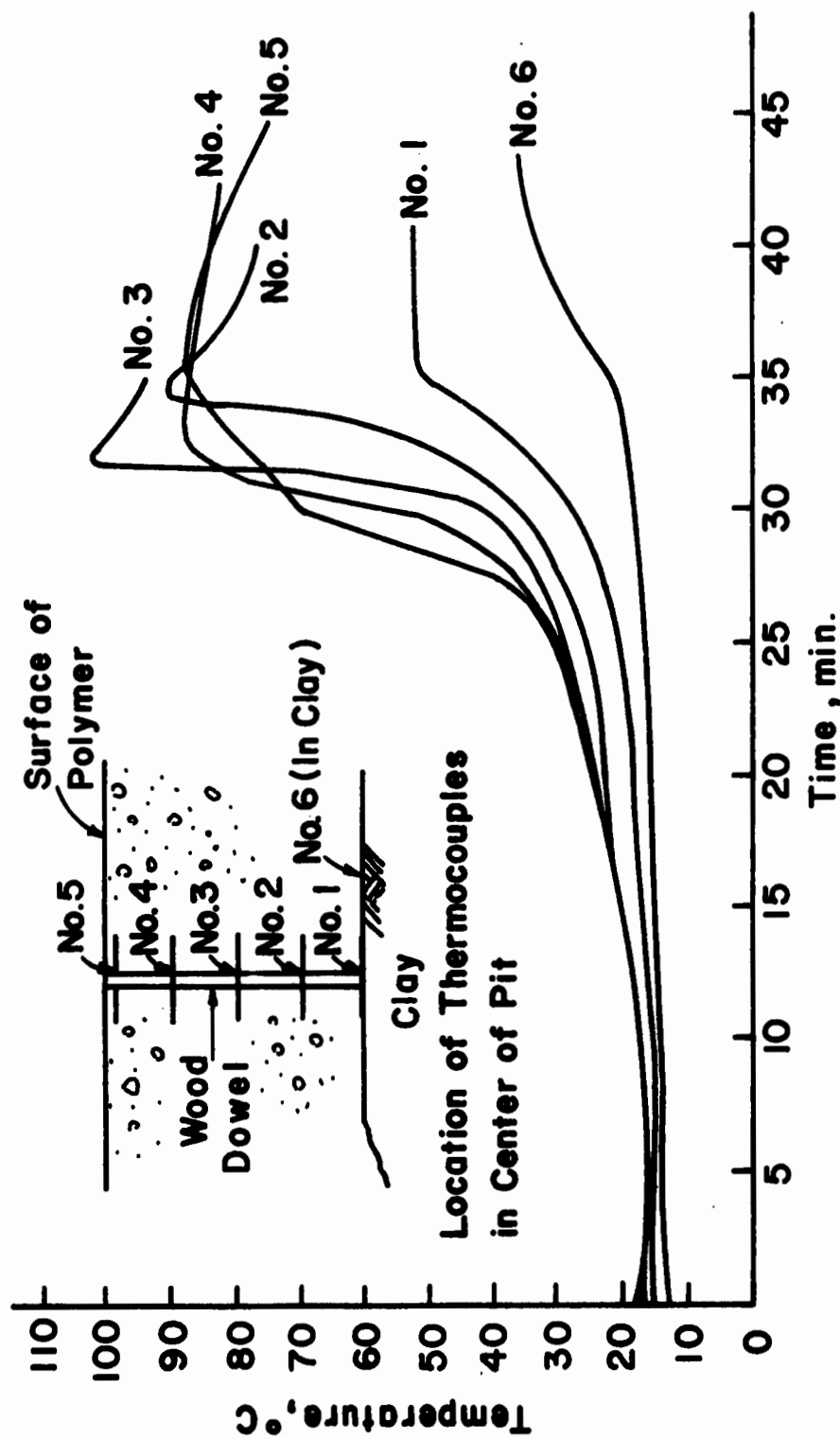


Figure 60. Temperature vs Time for 5-in Section of Pit No. 1.

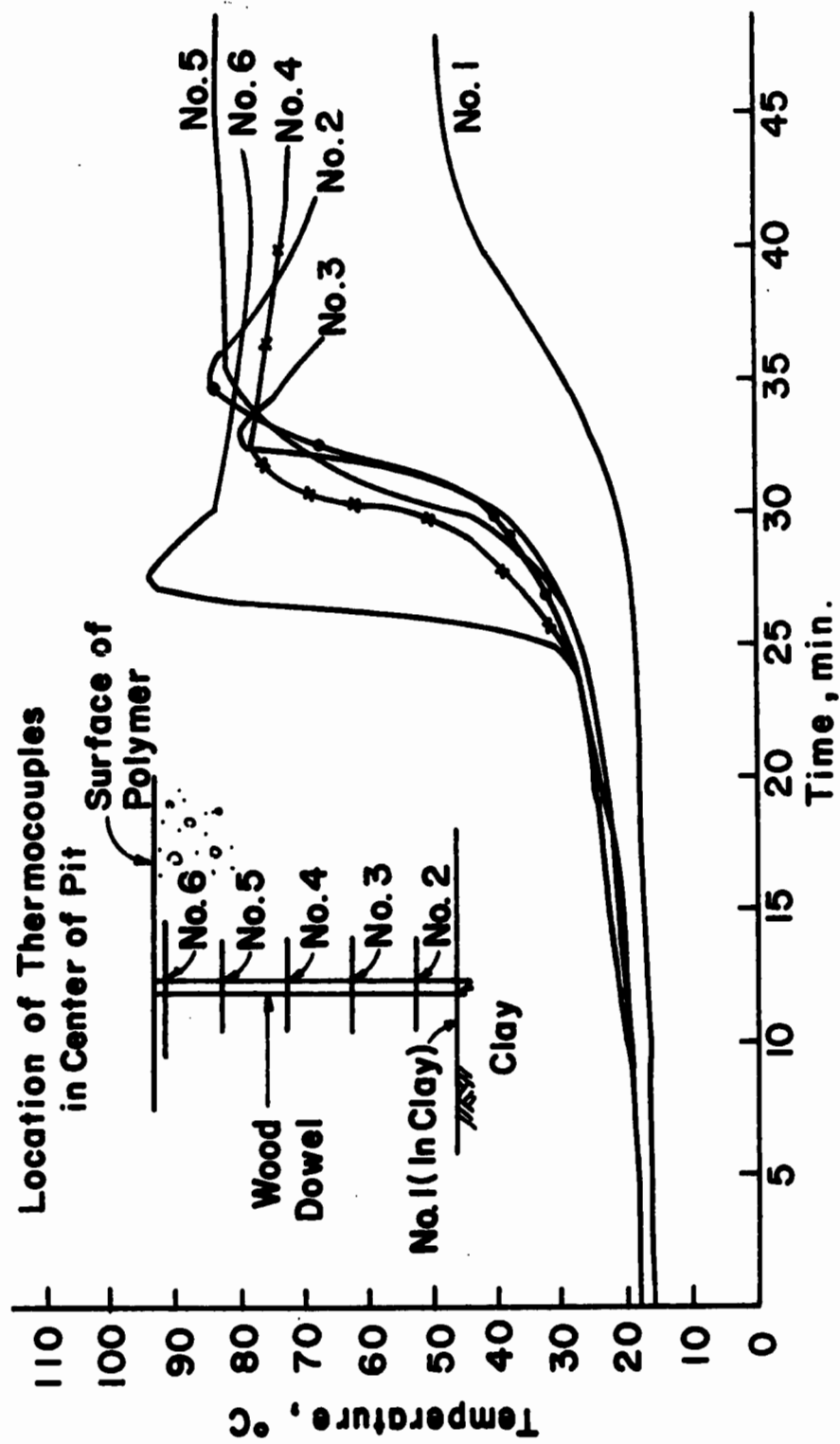


Figure 61. Time vs Temperature for 8-in Section of Pit No. 1.

Flexural beams prepared from the PC used in Pit No. 1 gave strengths of 1330 psi and 1250 psi at an age of 1 hour. These values are lower than those obtained in the laboratory study (approximately 1500 psi in one hour); however, they still far exceed the value set forth in the design criteria. It should be noted that a completely liquid system would allow better quality control for the PC and reduce the variability of the PC in the repair.

Nails were placed 18 ft apart in both the 5-in and 8-in thick sections to measure dimensional stability. The change in length for the 5-in slab was monitored and showed a 0.00174-in / in strain after 4 days. In the 8-in slab, the shrinkage was 0.00347 in/in. in 4 days. Laboratory tests have shown that after about 4 hours, the PC is dimensionally stable. The shrinkage increases as the PC cures and usually results in a crack at the edge of the repair. Usually the crack does not open sufficiently to prevent aggregate interlock. A crack did form around the edge of the repair of Pit No. 1 but it did not open sufficiently wide to impair performance.

The repair was tested with 150 coverages of the F-4 load cart and 70 coverages of the C-141 load cart. Analysis of the profile data reveals no significant changes in elevation from beginning to end of load cart testing. The average change in elevation was 0.002 ft (0.03 in), with the maximum difference at any location being 0.03 ft (0.4 in). Analysis of the profile lines reveals a maximum change of 0.08 ft (0.96 in) in 20 ft. This indicates that the riding quality would be adequate for air traffic.

After all tests were completed, a crack was observed in approximately the center of the 5-in slab. After 20 additional passes of the F-4 load cart, the crack grew from 19 3/8 in to 22 in in length. Additionally, a crack formed on either side of the original crack. One was 38 3/4 in long and the other 41 1/4 in long. After 60 passes of the F-4 load cart, the cracks measured 27, 38 3/4, and 42 in. The C-141 load cart was then used for 20 passes, causing no change in the length

of the cracks. The crack did not open sufficiently wide to allow differential vertical movement of the slabs.

In summary, all repair methods and materials were adequate for the load cart tests, even the 4.5-in UF PC slab over the CBR 3 clay. The tests revealed that PC is structurally adequate for airfield pavement repairs. As to time and equipment requirements, the cap method is probably the most efficient if the modified Concrete Mobile[®] is used and can be continuously supplied. As to mixes, the UF PC system offers the distinct advantage of being able to adjust the amount of chemicals to satisfy temperature demands in order to keep cure time relatively constant.

3.3 Performance of the Concrete Mobile[®]

The Concrete Mobile[®] (CM) was very effective for providing well-mixed, consistent PC. However, several difficulties were encountered in the use of the CM.

Earlier attempts to use MMA in the user-formulated PC were unsuccessful because of leakage in the MMA pump. The solution was to replace the diaphragm type pumps with a gear pump.

It was also determined that the fluid add-mix system supplied with the CM could not handle the viscous BzP dispersion which was intended for the user-formulated BzP. The modification of the fluid add-mix system could not be accomplished in time to proceed with the scheduled field repairs.

To meet the field test schedule, a procedure was developed for using 35 percent BzP powder, instead of the liquid dispersion, in the cement bin. Since the small amount of required BzP could not be accurately metered from the cement bin, the BzP was combined with enough sand and the PMMA powder to permit metering. This method resulted in good quality PC.

However, a fire which occurred during the cleaning of the CM after the PC was placed clouded the success of the CM. The flash fire started in the mixing chute at the rear of the CM and damaged the rubber bottom of the chute and some of the adjacent hydraulic lines.

The cause of the fire was most likely the result of a spark which ignited either the BzP dust or the MMA vapors. The BzP powder is fire resistant in bulk, but during the operation of the CM, a heavy cloud of BzP dust formed around the mixing area. It was necessary for personnel working near the mixing auger to wear respirators to filter the dust. After the fire, it was learned that the BzP dust is very flammable and can easily ignite. Only the dust burns; bulk BzP near the ignited dust will not burn. But the burning dust could have ignited the MMA still remaining in the mixing auger. The source of ignition was most likely due to a spark caused by friction between a stone and the mixing auger hardware.

Another possible cause of ignition was the MMA vapor in the mixing auger. During the actual placement of PC, the vapor concentrations were monitored at the end of the mixing auger and on the surface of the repair and reportedly were less than the actual explosive limits. However, during cleaning, MMA was sprayed on the mixing auger and chute as a solvent. It is possible that the vapor concentration may have reached the explosive limit.

The recommendations for further use of the modified Concrete Mobile[®] include:

1. BzP in dispersion form, as originally planned, should be used. This would eliminate the dusting problem.
2. Nonflammable solvents, such as trichloroethylene, should be used for cleaning instead of MMA.
3. Protective shields or skirting should be installed along the conveyor to prevent rocks from falling off the conveyor and becoming jammed in the hardware which may cause sparking.
4. Nonsparking materials should be used for the moving parts near the mixing chamber. The equipment should be grounded.

These modifications should eliminate the cause of the fire that occurred during the field test. However, it is imperative that personnel using MMA in the CM or in any other application should be well-trained in safety procedures. The danger of fire would

certainly be present if the CM were used in a hostile environment, such as in the vicinity of exploding ordinances.

SECTION IV

EXPERIMENTAL BEHAVIOR

4.0 Introduction

Laboratory studies began in Phase I and continued in Phase II to determine mechanical properties of polymer concrete (PC) (including flexural strength, modulus of elasticity, and compressive strength) and to determine fatigue behavior for PC and PC-repaired portland cement concrete (PCC) slabs.

4.1 Mechanical Properties

Mechanical properties have been determined for a wide range of monomer formulations and wet aggregate treatments (Section II). The initial tests were designed to screen the PC for properties to determine the relative strengths. Generally, one or more of the following tests were used: splitting tensile strength (3-in x 6-in cylinder); compressive strength (3-in x 6-in cylinder); and modulus of rupture or flexural strength (2-in x 2-in x 12-in or 3-in x 14-in beams). Splitting tensile tests are frequently used due to the simplicity of casting and testing specimens. These specimen sizes are not as large as required by ASTM standard tests, but the smaller size permitted many more tests to be performed.

Static tests to determine flexural strength (ASTM C78), compressive strength (ASTM C39), and modulus of elasticity (ASTM C39) were made for the MMA/TTEGDA formulation. Specimens made at 0°, 75°, and 100°F were tested at each temperature; i.e., a specimen cast at 0°F was tested at 0°, 75°, and 100°F. These properties are presented in Section II.

4.2 Fatigue Properties of PC Beams

Fatigue strength tests were conducted on 6-in x 6-in x 36-in PC beams using third-point loading with a 30-in span. Companion 3-in x 3-in x 14-in beams were cast at the same time

to provide a measure of the ultimate static strength of the beams.

Beams were cycled between a maximum stress and a minimum stress, which was greater than zero. The loading was applied at a frequency of 5 cycles/second until failure or to a maximum of 100,000 cycles. The maximum stress was held constant for each beam, but was varied from beam to beam to determine the limiting stress. If failure did not occur prior to termination of the cyclic loading, each beam was subjected to static ultimate load tests. Specimens were cast at 0°, 75°, and 100°F, and testing began 2 hours after casting.

An initial fatigue test was performed using maximum and minimum stresses of 700 and 175 psi, respectively. The modulus of rupture of the control beam was 1990 psi. The loading was applied for 2,000,000 cycles without any visible cracks occurring. The deflection at the loading corresponding to minimum stress increased from 0.0045 in to 0.0105 in during testing, or an increase of 133 percent. For maximum load, the deflection increased from 0.0085 in to 0.0145 in or 71 percent. The static flexural strength at the end of the test was 2580 psi, which was significantly greater than for the control beam. This increased strength may have been due in part to the additional curing that occurred during the 5-day testing period.

4.3 Fatigue Tests of PC Repairs

A laboratory experiment was designed to evaluate PC as a repair material for PCC that would satisfy the requirements of the United States Air Force.

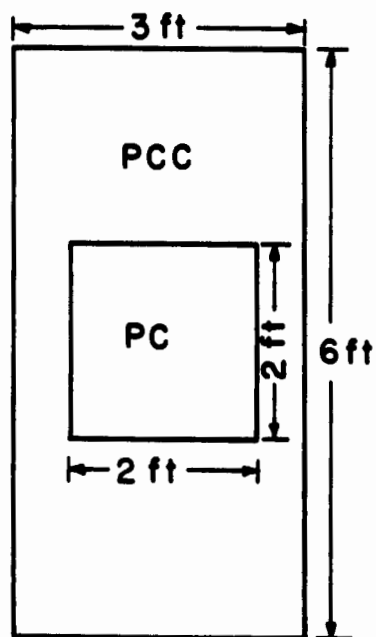
The tests were designed to study the fatigue characteristics of PC-repaired PCC slabs. All the slabs were evaluated for a simulated F-4 aircraft wheel load. In all the laboratory tests, the repair areas were rectangular in shape to facilitate analysis.

4.3.1 Laboratory Test Equipment

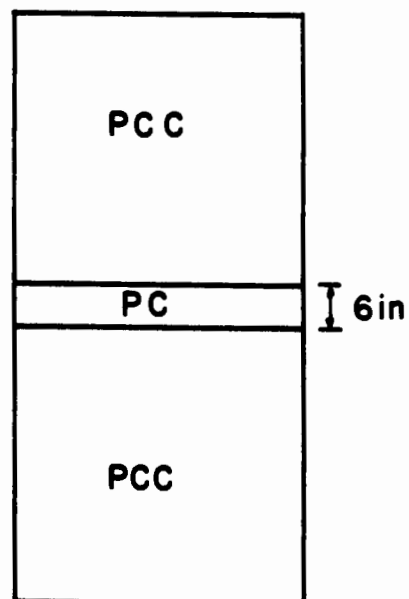
A common laboratory approach to simulate field conditions is through the modeling of a pavement slab exposed to a typical set of field conditions. Five slabs of different configurations of repair areas were chosen for testing (Figure 62). These slabs were tested for a single wheel load of an F-4, applied at its center. A load of 18 kips was transferred to the slab through two steel plates placed one above the other. The size of the plate in contact with the slab was 11-in x 6-in x 3/4-in thick and the one above it in contact with the load cell was 6-in x 6-in x 3/4-in thick. This effectively introduced a tire pressure of 272 psi as produced by an F-4 aircraft. To simulate a single wheel load of a C-141, a load of 18 kips was transferred to the slab through a steel plate 12-in x 8 1/2-in x 3/4-in thick to introduce a tire pressure of about 180 psi. As the F-4 loading was more critical than the C-141 loading, tests with the C-141 loading were not performed. The subgrade consisted of 6 in of neoprene rubber mats stacked in 1-in layers to provide a uniform elastic support with a K value of 160. A loading frame (Figure 63) was designed to accommodate 6-ft x 3-ft slabs for a maximum load of 100 kips. The load frame was anchored to the floor with bolts and a load cell was mounted on the frame. The load was applied by a hydraulic piston which was controlled by an MTS loading system (Figure 63); this permitted the application of the desired load at one cycle per second in the form of a sine wave. Deflections were measured with DCDTs (Direct Current Displacement Transducers) which were connected to an oscillograph. The oscillograph recorded the deflections.

4.3.2 Construction of Test Slabs

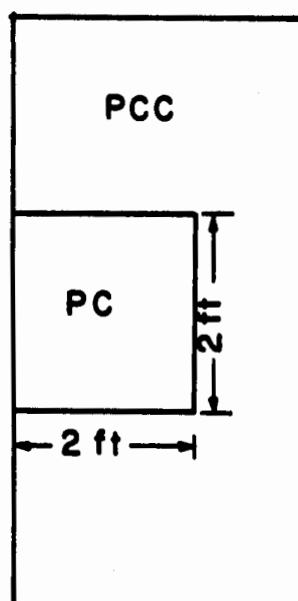
The test slabs (Figure 62) were cast at Balcones Research Center. The overall size of all test slabs was 6 ft x 3 ft x 4 in thick. Form work was designed to the shape of the PCC portions of the test slabs shown in Figure 62. Ready-mix concrete was used. A 6-in x 6-in steel welded wire fabric was



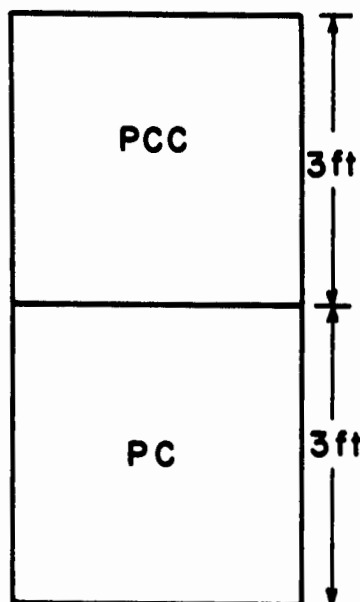
4 (a)



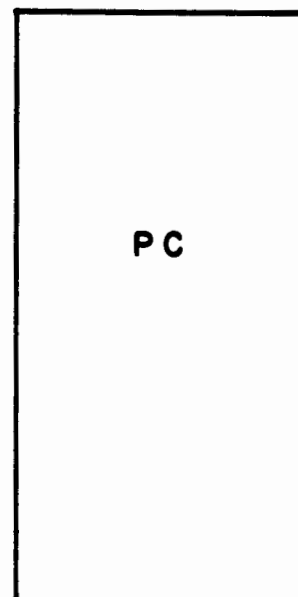
4 (b)



4 (c)



4 (d)



4 (e)

Figure 62. Test Slabs Showing Different Repair Configurations.

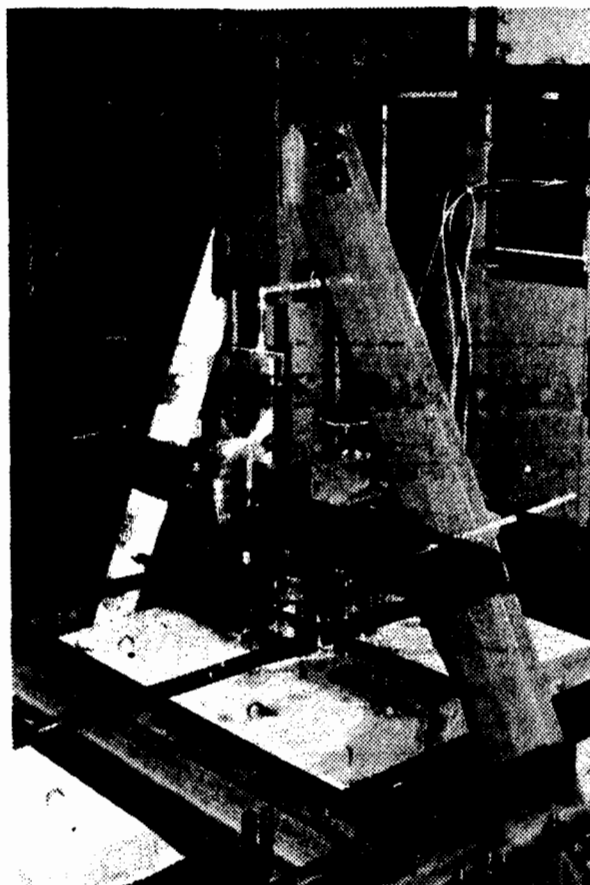


Figure 63. Fatigue Loading Frame.

used as reinforcement at approximately 1 inch from bottom to carry the tensile stresses induced while transporting the slab. Pickup points were designed and hooks were partially embedded in the slabs.

4.3.3 Laboratory Test Procedure

In all repairs conducted, monomer was prepared by volume. Monomer was premixed with DMT. The initiator, benzoyl peroxide, was mixed with the monomer as required. A formulation containing 95 percent MMA, 5 percent TMPTMA, 1 percent DMT and approximately 2 percent BzP was used for all repairs. This formulation was selected from tests previously performed as a part of this study. A 50:50 mixture of oven-dried all purpose sand and 3/8-in pea gravel was used for all repairs. A common procedure for preparation of the test slabs was adopted:

1. A 3/4-in thick sheet of plywood was placed on a level surface and a polyethylene sheet was spread over it.
2. Latex caulking was applied to the bottom of the slab around the repair area to provide a seal to the form which would prevent monomer leakage.
3. The slab was carefully placed on the polyethylene sheet.
4. The inner edge of the repair area was caulked and sealed.
5. Fine sand was sprinkled at the bottom of the repair to get a smooth surface.
6. The monomer formulation was prepared.
7. The monomer was first poured into the repair area to ensure that there was no leakage.
8. The mixture of sand and pea gravel was poured to one-third the depth of the repair.
9. Monomer was poured over the aggregate and the concrete was rodded. This process was repeated until the entire repair area was filled.
10. The top of the repair area was finished with fine sand and screeded to the level of the PCC slab.
11. Thermocouples were embedded in the polymer concrete to record the peak temperature.

12. One hour after the repair, the slab was moved to the test frame.
13. The rubber mats forming the subgrade were checked for alignment.
14. A polyethylene sheet was spread over the rubber mats, and a thin layer of hydrostone or white cement was spread over it.
15. The slab was placed over the thin layer of hydrostone to ensure uniform contact with the rubber mats.
16. The hydraulic pump connected to the load cell was started 15 minutes prior to placing the slab in the test frame to enable the pump to reach a constant working pressure.
17. DCDTs were positioned and calibrated. The positions of the DCDTs were marked on the slab.
18. The load cell was slowly lowered and the loading was increased from 0.5 kips to 18 kips in the form of a sine wave. A minimum load of 0.5 kips was maintained on the slab to protect the load cell. This loading rate was maintained until the failure of the slab.

In the case of repair areas with open ends, steel angles were used as sideforms. Steel angles were nailed to the plywood and their inner face was coated with mold release agent to prevent the polymer concrete from bonding to the steel.

4.4 Observations and Results

4.4.1 Slab 4(a)

Two slabs of type 4(a) were tested (Figure 64). During the first test the ends of the slab were not held down, and the slab failed as soon as it was loaded. Also, the bottom of the slab was not in uniform contact with the rubber mats. After making the necessary modifications to the test procedure, the second test slab was prepared. The repair was cast and the peak exotherm was 176°F after 26 minutes. Three-in diameter x

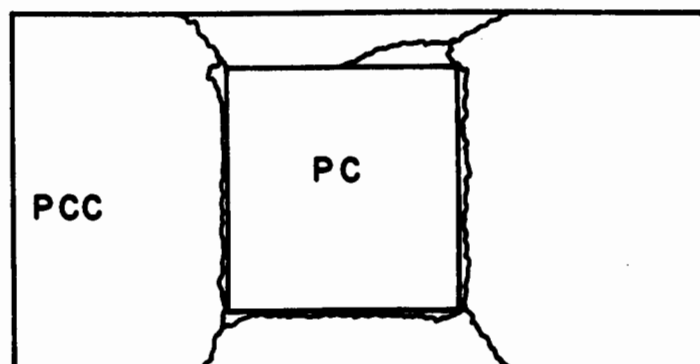
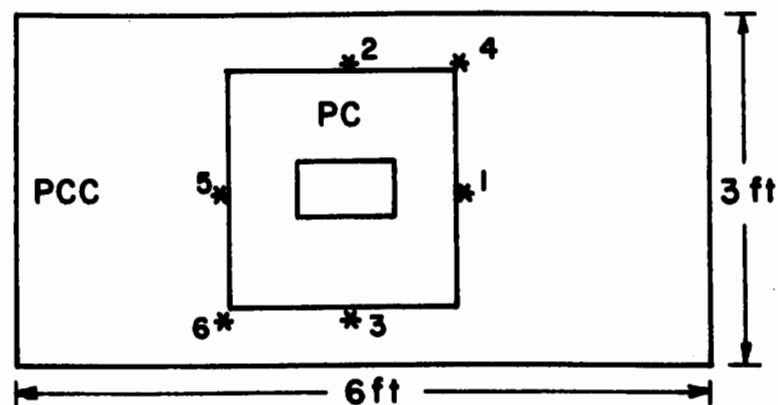
6-in long cylinders and 3-in x 3-in x 16-in beam specimens were cast simultaneously with the repair. The specimens were tested the following day. The average compressive strength was 8530 psi, the average splitting tensile strength was 1270 psi and the average modulus of rupture was 1920 psi.

After 10,000 cycles at a maximum load of 18 kips, hairline cracks were observed in the portland cement concrete. These cracks remained very small until 160,000 cycles. Cracks in the portland cement concrete around the polymer concrete were noticed after 120,000 cycles. Since no further cracking was observed until 160,000 cycles, the maximum load was increased to 27 kips. The plate in contact with the slab was changed to 12-in x 8 1/2 in x 3/4 in thick. The existing cracks widened, but no visible cracks developed. A small differential displacement could be noticed between the polymer concrete and the portland cement concrete. After an additional 23,000 cycles, the maximum load was increased to 36 kips. The differential displacement at the interface was clearly visible. No increase in the deflection readings were observed at either 27 kips or at 36 kips loading. The location of DCDTs, the deflections, and the observed crack pattern are shown in Figure 64.

