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16. Abstract

An investigation was made to determine the feasibility of using a polymer-concrete (PC) overlay to improve the durability of a bridge by sealing the concrete against water penetration. The overlay consisted of a thin (approximately 0.5-in.) layer of polymer and aggregate. Fine aggregate was placed to a depth of 1/4 in., and 3/8-in.-maximum-size aggregate was placed and rolled into the sand. Two monomer applications were made. Durability tests, which included freeze-thaw cycling, water tightness, sandblast abrasion, and skid resistance testing, were performed on both treated and untreated slabs.

The 24-hour water tightness test showed that the PC overlay could completely seal the concrete against water penetration, while the control specimens had about 2 in. to 2.5 in. (51 mm to 64 mm) of water penetration. The PC overlay proved to be more resistant than the control when subjected to the sandblast abrasion, especially after freeze-thaw cycling. Because the surfaces were sealed against water penetration, the PC overlay specimens showed a greater freeze-thaw durability than the controls, by a factor of at least two. Also, the PC overlay showed a better skid resistance than the control.

A field application of PC overlay was performed successfully on a bridge deck, which demonstrated the feasibility and practicality of using PC overlay.

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AN INVESTIGATION OF THE USE OF POLYMER-CONCRETE OVERLAYS FOR BRIDGE DECKS

by

Huey-Tsann Hsu
David W. Fowler
Mickey Miller
Donald R. Paul

Research Report Number 114-7

Polymer-Impregnated Concrete for Highway Applications
Research Project 3-9-71-114

conducted for

State Department of Highways and Public Transportation

in cooperation with the
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Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

March 1979

PREFACE

The authors are indebted to Frank Craig of District 3 for suggesting the idea for a polymer concrete overlay and for providing advice on the requirements. The cooperation of Robert H. Schleider, Jr., District Engineer, in providing a bridge deck on which the overlay could be demonstrated is also greatly appreciated.

The advice and cooperation of John Nixon, T.R. Kennedy, Ralph Banks, Donald O'Connor, and Andy Seely of the Department of Highways and Public Transportation and John Nichols of the Federal Highway Administration are gratefully acknowledged. Valuable assistance in the laboratory was provided by Mustafa Haddad, Amin Gobril, and Steve Summey. Valuable assistance was provided by Art Frakes who edited the report and Nancy Zett who typed and assembled the report.

Michael Hsu
David W. Fowler
Mickey Miller
Donald R. Paul

ABSTRACT

An investigation was made to determine the feasibility of using a polymer-concrete (PC) overlay to improve the durability of a bridge by sealing the concrete against water penetration. The overlay consisted of a thin (approximately 0.5-in.) layer of polymer and aggregate. Fine aggregate was placed to a depth of 1/4-in., and 3/8-in.-maximum-size aggregate was placed and rolled into the sand. Two monomer applications were made. The first monomer system consisted of 95 percent methyl methacrylate and 5 percent trimethylolpropane trimethacrylate in addition to accelerator and initiator. The second monomer system, which was placed approximately 30 minutes later, consisted of 48 percent methyl methacrylate, 32 percent methyl methacrylate syrup, 2-1/2 percent trimethylolpropane trimethacrylate, and 17-1/2 percent butyl acrylate (in addition to accelerator and initiator). The initiator and accelerator concentrations used were a function of the ambient temperature. Procedures were developed for laboratory tests and field application. Durability tests, which included freeze-thaw cycling, water tightness, sandblast abrasion, and skid resistance testing, were performed on both treated and untreated slabs.

The 24-hour water tightness test showed that the PC overlay could completely seal the concrete against water penetration, while

the control specimens had about 2-in. to 2.5-in. (51-mm to 64-mm) of water penetration. The PC overlay proved to be more resistant than the control when subjected to the sandblast abrasion, especially after freeze-thaw cycling. Because the surfaces were sealed against water penetration, the PC overlay specimens showed a greater freeze-thaw durability than the controls, by a factor of at least two. Also, the PC overlay showed a better skid resistance than the control.

A field application of PC overlay was performed successfully on a bridge deck at the intersection of U.S. 287 and Texas 148 in Henrietta, Texas, which demonstrated the feasibility and practicality of using PC overlay.

SUMMARY

The need for improved waterproofing of bridge decks has long been recognized. The use of polymer concrete was investigated to determine if a thin overlay was feasible and effective. After extensive laboratory tests, a 3/8 to 1/2-in. (1 to 1.3-cm) overlay was developed that provided an impermeable surface for water, excellent skid resistance, and good shear bond strength. The overlay consists of a thin layer of dry, well-graded concrete sand covered with a layer of 3/8-in. (1-cm) maximum size aggregate which is rolled into the sand with light pressure. A low viscosity monomer solution is sprayed onto the aggregate and allowed to soak for 30 minutes. A second, more viscous monomer solution is then applied and polymerization occurs in ∿30 minutes. An overlay was placed over an entire bridge deck at a cost of \$0.71 per sq ft (\$ 7.64 per sq m) for the chemicals.

Implementation Statement

A thin polymer concrete overlay has been developed for waterproofing bridge decks. The overlay can be applied with minimal equipment requirements and without skilled labor. The materials can be applied by hand. The overlay has been demonstrated on a bridge deck in District 3 at a cost of $0.71 per sq ft ($7.64 per sq m) for chemicals. It is estimated that the direct labor costs would be $0.25 per sq ft ($ 2.67 per sq m) or less. The polymer concrete overlay is ready for implementation and further overlays are planned in District 3.

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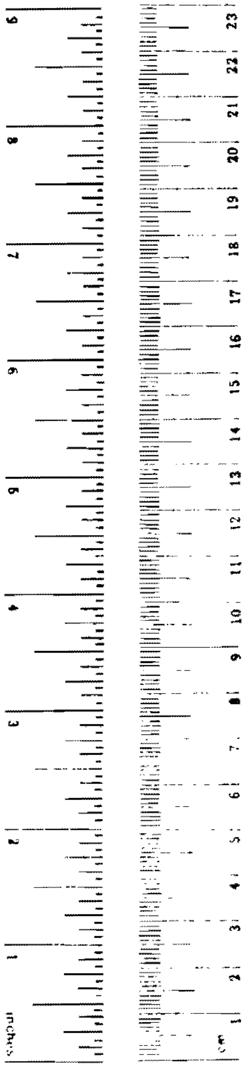
METRIC CONVERSION FACTORS

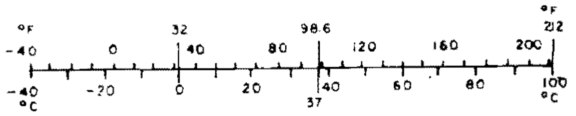
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CHAPTER 1

INTRODUCTION

1.1 Background

Portland cement concrete has long been shown to be an excellent construction material with good compressive strength and low cost. However, its permeability, allowing the intrusion of water and deicing salts, causes problems when it is used in bridge decks. In severe weather conditions, freeze-thaw cycling can cause cracking and spalling of the concrete. The cracking and spalling result in additional intrusion of water and deicing salts and eventually lead to the corrosion of the reinforcing bars. Even without freeze-thaw deterioration, corrosion of the reinforcing bars can occur due to the intrusion of water and salt, which accelerates the spalling and cracking of the portland cement concrete bridge decks and ultimately can result in a threat to the structural integrity of the bridge (21). This rapid deterioration of portland cement concrete bridge decks has become one of the most serious maintenance problems encountered in highway systems. Each year, millions of highway maintenance dollars are spent to repair this deterioration (21, 22, 23). The purpose of this study was to develop a thin layer of polymer-concrete. It was applied to the surface of a portland cement concrete bridge deck to prevent the intrusion of water and deicing salt and increase the durability.

Research on polymers in concrete in the United States was suggested by the United States Bureau of Reclamation (USBR), and began, in 1965, at the Brookhaven National Laboratory (BNL). The early research initially concentrated on bars of mortar and concrete cylinders soaked in monomer and then polymerized with radiation (7, 12, 13, 14, 15, 16). The increased strength and durability of the polymer-impregnated specimens resulted in further research in developing these advantageous properties.

Besides the research conducted by BNL and USBR, several federal and state agencies are currently performing research in concrete-polymer materials (17). The Center for Highway Research at The University of Texas at Austin, with funding provided by The Texas Department of Highways and Public Transportation, has performed considerable research toward improving the durability of bridge decks (2, 9, 18, 19, 20). Techniques for the impregnation of concrete with polymer have been used to treat highway bridge decks, warehouse floors, and the outlet walls and the stilling floors of dams (5, 24, 25). Polymer concrete has been used to repair cracked bridge abutments and badly deteriorated bridge decks (26, 16). All of these field applications show satisfactory results.

1.2 Scope

The investigation reported in this report describes a pilot study to develop the monomer system and application procedure for the polymer-concrete overlay and to evaluate its durability. The main objective of this research was to develop a practical field application procedure for applying the polymer-concrete overlay on the surface of a bridge deck to increase its durability.

Chapter 2 describes the chemicals used in this study and discusses some of the most important factors that influence the success of polymer-concrete (PC) overlays. Also, the application procedures are described.

Chapter 3 describes the tests developed to evaluate the durability of PC overlays.

Chapter 4 describes and discusses the results of the durability tests.

Chapter 5 describes the field work at the Balcones Research Center of The University of Texas at Austin and implementation of the PC overlay on a bridge deck at Henrietta, Texas. Also, the cost and safety are discussed.

Chapter 6 presents the conclusions and recommendations for future studies.

CHAPTER 2

MATERIALS AND APPLICATION PROCEDURES

2.1 Chemicals

Several chemicals are required to produce the polymer-concrete overlay. The most significant chemicals used in this study are described in this section.

2.1.1 Monomers

A monomer is a small molecule which can be chemically linked into a long chain-like structure of high molecular weight, called a polymer (5). Three different monomers were used in this study: methyl methacrylate (MMA), trimethylolpropane trimethacrylate (TMPTMA), and butyl acrylate (BA).

Methyl methacrylate (MMA), a clear, low viscosity monomer, is the basic monomer used in this study. It is easily polymerized at ambient temperatures in the range of 30 to 100°F when combined with initiators, cross-linking agents, and accelerators. After polymerization, it produces a high-strength polymer with excellent durability, at a relatively low cost. This monomer has a low viscosity, lower than water, well suited for penetration into the concrete.

A methyl methacrylate syrup was also employed in this work as a means to reduce monomer losses by leakage and evaporation. The syrup consists of a solution of poly (methyl methacrylate) dissolved in methyl methacrylate monomer, i.e., portions of the monomer are in the polymerized and unpolymerized state. Such syrups are commonly employed in the manufacture of acrylic polymers and coatings. They can differ in terms of the amount of polymer in the solution, i.e., solids level, and in the molecular weight of the polymer both of which affect the viscosity of the syrup. The syrup used in this case had a viscosity of 500 to 700 as received from the supplier, E.I. DuPont. A lower viscosity was achieved for most of its uses by dilution with additional MMA monomer.

Trimethylolpropane trimethacrylate (TMPTMA) is a cross-linking agent, which is used to link linear molecular chains of polymer, one chain to another. This cross-linking changes the one-dimensional molecular chains into three-dimensional structures. When the molecular chains are cross-linked, the polymer will become stiffer and stronger (6), but there is a corresponding increase in brittleness (7). The cross-linking agent can also increase the rate of polymerization. Another cross-linking agent used was trimethylolpropane triacrylate (TMPTA).

Butyl acrylate (BA) is a clear, water-like monomer with a strong sour odor. It is used in combination with MMA in order to increase the ductility of polymer-concrete overlays.

2.1.2 Initiators

The initiator, also known as the catalyst, is the agent added to begin the polymerization. Benzoyl peroxide (BP) was the initiator used most frequently in this research. It is commercially available in several forms: powder, 50 percent powder, 50 percent paste, and 40 percent paste. The other two initiators that were used are lauroyl peroxide (LP) and azobis isobutyronitrile (AIBN).

2.1.3 Accelerators

The accelerator, or promoter, is the agent added to increase the rate of polymerization. Dimethyl-p-toluidine (DMPT) was the accelerator used in this research. Dimethyl aniline (DMA) is another accelerator used to catalyze the reaction of the polymerization initiator, but it is not as active as DMPT.

2.2 Aggregate

Dry concrete sand and pea gravel are also required to produce the polymer-concrete overlay. The aggregate should be sound and free of dirt, asphalt, and other organic materials. In addition to providing strength, sand is used to embed the pea gravel and as a porous reservoir to hold the monomer to reduce evaporation and leakage losses. Pea gravel is used to improve the skid resistance by providing a rough surface. The gradations of aggregate used in this study are shown in Table 2.1.

2.3 Application Procedures

The following are some of the most important factors that influence the success of PC overlays.

Table 2.1. Gradations

Sieve Size	Sand From Colorado River, % Finer by Weight	Sand From Henrietta, Texas, % Finer by Weight
No. 4	99	90
No. 8	91	79
No. 16	77	67
No. 30	54	50
No. 50	22	17
No. 100	4	3

Sieve Size	Pea Gravel From Colorado River % Finer by Weight	Crushed Pea Gravel From Henrietta, TX % Finer by Weight
3/4 in.	100	100
3/8 in.	80	66
1/4 in.	9	20
1/8 in.	2	3

2.3.1 Surface Condition of Concrete

Obtaining an adequate bond strength between the PC overlay and the concrete surface can be complicated by several factors. First, the concrete surface should be dry prior to monomer application. There is no standard test for determining the moisture content in concrete, but it has been shown that the moisture in concrete inhibits the penetration of monomer (2, 4, 7). Higher bond stresses between PC overlay and concrete are obtained on slabs that have been oven-dried. Pretreatment drying in the laboratory is easily accomplished in ovens at 212^{o}F (100^{o}C). Drying in the field may have to rely mainly on solar heating, where climatic conditions permit. In small areas, drying the surface with portable heaters is also possible. Another factor that is quite important in developing a good bond is the degree of surface contamination. Asphalt, oil, road film, and other contaminants should be completely removed, preferably by sandblasting, when necessary.