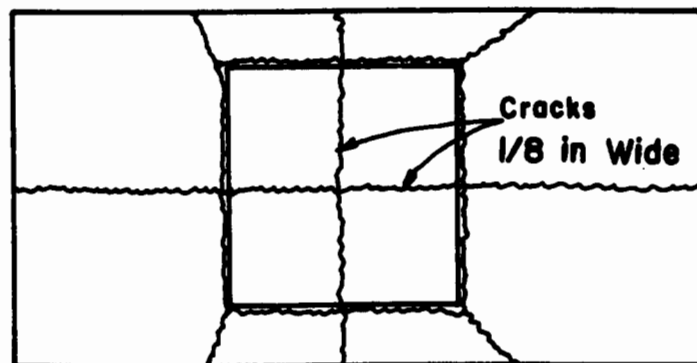
4.4.2 Slab 4(b)

Two identical portland cement concrete slabs measuring 2.75 ft x 3 ft x 4 in thick were bonded together by a 6-in strip of polymer concrete. The two portland cement concrete slabs had keyways on the side joining them together (Figure 65). The ambient temperature during the repair was 72°F. The peak temperature in the PC was 147°F after 54 minutes. The BzP was reduced to 1 percent in the formulation to allow more time for handling. Winds increased considerably towards the end of the repair, and considerable monomer evaporated from the top of the repair area. The top was then scraped and finished with a fresh batch of monomer of the same formulation. Test specimens were prepared and tested. The average compressive strength was 9620

DCDT						
Locations	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
Deflection	0.05	0.08	0.07	0.055	0.05	0.055



Cracking at Top



Cracking at Bottom

Figure 64. Test Slab 4(a).

DCDT Location	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Deflection	0.055	0.070	0.075	0.060

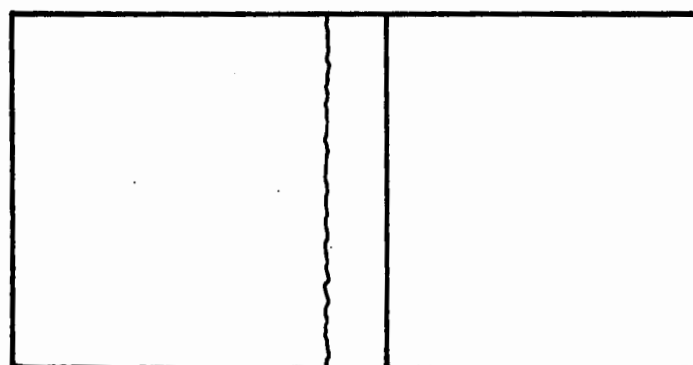
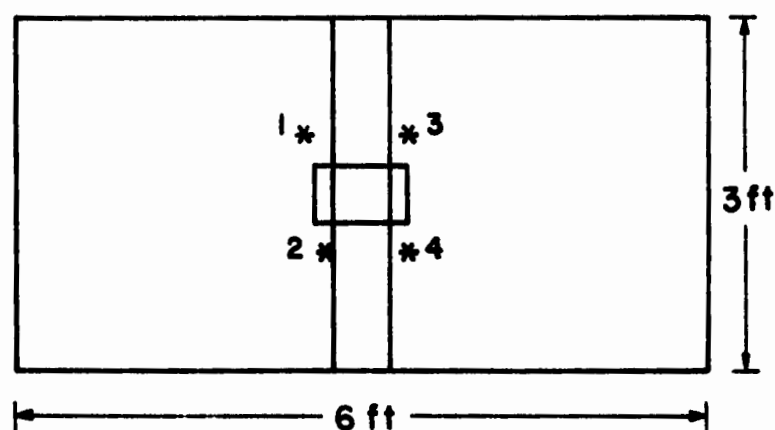
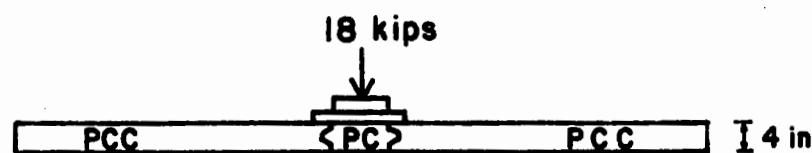


Figure 65. Test Slab 4(b).

psi, the average splitting tensile stress was 1300 psi, and the average modulus of rupture was 1930 psi.

A crack was observed at the interface of the polymer concrete and the portland cement concrete after 600 cycles. No more cracking was observed until the test was terminated at 10,250 cycles. For this slab, 10,000 cycles had been selected as a limit. The positions of the DCDTs, the deflections, and the crack pattern observed are shown in Figure 65.

4.4.3 Slab 4(c)

The ambient temperature during casting of the repair area was 71°F. The peak temperature in the PC was 152°F after 46 minutes.

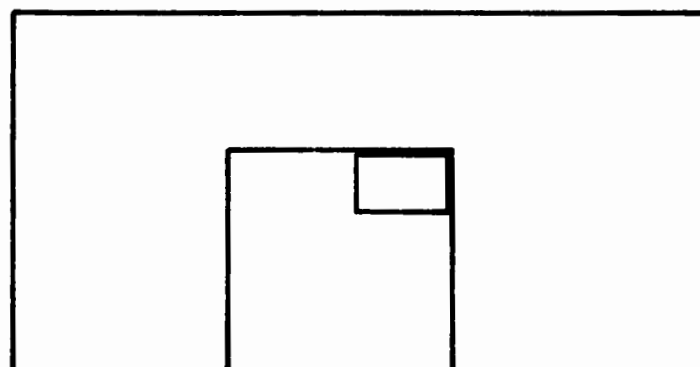
As the load was increased from 0.5 kips to 18 kips at one cycle per second, the slab cracked in the portland cement concrete close to the interface (Figure 66). No deflections could be recorded.

4.4.4 Slab 4(d)

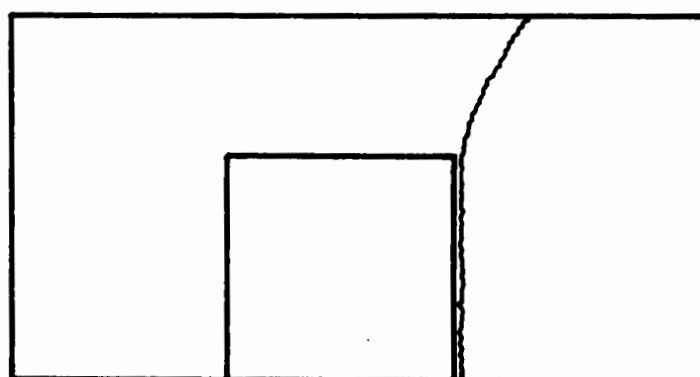
This slab consisted of two halves. A 3-ft x 3-ft x 4-in thick portland cement concrete slab was joined to a 3-ft x 3-ft x 4-in thick polymer concrete slab (Figure 67). Failure occurred as the slab cracked in the portland cement concrete close to the interface after 300 cycles. Load position, deflections, and crack pattern are shown in Figure 67.

4.4.5 Slab 4(e)

This slab was a 6-ft x 3-ft x 4-in thick polymer concrete slab. The slab was tested for a single load of 18 kips at the center. No cracks were observed until 200,000 cycles. The load was then increased to 27 kips when the slab cracked longitudinally and transversely after 60 cycles. Deflections could not be recorded for the 27 kip load test. Load position, DCDT positions, deflections, and crack pattern recorded are shown in Figure 68.



Load Position



Crack Pattern

Figure 66. Test Slab 4(c).

DCDT Locations	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
Deflections	0.055	0.080	0.080	0.070	0.080	0.050

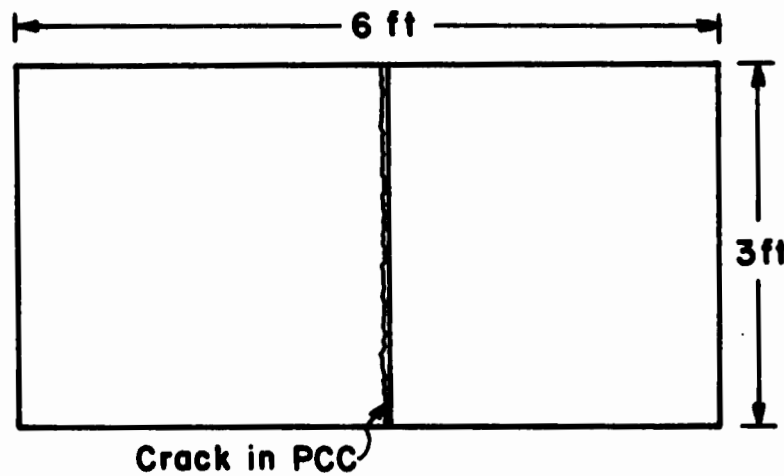
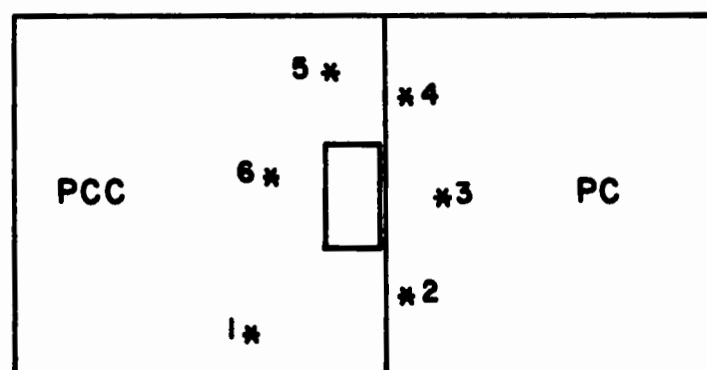
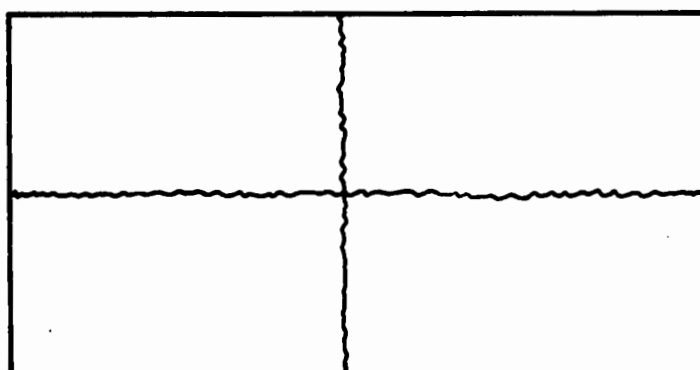
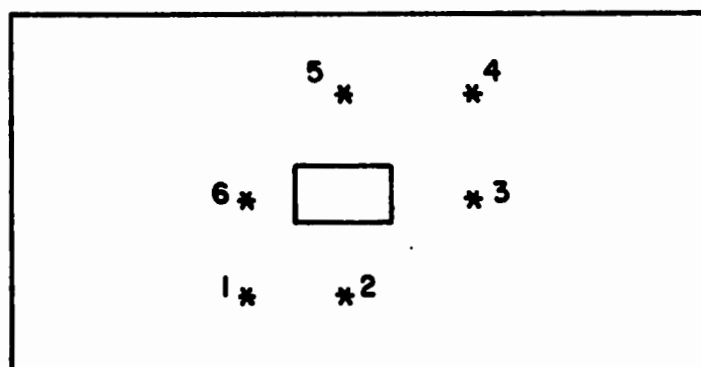


Figure 67. Test Slab 4(d).

DCDT	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
Location						
Deflection	0.05	0.08	0.065	0.06	0.08	0.065



Crack Pattern

Figure 68. Test Slab 4(e).

Except for slab 4(b) (Figure 65), all failures were observed in the portland cement concrete. Failures in the portland cement concrete indicated that there was load transfer from polymer concrete to regular concrete. Polymer concrete by itself withstood 200,000 cycles of an 18 kip load, proving its fatigue life to be adequate for a repair material for PCC pavements. A detailed stress analysis of the tested slabs, with the help of a computer program, is discussed in Section 4.5.

4.5 Computer Simulation of Slabs

The "Slab 49" computer program has been extensively used to predict the stresses in slabs. This program is the most recent improvement of the discrete element method of analysis for pavement slabs (5,6). The program uses the finite element theory to determine the slab deflections, bending moments, twisting moments, and principal stresses. Slab 49 simulates the slab by a series of perpendicular beams connected at elastic joints. The beams have bending stiffness and are connected to each other by torsion bars to simulate the Poisson effect, which is input as torsional stiffness. The load is applied over one or more elements to simulate the wheel action. The program has the advantage of accommodating more than one material type, varying subgrades, and discontinuities in the slab. The discontinuities are input as zero bending stiffness at the joints desired. This program was adopted because it allows the study of the PCC-PC interface area.

4.5.1 Program Input

A study of the range of variables showed that some had significant influence on the end result and others showed little influence. The problem in this case was to arrive at a set of values of the different variables which produced deflections to match the ones recorded in actual laboratory experiments. As cracking was observed near the interface, it was obvious that a reduction in bending stiffness across the joints at the interface

of portland cement concrete and polymer concrete would be of significant importance. Many trial values were considered and a 90-percent reduction in stiffness across the joints at the interface was found to be acceptable. Values for other variables, namely, modulus of elasticity of portland cement concrete and polymer concrete, and modulus of subgrade, were assumed from previous research (4). The modulus of elasticity for portland cement concrete was assumed as 4×10^6 psi and that for polymer concrete was assumed as 2×10^6 psi. The modulus of subgrade reaction was taken to be 165 pci (4). As the ends of the slab were held down in the experiment, the spring constant at the ends of the slab was assumed to be 10^4 lb/in.

4.5.2 Input

A 6-ft x 3-ft portland cement concrete slab 4 in thick (tpcc) overlays a subgrade whose modulus of reaction is 165 pci. A 2-ft x 2-ft polymer repair was assumed at the center of the slab. One main gear of the F-4 aircraft loads the center of the patch. Poisson's ratio for PCC was taken as 0.15 and for PC 0.30.

The basic inputs for "Slab 49" are the following:

- (1) Increment lengths (h_x and h_y) = 4 in (selected)
- (2) Bending stiffness (D_x and D_y) at each joint:

$$D_x = D_y = \frac{(E)(t)^3}{12(1-\gamma^2)}, \text{ where } E = \text{modulus of elasticity, psi}$$

t = material thickness, in

γ = Poisson's ratio

In this problem, for PCC joints,

$$D_x = D_y = \frac{(4 \times 10^6)(4)^3}{12(1-0.30^2)} = 23.44 \times 10^6 \text{ lb/in}$$

For PC joints,

$$D_x = D_y = \frac{(2 \times 10^6) (4)^3}{12 (1-0.30^2)} = 11.72 \times 10^6 \text{ lb/in}$$

(3) Torsional stiffness (C_x and C_y) of each mesh:

$$C_x = C_y = \frac{(E) (t)^3}{12 (1+\gamma)}, \text{ where } E = \text{modulus of elasticity, psi}$$

t = material thickness, in

γ = Poisson's ratio

In this problem, for PCC meshes,

$$C_x = C_y = \frac{(4 \times 10^6) (4)^3}{12 (1+0.15)} = 18.55 \times 10^6 \text{ lb/in}$$

For PC meshes,

$$C_x = C_y = \frac{(2 \times 10^6) (4)^3}{12 (1+0.30)} = 8.20 \times 10^6 \text{ lb/in}$$

(4) Spring value (S) at each joint:

$$S = (k) (h_x) (h_y) \text{ where } k = \text{modulus of support reaction, pci}$$

$h_x = h_y$ = increment lengths (in)

In this problem,

at PCC joints, $S = (165) (4) (4) = 2640 \text{ lb/in}$

at PC joints, $S = (165) (4) (4) = 2640 \text{ lb/in}$

(5) Load (Q) at the joint:

$Q + P$, where P load assigned to the joint (lb)

In this problem,

at joints (4,9), (5,9), (4,10), (5,10),

$$Q = 3000 \text{ lb}$$

at joints (4,8), (5,8), (4,11), (5,11),

$$Q = 1500 \text{ lb}$$

Total load on slab = $(4 \times 3000) + (4 \times 1500) = 18,000 \text{ lb}$

For a more complete description of the "Slab 49", the reader is referred to Reference 5.

4.6 Stress Analysis

The five slabs discussed in Chapter 4 were analyzed using the "Slab 49" computer program. Stresses at 162 locations on each slab was provided by the computer program. The deflections computed by "Slab 49" were matched with the deflections actually recorded during the laboratory tests. The locations of maximum stress have been shown in Figures 69 through 73.

4.6.1 Slab 4(a)

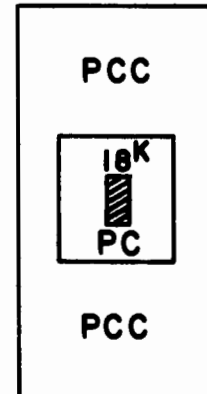
The deflections computed compared favorably with those recorded in the laboratory. The stresses computed were, therefore, considered good enough to predict the behavior of the slab. Beam tests conducted during this study have shown that PC has a maximum flexural strength of 1800-2300 psi. The flexural strength of PCC is estimated at 790 psi for 4000 psi concrete.

It is evident from Figure 69 that the maximum stresses were close to the loading plate. A maximum stress of 1210 psi was found at location (4,10) which was right under the load plate. At the interface, a stress of 500 psi was computed (Figure 69). The PCC probably had cracked at the bottom, but was not visible until the crack moved to the top. Cracking in the PCC around the polymer repair area was noticed after 10,000 cycles (Figure 64). When the load was increased to 27 kips, the maximum stress at location (4,9) rose to 1914 psi, which induced cracking in both PC and PCC. Evidently the stresses were higher than the allowable limits and cracking was obvious. PC showed excellent bonding properties to PCC, and the failure was solely due to overloading.

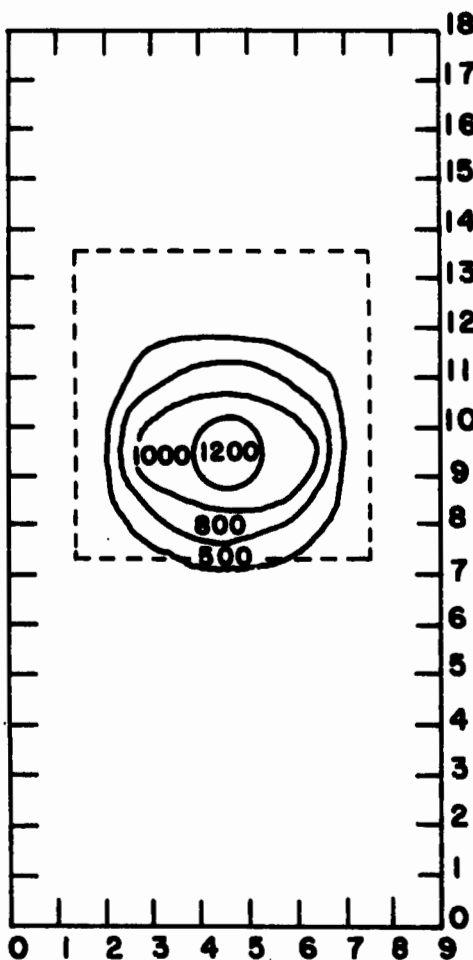
4.6.2 Slab 4(b)

The maximum stress of 790 psi occurred at location (4, 9). This point was exactly at the center in PC and under the loading pad (Figure 70). Stresses of over 700 psi were reached close to the interface of the PC and PCC (Figure 70). It was

Slab Size : 6 ft x 3 ft
 (2 ft x 2 ft PC Patch at Center)
 Load : 18K K=165 pci
 $h_x = h_y = 4$ in



Stations:	$\frac{x}{4}$	$\frac{y}{9}$	$\frac{x}{5}$	$\frac{y}{10}$	Load
	4	9	5	10	3.0K
	4	8	5	8	1.5K
	4	11	5	11	1.5K

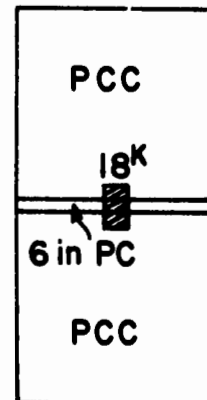


Location of Max Stress	
Location	Stress
(4, 10)	1210 psi
(5, 10)	1210 psi
(4, 9)	1206 psi
(5, 9)	1206 psi

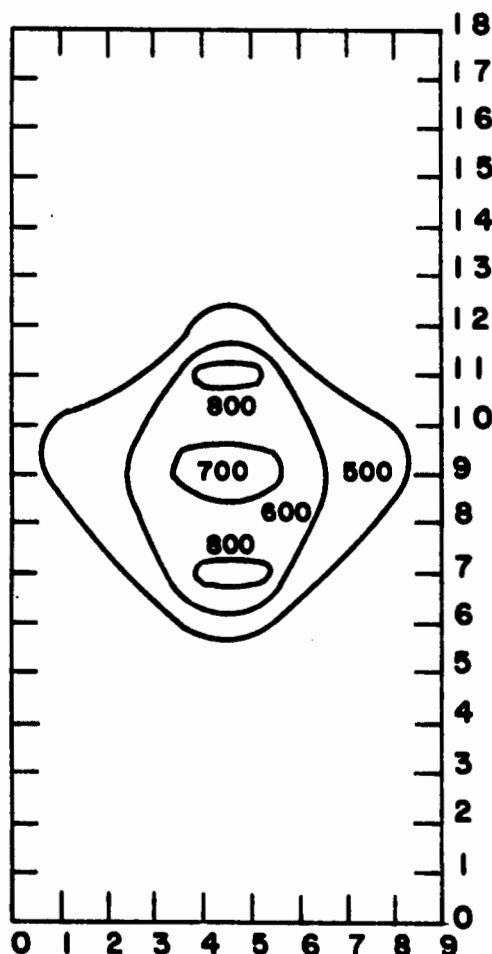
Deflections		
DCDT	Calc	Measured
1	.05915	0.05
2	.07170	0.08
3	.07170	0.07
4	.06170	0.055
5	.05535	0.050
6	.06657	0.055

Figure 69. Test Slab 4(a) Computer Stress Analysis.

Slab Size: 6 ft x 3 ft
 (Two 2.875 ft PCC Slabs Joined
 Together With 6 in PC)
 Load: 18K K=165 pci
 $h_x = h_y = 4$ in.



Stations: $\frac{x}{4}$ $\frac{y}{8}$ $\frac{x}{5}$ $\frac{y}{10}$ $\frac{\text{Load}}{3.0K}$



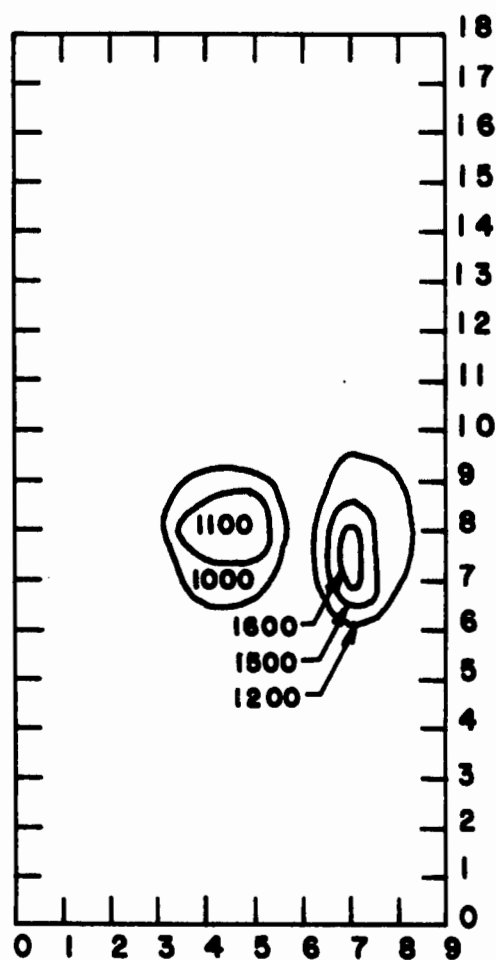
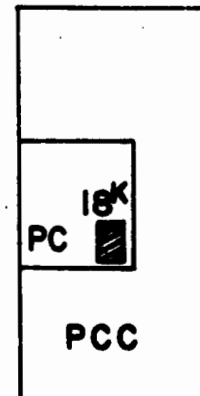
Location of Max Stress	
Location	Stress
(4, 9)	791.3 psi
(5, 9)	791.3 psi
(3, 9)	662.6 psi
(6, 9)	662.6 psi

Deflection		
DCDT	Calc	Measured
1	0.077	0.055
2	0.077	0.070
3	0.0888	0.075
4	0.0888	0.060

Figure 70. Test Slab 4(b) Computer Stress Analysis.

Slab Size: 6 ft x 3 ft
 (24 in x 22 in Repair Patch as Shown)
 Load: 18^K , $K=165$ pci
 $h_x = h_y = 4$ in

Stations: $\frac{x}{4}$ $\frac{y}{7}$ $\frac{x}{5}$ $\frac{y}{9}$ $\frac{\text{Load}}{3.0^K}$

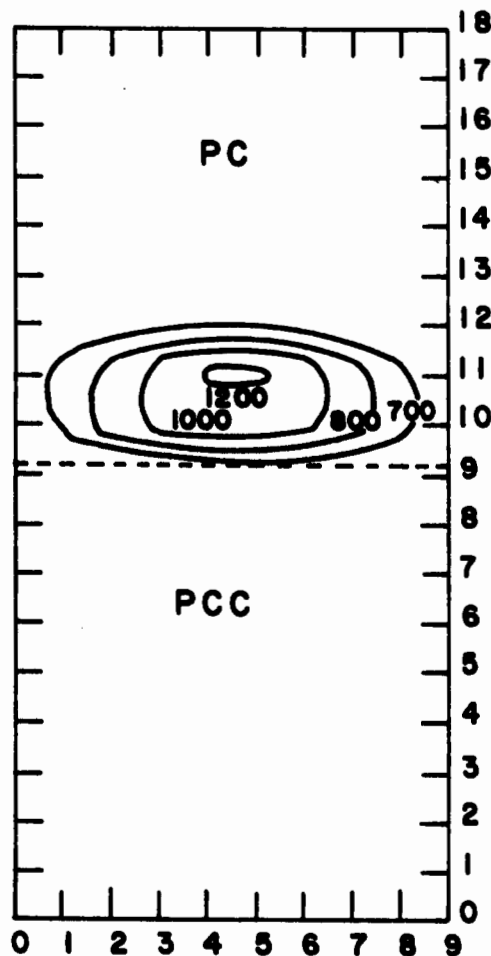
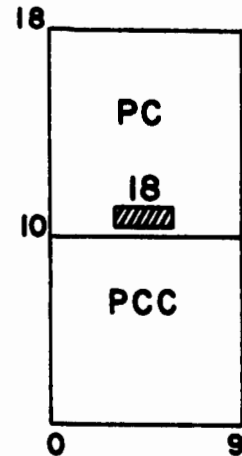


Location of Max Stress	
Location	Stress
(7, 8)	1620 psi
(7, 9)	1463 psi
(8, 8)	1416 psi
(8, 9)	1293 psi

Figure 71. Test Slab 4(c) Computer Stress Analysis.

Slab Size: 6 ft x 3 ft
 (3 ft x 3 ft PCC, 3 ft x 3 ft PC)
 Load: 18K, K=165 pci
 $h_x = h_y = 4$ in

Stations:	$\frac{x}{4}$	$\frac{y}{10}$	$\frac{x}{5}$	$\frac{y}{11}$	Load
	3	10	3	11	3.0K
	6	10	6	11	1.5K
					1.5K



Locations of Max Stress

Location	Stress
(4, 11)	1217 psi
(5, 11)	1217 psi
(4, 10)	1149 psi
(5, 10)	1149 psi

Deflection

DCDT	Calc	Measured
1	0.0546	0.055
2	0.07628	0.080
3	0.07024	0.080
4	0.07657	0.070
5	0.07037	0.080
6	0.06373	0.050

Figure 72. Test Slab 4(d) Computer Stress Analysis.