2.3.2 Monomer Viscosity

The viscosity, or fluidity, of a given monomer is one of the most important factors influencing the success of PC overlays. A good bond between the polymer and concrete is dependent upon the monomer's penetrating into the concrete pores before polymerization occurs. Figure 2.1 shows the effect of viscosity on the penetration of monomer into concrete (1). This clearly shows that the less viscous monomers are able to penetrate faster into the concrete than the

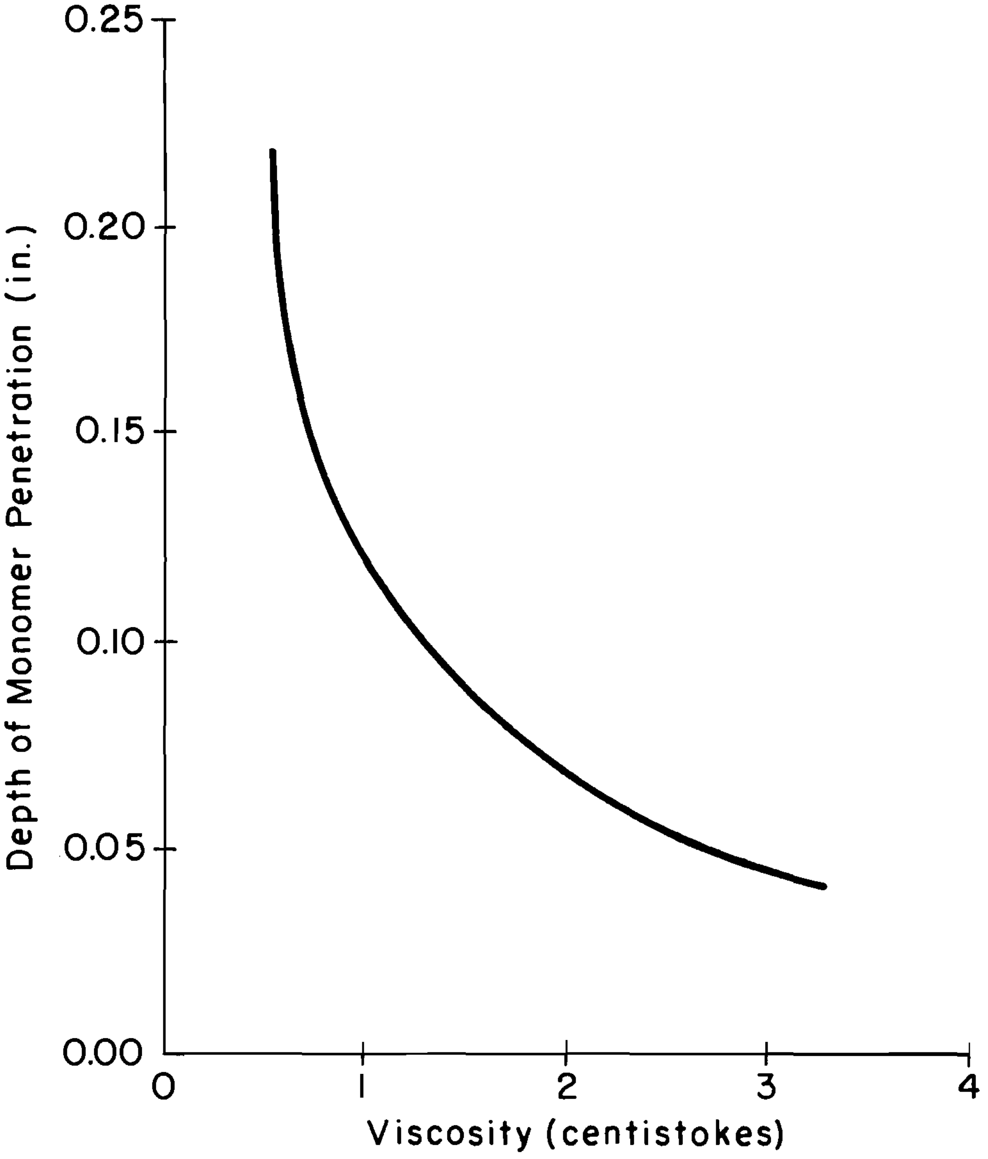


Fig. 2.1. Effect of Viscosity on Monomer Penetration into Concrete after a 30-minute Soaking (1).

more viscous monomers. This increased penetration should produce a stronger bond. In order to get a stronger bond strength between PC overlay and concrete, low viscosity monomers should be used, but, on the other hand, because of the loss of monomer due to evaporation, run-off, and leakage, more viscous monomers are desirable. Because of the diametrically opposed requirements, a two-step monomer application, a less viscous monomer system is applied and permitted to soak into the concrete for approximately thirty minutes. Then, a more viscous monomer system is applied to fill up the voids between the coarse aggregate.

Previous test results (2, 3) suggest that the driving force for the monomer flow is the inbibition of the monomer by capillary forces, rather than the hydrostatic head produced by the depth of monomer. The rate of the capillary penetration is dependent upon the viscosity of the monomer system and the permeability of the concrete. A thin layer of sand saturated with monomer was used as a porous reservoir for the monomer during soaking.

2.3.3 Monomer Evaporation

One of the major problems encountered in the study of polymer-concrete overlays, which have a large surface-volume ratio, is the evaporation of volatile monomers. Evaporation results not only in an undesirable loss of monomer but also causes a change in the concentration of the monomer system. Monomer loss due to evaporation is related to the length of the cure time, the temperature, and wind velocity. However, it was found that spreading a shallow layer (approximately 1/4-in. or 6.4-mm) of dry concrete sand on the surface of the slab can minimize the evaporation loss and reduce run-off. Concrete sand serves to hold the monomer, even on sloped slabs, thereby permitting longer soaking time, deeper penetration, and better saturation of the concrete. To further minimize the evaporation loss, a membrane, e.g., polyethylene film, should be used to cover the PC overlay while the monomer is soaking and curing. It is also desirable to apply the PC overlay at temperatures of 75 to 85^{o}F (24 to 29^{o}C). Higher temperatures result in excessive evaporation, and lower temperatures require longer polymerization times or larger amounts of initiators and accelerators.

2.3.4 Soaking Time

Soaking times of 15 and 30 min. for the first monomer application were tried in this study. Obviously, a longer soaking time yields deeper penetration. Even for low viscosity monomers, the rate of penetration decreases with soaking time (4). A penetration depth of 1/8-in. (3.2-mm), was achieved in 15 min., but the 30-min. soaking time gave a more uniform penetration and better bond. A 30-min. soaking time was adopted in this study, primarily to give more time to prepare the second monomer application.

2.3.5 Surface Roughness

Concrete slabs with rough surfaces proved to develop a better bond between PC overlay and concrete than those with smooth surfaces.

Also, a wire brush- or broom-finished surface was more easily penetrated by the monomer. This was probably because the brushing technique broke up the surface film which was formed during hydration of the concrete (4).

2.3.6 Aggregate Proportion

In this study, the aggregate application was separated into two steps: first, 2.0 psf of concrete sand was spread about 1/8-in. to 1/4-in. thick, then 1.8 psf of 3/8-in.-maximum-size aggregate was applied to the sand to produce a total thickness of about 1/2-in. Originally, the coarse aggregate was mixed with sand in the weight proportion of 2:8, or 6:4 for the second application of aggregate, but too much sand remained on the surface. The amount, 1.8 psf, of coarse aggregate was chosen because a single layer of coarse aggregate, embedded into the fine aggregate, was desirable. This resulted in a good bond between the coarse and fine aggregate. It can be achieved by rolling the aggregate with a light pressure before the monomer application.

2.3.7 Monomer Treatment

Usually, the monomer was sprinkled from the upper end to the lower end of a sloping concrete slab to allow the monomer to flow by gravity. A fine spray should be used to prevent erosion of the aggregate. In order to prevent excess monomer which would form a hard, glossy surface, the proper amount of monomer should be estimated as accurately as possible. If there is excess monomer, additional sand or coarse aggregate should be placed to absorb the monomer.

2.4 Laboratory Treatment

In the beginning of this study, tests were performed indoors in the laboratory. Efforts were concentrated on developing a feasible technique to perform PC overlays on concrete slabs. Simplicity, practicality and economy were the primary objectives throughout the research. After obtaining promising results from many laboratory tests, tests were performed outdoors to simulate actual field conditions. PC overlay tests over larger areas, discussed in Chapter 5, were performed at Balcones Research Center of The University of Texas at Austin. The durability tests and results for PC overlays are discussed in Chapter 3 and Chapter 4.

2.4.1 Concrete Specimen Treatments

In order to develop a feasible PC overlay for bridge decks, many laboratory tests were performed on 13-in. x 13-in. x 1-in. concrete slabs. (Initially, 2-inch-thick slabs were used.) These slabs were cured for seven days under moist burlap and then air-dried for 21 days. Some of these slabs were then dried for a minimum of seven days at 210°F. After drying, the slabs were removed from the oven, wrapped in polyethylene film, and allowed to cool to room temperature. Other slabs after curing were left outdoors under ambient weather conditions. The concrete mix proportions and indirect tension and compression stresses are shown in the appendix.

2.4.2 Monomer System

In order to determine an optimum monomer system for achieving a good bond between PC overlay and concrete, good skid resistance, and satisfactory durability, and to study workability of the material, many monomer systems were tried in this study (Table 2.2). Identifying a monomer system with a viscosity which will minimize the loss of monomer due to evaporation, run-off, and leakage, was a major goal of this part of the study. Initially, a finely ground polymethyl methacrylate (Grade 2010 Elvacite, produced by DuPont) was added to the MMA solution to increase the viscosity, but it required considerable time to dissolve. Efforts were then concentrated upon developing a feasible monomer system using other materials. The first trial with PCOL-1, showed that the soak time (working time from adding BzP and DMPT until monomer gels) of the first monomer application, 18 minutes, was too short. Several tests (PCOL-2 through PCOL-9) were then performed with the monomer system developed in previous research to make polymer-concrete for repairing concrete, except that the first monomer application used BzP, an initiator, without DMPT (an accelerator). The accelerator was omitted to provide a longer pot life to permit the first monomer application to penetrate deeper into the concrete to achieve a strong bond between PC overlay and concrete. After thirty minutes of soaking, the second monomer system was applied. The heat generated during polymerization of the more reactive second monomer application caused the first monomer application to polymerize. The PC overlay was acceptable except for evaporation loss due to the large

Table 2.2. Mix Proportions of Monomer Systems (% by weight).

	FIRST MONOMER SYSTEM TREATMENT						SECOND MONOMER SYSTEM TREATMENT								
TEST NO.	MMA	TMP TMA	TMP TA	BzP	DMPT	Soak Time (Min.)	MMA	MMA SYRUP	TMP TMA	TMP TA	PETA	BA	BzP	DMPT	TEMP. °F
PCOL-1	95	5		1	1/2	18	90		10				1	1	75
PCOL-2 to PCOL-9	95	5		1		30	90		10				1	1	75
PCOL-11	95	5		1		30	90				10		1	1/2	75
PCOL-12	95	5		1	1/4	15	90				10		1	1/2	75
PCOL-13	95		5	1	1/4	15	90				10		1	1/2	75
PCOL-14	95		5	1	1/4	15	36	54			10		1	1/2	75
PCOL-15	95		5	1	1/4	15	54	36			10		1	1/2	75
PCOL-16	95		5	1	3/8	15	36	54			10		1	3/8	75
PCOL-17 to PCOL-19	90	10		1	3/8	15	36	54		10			3/4	1/4	75
PCOL-20	95		5	1	1/4	600	36	54		10			3/4	1/4	75
PCOL-21	90	10		1	3/8	15	36	54	10				1/2	1/8	75
PCOL-22, PCOL-26	90	10		1	3/8	15	36	54	10				3/4	1/4	75
PCOL-23 to PCOL-25	90	10		1	3/8	30	36	54	10				3/4	1/4	75

Table 2.2 (Continued)

	FIRST MONOMER SYSTEM TREATMENT						SECOND MONOMER SYSTEM TREATMENT								
TEST NO.	MMA	TMP TMA	TMP TA	BzP	DMPT	Soak Time (Min.)	MMA	MMA SYRUP	TMP TMA	TMP TA	PETA	BA	BzP	DMPT	TEMP °F
PCOL-27 to PCOL-31	90	10		9/8	3/8	30	36	54	10				3/4	1/8	75
PCOL-32 to PCOL-37	90	10		1	1/8	30	16	64	2-1/2			17-1/2	3/4	1/8	90
PCOL-38	90	10		9/8		30	16	64	2-1/2			17-1/2	3/4	1/8	90
PCOL-39	90	10		1	1/4	30	16	64	2-1/2			17-1/2	3/4	1/4	90
PCOL-40	90	10		9/8	1/4	15	16	64	2-1/2			17-1/2	3/4	1/4	90
PCOL-41, 44 to 48	95	5		3/4	3/10	30	16	64	2-1/2			17-1/2	3/4	1/4	90
PCOL-42 to PCOL-43	95	5		.8	.32	30	16	64	2-1/2			17-1/2	3/4	3/16	90
PCOL-49 to PCOL-51	95	5		.8	.38	30	32	48	2-1/2			17-1/2	3/4	1/4	90
PCOL-52							32	48	2-1/2			17-1/2	3/4	1/4	90
PCOL-53	95	5		.8	.38										90
PCOL-54	95	5		.8	.38	30	48	32	2-1/2			17-1/2	.75	.375	90
PCOL-55	95	5		1	1/2	30	48	32	2-1/2			17-1/2	.8	.4	73

Table 2.2 (Continued)

	FIRST MONOMER SYSTEM TREATMENT						SECOND MONOMER SYSTEM TREATMENT								
TEST NO.	MMA	TMP TMA	TMP TA	BzP	DMPT	Soak Time (Min.)	MMA	MMA SYRUP	TMP TMA	TMP TA	PETA	BA	BzP	DMPT	TEMP. °F
PCOL-56, 57	95	5		.925	.46	30	48	32	2-1/2			17-1/2	.8	.4	75
PCOL-58, 59	95	5		1-1/2	.75	30	48	32	2-1/2			17-1/2	1.4	.7	50
PCOL-60, 61	95	5		1-1/4	.625	30	48	32	2-1/2			17-1/2	1.17	.58	70
PCOL-62, 63	95	5		3.5	1.75	30	48	32	2-1/2			17-1/2	3.5	1.75	30

surface-volume ratio of PC overlay and low viscosity of the monomer. In tests on PCOL-1 through PCOL-9, sufficient accelerator was used in the second monomer application to shorten the pot life to less than twenty minutes; in some cases, it is possible for the second monomer application to gel in ten minutes. This is undesirable for practical use, especially in field work which involves a large amount of monomer. It might cause the monomer to gel in the hose before it is applied. Subsequently, a small amount, 0.25 percent, of DMPT was added to the first monomer application, tests PCOL-12 through PCOL-15, and the percentage of DMPT in the second monomer application was reduced to 0.5 percent.

For tests PCOL-11 through PCOL-16, a viscous syrup-like chemical, pentaerythritol triacrylate (PETA), was tried in the second monomer application to increase the viscosity, but it did not produce satisfactory results. A few minutes warming in a hot water bath was necessary for the solids in PETA to melt. Vigorous stirring before use was required due to its precipitation. Another cross-linking agent, trimethylolpropane triacrylate (TMPTA), was tried with monomer systems of tests PCOL-13 through PCOL-20. The results were not as good as those with TMPTMA (Section 4.1). Therefore, PETA and TMPTA were eliminated from subsequent tests.

Meanwhile, several tests (PCOL-12 through PCOL-26) were performed with a shorter soaking time, 15 min., and showed little difference in monomer penetration depth when compared with those soaked for 30 min. They almost reached the same depth, 1/16-in. to

1/8-in. The only difference was that the longer soaking time resulted in a more uniform penetration. Therefore, a soaking time of 30 min. was adopted for the tests following PCOL-26.