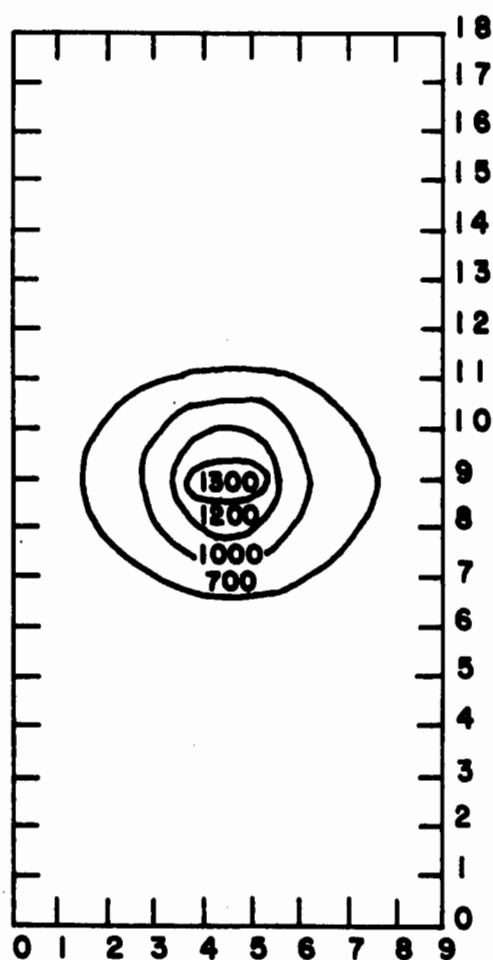
Slab Size: 6 ft x 3 ft

PC Slab

Load: 18^K at Center, K = 165 pci

$h_x = h_y = 4$ in

Stations:	$\frac{x}{4}$	$\frac{y}{8}$	$\frac{x}{5}$	$\frac{y}{10}$	$\frac{\text{Load}}{3.0K}$
-----------	---------------	---------------	---------------	----------------	----------------------------



Location of Max Stress

<u>Location</u>	<u>Stress</u>
(4, 8)	1208 psi
(5, 8)	1209 psi
(5, 9)	1349 psi
(4, 9)	1346 psi

Deflection

<u>DCDT</u>	<u>Calc</u>	<u>Measured</u>
1	0.05122	0.050
2	0.06374	0.080
3	0.05422	0.065
4	0.05142	0.060
5	0.06413	0.080
6	0.05422	0.065

Figure 73. Test Slab 4(e) Computer Stress Analysis, 18 kip Load.

observed that the interface failed after 600 cycles of an 18-kip load at the rate of one cycle per second. Stresses of about 800 psi were reached in the PCC. A crack at the interface may have been introduced when picking up and placing the slab in the frame. This crack went unnoticed until it appeared at the top. The two halves were probably held in place by the loading pad which was centered on the PC repair.

4.6.3 Slab 4(c)

Since no deflections could be recorded in the laboratory, the behavior of this slab is solely predicted by the computer program. A maximum stress of 1620 psi was reached at location (7,8) in the PCC. Though the slab was loaded in the PC, most of the locations with high stresses were found in the PCC area close to the repair area. Evidently there was almost complete load transfer, which indicates the excellent bonding properties of PC. The high stresses (Figure 71) in the PCC were evidently the cause of failure at the time of loading.

4.6.4 Slab 4(d)

Since the measured deflections were in good agreement with the computed deflections, the computed stresses were considered sufficiently accurate to predict the behavior of the slab. The maximum stress was 1220 psi at location (4,11) in the PC (Figure 72). Stresses of around 700 psi were found close to the interface. Evidently the tensile stress in the PCC was high enough to produce cracking at the bottom. This crack was not visible until it reached the top. The high stresses explain the early failure of the slab.

4.6.5 Slab 4(e)

The computed deflections were shown in Figure 73. The maximum stresses computed for an 18-kip load were far below the ultimate stress of 1900 psi. A maximum stress of 1350 psi was found at location (5,9). As the load was increased to 27

kips, the maximum stress at location (5,9) increased to 2010 psi, which introduced longitudinal and transverse cracking in the polymer concrete. The stress contours show the stress levels at the bottom and account for the observed crack pattern (Figure 74).

From the stress analyses, a general pattern of behavior of polymer-repaired portland cement concrete slabs can be predicted. In all cases, the cracks developed due to high tensile stresses. As PC is stronger than PCC, the cracking occurred in PCC. Most probably the stresses predicted by the computer program for the PCC around the PC were much lower than those that actually occurred. Due to the large difference in the stiffness between PC and PCC, there probably was a large transfer of stresses through the interface from the PC to the PCC, which resulted in large concentration of stresses in the PCC around the repair area. Since all failures were observed in the PCC, it is obvious that the bond between the PC and PCC was exceptionally good. A reduction in stiffness across the interface was to account for the cracked condition of the PCC around the repair areas. Another reason for the failure of the slabs could be due to high tensile stresses transferred to the PCC from the PC resulting from shrinkage in the PC. This initiated a small crack at the bottom, which went unnoticed until it was observed on the top.

4.7 Fatigue Characteristics of Repairs

Performance studies on portland cement concrete slabs have shown that the major cause of failure is the repeated application of flexural stresses¹⁴. Fatigue strength can be defined as the ratio between applied stress and concrete strength at any

¹⁴ Yimprasert, P., and McCullough, B.F. Fatigue and Stress Analysis Concepts for Modifying the Rigid Pavement Design System, Research Report 123-16. Austin, Texas: The Center for Transportation Research, The University of Texas at Austin, January 1973.

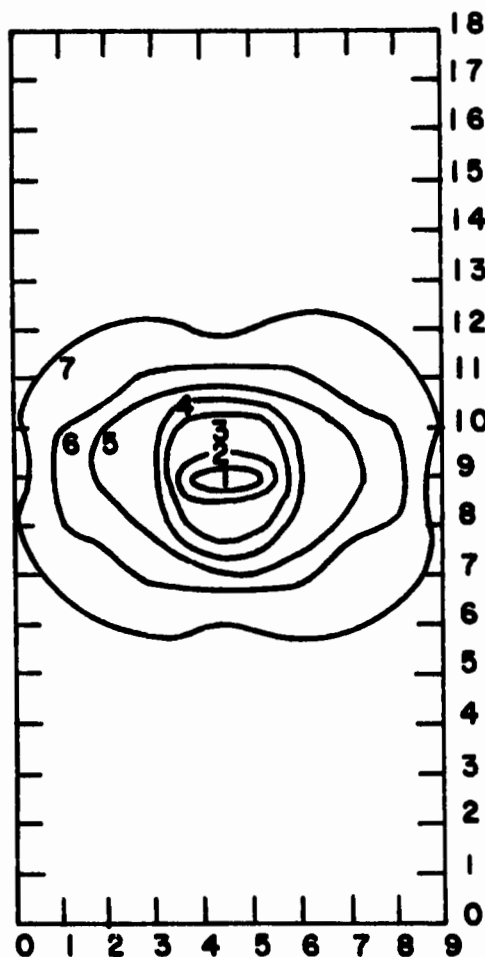
Slab Size: 6 ft x 3 ft

PC Slab

Load: 27K at Center, $K = 165$ pci

$h_x = h_y = 4$ in

Stations: $\frac{x}{4}$ $\frac{y}{8}$ $\frac{x}{5}$ $\frac{y}{10}$ $\frac{\text{Load}}{4.5K}$



Location of Max Stress

<u>Location</u>	<u>Stress</u>
(4, 9)	2010 psi
(5, 9)	2010 psi
(5, 8)	1804 psi
(6, 8)	1804 psi

1	2000 psi
2	1900 psi
3	1700 psi
4	1500 psi
5	1200 psi
6	1000 psi
7	600 psi

Figure 74. Test Slab 4(e) Computer Stress Analysis, 27-kip Load.

number of applications. To understand the fatigue behavior of PCC slabs repaired with PC, it is essential to understand the behavior of PCC slabs under repeated applications of load. Tests conducted by Murdock and Kesler show a significant increase in the number of applications to failure as the "R" value increases¹⁵.

A typical fatigue equation used for portland cement concrete is:

$$N = A \left(\frac{f}{\sigma} \right)^B \quad (1)$$

where

σ = stress in the material due to appropriate aircraft loading and other conditions

f = the design flexural strength of the material

N = allowable number of repetitions for the strength and stress conditions

A & B = coefficients from testing of the material

All static tests on PC have indicated that it is superior in strength to PCC. The coefficients developed for PCC would be conservative when applied to PC. Therefore, the equation for PCC was used for PC in this analysis

$$N = 23440 \left(\frac{f}{\sigma} \right)^{3.2} \quad (2)$$

The validity of this equation is currently being investigated at The University of Texas.

The slabs tested in the laboratory (Figure 62) were subjected to large flexural stresses at a very small "R" value. The slabs were loaded at one cycle per second from 0.5 to 18 kips producing an "R" value of 1/36. The primary concern was the failure of PCC and not PC. PC with a modulus of elasticity of

¹⁵ Yimprasert, P., and McCullough, B.F. Fatigue and Stress Analysis Concepts for Modifying the Rigid Pavement Design System, Research Report 123-16. Austin, Texas: The Center for Transportation Research, The University of Texas at Austin, January 1973.

2×10^6 psi as compared to PCC of 4×10^6 psi produced large stresses in the PCC close to the interface due to transfer of stresses from a less stiff to a stiffer material. Results obtained from "Slab 49" for slab 4(a) showed a maximum stress of 500 psi in the PCC close to the interface at location (5,7) (Figure 69). From Figure 26, though an R value of 1/36 is not shown, it is obvious that that probability of failure at about 10,000 cycles would be high, as was observed in the laboratory. This could be inferred for slabs 4(c) and 4(d).

In case of slab 4(e), a maximum stress of 1350 psi was computed (Figure 73). From equation (2)

$$N = 23440 \left(\frac{1900}{1350} \right)^{3.21} \approx 69,000 \text{ cycles}$$

From laboratory tests it was found that the PC slab did not show any signs of failure after 200,000 cycles. This test showed that equation (2) could still be conservative.

4.8 Conclusions

Based on these laboratory tests, the PC repairs of PCC pavements would perform satisfactorily. Slabs 4(a) and 4(e) would most likely represent the type of repairs found in the field, either small confined repairs or large repairs where the repair would be essentially an independent slab. These two experimental slabs had a fatigue life much greater than the Air Force requirement of 100,000 cycles.

SECTION V

ANALYTICAL BEHAVIOR OF REPAIRS

5.0 Background

The material properties, anticipated loading conditions, and desired quality of repair must be known or assumed to make a selection of the thickness of polymer concrete to be used in the bomb damaged area being considered for repair. In this section, a procedure is developed to permit the determination of thickness for a given location in a minimum time. First, the problem is modeled, and then the more sensitive variables are determined for preparing design charts to predict thickness for a specific condition. This material is then summarized into a design procedure.

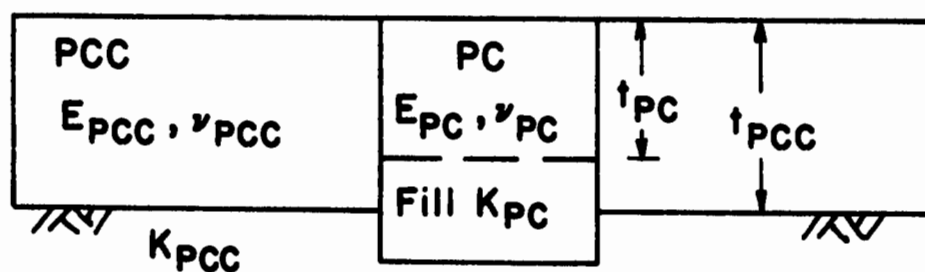
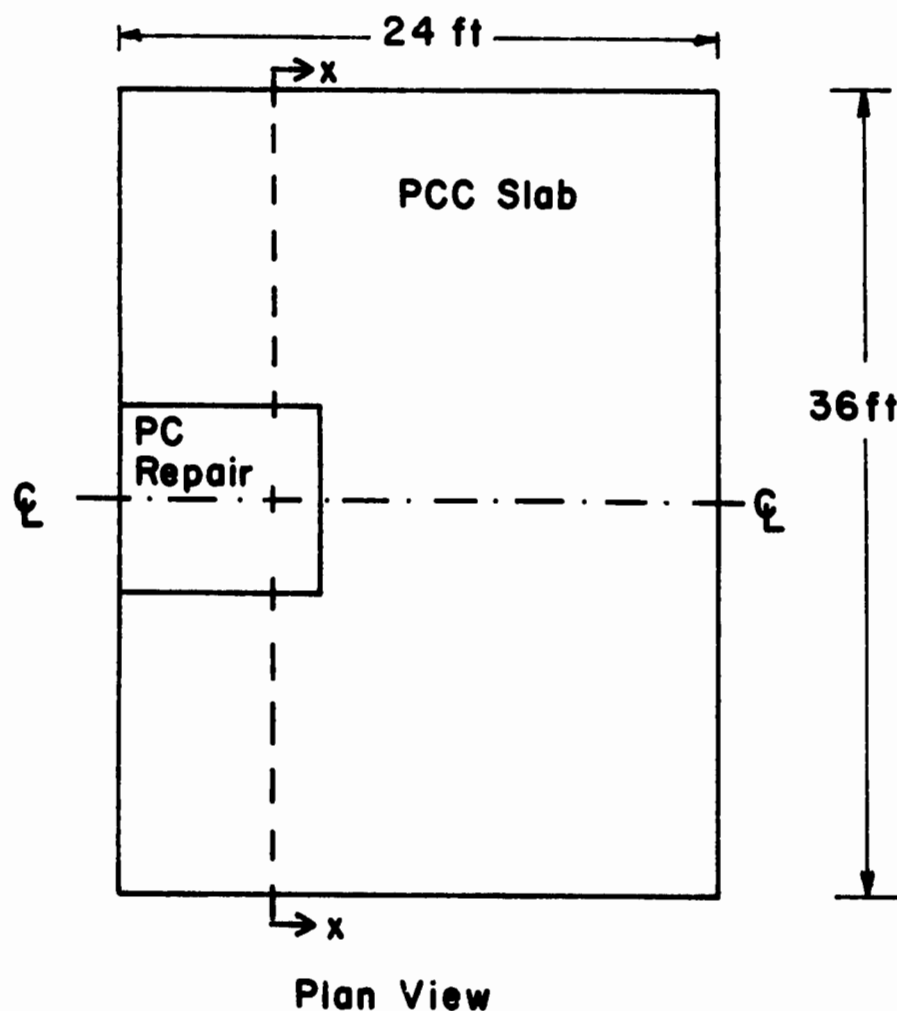
5.1 Modeling Runway Repair Area

The objective of this section is to analytically model the behavior of polymer concrete repairs of a portland cement concrete pavement to develop criteria for the thickness of the repair considering significant variables. The behavior of repairs is predicted over a practical range of the environmental and loading conditions, supplied by AFESC, that are expected at NATO bases in Europe.

It is essential in any analytical approach that techniques be used to properly model the load, geometry, and material properties to reliably predict the stresses in the pavement. One technique that has been used rather extensively in this study is the Slab 49 program, developed by Matlock and Hudson and reported in Discontinuous Orthotropic Plates and Pavement Slabs¹⁶.

Figure 75 presents a plan view, and a longitudinal cross section of a runway pavement slab containing a repair area. A

¹⁶ Hudson, W. Ronald, and Matlock, Hudson. Discontinuous Orthotropic Plates and Pavement Slabs, Research Report 56-6. Austin, Texas, May 1966.



Cross-Sectional View XX

Figure 75. Runway Repair.

typical slab 24 x 36 ft was selected for study. This size has been found to be adequate for studying the stress and deflection distribution for aircraft loadings.

AFESC designated two aircraft types for loading, the F-4 and the C-141. These are representative users of the facilities at the NATO bases in Europe.

For the polymer concrete repairs, three sizes were selected: 5 ft x 5 ft, 17 ft x 17 ft, and 24 ft x 36 ft. The thickness of the polymer concrete repairs range from 5 to 10 in, in 1/2-in increments. The support values selected were 50, 100, 200, and 300 pounds per cubic in (pci), with the 50 pci representing a backfill with a minimum compaction.

For the existing portland cement concrete, thicknesses of 8, 12, and 16 in were considered. The support values selected were 100, 300, and 500 pci. Again, these numbers represented the range of conditions expected at the NATO bases in Europe.

The following parameters were held constant in the study:

$$\begin{aligned} E_{pc} &= 2 \times 10^6 \text{ psi} \\ \mu_{pc} &= 0.30 \\ E_{pcc} &= 4 \times 10^6 \text{ psi} \\ \mu_{pcc} &= 0.15 \end{aligned}$$

AFESC directed that the procedures be developed to include the F-4 and C-141 aircraft since these are representative users of the runways at NATO bases. Figure 76 presents a footprint of the gear configurations of both aircraft. Also shown are the weights and the tire pressures. Previous investigations have indicated that the stress will vary depending upon the placement of the wheel relative to the edge, corner, and interior locations. Figure 77 presents the slab loading conditions expected in the field for the various aircraft types and repair conditions. Basically, the conditions range from an interior location, represented by Position 1, to a corner-edge condition, represented by Position 6. The maximum flexural stress beneath the gear must be determined for all the factors considered to ascertain the

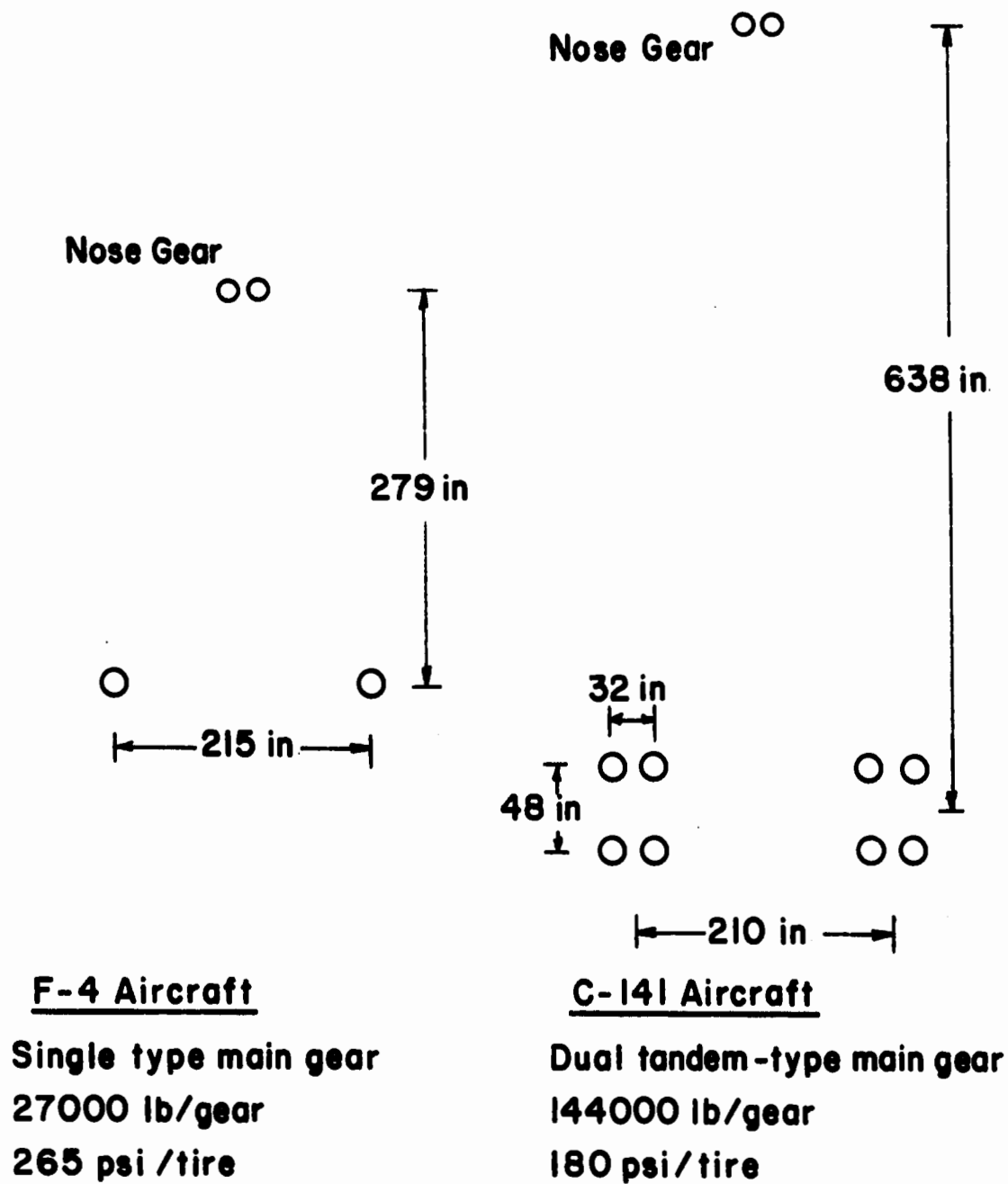
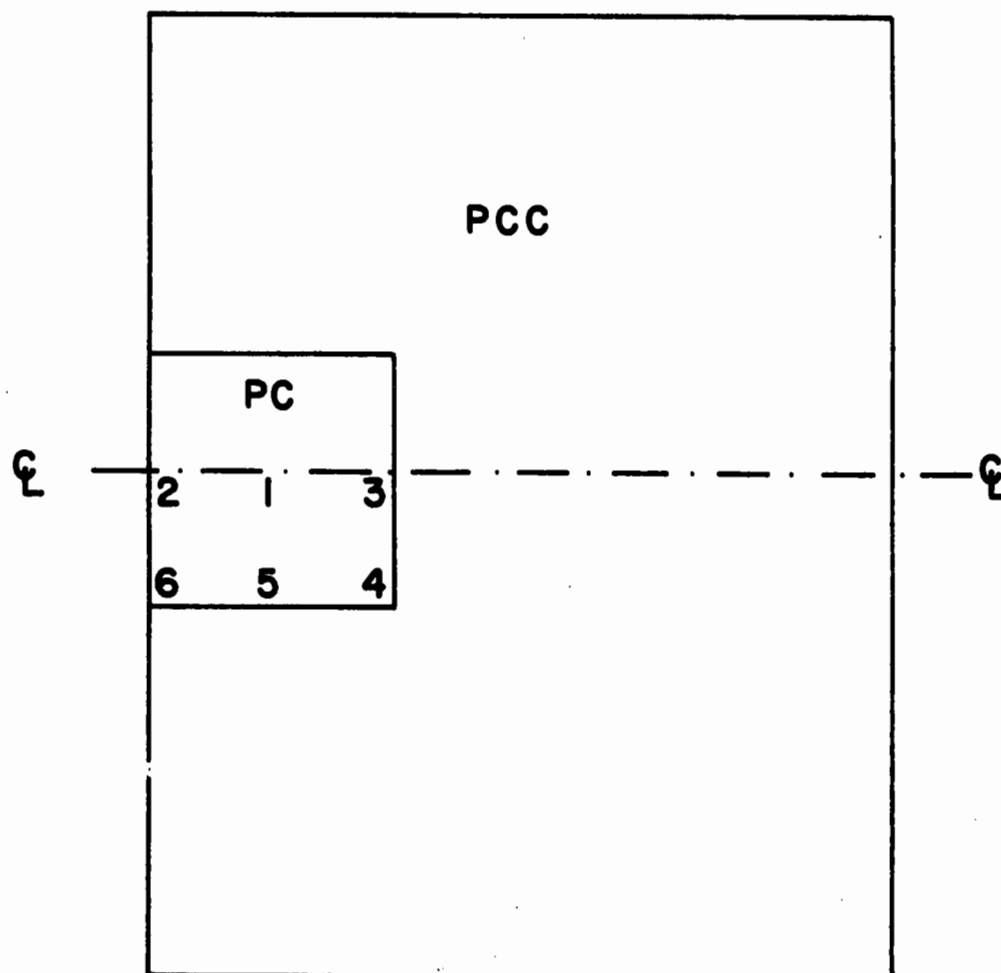


Figure 76. Aircraft Load and Gear Configurations.



- Position 1 - Center of Patch**
- Position 2 - Outside Edge**
- Position 3 - Horizontal PC-PCC Interface**
- Position 4 - Corner PC-PCC Interface**
- Position 5 - Vertical PC-PCC Interface**
- Position 6 - Outside Corner**

Figure 77. Horizontal Load Position for F-4 and C-141 Aircraft.

critical condition. For the C-141 aircraft, the loads for Positions 1, 2, and 3 were varied slightly as shown in Figure 78, since the tire-gear configuration was tandem. For one placement, the front wheels were placed directly on the repair area centerline, and for the other position, the center of the gear was placed at the center of the patch, as illustrated in the figure.

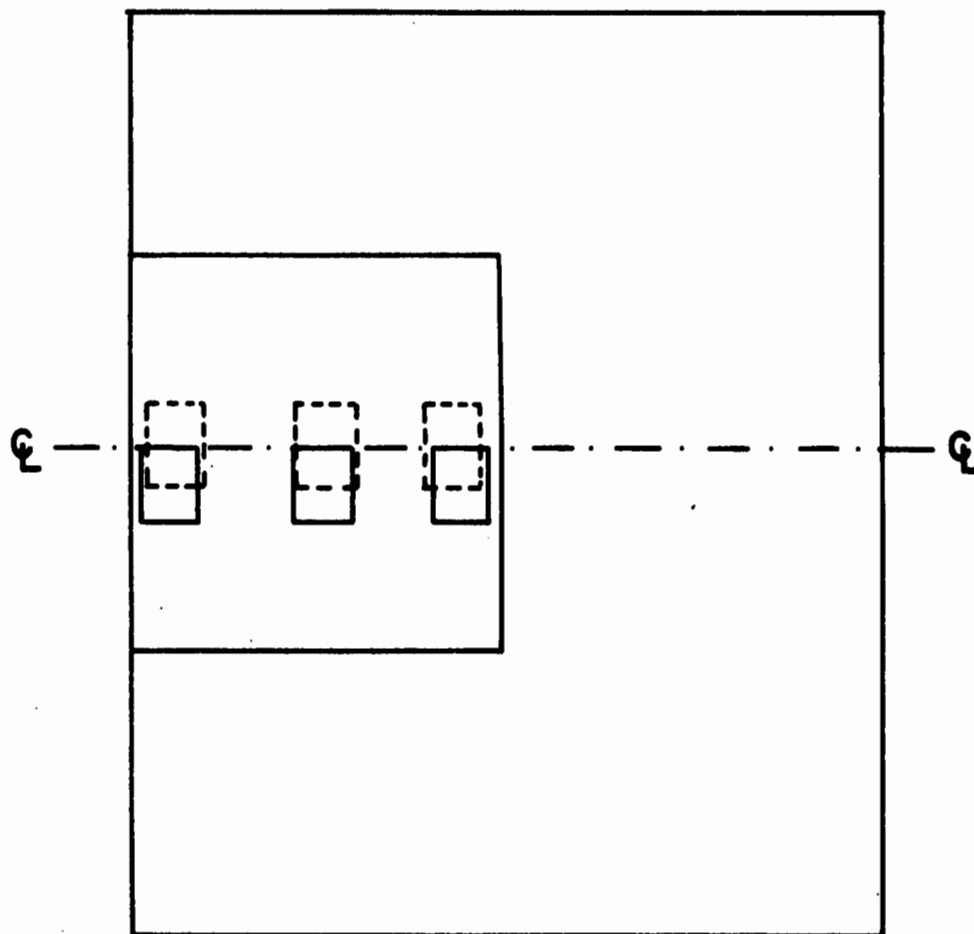
5.2 Sensitivity Study of Variables

The nature of this study presented a large range of conditions for investigation and, as the study progressed, it was obvious that some of the variables had low sensitivity and thus had no significant influence on the results. In the following paragraphs, these factors are discussed briefly to provide background for the reasons some variables are not considered in the analysis.

Relative to the nose gears, the presence or absence of the nose gear did not significantly influence the maximum stress conditions; this may be attributed to the fact that the wheel base distances are 279 and 636 in for the F-4 and the C-141, respectively. Thus, the nose gear did not have an influence on the results and, for most of the calculations, the nose gear was not considered. In addition, the maximum stress was not influenced by the adjacent gear since the wheel tread distances were 210 and 215 in, respectively. The stresses, reported in subsection 5.3, are the result of studies on one gear and thus would not be different if the entire configuration had been considered.

Considering the horizontal position of the gear, it was found (Figure 77) that Positions 1, 2, and 3 were critical, while the other positions were less critical, since they received support from the stiffness of the surrounding portland cement concrete. Therefore, the information reported in later sections is relative to Positions 1, 2, and 3.