A high viscosity monomer, MMA syrup, was obtained. The MMA syrup could be easily mixed in the MMA solution and gave a satisfactory viscosity. Initially, MMA to MMA syrup ratios of 2:3 and 1:4 were tried in tests PCOL-16 through PCOL-52. The resulting viscosity seemed about right in the small-scale laboratory tests, but, as the large-scale field tests at Balcones Research Center of The University of Texas at Austin were performed, it became apparent that the viscosity of the second monomer application was too great to efficiently fill the voids between coarse aggregate. Usually, there was a glossy surface on the PC overlay. The ratio between MMA and MMA syrup was finally adjusted to 3:2 in tests PCOL-54 through 61. The results from field tests showed that this produced about the optimum viscosity.

In order to increase the ductility of PC overlays to accommodate the thermal expansion stress, an amount of 17-1/2 percent butyl acrylate was added in the second monomer application following the test of PCOL-32.

From the tests, a tentative optimum monomer system was obtained: 95 percent MMA, 5 percent TMPTMA for the first monomer application; 48 percent MMA, 32 percent MMA syrup, 2-1/2 percent TMPTMA, 17-1/2 percent BA for the second monomer application.

Another major goal of this part of the study was to find the correct concentrations of initiator and accelerator. Initially, 1 percent BP and 1/4 percent DMPT for the first monomer application and 1 percent BP and 1/2 percent DMPT for the second monomer application were tried in tests PCOL-12 through PCOL-15. The results were acceptable. A slight change of BP and DMPT was tried to tests PCOL-16 through PCOL-31. From previous research (8, 16), it was known that increased percentages of initiator and accelerator were required as the ambient temperature decreased. Obviously, a certain optimum combination of the concentrations of initiator and accelerator exists for each different monomer system at different ambient temperatures. Tests following PCOL-41 used different concentrations of initiator and accelerator for the same monomer system at different ambient temperatures. Tentative recommended percentages of BP and DMPT for a monomer system of 95 percent MMA and 5 percent TMPTMA are shown in Fig. 2.2 (8).

2.4.3 Application Procedure

Initially, the first monomer application was sprinkled prior to sand spreading. After 30 minutes of soaking in the 1/4-in.-thick sand layer (the first aggregate application), a mixture of 70 percent (by weight) pea gravel and 30 percent concrete sand as the second aggregate application was spread on top of the sand and compacted with a concrete cylinder. Then, the viscous second monomer application was sprayed on the surface to fill the voids between the aggregate. Because of the segregation of dry sand and pea gravel in the

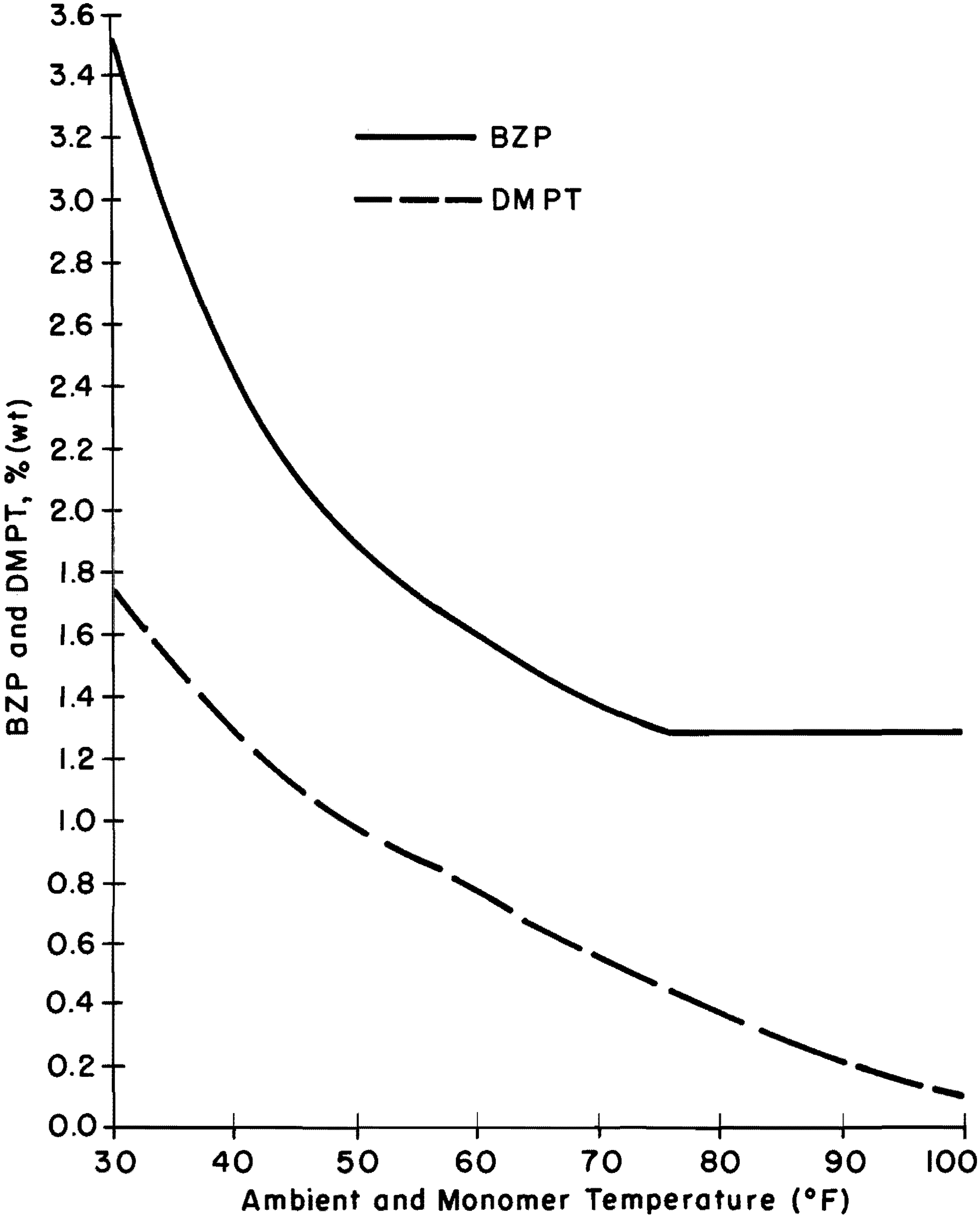


Fig. 2.2. Tentative Recommended Percentages of BzP and DMPT. (Ref. 8)

second aggregate application, usually some sand spots remained on the surface of the PC overlay. Later, prewetting of the mixture of sand and pea gravel with monomer and an adjusted ratio of 4:1 between pea gravel and sand were tried, but some sand spots still remained on the surface. Tests were then performed using only gravel in the second aggregate application and the results were good. In consideration of the simplicity, practicality, and economy desired in future field work, prewetting the second aggregate application with monomer was eliminated from subsequent tests. A more efficient and simpler procedure, which as follows, was finally developed and showed satisfactory results.

1. The 13-in. x 13-in. x 1-in. thick broom-brushed air- or oven-dried concrete slab was cleaned.
2. Four 1/2-in. x 1/2-in. x 12-1/2-in. wood strips were bonded to the surface with latex caulking (Fig. 2.3) to confine the monomer. These four wood strips framed an area of one square foot (Fig. 2.4).
3. Approximately 2.0 psf of dry concrete sand were spread on the slab to a thickness of 1/8-in. to 1/4-in. (Fig. 2.5).
4. Approximately 1.8 psf of 3/8-in.-maximum-size aggregate were spread on the top of the sand to produce a total thickness of 3/8-in. to 1/2-in.

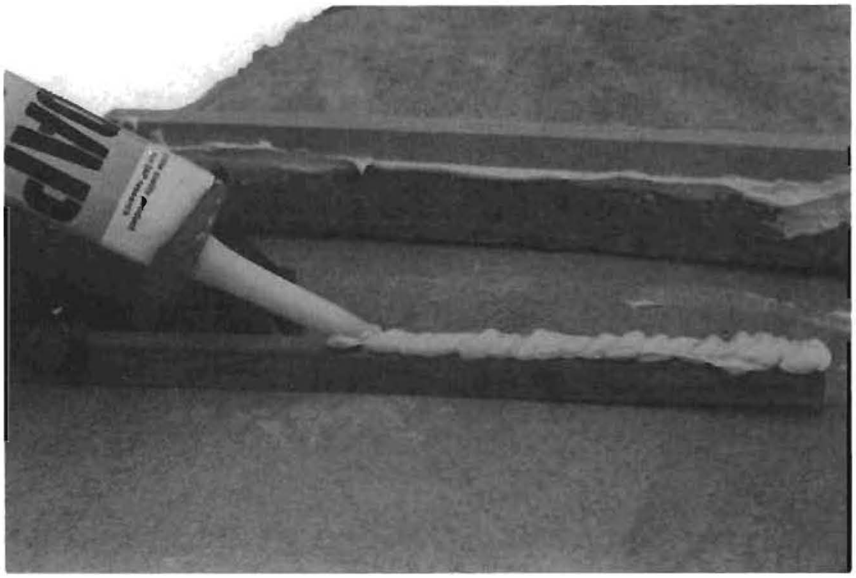


Fig. 2.3. Caulking Compound Applied to Wood Strip.

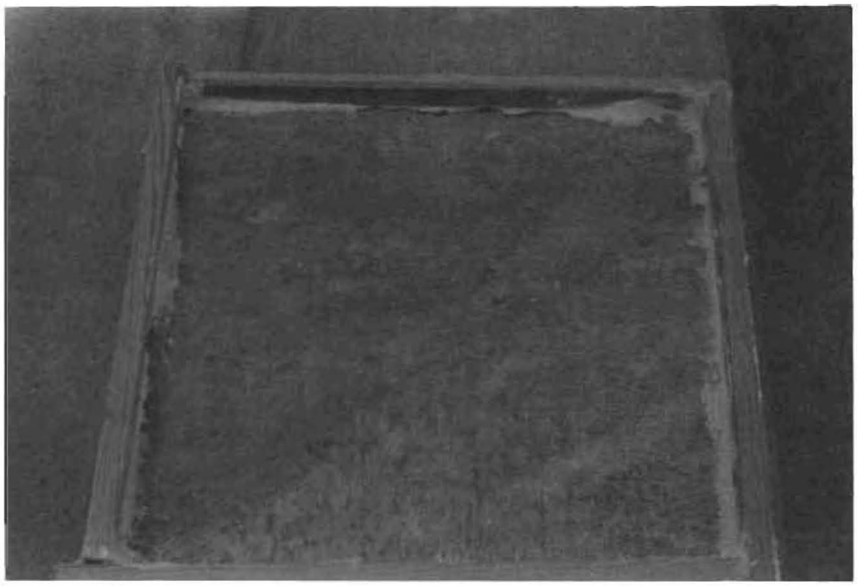


Fig. 2.4. Concrete Slab with Wood Strip Applied.

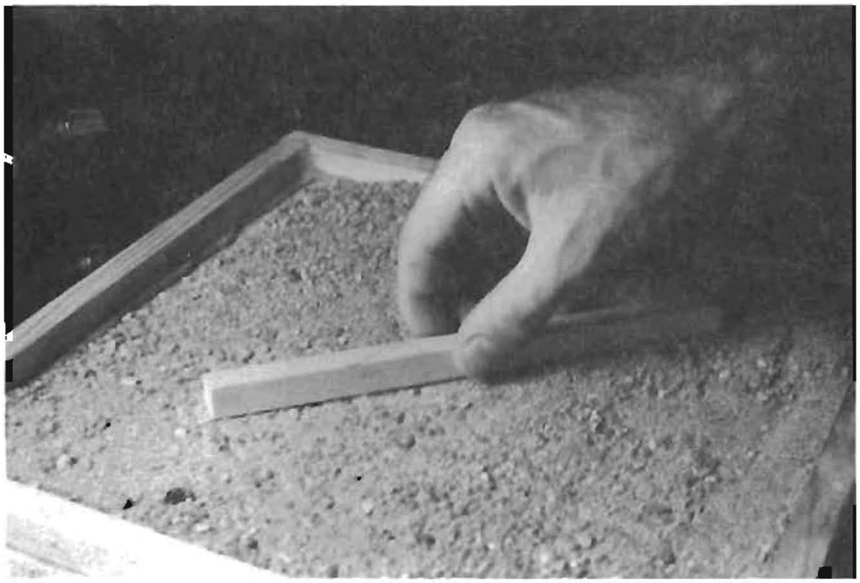


Fig. 2.5. Sand Screeded to 1/4-in.

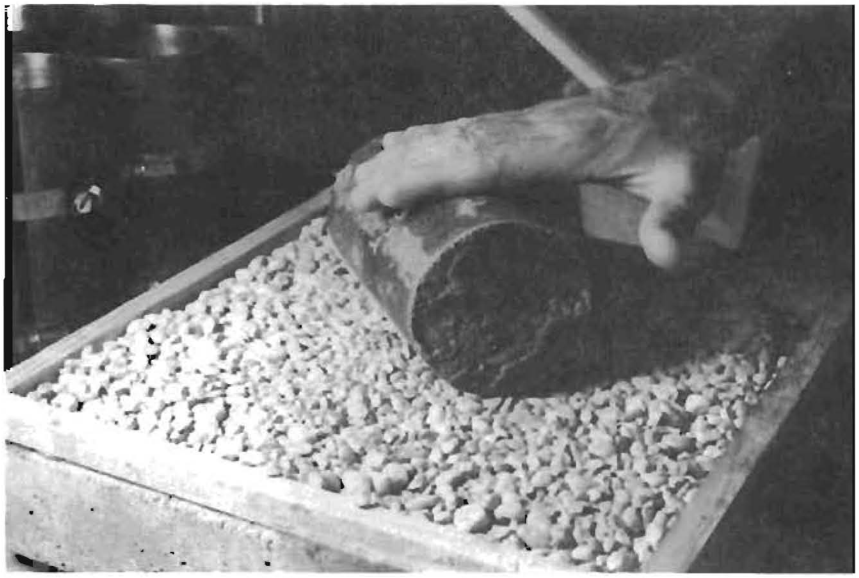


Fig. 2.6. Aggregate Compacted with 3-in.-Diameter Cylinder.

5. The overlay was compacted by rolling with a 3-in.-diameter cylinder (Fig. 2.6) to embed the coarse aggregate into the sand layer (Section 2.3.6).
6. The first monomer application was applied to the overlay and the aggregate was kept saturated for 30 minutes.
7. The second monomer system was applied to fill the voids in the coarse aggregate (Section 2.3.7).

CHAPTER 3

DURABILITY EVALUATION PROCEDURE

3.1 Introduction

The purpose of the PC overlay is to increase the durability of a concrete bridge deck by providing a thin water-proof surface and to improve the skid resistance. This chapter describes the durability tests that were performed. The test results are discussed in Chapter 4.