In the case of the 5- x 5-ft polymer concrete patch, Positions 1, 2, and 3 are very close to each other; subsequently, only Position 2 (edge) was considered because it is most



Position  = Tires of Gear at Center of Repair

Position  = Center of Gear at Center of Repair

Figure 78. C-141 Aircraft Vertical Gear Position.

critical. In the case of the 17- x 17-ft polymer concrete patch and the 24- x 36-ft polymer patch, the study showed that Position 3 had a very low value of flexural stress compared to Positions 1 and 2 for the F-4 aircraft load. Thus, this position was considered to have relatively little influence on the life of the repair. The loading with the C-141 area shows that Position 3 gives a higher stress than Position 1. This is attributed to the wide load distribution of the C-141 main gear which, unlike the F-4 main gear, is not influenced by the surrounding portland cement concrete. Although Position 1 gave flexural stresses that are not significantly lower than those obtained in Position 3, it was decided that the design for Position 3 would satisfy the condition of Position 1.

In summary, only Position 2 (representing an edge condition) and Position 1 (representing an interior condition) were considered significant for the F-4. Only Position 2 (representing an edge condition) and Position 3 (representing an interior condition) were considered significant for the C-141.

For the C-141 aircraft, which has a dual tandem gear configuration, the two positions shown in Figure 78 were analyzed and the results indicated that loading the gear tires on the center of the repair gave the most critical stresses, and this position was used for further analysis.

Another problem investigated for the C-141 dual tandem gear was the location of the maximum flexural stresses. The results showed that they occur directly under the tire.

The results presented in Figures 79 and 80 indicate that varying the runway support had no influence on the flexural stresses. The runway support was then fixed at 300 pci, which was slightly above the average (250 psi) existing at European bases. Although the 300 pci did not influence the results, it permitted the user to consider repair support K_{pc} 's up to 300 pci, because of the primary assumption, i.e., $K_{repair} \leq K_{runway}$.

For a 17- x 17-ft repair, varying the runway thickness did not influence the flexural stresses significantly (Figure 81).

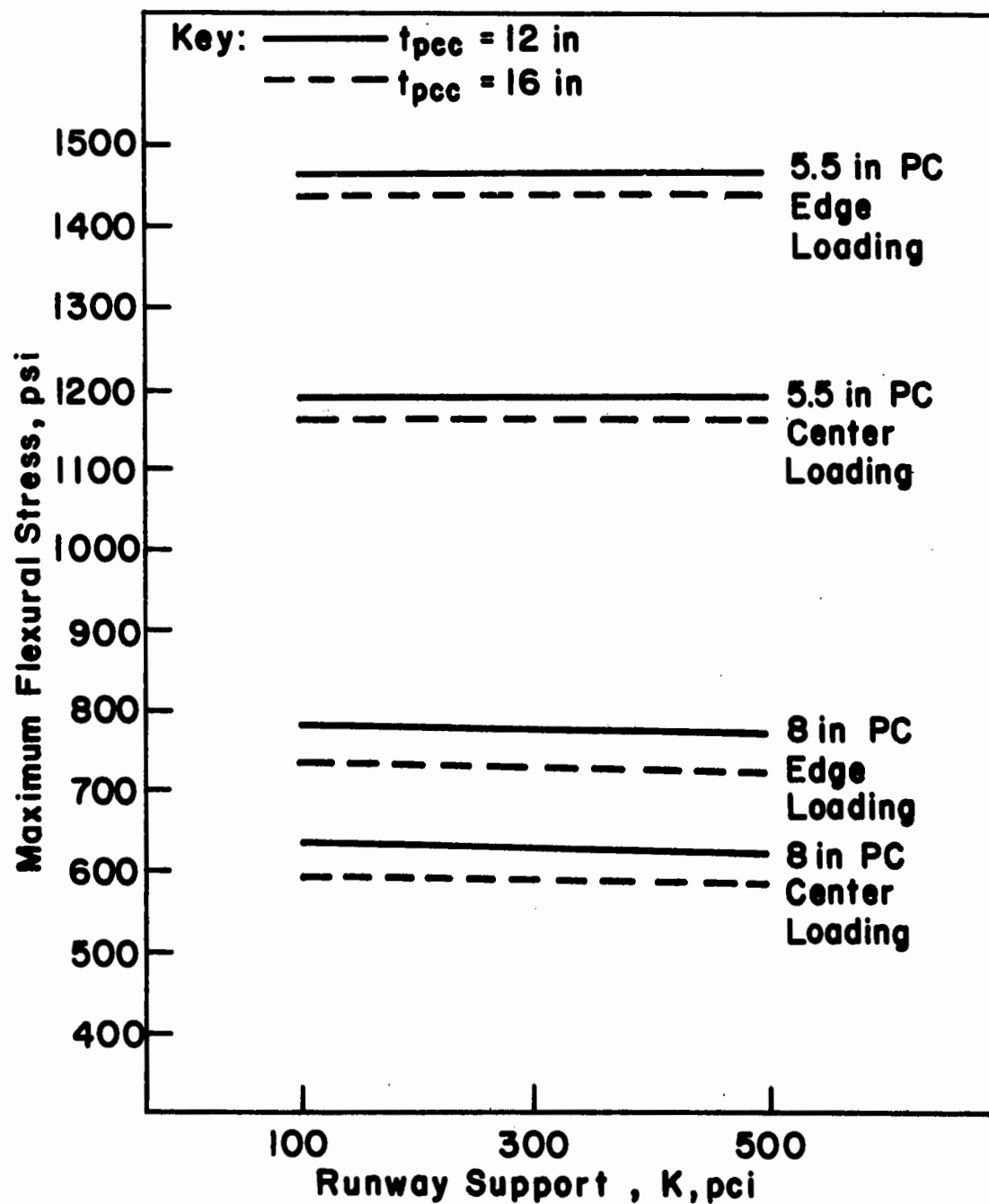


Figure 79. Stress Versus Runway Support for F-4 Loading 5- x 4.5-Foot Repair and $K_{pc} = 50$ pci.

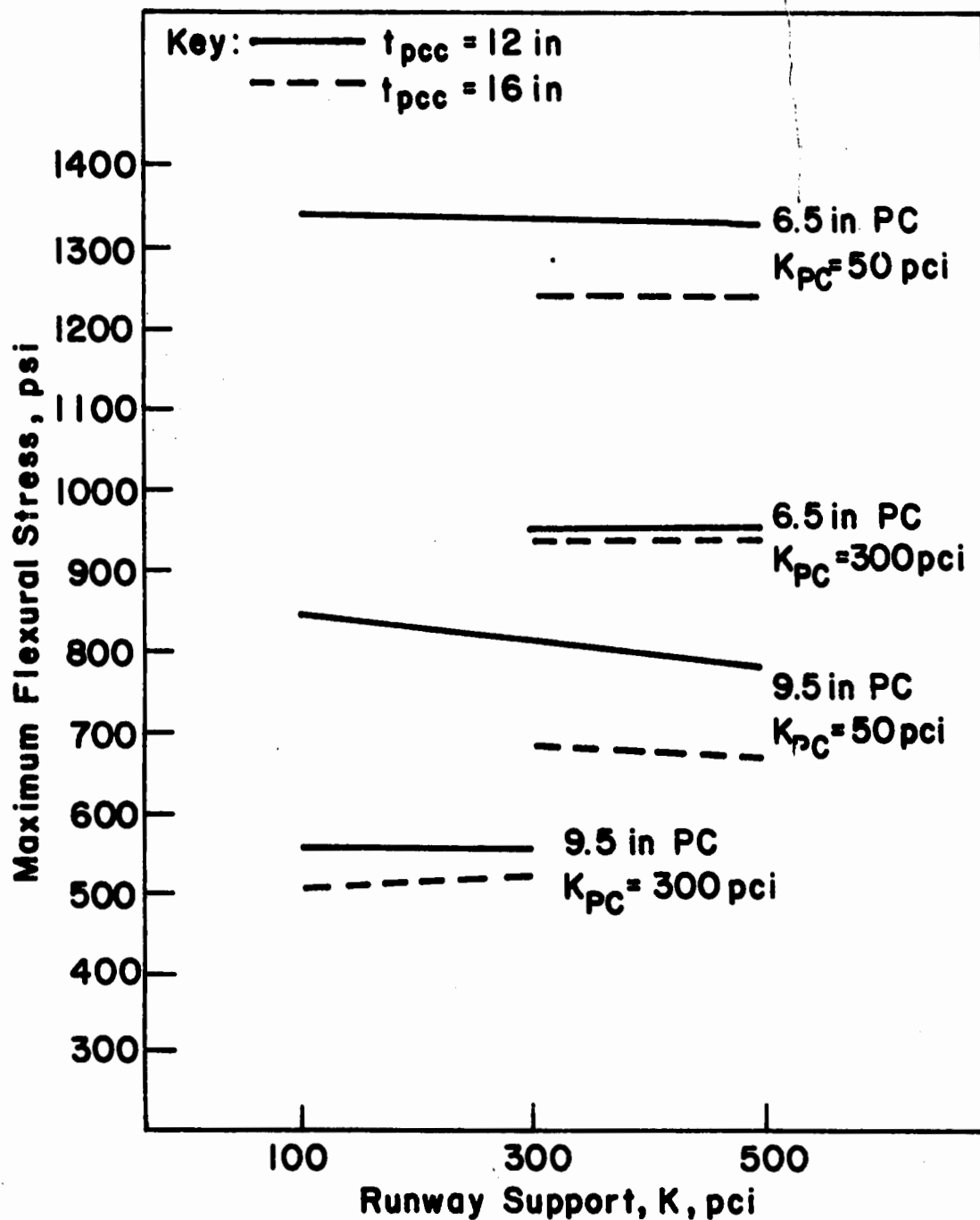


Figure 80. Maximum Flexural Stress Versus Runway Support for C-141 Loading and 5- x 4.5-Foot Repair.

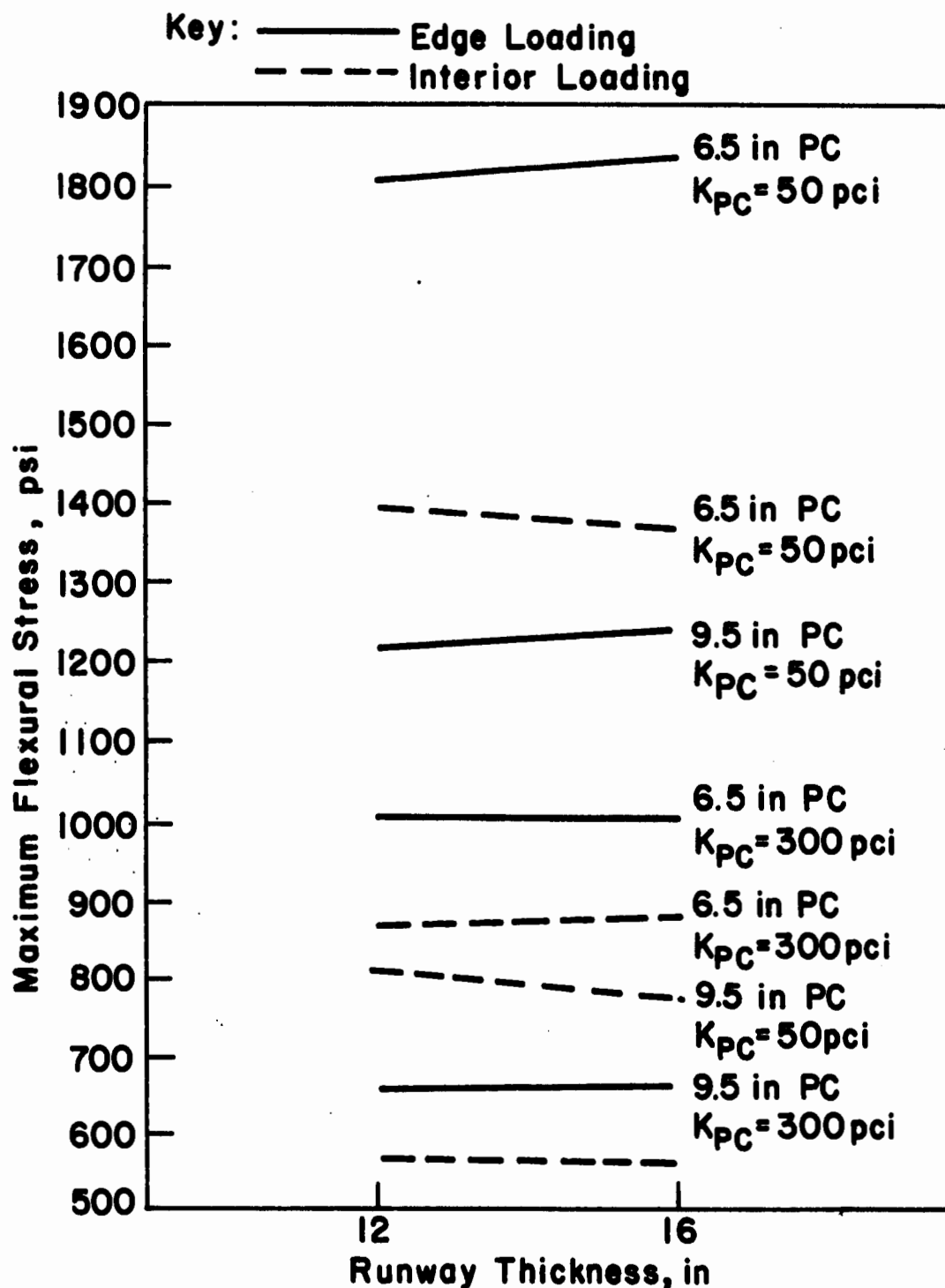


Figure 81. Maximum Flexural Stress Versus Runway Thickness for 17 x 17-Foot Repair and C-141 Aircraft.

The runway thickness was then fixed at 12 in. The value of 12 in was selected because it represents a typical thickness encountered in the field and it did not influence the results. For a 5- x 5-ft repair, the runway thickness had definite influence. The values of 12 in and 16 in were used as representing thin and thick pavements, respectively, while the value of 8 in was rejected because very high stresses were obtained by loading an 8-in pcc slab, indicating that the runway is underdesigned.

The repair support had an influence on the results, and the values 50 pci and 300 pci were selected as representing the extremes (poor and strong support).

The stresses resulting from all conditions where $K_{pc} = 300$ pci and Position 2 (edge) was loaded are plotted and the boundaries of stresses for the F-4 and the C-141 are shown in Figure 82. Because the range of stress was small, only the upper boundary of each of the F-4 and the C-141 were used as representing the edge loading, with $K_{pc} = 300$ pci for all conditions, thus reducing the scope of analysis.

5.3 Design Charts

After the sensitivity study was completed, design charts were prepared containing only the significant variables as defined by the sensitivity study. Figures 83 through 86 are design charts that present the maximum flexural stress in terms of the polymer concrete repair depth for a range in conditions. On the chart, qualitative variables were used, whereas the previous information was developed in terms of quantitative factors. The qualitative factors were:

- Small repair size: 25 to 299 sq ft,
- Large repair size: 300 to 999 sq ft,
- Major replacement: 1000 or greater sq ft,
- Strong repair support: 300 pci plus,
- Poor repair support: 50 pci,
- The thick existing runway: 16-in thickness
- The thin existing runway: 12-in thickness

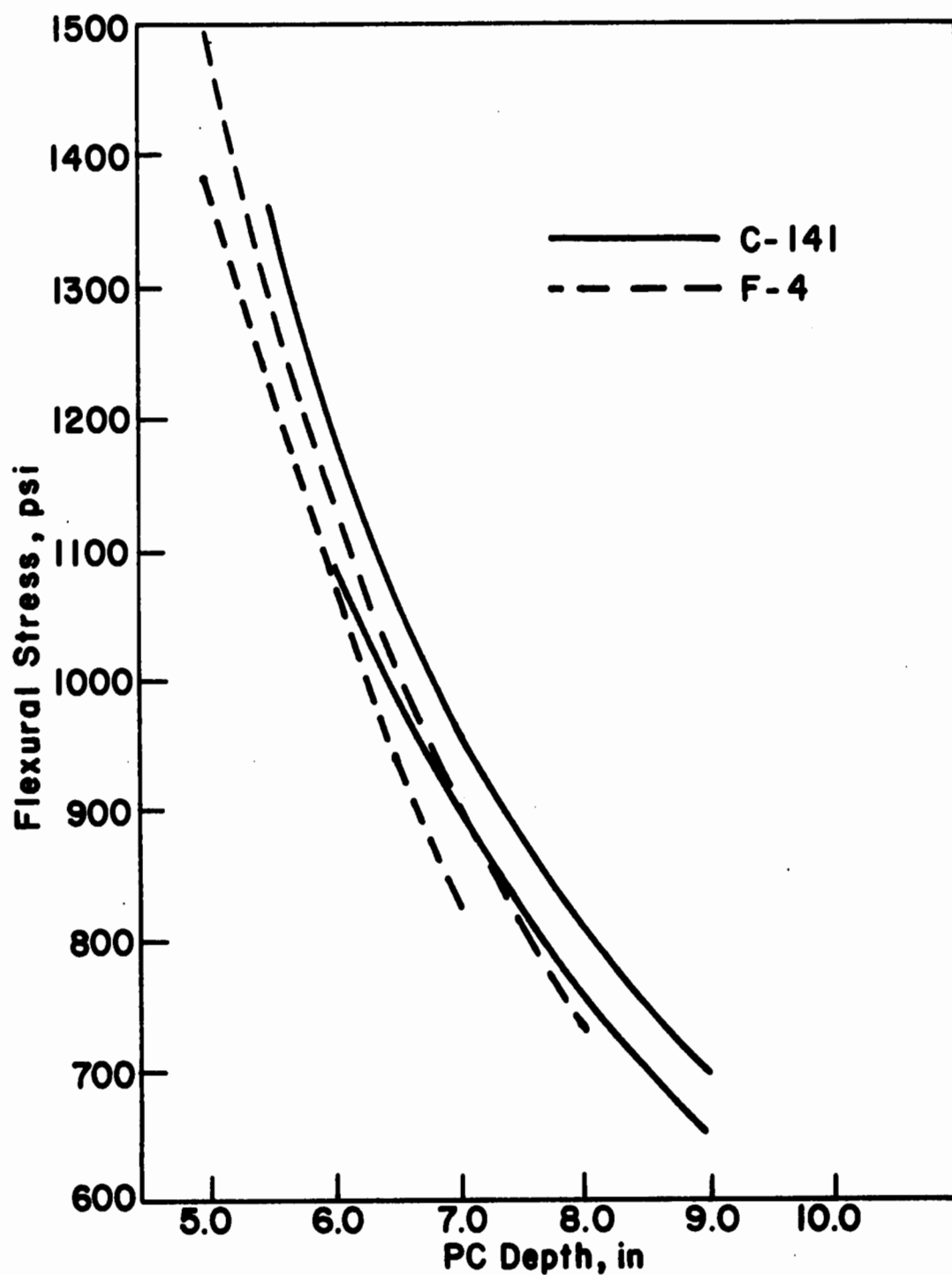


Figure 82. Flexural Stress Versus PC Depth for Edge Loading and $K_{pc} = 300$ pci.

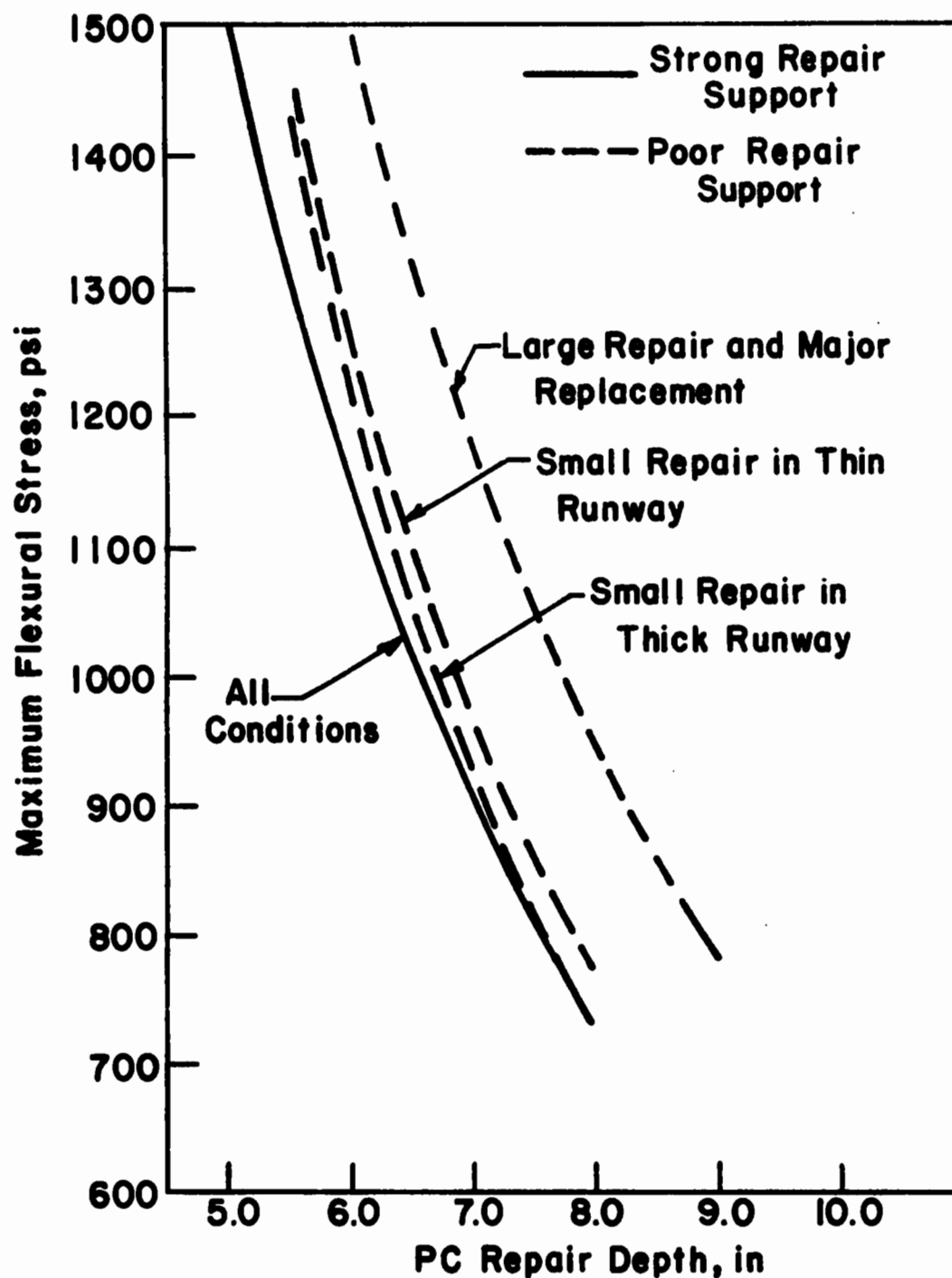


Figure 83. Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Edge Loading.

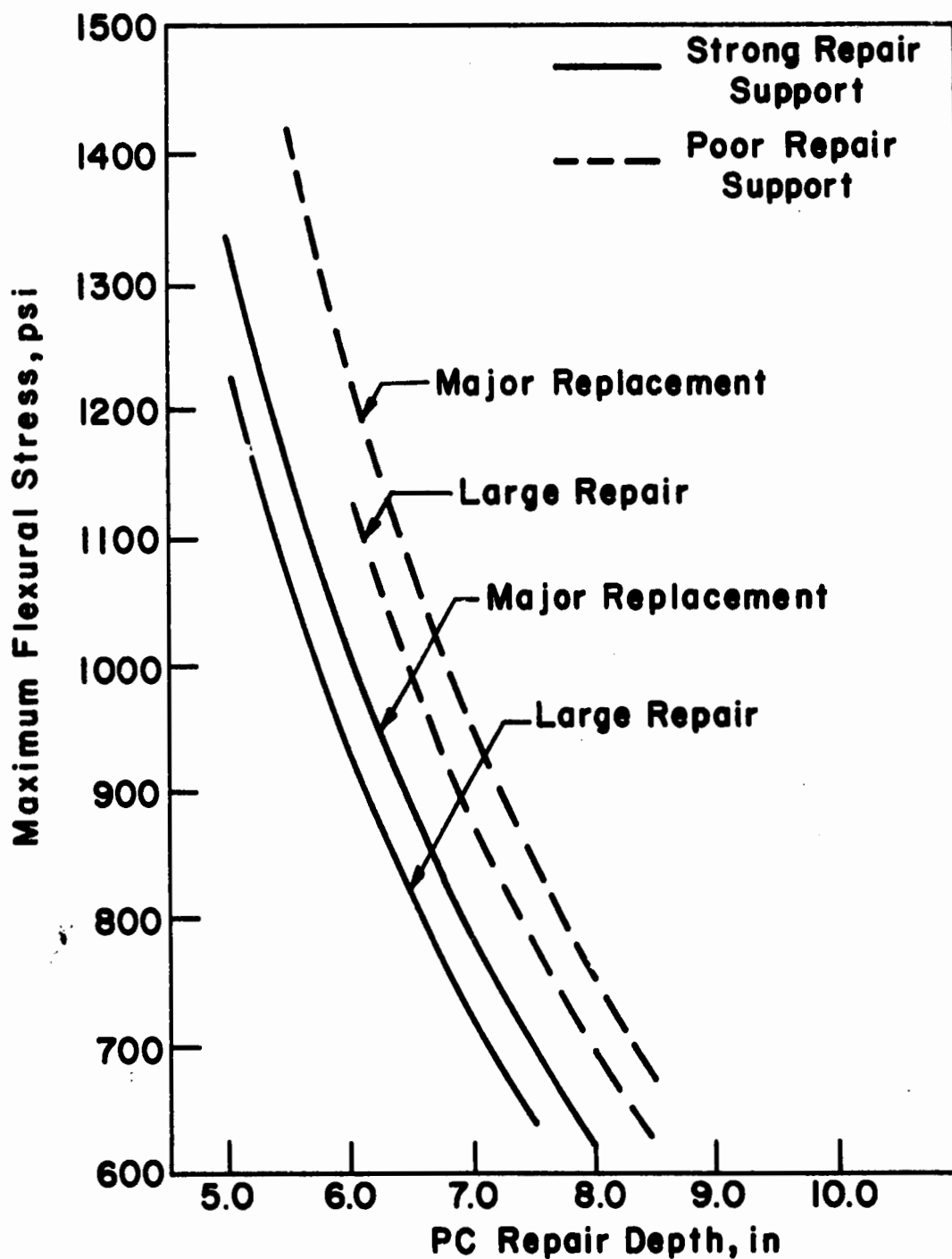


Figure 84. Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Interior Loading.

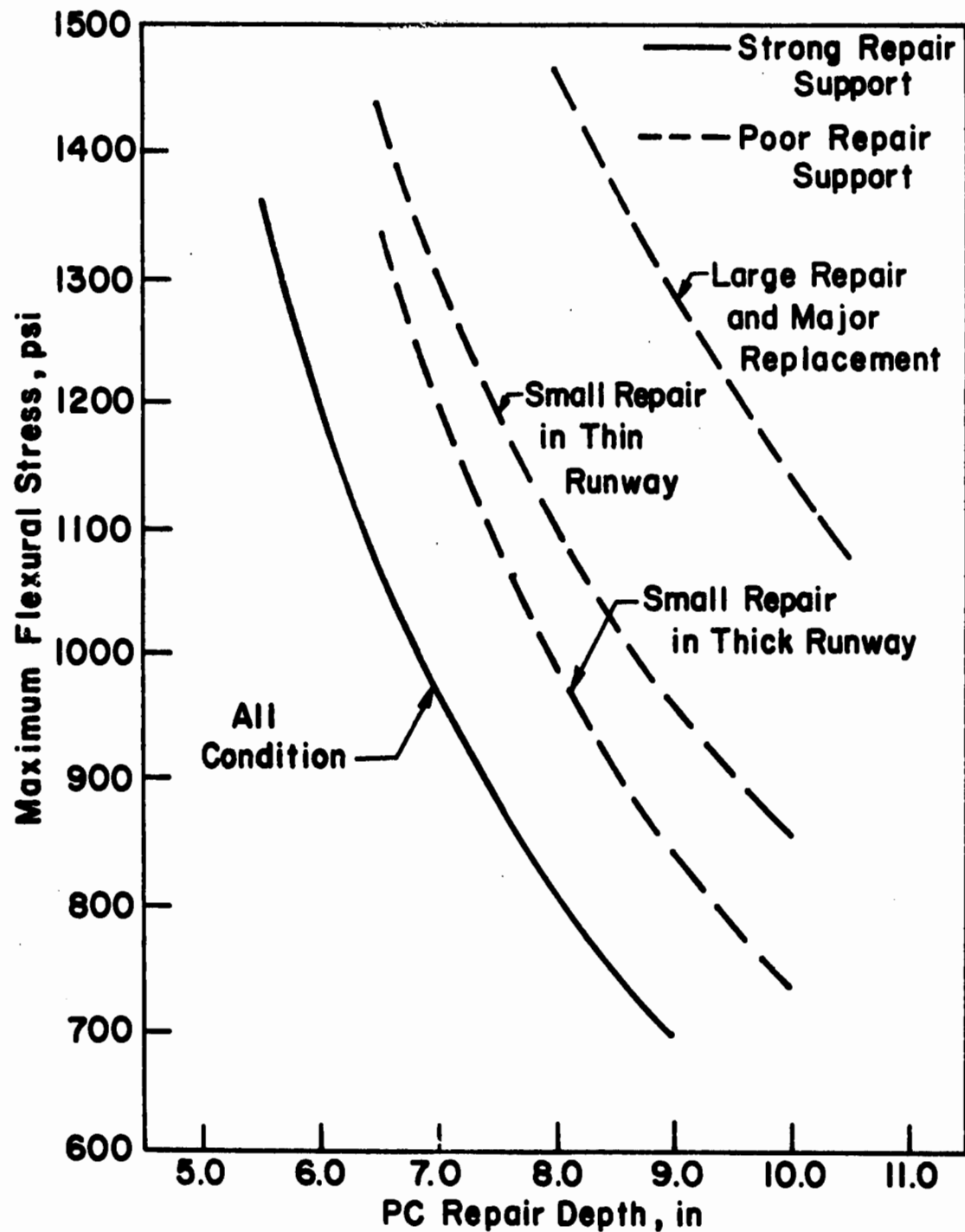


Figure 85. Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Edge Loading.