3.2 Bond Stress Test Procedure

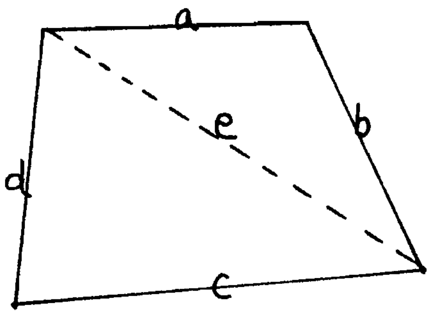
Several test techniques to determine the bond strength between PC overlay and concrete were developed in this study. Initially, a two-sided bond test was devised by applying PC overlays on both the top and the bottom of a portland cement concrete slab, as discussed in Section 2.4.3. After polymerization, the 13-in. x 13-in. x 2-in. thick concrete slab with PC overlays was cut into four pieces (each with approximately 25-sq. in. of surface area). The four edges were trimmed with a diamond-bladed saw. For this two-sided bond test, a vertical force was applied to shear the PC overlays from two sides via steel bars, as shown in Fig. 3.1. The bond stress was calculated by taking the vertical force and dividing by the total area of the two sides. The area of the quadrilateral can be obtained by regarding the quadrilateral as a combination of two scalene triangles. The area of a scalene is calculated as follows:

$S1 = (a + b + e) / 2$

$S2 = (c + d + e) / 2$

A = area of a quadrilateral

$$= \sqrt{S1\ (S1-a)\ (S1-b)\ (S1-e) + S2\ (S2-c)\ (S2-d)\ (S2-e)}$$



The bond stress calculated by this two-sided bond test cannot accurately represent the real bond stress of the PC overlay on the finished surface because the roughness of the finished surface is different from that of the formed surface. The bond to the smooth surface is lower than that to the finished surface.

A modified bond test, shown in Fig. 3.2, was later designed, with a thinner (1-in.) concrete slab, with a PC overlay on the finished surface only and a lateral support. A vertical force was applied through a steel bar on the edge of the PC overlay specimen to shear it. A lateral support was placed perpendicular to the slab to prevent rotation caused by the secondary moment due to the eccentricity between the two vertical forces. After several bond tests were

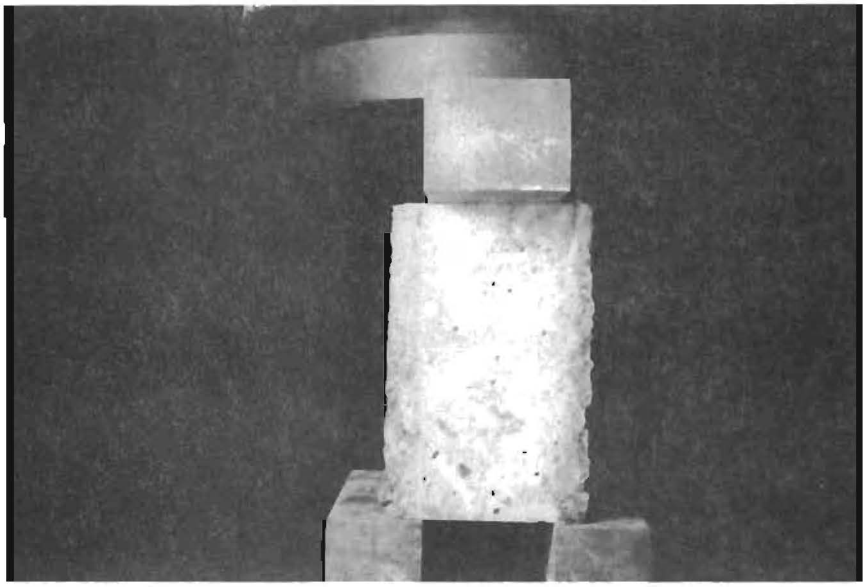


Fig. 3.1. Two-Sided Bond Test.

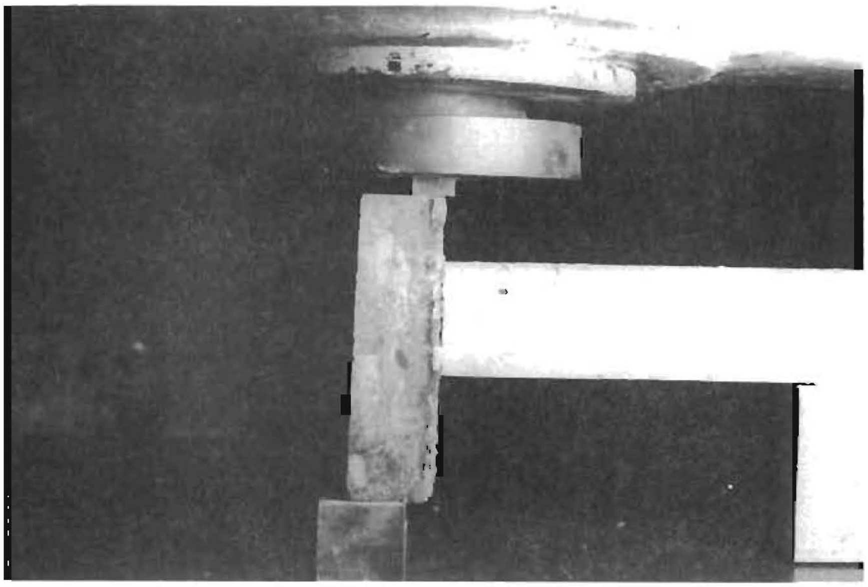


Fig. 3.2. One-Sided Bond Test with Lateral Support.

performed, the lateral support was found unnecessary because the eccentricity between the two vertical forces was small. By this test (Fig. 3.3), the bond stress between the PC overlay and the concrete can be obtained.

3.3 Freeze-Thaw Test

It is believed that freeze-thaw behavior is one of the primary mechanisms involved in bridge deck deterioration. If the PC overlay can maintain its resistance to water penetration during the freeze-thaw cycling, the problems of spalling and cracking can be minimized (2).

Tests were performed on 10-in. x 10-in. x 5-1/2-in. specimens in accordance with the procedures developed in previous research (2, 9).

After the oven- or air-drying process (Section 2.4.1), the PC overlay was applied to the surface of the concrete slab. Then, an 8-in.-diameter metal ring was bonded to the surface of the overlay with a silicone adhesive. The sides of the specimen were coated with epoxy to prevent moisture intrusion to simulate the actual condition in a bridge deck. Four stainless steel reference tabs were bonded 8-in. apart on the vertical face of the specimen approximately 1/2-in. below the top surface and 1/2-in. above the bottom surface. A typical specimen with reference tabs is shown in Fig. 3.4. Next, the epoxy was cured for 24 hours at room temperature (75^{o}F), after which initial horizontal length measurements were made with an 8-in. Berry gauge, as shown in Fig. 3.5.