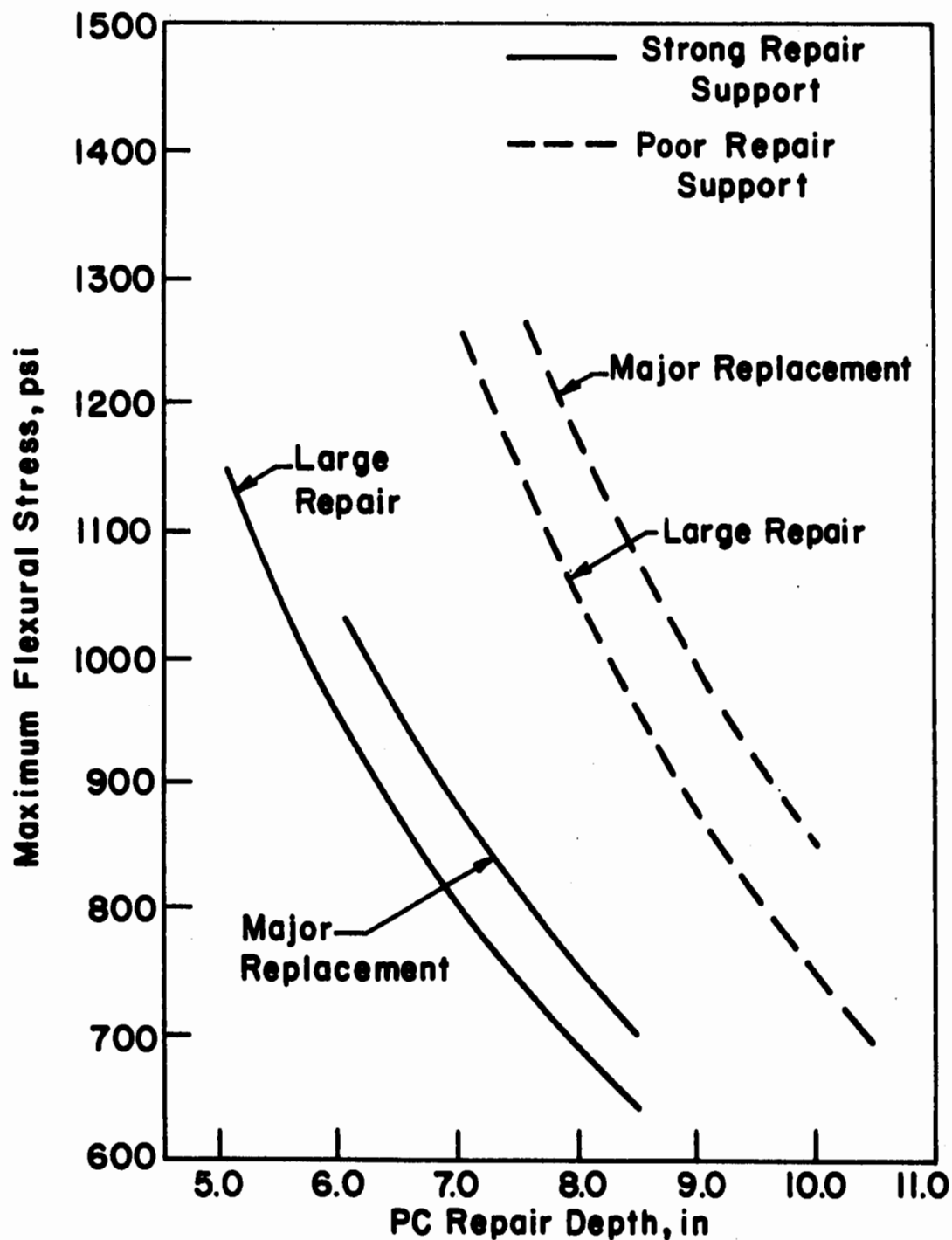


Figure 86. Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Interior Loading.

Figures 83 and 84 present the maximum flexural stress in polymer concrete versus polymer concrete repaired area thickness for the F-4 aircraft for edge and interior loading, respectively. Figures 85 and 86 present the same information for the C-141 aircraft for the edge and interior loading, respectively.

For simple use of the charts, only the edge loading should be considered for the small repairs, whereas for larger repairs and major replacement, both edge or interior loading conditions should be considered. In using the chart, the value of the repair support may be interpolated. For the repair size, a size is determined and then the range that encompasses the appropriate figure is found. For example, if the repair area is 225 sq ft, the user would select the larger repair size for determining the polymer concrete thickness. If the repair area encompasses the edge, the edge condition should be selected. If the repair area is surrounded by the existing pavement, an interior loading condition is used.

The allowable stress level to be used in the equation must be derived as a function of the number of repetitions. Therefore, the fatigue concept is applicable here. The following equation represents a typical fatigue equation that is used for portland cement concrete:

$$N = A \left(\frac{f}{\sigma} \right)^B \quad (1)$$

where σ = the stress in the concrete due to the appropriate aircraft loading and other condition;
 f = the flexural strength of the polymer concrete;
 N = the allowable number of repetitions for the strength and stress condition; and

A & B = coefficient for testing of the specific materials

The above equation has been used for the design of portland cement concrete and asphalt concrete for a substantial period of time and is felt to be applicable here. The coefficients A and B have not yet been developed for polymer concrete. Since all static tests on polymer concrete have indicated that this is

vastly superior to the normal portland cement concrete, it was felt that the use of coefficients developed for portland cement concrete would be conservative. Therefore, Equation (1) is defined as follows for polymer concrete:

$$N = 23,440 \left(\frac{f}{\sigma}\right)^{3.21} \quad (2)$$

where all variables are as defined previously.

5.4 Design Procedure

The following is a sequential procedure that may be used to determine the thickness of polymer concrete repair:

1. The thickness of the existing concrete pavement and relative applications of each type of aircraft of the two design aircraft, i.e., C-141 and F-4, should be determined. A judgment should be made as to the compaction condition to be used in the field or repair area, i.e., poor or good. In addition, a decision should be made as to the length of time that design applications are to be applied.
2. The user surveys the repair area and makes qualitative decisions as to small, large, or major repair replacement, and a decision is made as to whether the repair is an edge, i.e., whether the repair is surrounded by existing pavement.
3. The allowable stress for the aircraft is computed for each aircraft type using the following equation:

$$\sigma = f \left(\frac{23440}{N}\right)^{0.31} \quad (3)$$

4. The user then determines the polymer concrete repair by entering the appropriate figure from Figures 83 through 86 to represent the aircraft type and loading condition. The allowable stress from step 3 is entered at the vertical axis projected horizontally to the appropriate repair area and support condition. At that

intersection, the line is projected vertically and the thickness is read on the horizontal scale.

SECTION VI

SUMMARY AND CONCLUSIONS

6.0 SUMMARY

The use of methyl methacrylate polymer concrete has been investigated for bomb damaged runway repair. Criteria included: (1) set times of 1 hour or less at temperatures in the range of -25°F to 125°F, (2) set times of 1 hour or less when in contact with asphalt, and (3) adequate strength development when used with wet aggregate. Mechanical properties (flexural strength, modulus of elasticity and fatigue strength) have been determined. User-formulated and commercially available prepackaged materials were investigated. The effect of aggregate size and gradation was studied.

Preliminary repair procedures were developed for four types of bomb damage: (1) surface spalls, (2) small craters, (3) large craters, and (4) camouflet. Techniques for placing the polymer concrete were studied. Field tests were performed for spalls and simulated small craters to evaluate several methods of repair. The field test repairs were load cart tested. The most satisfactory methods were selected and are presented in the implementation manual.

Polymer concrete was investigated in the laboratory to determine fatigue strength of beams and repaired slabs, compressive strength, flexural strength, and modulus of elasticity. Several repair configurations on 3- x 6-ft slabs were tested using applied loads which simulated the F-4 and C-141 aircraft until failure occurred or for a maximum of 100,000 load cycles.

Analytical behavior of repairs was made for a wide range of repair sizes, edge conditions, thicknesses, and support conditions. Both F-4 and C-141 aircraft loadings were considered. Design curves were developed to simplify the determination of repair thickness.

6.1 Conclusions

Based upon the studies completed in Phase I, the following conclusions can be made:

6.1.1 Materials Characterization

1. Monomer systems consisting of MMA/TMPTMA or MMA/TTEGDA behave similarly; the TTEGDA was discontinued because of problems with skin irritancy. MMA/TMPTMA was polymerized in 1 hour or less at temperatures as low as -25°F and at 125°F . The effect of monomer temperature exerts a very strong influence on the setting time. At -25°F , about 10 times more promoter (DMT) and 5 times more initiator (BzP) were required for curing the MMA/TMPTMA than at a temperature of 100°F .

2. The effect of casting temperature on flexural strength was not found to be very significant; however, flexural strength increased about 20 percent for a testing temperature of 0°F as compared to a testing temperature of 135°F .

3. The compressive strength of PC was found to reach 6000 psi in one hour and the maximum strength (9000 psi) was achieved in 8 to 12 hours.

4. The loading rates used in this study, 47.16 psi/sec and 23.58 psi/sec, produced only slight differences in the strength and behavior.

5. The flexural strengths of PC made with dry aggregate were generally found to be about 2000 psi or higher within 1 or 2 hours at ambient conditions.

6. Prepackaged PC systems produced PC with similar properties as the user-formulated system.

7. The use of different aggregate sizes and gradation did not appreciably alter the mechanical properties; however, the strength of Silikal[®] was reduced with increasing amounts of coarse aggregate. An aggregate-to-mortar ratio of 1.2 yielded a 2-hr flexural strength, about 15 percent less than for pure mortar beams. For a 24-hr cure the strength reduction amounted to about 35 percent.

8. Compressive and tensile strength of PC made with wet aggregate was reduced very significantly with increasing moisture content for both limestone and silicious aggregate. Of the many techniques studied to increase the strength, the use of silane-coated aggregate and the use of steel fibers added to the PC mix were found to be the most effective in maintaining adequate tensile strength with increasing moisture content. However, even using these techniques, a moisture content of 5 percent results in a strength loss approaching 60 percent.

9. The polymerization of MMA in the presence of asphalt required 11 to 18 minutes at 100°F and 80 to 85 minutes (more than the 1-hr time required by AFESC criteria) for 0°F. The shear strengths, measured at 2 hrs for all test temperatures, were 8 psi and 21 psi for the UT formulation at 100°F and 75°F, respectively; 60 psi and 95 psi for Silikal[®], and 130 psi and 136 psi for asphaltic concrete. At 0°F, the shear strengths ranged from 273 psi for the UT formulation to 445 psi for asphaltic concrete.

10. A thickened contractor-formulated system was developed which improved workability. The monomer formulation was similar to the basic user-formulated system except that up to 5 percent PMMA powder (based on aggregate weight) was added. Compressive strengths in excess of 9000 psi were obtained for 3 percent PMMA.

11. Fatigue tests were performed using different percentages of the static flexural strength and for different ratios of minimum to maximum stress. At stress levels of 65 percent or less of static strength, all beams withstood more than 100,000 cycles.

12. The use of MMA requires greater safety measures than are required for normal portland cement concrete. MMA is flammable and mildly toxic. MMA polymer concrete has been used for several years in the construction industry without serious safety-related problems; however, its use under hostile conditions to be expected in wartime would require more stringent safety measures than used in normal construction.

6.1.2 Repair Procedures

1. Two PC systems are recommended for use: (1) user-formulated MMA system using an in-line mixing system for applying the monomer over the preplaced aggregate and (2) pre-packaged commercially-available PC systems extended with coarse aggregate batched in a Modified Concrete Mobile[®].

2. Spall repairs can be made using debris if it is free of asphalt and has a maximum aggregate size of 3/4 in or less; if the aggregate size is larger than 3/4 in, fine aggregate must be added. The user-formulated monomer system is recommended in conjunction with the in-line mixing system.

3. Small crater and camouflet repairs can be made using the cap method for small areas and precast units for larger areas. In either method, the crater is filled within 10 to 14 in of the surface with debris and then compacted with a vibratory roller. A leveling course of select material is placed.

a. Cap method. The leveling course is primed and sealed using the in-line mixing system prior to using the pre-placed aggregate method or the premixed PC to make the repair.

b. Precast slab method. Precast units should be sized to be modular with the existing pavement slabs. The slabs should be positioned to provide 4- to 6-in joints. The slabs may be either placed flush with PC used to fill the joints, or slabs may be recessed with PC used in the joints and as an overlay. Both user-formulated and prepackaged PC can be used for these repairs.

4. Larger crater repairs can be made with the precast slab method using either the user-formulated or prepackaged PC systems.

6.1.3 Experimental behavior

1. Laboratory studies indicated that polymer concrete repairs have high resistance to cyclic loadings even when cracking is present in the repair.

2. The confined laboratory repairs (repairs surrounded by

existing pavement) provided the best performance. Even if the repair is at the edge of the pavement, the likelihood of an edge loading is small. Hence, the repair can be considered confined.

3. The highest stresses in the repair are generated at the interface between the repair and on the existing pavement. Care should be taken to insure adequate bond and depth of repair at the interface.

6.1.4 Analytical Behavior

1. The nose gear has no influence on the stresses and may be neglected in the analysis.

2. The critical positions for the location of the gear were on a horizontal centerline at each edge and at the center of the repair. For the F-4, the critical locations were the center and the outside edge; for the C-141, the inside edge abutting the PCC pavement was critical.

3. The value of the perimeter runway (PCC) support has no significant effect on flexural stresses.

4. For larger repairs, the runway thickness has little influence on the flexural stresses; for small repairs, the effect is insignificant.

5. Repair support values must be considered; limiting values of 300 pci and 50 pci were used.

6. Design charts are presented to simplify the design of the PC repairs.

6.1.5 Proposed Implementation Manual

A proposed implementation manual was developed to describe materials and equipment, define design procedures, provide instructions on making repairs, and define safety and handling requirements.

APPENDIX
PROPOSED IMPLEMENTATION MANUAL

1.0 MATERIALS

1.1 Introduction

There are several materials used in the production of polymer concrete, including several chemicals. These materials are briefly described in this chapter. Additional information pertaining to safety and handling is presented in Section 7 of the Implementation Manual.

1.2 Monomer System

The monomer system consists of several chemicals which must be mixed in the correct proportions to produce a cure in the desired time (less than 1 hour).

1.2.1 Monomer

The basic monomer is methyl methacrylate (MMA). MMA is the monomer from which Lucite[®] and Plexiglas[®] are made. MMA is a clear, volatile liquid that looks like water and has about the same viscosity as water. It has a sharp, pungent odor; about 1 part per million can be detected by smell. MMA can be obtained in units of 5 gallons, 55 gallons or tank car lots. It should always contain an inhibitor, MEHQ, which is described in a subsequent paragraph. For long storage times, the inhibitor level should be monitored as described in the Section on Safety and Handling.

1.2.2 Cross-Linking Agent

A cross-linking agent, which is a special type of monomer, is added to the MMA in small quantities to increase the cure rate. The cross-linking agent is trimethylolpropane trimethacrylate (TMPTMA). TMPTMA is a slightly yellow liquid with the viscosity of light oil. It is not nearly as volatile as MMA and has little odor. It should always be inhibited with either MEHQ or HQ, described in a subsequent paragraph.

1.2.3 Inhibitors

Inhibitors are additives used in MMA or TMPTMA to prevent premature polymerization which can be caused by excessive temperatures, contaminants, or other reasons. The two most common inhibitors are methyl ester of hydroquinone (MEHQ) and hydroquinone (HQ). For MMA, MEHQ is added at the rate of from 10 to 100 parts per million. TMPTMA usually contains from 100 to 125 parts per million of MEHQ or 60 to 100 parts per million of HQ. The higher levels should be specified when long storage times and/or high storage temperatures are anticipated. The level of inhibitor should be monitored at 6-month intervals by the procedure outlined in Section 7 of this manual.

1.2.4 Promoter

A promoter is used in very small quantities to increase the decomposition rate of the initiator, which results in faster curing. The promoter, dimethyl-p-toluidine (DMT), is a liquid with a viscosity about the same as water. Either the distilled or undistilled, which is less expensive, can be used. If promoters are stored separately in concentrated form, caution must be exercised to prevent contact between the DMT and the initiator, BzP. Mixture of the two materials in concentrated form can react explosively. When the DMT is already mixed in the MMA, the initiator can be added with no danger.

1.2.5 Initiator

The initiator, benzoyl peroxide (BzP), is required to begin the polymerization, or cure. The BzP is added in relatively small amounts to the monomer just prior to adding the monomer to the aggregate. BzP comes in several forms, but the recommended type is a 40-percent concentration (commonly referred to as 40-percent dispersion) manufactured by Reichhold Chemicals, Inc. (Superox 742[®]). BzP in 40-percent concentration is available from other manufacturers, but the (Superox 742[®]) is the only material that has performed satisfactorily for pumping applications.

The BzP dispersion is white with a viscosity of a heavy motor oil and it readily dissolves in MMA. Under no circumstances should nearly pure BzP in a dry, granular solid form be used since it can react in an explosive manner to heat, shock, or contact with other chemicals. Even the 40-percent dispersion should not be mixed with concentrated DMT.

1.2.6 Thickening Agent

Finely granulated polymethyl methacrylate (PMMA), which is the solidified form of MMA, is sometimes added to the PC mix to make it more cohesive. The PMMA, added in small amounts, absorbs some of the MMA and results in a workability more nearly like normal portland cement concrete.

1.3 Commercially Prepackaged Polymer Concrete Systems

Several two-component prepackaged PC systems are available. The brands include Silikal[®], Crylcon[®], and Concrecive[®]. These systems contain a liquid component, which is primarily MMA, and a powder component, which contains fine aggregate, colorants, initiator, and thickener. For PC depths of several inches and/or large volumes, coarse aggregate can be added to the PC to extend it. These materials must be mixed prior to placement. Most of the prepackaged systems have separate cold weather and hot weather formulas.

1.4 Steel Fibers

Steel fibers can be added to the PC mix to minimize the reduction in strength due to wet aggregate and/or to increase the ductility and toughness of the PC. The recommended fibers (Bekaert ZL 30/50[®]) are hooked at each end to provide better bond. The fibers are generally glued together in groups of 5 to 20 with a water soluble adhesive which results in a more uniform dispersion throughout a portland cement concrete mix. For use with PC, however, the usual adhesive is not soluble in MMA.

Either adhesive which is soluble in MMA must be specified or the fibers must be ordered loose.

1.5 Mold Release Agents

Mold release agents should be used when PC is cast in molds or removable forms. Without mold release agents, the PC tends to develop a strong bond to most materials. There are many materials which will provide some degree of mold release. The recommended material is a buffered fluorocarbon (Mold-Whiz F-57[®]) which can be painted or wiped onto the form or mold surface. About an hour after applying the mold release, a spray lubricant (LPS-3 or LPS-7) can be sprayed onto the mold release surface for even better results when moisture is present in aggregate.

1.6 Caulking Compounds

Since the monomer has a very low viscosity, it is important to make the mold or form joints water tight. Acrylic, latex or silicone caulking compound applied with a caulking gun is the recommended material for this application.

1.7 Methylene Chloride

Methylene chloride (MeCl) is a nonflammable solvent used to clean hoses, mixers, tools and other equipment used for producing or finishing polymer concrete. It is readily available from many chemical supply stores.

1.8 Aggregates

1.8.1 Types

Any aggregate suitable for use in normal weight structural portland cement concrete (PCC) may be used in polymer concrete (PC). Generally, higher strengths are obtained with crushed limestone coarse aggregates and well-graded silicious fine aggregates.

1.8.2 Gradation

Aggregates graded for structural PCC are suitable for use in PC. The basic mixture is 50-percent coarse aggregate (CA) and 50-percent fine aggregate (FA) by weight. Since most aggregates for structural PCC are similar in unit weight, a 50:50 mixture of CA and FA by volume is also suitable for use in PC. For large repairs (greater than 2-ft diameter and 4-in deep), a 1 1/2-in maximum top size is recommended. For small or shallow repairs, a "pea gravel" and fine aggregate mixture will generally give the best results. For commercially available PC such as Silikal[®], only coarse aggregate is required. The manufacturer's recommendations should be followed.

The following gradations have given excellent results in both the laboratory and field tests.

Coarse Aggregates

<u>Retained on</u>	<u>Percent</u>
1 1/2-in sieve	0
3/4-in sieve	30-65
3/8-in sieve	70-90
No. 4 sieve	95-100

Fine Aggregates

<u>Retained on</u>	<u>Percent</u>
3/8-in sieve	0
No. 4 sieve	0-5
No. 8 sieve	0-20
No. 16 sieve	15-30
No. 30 sieve	35-75
No. 50 sieve	70-90
No. 100 sieve	90-100
No. 200 sieve	97-100

1.8.3 Storage and Handling

Aggregates should be stored in a well-drained, protected area, in a dry condition. When such storage is unavailable, the aggregates should be stockpiled in a well-drained area,

allowed to air dry as much as possible and covered with plastic sheets or other moisture barrier until needed.

Aggregates for PC can be handled in the same manner as aggregates for PCC. Care should be exercised to avoid exposing the aggregates to moisture.

2.0 EQUIPMENT

2.1 Introduction

The primary equipment required for polymer concrete repairs are in-line mixing systems and/or mobile concrete batching facilities. Some modifications and special supporting equipment are required. The equipment needs are summarized in this chapter.

2.2 Mixing and Batching Equipment

2.2.1 In-Line Mixing Systems

The recommended equipment is the High Volume Hydraulic Injection System (H.I.S.) (Figure 2.1) manufactured by Venus Products, Inc., Kent, Washington. The unit has a capacity of approximately 9 gallons per minute, which would permit up to 10 cubic yards per hour per pump for continuous operation; however, the actual intermittent operation of the gun would result in a production of not more than 5 cubic yards per hour per pump, or 10 cubic yards for two pumps. It is recommended that the in-line H.I.S. units be trailer-mounted and include the following (Figure 2.2):

1. Two large volume H.I.S. pumps equipped with:
 - a. two injector guns for each pump (a total of 4 guns)
 - b. 25-foot methylene chloride-resistant hoses attached to each gun
 - c. H.I.S. slave-pumps equipped for 8-percent BzP dispersion and 5-percent DMT
2. 500-gallon monomer storage tank
3. 55-gallon drum of 40 percent BzP dispersion
4. 55-gallon drum of DMT
5. 120-cubic foot per minute air compressor/generator equipped with high efficiency water trap before air lines
6. Air storage tank
7. Safety equipment on or near the trailer should include:
 - a. large volume dry chemical type fire extinguishers

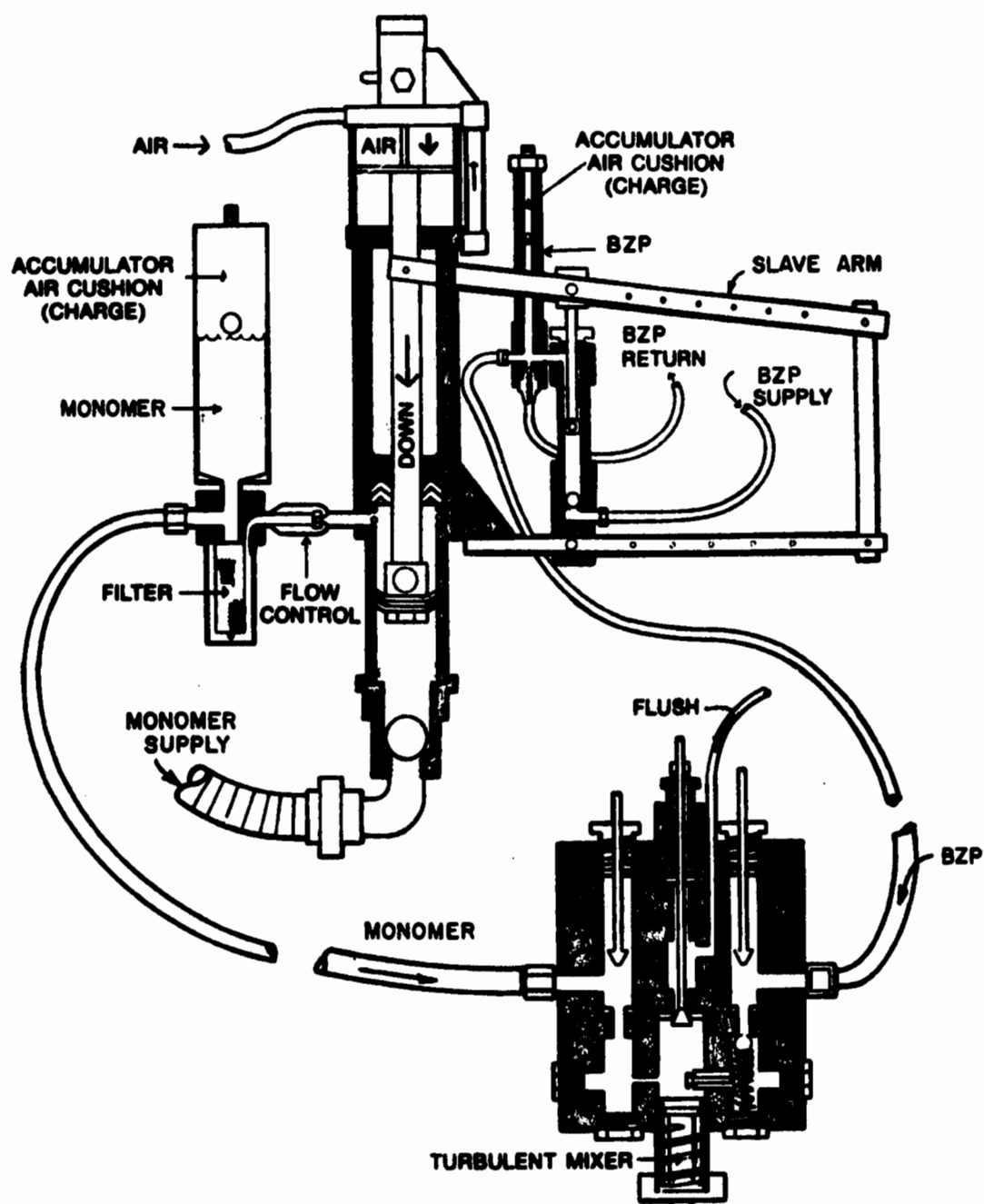


Figure 2.1. Schematic of Hydraulic Injection System (courtesy of Venus Products, Inc.)

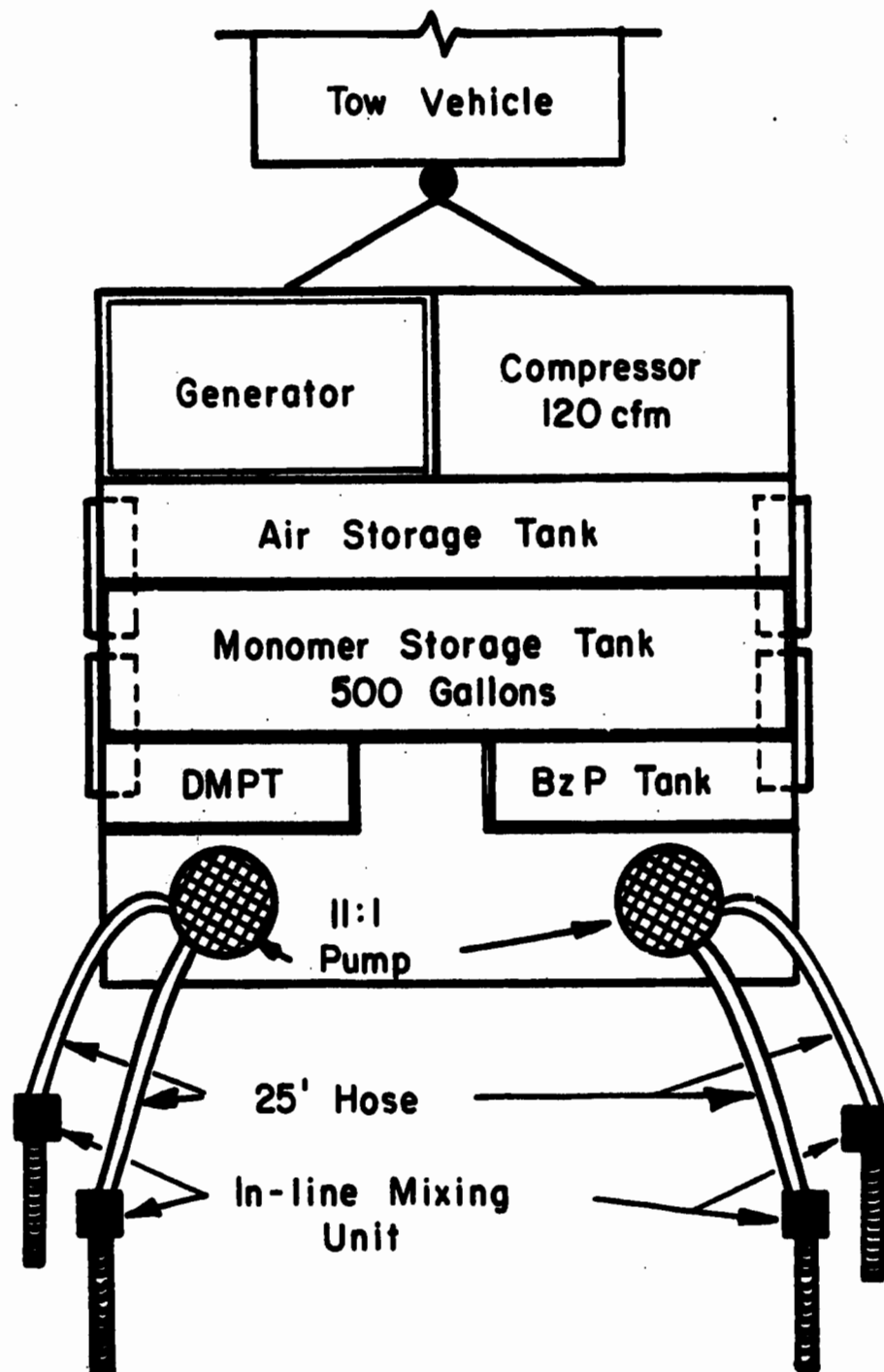


Figure 2.2. Trailer-Mounted Hydraulic Injection System.

- b. fire-resistant clothing, goggles, respirators, boots and gloves
- c. eye wash station

2.2.2 Support Equipment

- 1. tow vehicle for trailer
- 2. front end loader
- 3. dump trailer (size and number depends on length of haul)
- 4. tow vehicle for finishing operation

2.3 Concrete Mobile Batching Facility

The recommended mobile batching facility is the Concrete Mobile[®] manufactured by Daffin Mobile Products, Division of Barber-Greene, Lancaster, Pennsylvania. This unit is capable of producing up to 60 cubic yards per hour. The unit is designed for the production batching of portland cement concrete, and some modifications are required to accommodate batching of MMA-based polymer concrete. Modifications should include:

- 1. All gaskets, seals, and hose linings should be Teflon[®], silicone, or polyethylene.
- 2. Gear pump, without gaskets or seals in contact with monomer, should be provided for monomer transfer.
- 3. A positive displacement pump should be provided that can be adjusted to pump different levels of DMT. An in-line static head mixer should be used to add DMT into monomer line.
- 4. For BzP dispersion, a positive displacement pump which is adjustable to add varying levels of BzP, is needed. Lined hoses and stainless steel or polyethylene contact materials are required.
- 5. A flush system should be provided which includes an air-pressurized flush tank for cleaning initiated monomer-contact areas, e.g., mixing auger and chute, polyethylene lined hoses, gaskets, and seals.

6. Only nonsparking materials should be used at the delivery end of the conveyor belt and in the mixing chamber.
7. A chamber for storing and adding steel fibers should be added.
8. A storage chamber for adding PMMA powder in varying amounts should be included.
9. Large chemical fire extinguishers should be mounted on the unit near the monomer tank and near the mixing chamber.
10. Portable eye wash stations should be readily available.
11. Fire-resistant clothing, goggles, boots, gloves should be worn during repair operations.

Support equipment includes:

1. Dump trucks (number and size depend upon length of haul)
2. Tow truck for CM
3. Front end loaders
4. Pump truck for monomer
5. Tow vehicle for finishing operations

3.0 DESIGN PROCEDURE FOR DETERMINING REPAIR DEPTH

3.1 Determine Flexural Strength of Polymer Concrete

1. Prepare standard 6-in x 6-in x 21-in concrete beam molds. Coat with a mold release agent listed in Section 1 of this manual. Molds should be prepared for making PC with several aggregate moisture contents. The following number for molds and moisture contents are recommended:

Moisture Content (%)	Number of Beam Specimens	
	With Fibers	Without Fibers
0	10	10
1	5	5
3	5	5
4	5	5
5	5	5

2. Aggregate should be oven-dried at $\sim 250^{\circ}\text{F}$. Drying should continue until no weight loss occurs during a 24-hour period. Aggregate should be cooled to room temperature. The container containing aggregate should be sealed to prevent the aggregate from absorbing moisture from the air.
3. Prior to mixing the PC, the cooled aggregate should have water added to provide the desired moisture content (except for specimens with no moisture). The container with the aggregate and water should be sealed and the aggregate should be permitted to absorb the water for 24 hours. If both fine and coarse aggregates are to be used in the PC, they should be premixed in the proper ratios before water is added. Any excess moisture after 24 hours should be poured off prior to batching the PC and the aggregate should be reweighed to determine the

amount of moisture absorbed. The moisture content (MC) is defined as:

$$MC = \frac{\text{weight of wet aggregate} - \text{weight of oven-dry aggregate}}{\text{weight of oven-dry aggregate}} \times 100$$

4. The PC should be batched using the instructions in Section 4 of this manual for the temperature at casting. The PC should be rodded the same as portland cement concrete and given a trowel finish.
5. Testing should be according to ASTM C78-64 and should be performed at one hour after mixing the PC, or as soon after 1 hour as is possible. The flexural strengths should be calculated in pounds per square inch according to ASTM C78-64.
6. The 95-percent confidence values should be calculated for each moisture content and for specimens with fibers and for specimens without fibers. The following method should be used:
 - a. Calculate the average flexural strength, $\bar{f}_{avg}$.

$$\bar{f}_{avg} = \frac{\text{sum of the flexure strength (f)}}{\text{number of specimens (N)}}$$

- b. Calculate the standard deviation, σ

$$\sigma = \sqrt{\frac{\text{sum of } (f_i - \bar{f}_{avg})^2}{N-1}}$$

where each specimen strength, f_i , is used to calculate $(f_i - \bar{f}_{avg})^2$ and these values are then added together and divided by $N-1$.

- c. The 95-percent confidence strength (f_{95}) is $\bar{f}_{avg} - 1.65\sigma$.

Example: The following flexural strengths are obtained for MC = 1.0 for beams without fibers:

1100, 1260, 1180, 1090, and 1120.

$$\bar{f}_{avg} = \frac{1100 + 1260 + 1180 + 1090 + 1120}{5} = 1150 \text{ psi}$$

$$\sigma = \left[\frac{(1100 - 1150)^2 + (1260 - 1150)^2 + (1180 - 1150)^2 + (1090 - 1150)^2 + (1120 - 1150)^2}{5-1} \right]^{1/2}$$

$$\sigma = 71$$

$$f_{95} = 1150 - 1.65(71) = 1033 \text{ psi}$$

3.2 Correcting for Aggregate Moisture Content

1. Plot a graph of the flexural strengths (95-percent confidence values) for specimens with fibers for each moisture content obtained from step 6 of "Determining Flexural Strength." Repeat for specimens without fibers.
2. Knowing or estimating the moisture content in the aggregate stockpile, the PC strength available for design can be obtained from the graph, with or without steel fibers present.

Example: The values of f_{95} are found for other moisture contents with and without fibers and the following table of values is prepared:

	0	1	2	3	5
f_{95} (without fibers)	2131	1033	554	479	440
f_{95} (with fibers)	2158	1295	1038	947	893

The graph in Figure 3.1 shows these values plotted. For the moisture content of the stockpile, the value of the flexural strength can be obtained. If the moisture content of the stockpile is 1.2 percent, the flexural strength is about 900 psi without fibers and about 1200 psi with fibers.

3. As an alternative to Step No. 2, the relationship in Figure 3.2 may be used as guidance if only test data for zero moisture is known. A value of "K" may be taken from the graph and used with the flexural strength at zero moisture as follows to compute the corrected strength:

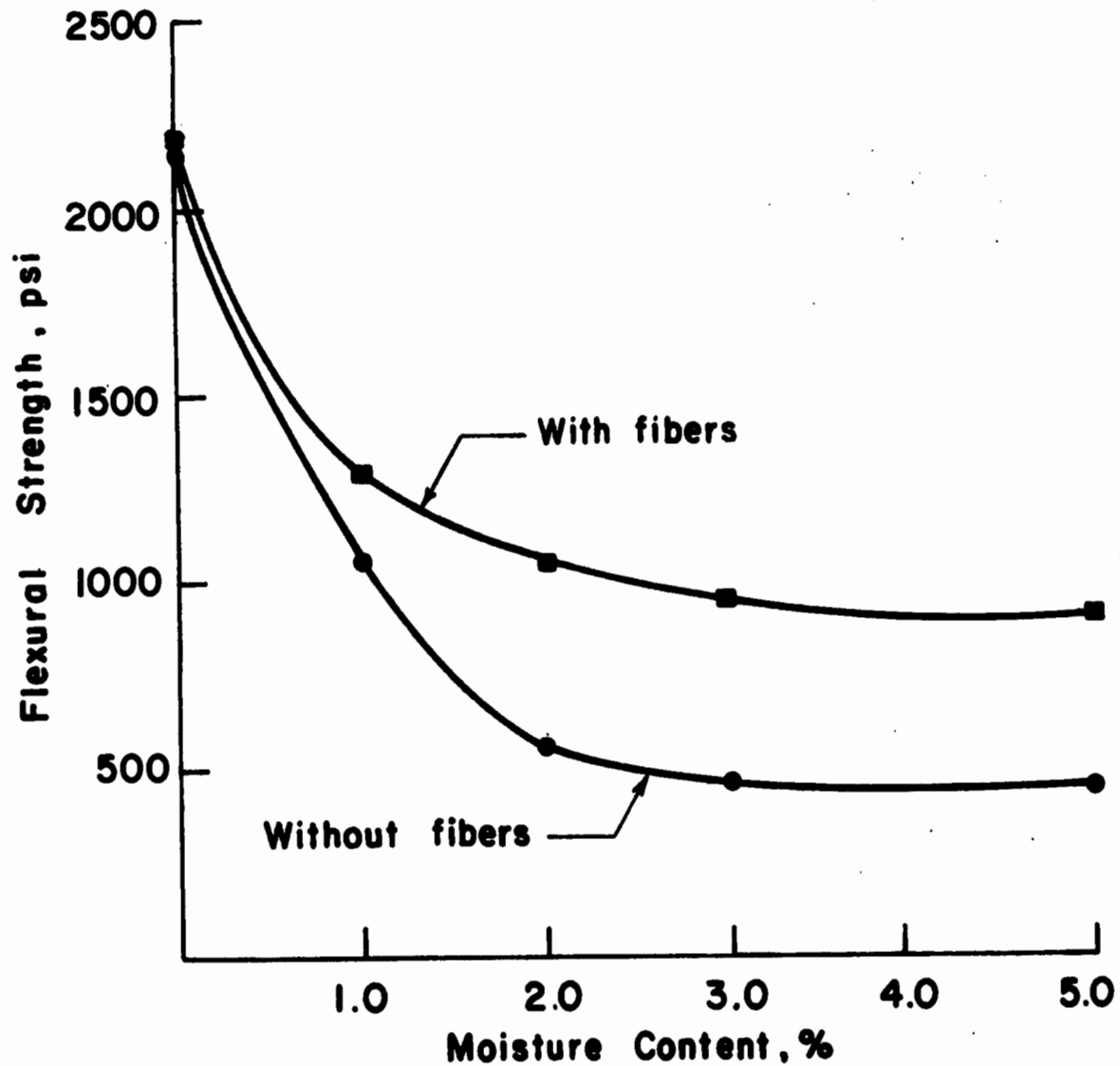


Figure 3.1. Flexural Strength versus Moisture Content for Example Problem.

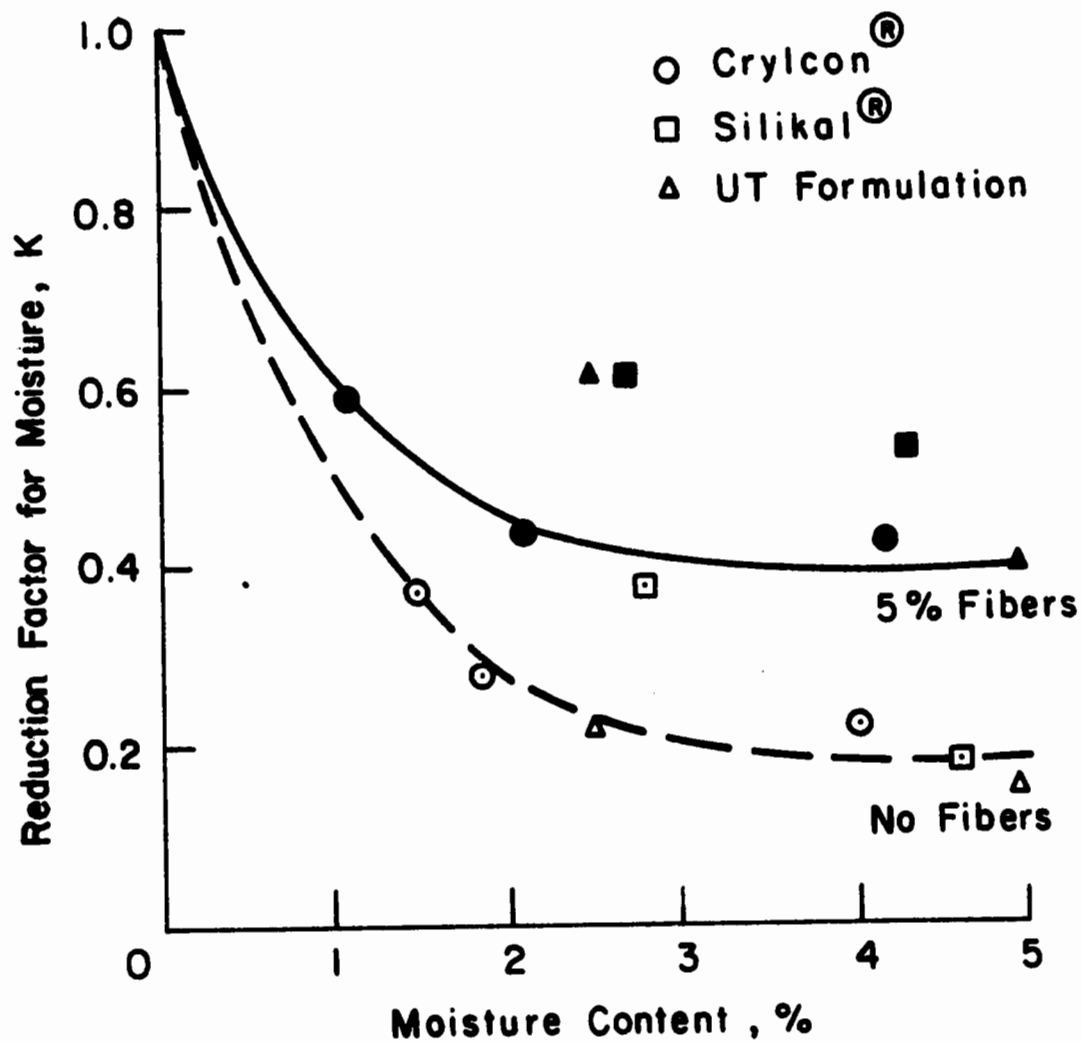


Figure 3.2. Guidelines for Correcting Flexural Strength for Aggregate Moisture If No Test Data is Available.

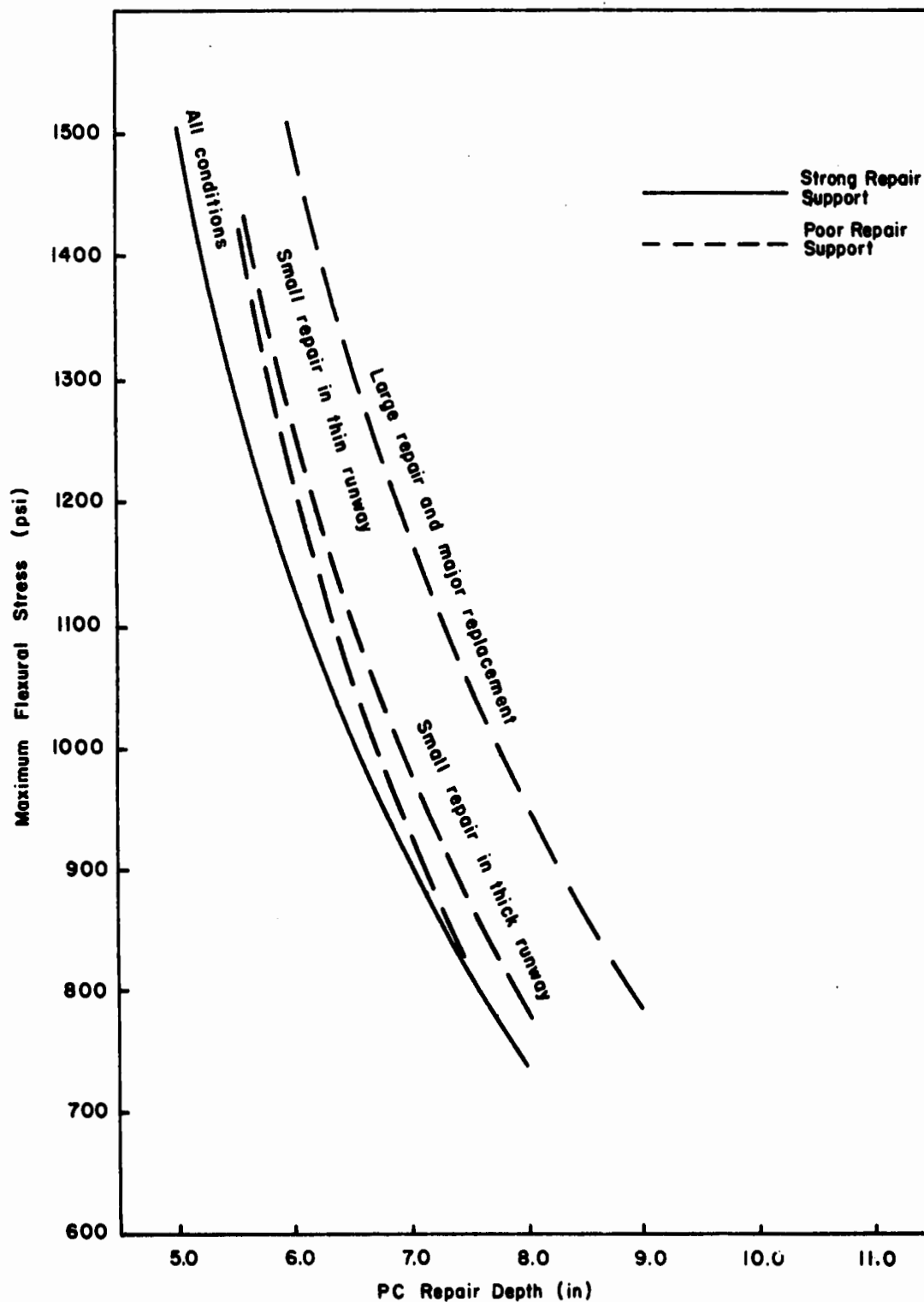


Figure 3.3. Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Edge Loading.

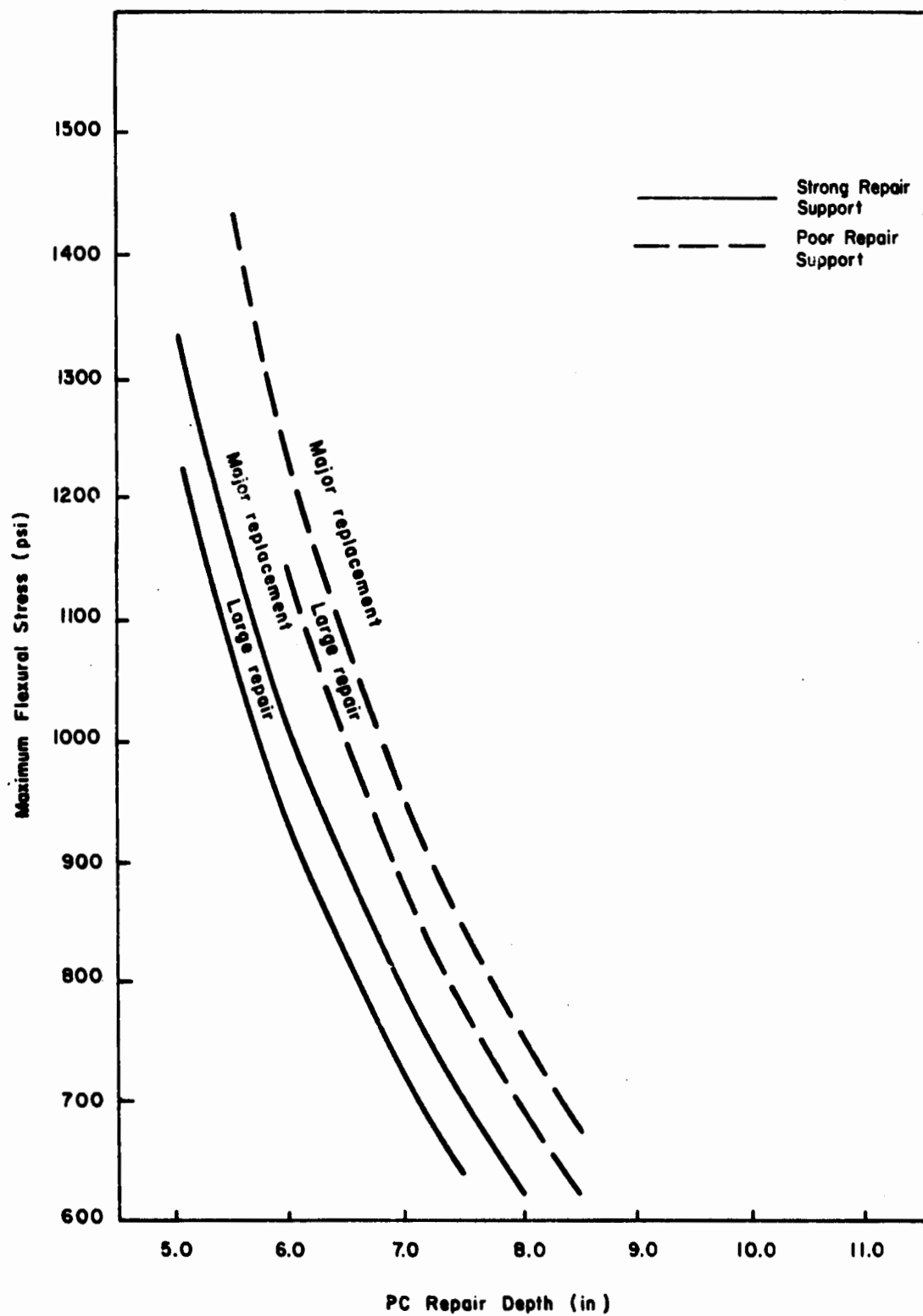


Figure 3.4. Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Interior Loading.

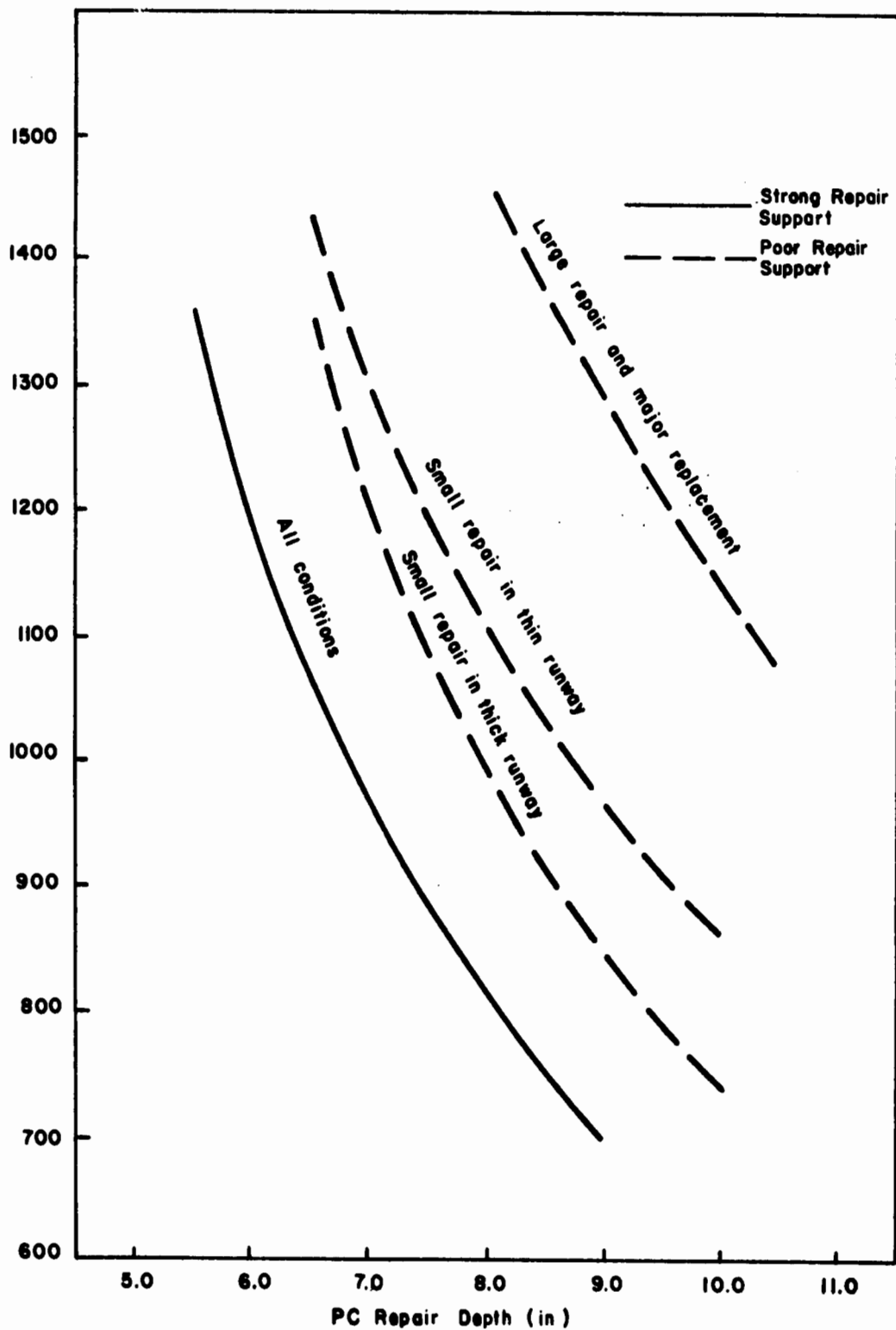


Figure 3.5. Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Edge Loading.

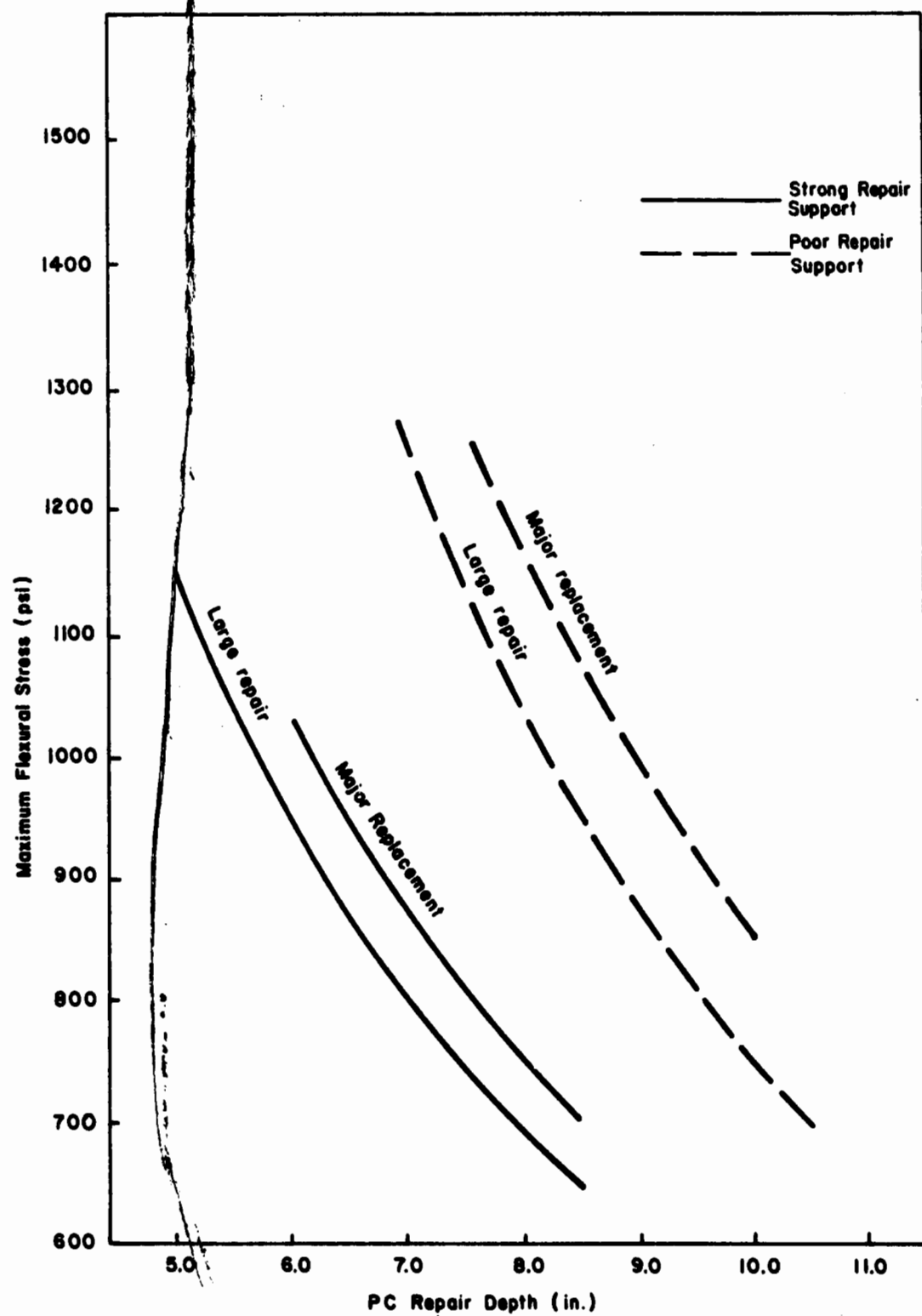


Figure 3.6. Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Interior Loading.

$$f' = K \cdot f_{95} \text{ (@ zero moisture)}$$

Example:

Stockpile Moisture Content = 1.2%

Without fibers, $K = 0.42$

f' (without fibers) = $2131 \cdot 0.42 = 895$ psi

With fibers, $K = 0.57$

f' (with fibers) = $2158 \cdot 0.57 = 1230$ psi

3.3 Determine Pavement Thickness

1. Steps should be taken to determine the thickness of the existing concrete pavement and the relative application of each type of aircraft of the two design aircraft, i.e., C-141 and F-4. A judgment should be made as to the compaction condition to be used in the field or repair area, i.e., poor or good. In addition, a decision should be made as to the length of time that design applications are to be applied.
2. The user reviews the repair area and makes qualitative decisions as to small, large, or major repair replacement. A decision is made as to whether the repair is an edge, i.e., whether the repair is surrounded by existing pavement. On the chart, qualitative variables are used whereas the previous information has been developed in terms of quantitative factors. The qualitative factors are:
 - small repair size equals 25-299 square feet,
 - large repair size equals 300-999 square feet,
 - major replacement equals 1000 or greater square feet,
 - strong repair support equals 300 pci plus,
 - poor repair support equals 50 pci,
 - the "thick" existing runway has a thickness of 16 in,
 - the "thin" existing runway has a thickness of 12 in.

3. The allowable working stress for the aircraft is computed for each aircraft type using the following equation:

$$\sigma = \left(\frac{23440}{N}\right)^{0.31} \cdot f' \quad (4)$$

where:

N = design load repetition of 10,000 and 100,000 load repetitions, equation (4) may be reduced to:

$$\sigma = (\text{for 10,000 reps}) = 1.302 f'$$

$$\sigma = (\text{for 100,000 reps}) = 0.638 f'$$

Example for PC with no fibers:

$$\sigma (\text{for 10,000 reps}) = 1.302 \cdot 895 = 1165 \text{ psi}$$

$$\sigma (\text{for 100,000 reps}) = 0.638 \cdot 895 = 570 \text{ psi}$$

4. The user then determines the polymer concrete repair thickness by entering the appropriate figure from Figures 3.3 through 3.6 to represent the aircraft type and loading condition. The allowable stress from step 3 is entered at the vertical axis projected horizontally to the appropriate repair area and support condition. At that intersection, the line is projected vertically and the thickness is read on the horizontal scale.

Example: For 10,000 repetitions of F-4 loading and an edge condition:

Using Figure 3.3 and an allowable working stress of 1165 psi, the required pavement repair thickness is 7.2 in (say 7 in).

4.0 MONOMER SYSTEM

4.1 Introduction

The monomer system consists of four (4) components: methyl methacrylate (MMA), trimetholpropane trimethacrylate (TMPTMA), dimethyl-p-toluidine (DMT) and benzoyl peroxide (BzP). A list of the materials and some of the manufacturers is given in 4.2.

The monomer formulation is 95-percent MMA and 5-percent TMPTMA. Sufficient promoter (DMT) and initiator (BzP) must be added to polymerize (cure) the monomer. Figure 4.1 gives the amount of BzP and DMT as a function of ambient temperature. It should be noted that exact amounts of BzP and DMT do not have to be used for each temperature; a wide band is used for the curves. The values of DMT and BzP may be used for specific temperature ranges as shown in Table 4.1.

TABLE 4.1 RECOMMENDED LEVELS OF DMT
AND BZP AS A FUNCTION OF
AMBIENT TEMPERATURE.

Component	Temperature, °F						
	-25	0	10	20-40	40-60	60-90	90-100
BzP, %	5.0	4.5	3.8	3.0	2.0	1.25	1.0
DMT, %	3.0	2.5	2.5	1.7	1.0	0.6	0.3

It is important to note that the BzP generally comes in diluted form, and the amount of BzP to be used is the concentrated amount. For example, if a 40-percent BzP dispersion is used and one percent is required, the amount of dispersion to be used is 1 percent = 2.5 percent.

Example

Determine the volumes of MMA, TMPTMA and DMT that would be required to produce 55 gallons of monomer ready for initiator to

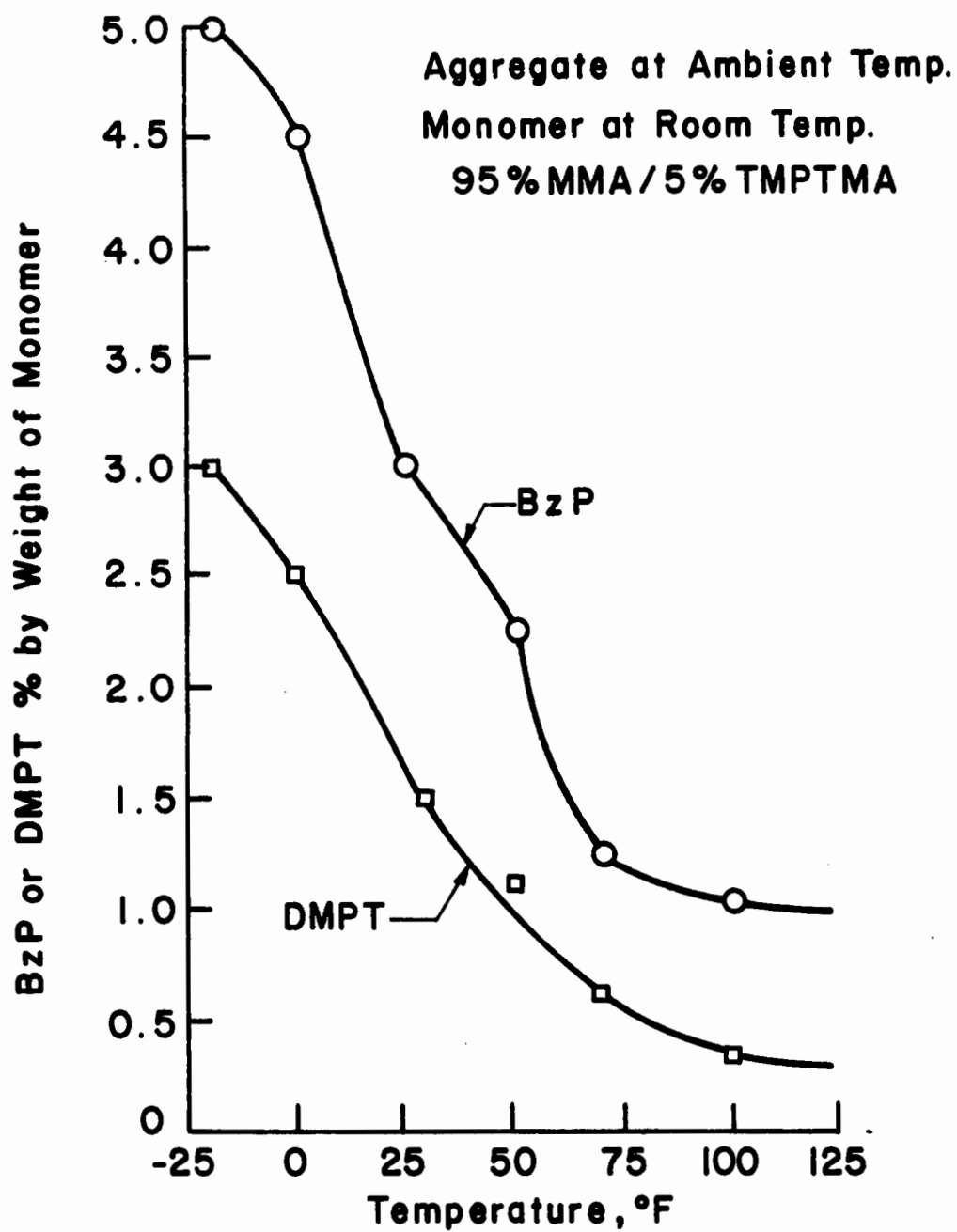


Figure 4.1. Required Levels of BzP and DMT for Curing With All Materials at Ambient Temperature.

be added. Find the required amount of initiator. Assume an ambient temperature of 75°F.

1. Determine amount of DMT required for 75°F. From Figure 4.1, use ~0.60 percent.
2. Determine volume of MMA, TMPTMA and DMT to produce 55 gallons of monomer. (The BzP is added later). Note that the volume percent is not the same as weight percent since the specific gravities (SG) of the components are not equal.

Component	SG	Weight Percent, (WP)	$\frac{WP}{SG}$	Volume Percent (VP) ^a	Total Volume, gallons ^b
MMA	0.95	95	100.00	94.90	52.20
TMPTMA	1.06	5	4.72	4.48	2.46
DMT	0.925	0.6	<u>0.65</u>	.616	0.34
Sum (A) 105.37					

$$^a \text{volume percent (VP)} = \frac{WP/SG}{\text{Sum (A)}} \times 100$$

$$^b \text{total volume} = \frac{55 \text{ gallons} \times VP}{100}$$

Component	Weight Percent, (WP)	Percent of Total Weight ^c
MMA	95	94.43
TMPTMA	5	4.97
DMT	<u>0.6</u>	0.60
Sum (B) = 100.6		

$$^c \text{percent of total weight} = \frac{\text{weight percent}}{\text{sum (B)}} = 100$$

3. Determine the amount of BzP to be added to 55 gallons of monomer. Assume 40 percent dispersion.
From Figure 4.1, use 1.25 percent.

Component	SG	Total Volume gallons ^d	Weight pounds ^e
MMA	0.95	52.20	413.0
TMPTMA	1.06	2.46	21.7
Sum (C) =			434.7

^d from previous table

^e weight = total volume x SG x 8.33 lbs/gal

Weight of BzP = Sum (C) x $\frac{1.25}{100}$ = 434.7 x 0.0125

Weight of 40-percent dispersion = $\frac{5.43}{0.40}$ = 13.58 pounds

4.2 Sources and Costs of Chemicals^f

1. MMA, (METHYL METHACRYLATE) WITH MEHQ @ 10 PPM

SOURCE	PRICE (PER POUND)	
	No. of Drums	Price
1. Rohm and Haas Company	30-53	0.67
	15-29	0.68
	5-14	0.69
	3- 4	0.71
	1- 2	0.73
2. E.I. DuPont de Nemours & Co., Inc.	30-53	0.67
	15-29	0.68
	5-14	0.69
	3- 4	0.71
	1- 2	0.77

^f Complete addresses and phone numbers of each chemical supplier are listed in alphabetical order at end of pricing pages. Costs are for November 1981.

	PRICE (PER POUND)	
	No. of Drums	Price
3. American Cyanamid	30-53	0.67
	15-29	0.67
	5-14	0.68
	3- 4	0.72
	1- 2	0.72
2. TMPTMA, (TRIMETHOLPROPANE TRIMETHACRYLATE)		
WITH HQ 100 PPM		

SOURCE	PRICE (PER POUND)	
	No. of Drums	Price
1. Rohm and Haas Company	10	1.78
Product Name:	4- 9	1.83
"Rocryl X-980"®	1- 3	1.88
	5 gal	3.00
2. Sartomer Company	10	1.83
Product Name: SR-350®	4- 9	1.88
	1- 3	1.93
	44	1.75
	30	31
3. Ware Chemical Company	10	1.79
Product Name: "Chemlink 30"®	4- 9	1.83
"Chemlink 31"®	1- 3	1.88
	1 5-gal	2.88
	pail	2.80

3. BENZOYL PEROXIDE (BzP, BPO)		
SOURCE	PRICE (PER POUND)	
	No. of Drums	Price
1. U.S. Peroxygen,	225 lb drum	2.08
Div. of Witco Chem. Co.	380 lb drum	N.A.
		in this size
2. Reichhold Chemical Company	less than 10	
Product Code Name:	pails	2.02
"46-742 or Superox 742"®	more than 10	
	pails	1.97
3. Noury Chemical Corporation	more than 500	
Product Notation: "40E"®	lb	2.30
	less than 500	
	lb	2.55
4. Lucidol, Div. of	more than 500	
Pennwalt Corp.	lb	2.79
Product Name: "Lubricol"®	less than 500	
	lb	3.07

		PRICE (PER POUND)	
		<u>No. of Drums</u>	<u>Price</u>
4.	Norac Company (only recommended type for pumping)		
4.	PMMA (POLYMETHYLMETHACRYLATE, POWDER)		
<u>SOURCE</u>		PRICE (PER POUND)	
		<u>No. of Drums</u>	<u>Price</u>
1.	E.I. DuPont de Nemours & Co.	CRYLCON EP 4160	
		2000-4999 lb	1.42
		1000-1999 lb	1.44
		220- 999 lb	1.51
		- 50 lb	1.70
5.	DMPT (DIMETHYL PARATOLUIDINE)		
<u>SOURCE</u>		PRICE (PER POUND)	
		<u>No. of Drums</u>	<u>Price</u>
1.	RSA Corporation	1 qt	15.00
		1 gal (7.5 lb)	50.00
		5 gal (38 lb)	5.00
		1 415 lb drum	3.80
6.	PREPACKAGED CONCRETE SYSTEMS (POLYMER CONCRETE)		
A.	E.I. DuPont de Nemours and Company, Inc.		
		PRICE (PER POUND)	
		<u>Quantity</u>	<u>Price</u>
DuPont Liquid Component Monomers		10-79 cases	1.34
Product Designation:		3- 9 cases	1.35
3009 and 3010 (Crylcon®)		1- 2 cases	1.36
DuPont Liquid Component Primers		10-79 cases	1.34
Product Designation:		3- 9 cases	1.35
3039 and 3040 (Crylcon®)		1- 2 cases	1.36
DuPont Component (50% BPO Powder)		5000-24000 lb	1.33
Product Designation:		2000- 4999 lb	1.34
3045 (Crylcon®)		1000- 1999 lb	1.36
		200- 999 lb	1.40
		50- 199 lb	1.50

	PRICE (PER POUND)	
	<u>Quantity</u>	<u>Price</u>
DuPont Component (50% BPO Powder)	0- 500 lb	7.50
	500 or more lb	4.70
Product Designation: 3045 (Crylcon®)		

may be replaced with liquid 40% dispersions of BPO at a 120% of the wt basis of Crylcon 3045^R

B. Silikal of North America, Inc.

Type R7 - High Strength Overlay PC
 Type R8 - Industrial Acid Resistant Floor PC
 Type R9 - Thixotropic Vertical Application PC
 Type R17 - General Patching PC (Surfaces Similar Concrete)

All materials approximately \$0.50 - \$1.00/lb.

7. Mold Release Agents

Source

1. Axel Plastics Research Laboratories, Inc.
 Product Name: Mold-Wiz F-57®
 Buffered Fluorocarbon
2. LPS Research Laboratories, Inc.
 Product: Spray Lubricant
 LPS-3 or LPS-7®

ALPHABETICAL LISTING OF CHEMICAL SUPPLIERS

AMERICAN CYANAMID COMPANY
 Organic Chemical Division
 Bound Brook, NJ 08805

Mike Taleho, Sales
 Jim Dusbacky, Technical
 Representative
 Phone: 201/356-2000

AXEL PLASTICS RESEARCH LABORATORIES, INC.
 P.O. Box 858
 58-20 Broadway
 Woodside, NY 11377

Phone: 212/672-8300

CELANESE CHEMICAL COMPANY
 P.O. Box 937
 Pampa, TX 79065

Joyce Spong
 Houston Representative
 Phone: 712/621-8400

E.I. DUPONT DE NEMOURS AND COMPANY, INC.

Polymer Products Division
Chestnut Run
Wilmington, DE 19898

Bob Feild, Representative
Phone: 302/999-3887

LPS RESEARCH LABORATORIES, INC.

Los Angeles, CA 90025

LUCIDOL, DIVISION PENNWALT CORPORATION

1740 Military Road
Buffalo, NY 14240

Doug Bolton or Judy Midreal
Phone: 716/877-1740

NORAC COMPANY

405 South Motor Avenue
Azusa, CA 91702

Phone: 213/334-2908

NOURY CHEMICAL CORPORATION

Burt, New York 14028

Dotty Kendrick or
Bob Markevich
Phone: 716/778-8554

REICHOLD CHEMICALS, INC.

2601 Reichhold Road
P.O. Box 9405
Austin, TX 78766

Kathryn Gann
Phone: 512/836-1426

ROHM AND HAAS COMPANY

Independence Mall West
Philadelphia, PA 19105

Dorothy Dondici
Phone: 215/592-3236

SARTOMER COMPANY

Bolmar and Nields Street
Westchester, PA 19380

Charles Demos
Phone: 215/692-8400

SILIKAL OF NORTH AMERICA, INC.

305 Orange Street
Bridgeport, CT 06607

Manfred Grove
Phone: 203/333-1013

U.S. PEROXYGEN, DIVISION OF
WITCO CHEMICAL CORPORATION

850 Morton Avenue
Richmond, CA 94804

Nancy Bentson
Phone: 415/233-5911

R.S.A. CORPORATION

690 Saw Mill River Road
Ardsley, NY 10502

Elisabeth Anthony
Phone: 914/693-1818
914/693-2493

WARE CHEMICAL COMPANY

1525 Stratford Avenue
P.O. Box 262
Stratford, CT 06497

Kate Stewart
Phone: 203/377-5550

5.0 MIXING OR BATCHING PC

5.1 Introduction

Two methods are proposed for mixing or batching PC. The in-line mixing system is proposed for deep and shallow spalls. The mobile concrete batching facility, e.g., modified Concrete Mobile[®], is proposed for crater repairs. This chapter contains instructions for the use of this equipment.

5.2 In-Line Mixing System

The in-line mixing system permits better control of curing rates for PC since the flow rate of BzP and DMT can be easily adjusted. Because the chemicals are mixed at the gun head and immediately injected, there is no waste due to excess monomer being batched. The clean-up is minimal with only a 60-second flushing with methylene chloride.

The primary disadvantage is that when monomer is injected at maximum flow rates, there is a tendency to segregate the fine and coarse aggregate at the nozzle. It is recommended that two or more guns be connected to each pump to reduce the monomer flow from each gun.

5.2.1 Set-Up Instructions

1. Fill pump-well with 30W motor oil.
2. Fill flush tank with MeCl.
3. Turn on air compressor and regulate operating pressure to under 120 psi.
4. Regulate air pressure to 60 psi to flush tank.
5. Fill holding tank with MMA and TMPTMA.
6. Open valve at bottom of monomer holding tank and turn on monomer pump.
7. Pull gun trigger until monomer shoots out of gun.
8. Flush for 2 seconds with MeCl.

9. Insert DMT pump inlet hose into DMT and hand-operate pump until DMT can be seen in the accumulator tube.
10. Install DMPT slave pump onto slave at correct position for proper percentage (from temperature curves).
11. Insert BzP pump inlet hose into BzP dispersion and prime pump with gun trigger pulled until dispersion runs out of end of gun. Then release gun trigger.
12. Flush gun with MeCL for 5 seconds.
13. Install BzP pump into correct position on the monomer pump slave arm for proper percentage according to the ambient temperature.
14. Connect gun to spray bar or injector nozzle.
15. System is ready for use.

5.2.2 Repair Procedure

1. After spalls are filled with aggregate, place the gun nozzle into the aggregate and inject monomer into the bottom of the repair until monomer is ponded on the surface.
2. Screed surface.
3. Broadcast sand on the surface where monomer has ponded.

5.2.3 Cleanup

1. When gun is not used for more than 3 minutes, flush gun with MeCl for 30 seconds to prevent polymerization of monomer which would clog the mixing nozzle.
2. When the repairs are finished, flush the monomer lines and tank and BzP lines out with MeCl and then fill with a suitable inert plasticizer such as DBP, DOP or DIOP.

5.3 Mobile Concrete Batching Unit (Modified Concrete Mobile[®])

The modified Concrete Mobile[®] (CM) can be used for either contractor-formulated PC or for commercially available PC, e.g., Silikal[®] or Crylcon[®]. The use of commercially available PC will be described. The advantage of the CM is that it produces up to 60 cubic yards per hour with uniform consistency and with a batching time of less than 1 hour. The batching is continuous. However, large volume repairs require that the component materials must be supplied rapidly.

5.3.1 Setup Instructions

1. Fill sand bin with gray powder component.
2. Fill stone bin with coarse aggregate.
3. Fill monomer tank with monomer system including any extra promoter, if necessary for cold temperature conditions.
4. Fill flush tank with MeCl.
5. Set sand bin gate (for gray powder) at 12.3.
6. Set cement meter counter for 57.

5.3.2 Operation of CM

1. Start up CM. Check tachometer to be certain that CM is operating at RPM suggested by manufacturer.
2. Start main conveyor; after a few seconds, start mix conveyor.
3. Be certain mixer auger bypass valve is closed.
4. Set monomer valve (fluid dial) to 14.
5. Increase angle of mixing auger chute to insure best mixing and smooth delivery.
6. Refill aggregate and powder bins and monomer tank as required.
7. Turn off conveyor when materials are expended or when repair is completed.

5.3.3 Cleanup

Flush mixing compartment and chute with MeCl immediately. Do not flush with MMA.

6.0 REPAIR METHODS

6.1 Spall Repairs (Figure 6.1)

Spalls which do not penetrate the existing pavement layers can be most rapidly repaired using the in-line mixing system with several guns. The procedure is outlined as follows:

1. Remove standing water, if present.
NOTE: Debris need not be removed unless it contains large chunks of asphalt.
2. Place 50:50 sand-gravel mixture in repair until level with pavement surface grade.
3. Push in-line mixing gun into surface and fill spall with polymer mixture.
4. Add sand and PMMA to surface and strike off level with pavement surface grade.

6.1.1 Alternative Method (Modified Concrete Mobile®)

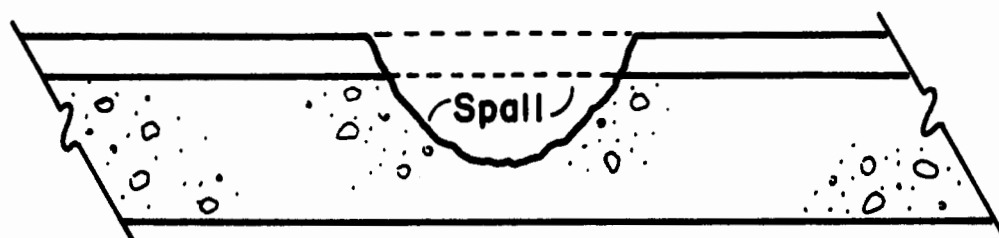
1. Remove standing water, if present.
2. Fill spall with PC; some vibration or rodding will be necessary to completely fill void.
3. Strike off level with pavement surface grade.

6.2 Crater Repairs

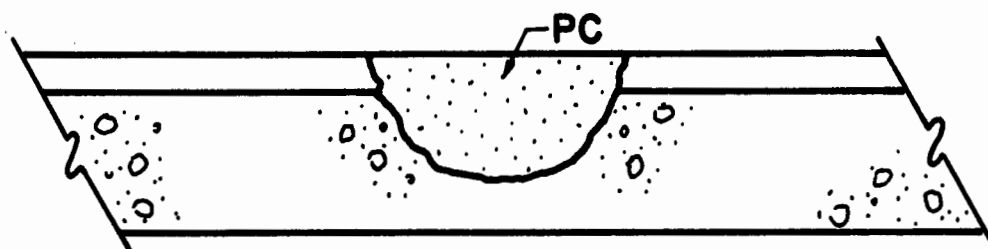
When the crater penetrates the existing pavement layers into the subgrade, two methods of repair are proposed.

6.2.1 Cap Method (Figure 6.2)

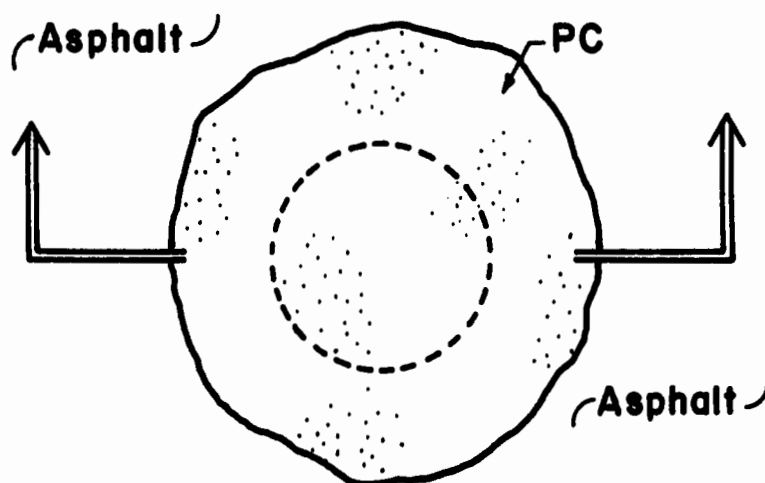
1. Place debris or fill material to within T plus 2 in. (Figure 6.2) of the existing pavement surface grade. Some attempt should be made to minimize large voids in the fill section.
2. A 2-in sand level-up layer will provide a more uniform thickness of the PC surface layer. However, the level-up layer is not necessary for the adequacy of the repair.



Section Before Repair



Section After Repair



Plan View After Repair

Figure 6.1. Typical Spall Repair.

T = Thickness Determined by
Design

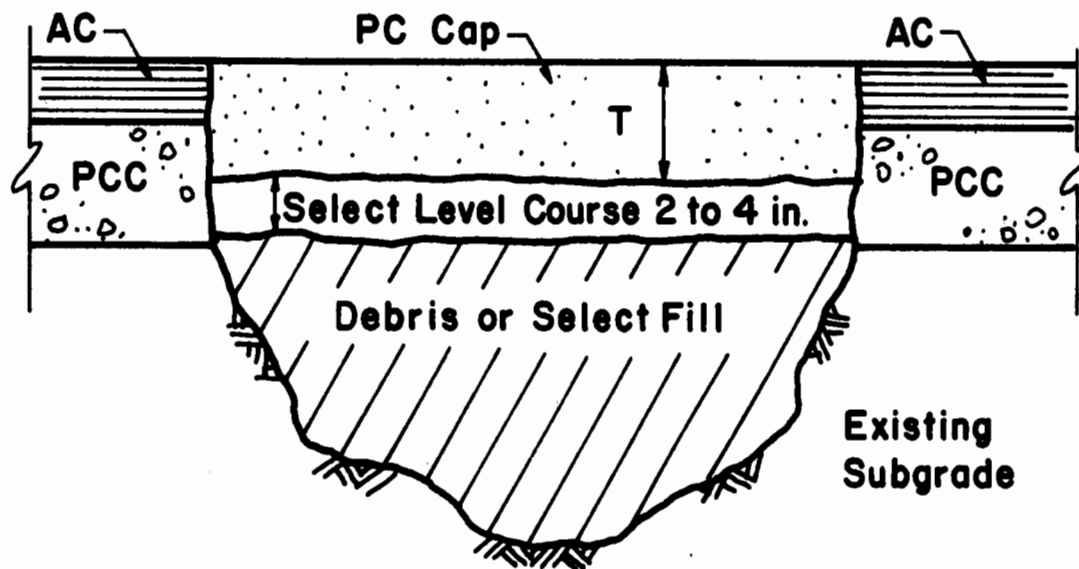


Figure 6.2. Typical Cross Section of Small
Crater Repair - Cap Method.

3. Place PC using Concrete Mobile[®] to level with pavement surface grade.
4. Strike off using metal screed.

NOTE: If sand level-up layer is used, PC cap must be at least T-in thick. If sand layer is not used, the PC cap should average T plus 2 in in thickness with no section less than T-in thick.

6.2.2 Precast Method (Figure 6.3)

1. Place debris or fill material to within 16 to 20 in of the existing pavement surface grade. This assumes that the precast slabs are 12 in thick.
2. Place a 2-in thick sand layer to provide seating for the precast slabs.
3. Place precast slabs with a 4- to 8-in gap between slabs.
4. Place PC using Concrete Mobile[®]. Some vibration or rodding may be necessary to completely fill gaps between precast slabs.
5. Cover precast slabs with PC to level off pavement surface grade and strike off with metal screed.

NOTE: A minimum of 2 in of cover is required over the precast slabs.

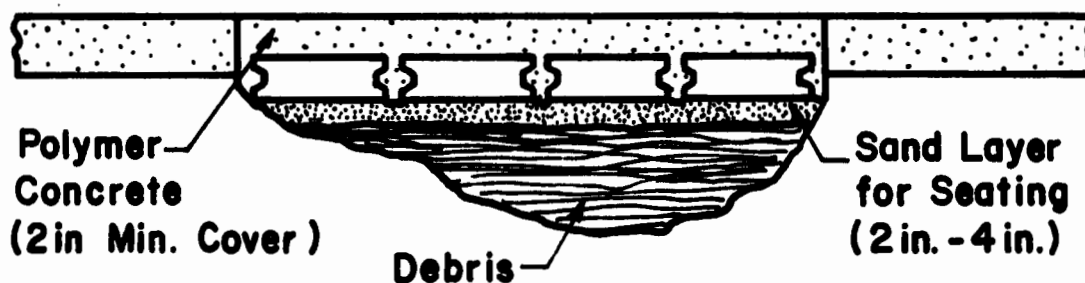
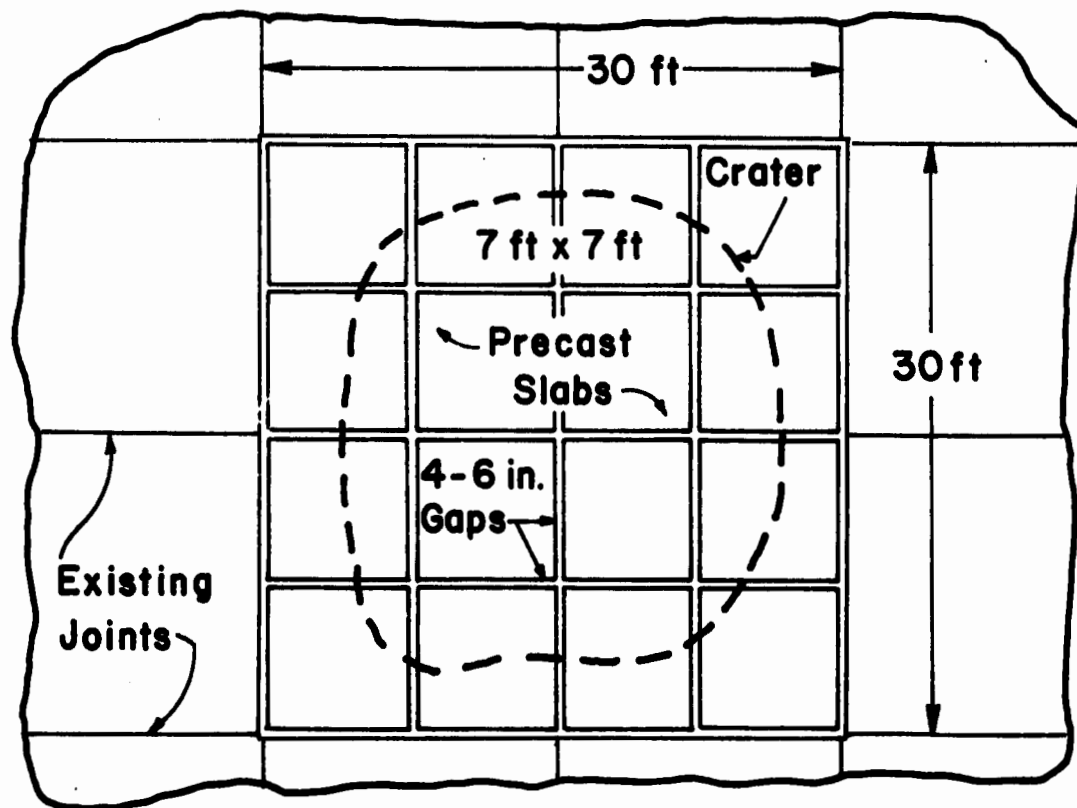


Figure 6.3. Precast Repair for Crater.

7.0 SAFETY AND HANDLING

7.1 Introduction

The chemicals used in making polymer concrete require careful attention to safety and handling. Most of the chemicals are at least mildly toxic and flammable, but, with proper safety and handling, these materials can be used safely.

Education of personnel using or handling the chemicals should be an integral part of the training program. All personnel who are engaged in either handling or applying the chemicals should be thoroughly and regularly briefed on the handling of the chemicals, the use of safety equipment, fire prevention, fire control and first aid procedures. Only essential personnel should handle the chemicals, and safety equipment should be readily available and in proper condition.

7.2 Physiological Effects and Safety

Table 7.1 summarizes the symptoms and first aid requirements for the chemicals used in producing PC. Medical personnel should become familiar with the chemicals used so that in the event of an emergency, no time is lost in treating injured workers.

Safety equipment should include protective clothing such as splash-proof safety goggles, impervious and flame-resistant aprons, gloves and boots. Where ventilation is poor and/or where monomer vapor concentrations are high, organic vapor respirators should be used.

Any skin contact with the chemicals, especially DMPT, should be avoided. If a splash or spill should result in some chemicals making contact with the skin, the area should be washed immediately for 15 minutes with clean water, after which medical assistance should be obtained. A portable eyewash station is recommended at all storage and application sites.

Excessive MMA and DMT vapor concentrations should be avoided. The Occupational Safety and Health Administration (OSHA) has specified a limit, based on an 8-hour timeweighted

TABLE 7.1 PHYSIOLOGICAL EFFECTS AND PROTECTIVE MEASURES.

MMA	Skin Contact	Eye Contact	Inhalation	Ingestion
Symptom	Can cause mild irritation or rash. Possible sensitizer.	Burning sensation; extreme cases can cause corneal damage.	Irritating smell at very low levels becoming painful to eyes, ears, nose, and throat at higher levels. Headache may result from long exposure. OSHA specifies exposure limit of 100 ppm for 8-hour time weighted average.	Dermatitis and narcosis may develop.
First Aid	Wash thoroughly with soap and water.	Flush eyes immediately with water for 15 minutes. Seek medical assistance.	Remove person to fresh air; apply artificial respiration in extreme cases.	Induce vomiting; obtain medical attention.
Protective Measures	Wear impervious gloves, boots, aprons.	Wear splash-proof goggles; have eyewash nearby.	Provide adequate ventilation in closed spaces. Wear organic respirators.	

TABLE 7.1 PHYSIOLOGICAL EFFECTS AND PROTECTIVE MEASURES. (continued)

TMPTMA	Skin Contact	Eye Contact	Inhalation	Ingestion
	Not as irritating as MMA, but similar precautions should be taken.	Less irritating than MMA; but similar precautions should be taken.	Low volatility; no special ventilation or respirators required.	Similar to MMA.
<u>DMT</u> Sympton	Very toxic, easily absorbed through skin. Symptoms include nausea, dizziness, weakness and cyanosis.	Same as for skin.	Vapors toxic; cyanosis symptoms.	Very toxic.
First Aid	Immediately wash affected area with soap and water; remove contaminated clothing.		Remove to fresh air. Use artificial respiration for troubled breathing.	Induce vomiting.
Protective Measures	Wear impervious gloves, boots, and apron.	Wear splash-proof goggles.		
<u>BzP</u> Sympton	Mild irritant.	Mild irritant.	No problem with liquid dispersion.	Not particularly toxic.
First Aid	Wash well with soap and water.	Flush eyes with water for 15 minutes. Seek medical attention.		Induce vomiting.

average, of 100 parts per million (ppm) although few workers could probably comfortably endure such a high concentration for very long since less than 1 ppm can be detected by many people.

Headaches sometimes result from lengthy exposure. If over-exposure occurs, the person should be removed to fresh air. Artificial respiration should be administered in severe cases.

Should any of the chemicals be accidentally swallowed, vomiting should be induced and medical attention should be obtained immediately.

7.3 Flammability and Fire Protection

Table 7.2 summarizes fire protection and flammability. All of the chemicals, especially MMA and BzP, are flammable, similar to gasoline. Therefore, all open flame, sparks, or other sources of ignition, including cigarettes, should be kept at least 50 feet from any of the chemicals in open areas and not allowed in enclosed areas.

Contamination should be avoided. Direct contamination of BzP with concentrated DMPT could easily generate enough heat and flammable gases to start a fire; hence, both of those must be stored or handled separately. When mixing the monomer for polymerization, the DMPT should be mixed into the MMA/TMPTMA solution thoroughly before any BzP is mixed in.

Other fire prevention measures include grounding all metal storage and mixing containers, and posting "no smoking" signs at storage and preparation sites. Fire extinguishers should be dry chemical, foam or carbon dioxide types and should be on hand wherever the chemicals are stored or used.

7.4 Storage and Handling

Although safety in handling has been emphasized, careful storage practices are also necessary. Because of the flammability of the chemicals, several precautions should be apparent. Table 7.3 summarizes flammability and fire protection requirements.

TABLE 7.2 FLAMMABILITY AND PRECAUTIONS.

MMA

1. Very flammable; similar to gasoline.
2. Avoid heat, flame, or sparks.
3. Extinguish fire with CO₂, dry chemicals, or foam.
4. Cool heated drums with cold water spray.
5. Avoid contamination with BzP until ready for field application.
6. Wear breathing apparatus when fighting MMA fire.

TMPTMA

1. Flammable.
2. Avoid heat, flame, or sparks.
3. Extinguish fire with CO₂, dry chemicals, or foam.
4. Cool heated drums with cold water spray.
5. Avoid contamination with peroxides, oxidizing agents, iron rust, strong bases.
6. Carbon monoxide and carbon dioxide are products of decomposition.

BzP

1. Flammable; burns vigorously, difficult to extinguish.
2. Avoid heat, flame or sparks.
3. Extinguish fire from a distance with water, CO₂, dry chemicals, or foam.
4. Cool heated drums with cold water spray.
5. Avoid contamination with acids, DMT, and other reducing agents, most metals or other oxidizing agents.
6. Diphenyl (white smoke) byproduct of flameless decomposition from chemical contamination. Diphenyl is toxic and extremely flammable gas.
7. Evacuate personnel from immediate area of fire.

TABLE 7.2 FLAMMABILITY AND PRECAUTIONS (Continued).

DMT

1. Flammable
2. Avoid heat, flame, or sparks.
3. Extinguish fire from a distance with water, CO₂, dry chemicals, or foam.
4. Cool heated drums with cold water spray.
5. Avoid contamination with oxidizing agents, especially BzP in bulk.
6. Wear self-contained breathing apparatus when fighting DMT fire.

TABLE 7.3 STORAGE REQUIREMENTS.

MMA	1. Keep away from sources of heat, sparks, or direct sunlight. 2. Ground all handling equipment. 3. Store between 60 and 80°F. 4. Check inhibitor level once each year to maintain minimum of 10 ppm MEHQ. 5. Prevent storage drums or containers from corroding. 6. Ventilate storage area.
TMPTMA	Same as MMA except maintain minimum of 100 ppm of MEHQ.
BzP	Same as MMA except: 1. Never store in metal or glass containers. 2. For best results, use in 12 months or less. 3. Never store near DMT since contact in bulk can cause fire or explosion. 4. Store at 70°F or below.
DMT	Same as MMA. Do not permit contact with BzP in bulk.

All chemicals should be stored in tightly closed containers, preferably the original shipping containers. These containers should be kept clean and dry and clearly labeled to avoid any contamination with other chemicals. Storage of all chemicals should be at temperatures not less than 60°F to insure fast setting times in cold weather.

It is extremely important to store and handle the BzP separate from the DMPT. Otherwise, any accidental leakage or spillage could cause a fire.

Monomers must also have special considerations regarding storage. Because of their natural tendency to polymerize, inhibitors must be added by the manufacturers prior to shipping to insure longer predictable shelf life. During storage of the MMA or TMPTMA, the inhibitor is slowly used up and will then auto polymerize with the accompanying temperature and vapor pressure build up in the closed container. Eventually, this could cause the drum to burst. As long as MMA has 10 parts of MEHQ per million added to it and is stored at or below 75°F (25°C), it should remain in good condition for 2 or 3 years. TMPTMA needs 100 parts MEHQ per million at the 75°F storage temperature to remain stable. At least once each 6 months, the inhibitor levels should be checked.

When initiator is added to monomer, it speeds up the neutralization of the inhibitor and actually accelerates the natural polymerization process. For this reason, initiated monomer (monomer containing BzP) should never be stored.

Direct sunlight or higher ambient temperatures could cause autopolymerization of the monomers in the drums and should be avoided.

When chemicals have been spilled or have leaked, proper disposal methods must be followed. The first step is to absorb the chemical into a large quantity of sand or clay or any other nonflammable absorbent. The contaminated absorbent is then placed into a large strong plastic bag. (In the case of very large spills, the contaminated material should be placed into an

open pit). Then wet the contaminated absorbent with water and bury it in an acceptable dump or land fill area.

Excess initiated monomer should be promoted with DMT and made into polymer concrete by adding sand and allowing the mixture to cure before disposing in a land fill. Full or partial drums of MMA can be disposed of by adding initiator and promoter according to Table 4.1 and pouring it into aggregate-filled drums or other containers.

Empty chemical containers must not be reused. Empty containers are likely to become contaminated and filled with potentially explosive mixtures of air and heavy chemical vapors. Under no circumstances should the tops be cut off the drums since sparks or heat from any cutting process could ignite the vapors in the drum, causing an explosion.

ANNEX TO THE APPENDIX

DETERMINATION OF INHIBITOR CONCENTRATION IN MONOMERS BY THE PEAK EXOTHERM METHOD^a

A. Introduction

This method is applicable to most inhibitor-monomer systems; however, a calibration curve must be made for each system. The only time where an actual inhibitor concentration determination cannot be made is with a mixed monomer system. In this case, since there are two inhibitors, the peak exotherm method cannot distinguish between the two and therefore only a comparison to the original peak exotherm time can be made. An increase of time tells one that the monomer system is more stable than it was originally and a decrease in time means that the system is less stable.

A detailed description will be given for the measurement of hydroquinone (HQ) in methyl methacrylate (MMA) and this procedure can be applied to other inhibitor-monomer systems such as methyl ester of hydroquinone (MEHQ).

B. Equipment and Reagents

The following equipment is required for the determination of inhibitor concentrations:

1. Temperature bath: e.g., Lauda K 2/R with 0° - 100°C regulator or equivalent.
2. Recorder using J thermocouple to measure 0° to 250°C $\pm 0.1^\circ\text{C}$.
3. Test tubes (16 mm x 150 mm).
4. Thermocouple wells (3 mm x 150 mm).
5. Purified hydroquinone with melting point of 171° to 173°C.
6. Hydroquinone-free methyl methacrylate (Section 6).

^aAdapted from a report by J. Fontana and P. Colombo, Department of Applied Science, Brookhaven National Laboratory, Upton, NY.

C. Procedure for Preparation of HQ Free Material

Using a 500 ml separatory funnel, extract the required amount of water insoluble inhibited MMA with successive amounts of 15 wt % sodium hydroxide solution containing 10 wt % sodium chloride. Use a ratio of 5 parts by volume of monomer to 1 part of caustic solution. Continue the extraction until the caustic layer (lower portion of separatory funnel) is practically colorless; then wash with distilled water until the final water wash, when tested with phenolphthalein paper, is neutral. The extracted material is then dried over anhydrous sodium sulfate or silica gel until clear and finally filtered. The uninhibited monomer is stored in a brown bottle, having a screw top with an aluminum foil liner, under refrigeration until it is ready to be used. The monomer can generally be stored under refrigeration for 90 days. However, before it is used in this procedure, a few drops should be added to 100 cc of methyl alcohol. If any precipitate is seen, the monomer should be discarded and a fresh batch should be made.

D. Procedure

1. Using HQ-free monomer, make solutions containing 15, 30, 45, 60, 75 ppm by weight of hydroquinone (or MEHQ).

Example:

100.0 gm of HQ-free methyl methacrylate

0.003 gm of Hydroquinone

$$\frac{0.003}{100.3} = \frac{30}{10^6} = 30 \text{ ppm hydroquinone}$$

2. Transfer 10 gm of monomer with a known quantity of inhibitor to a 16 x 150 mm test tube and add 1 percent by weight (0.10 gm) of benzoyl peroxide. Shake vigorously until the peroxide is completely in solution.
3. Place the "J" thermocouple from the temperature recorder into the glass thermocouple well. Push the glass thermocouple well through a rubber stopper that will fit

- the top of the test tube containing the MMA. Let the thermocouple well submerge into the liquid halfway.
4. Start the recorder and then place the test tube containing the monomer and thermocouple into the temperature bath which has been set at 70°C.
 5. On the temperature recorder chart paper, mark the point of test tube insertion into the temperature bath. Allow the run to continue past the point that the peak exotherm occurs. This is the point where monomer polymerization takes place.
 6. Measure the time in minutes from the initial insertion into the temperature bath to the point of the peak exotherm as shown in Figure A.1.
 7. Measure the peak exotherms for all the concentrations of hydroquinone previously mentioned.
 8. Plot the inhibitor concentration in ppm on the abscissa vs the time of peak exotherm in minutes as the ordinate. The resulting curve should be a straight line through the plotted points. This is the calibration curve for hydroquinone in methyl methacrylate. Figure A.2 is a calibration curve for the determination of hydroquinone in methyl methacrylate.
 9. A sample containing an unknown quantity of hydroquinone can be checked by adding the benzoyl peroxide and then measuring its peak exotherm time. Read the inhibitor concentration from the intersection of the peak exotherm time of the unknown with the calibration curve.

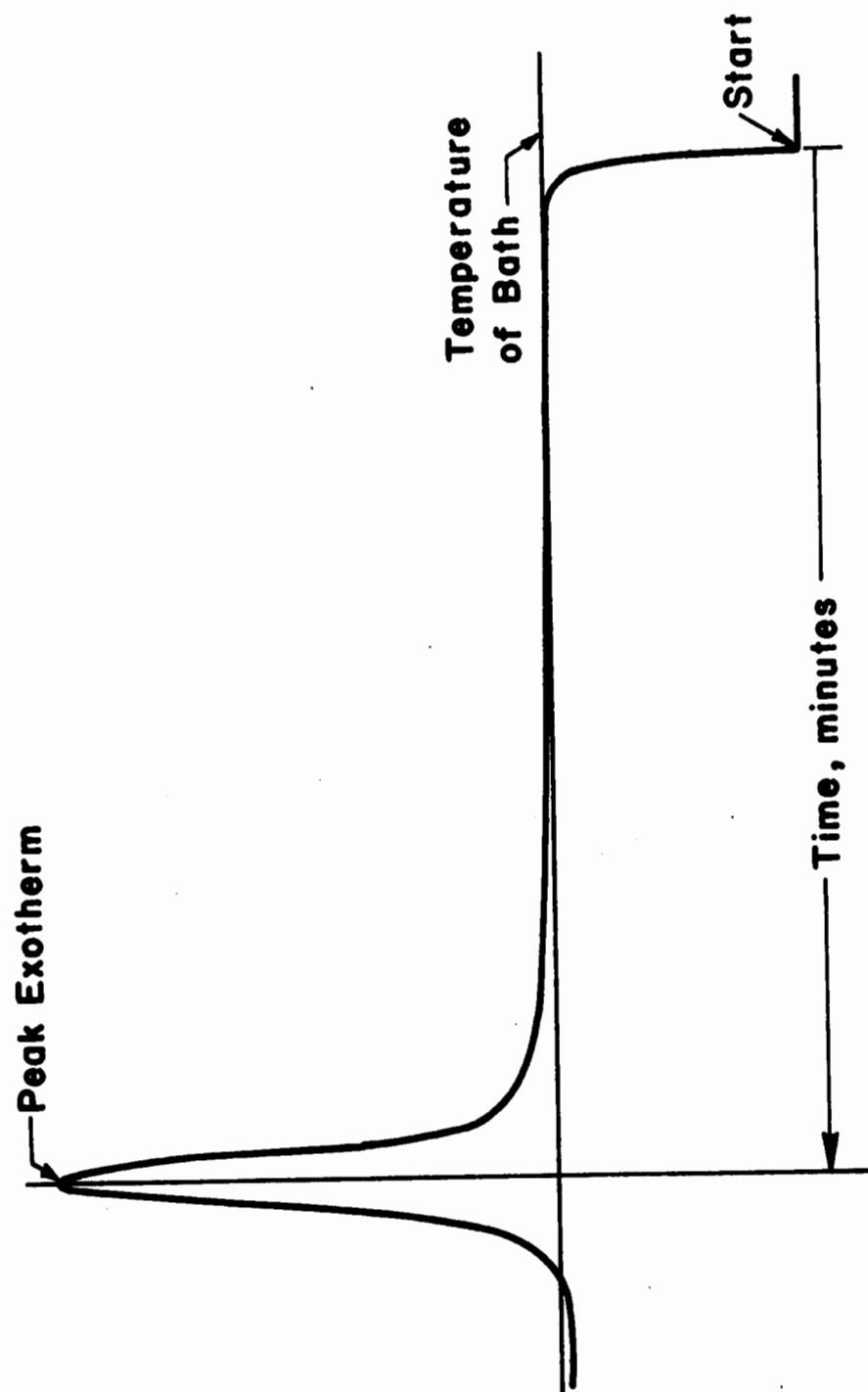


Figure A.1. Exotherm Versus Time for MMA With
1 percent BzP at 70°C.

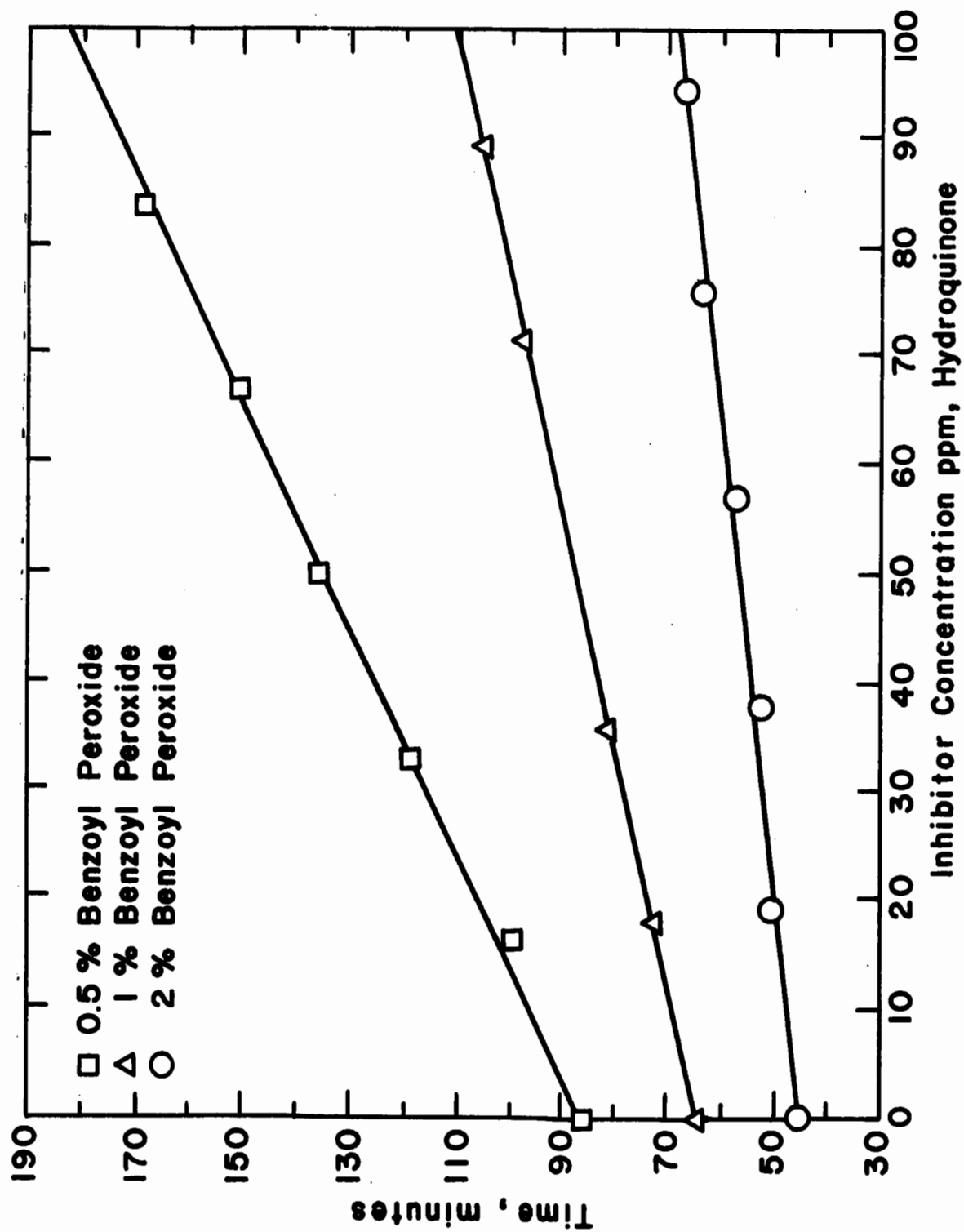


Figure A.2. Time to Peak Exotherm Versus Inhibitor Concentration for 70°C.

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