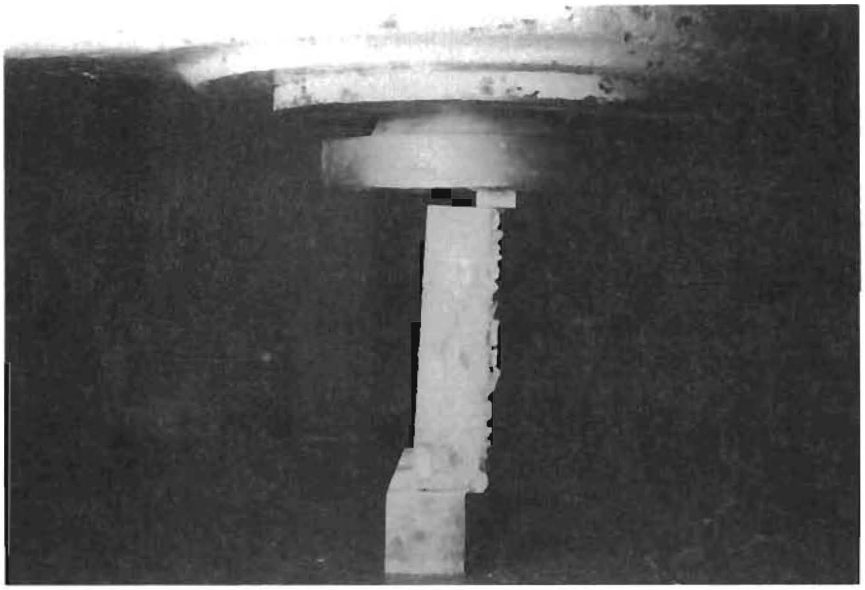


Fig. 3.3. One-Sided Bond Test without Lateral Support.

Fig. 3.4. Freeze-Thaw Specimen with Reference Tabs for Strain Measurement.

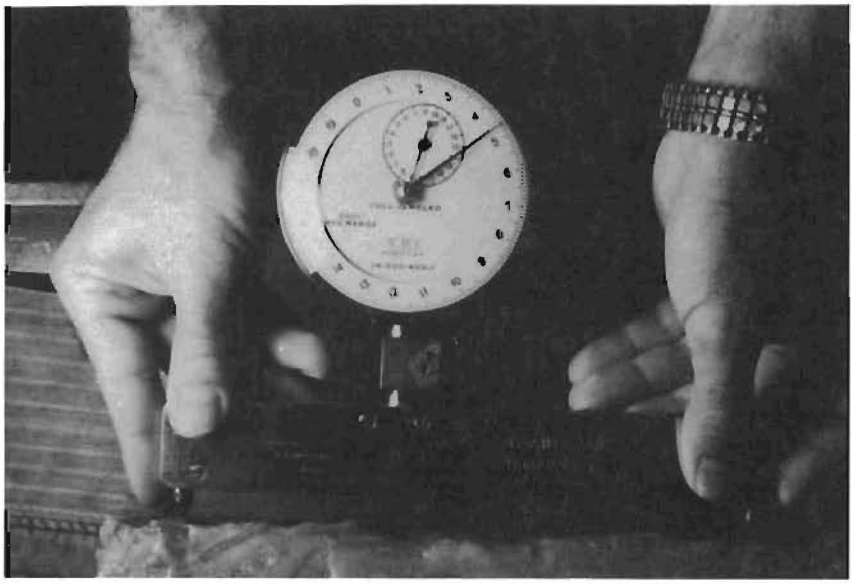


Fig. 3.5. Measurement of Horizontal Strain of Freeze-Thaw Specimen by Use of Berry Gage.

Specimens were frozen overnight at 0°F and thawed at room temperature during the day. One complete cycle of freezing and thawing was obtained each day. After one dry freeze-thaw cycle, 1/4-in. of tap water was ponded within the metal ring. Length measurements were made immediately after specimens were removed from the freezing chamber room, at approximately ten freeze-thaw cycle intervals. A final reading was taken after the specimen had completed the last cycle and then aged for about 24 hours at room temperature. Visual observations were made periodically to determine the extent of surface scaling and/or cracking. Tests of specimens which exhibited severe deterioration and inability to hold the ponded water during the thaw cycle were terminated prior to completion of the test. Specimens which did not fail were used for water tightness tests and sandblast tests.

3.4 Water Tightness

Two treated and two untreated slabs were subjected to water tightness tests before and after the termination of the freeze-thaw tests. The procedures used in this study were similar to those developed in earlier research (2, 9, 10).

After the oven- or air-drying process (Section 2.4.1), the PC overlay was applied to the top surface of the concrete slab. The four vertical sides were coated with epoxy to prevent water penetration through these faces. The specimen was immersed, overlay side down, in a vat of water to a depth of 5-in. above the overlay surface. The specimen was supported off the bottom of the tank. The 5-in. water head was maintained for a period of 24 hours, after which the specimen was immediately split open and the depth of water penetration was marked.

3.5 Sandblast Abrasion

After the water tightness test was completed, the two halves of each specimen were sawed and retained for sandblast abrasion tests. The edges with the epoxy coating were cut off, leaving a usable specimen of approximately 4-in. x 9-in. x 1-1/2-in. to 2-in. thick. The test was performed mainly in accordance with the procedures given in ASTM C 418-76 except for a required modification due to the rough surface of the PC overlay. The apparatus is shown in Fig. 3.6.

All the 4-in. x 9-in. x 1-1/2-in. to 2-in. thick specimens were air-dried at room temperature for a minimum of seven days to stabilize the moisture content in the specimens. In order to prevent any further polymerization, these specimens were air-dried instead of being oven-dried to simulate an actual PC overlay. Due to the roughness of PC overlay surfaces (Fig. 3.7), neither the abraded volume nor the depth of the abraded cavity could be accurately measured. The results of the abrasion tests were relative values, comparing PC overlay treated and untreated specimens. The weight loss due to abrasion was measured instead of the depth and volume of the abraded cavity.

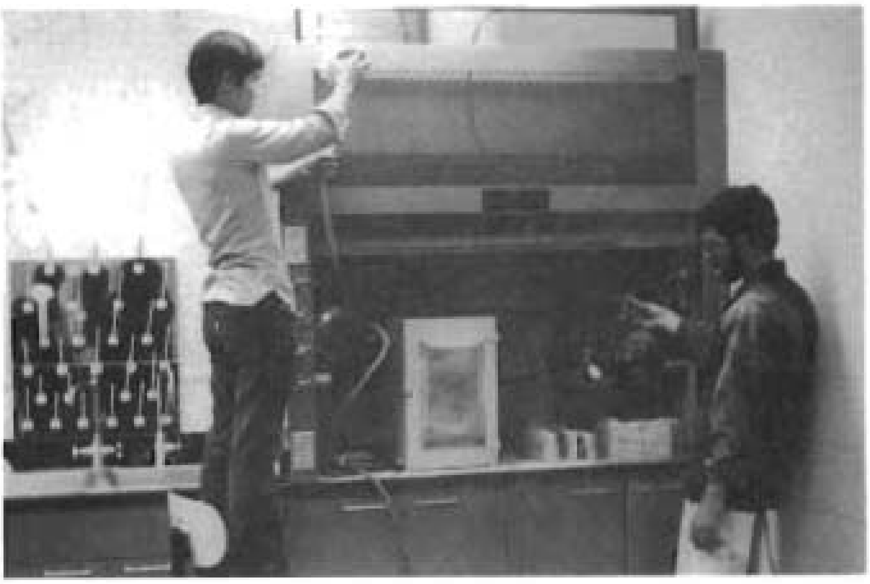


Fig. 3.6. Sandblast Abrasion Test.

Fig. 3.7. PC-Overlay Specimen for Sandblast Abrasion Test.

3.6 Skid Resistance

Surface friction values were determined by use of the British Portable Tester (BPT), as shown in Fig. 3.8, in accordance with the procedures given in ASTM E 303-69. A 3-in.-wide rubber pad with a 5-in. contact path, as specified, was used. Values were measured at two different locations on each specimen. Although the BPT measurement has some shortcomings, including a small test area, the condition of the shoe, the velocity of the pendulum, and the roughness of the tested surface, the BPT has been a useful instrument for laboratory work and spot testing in the field. It does give reasonable comparisons of surface roughness with skid trailers up to about 30 miles per hour (27).

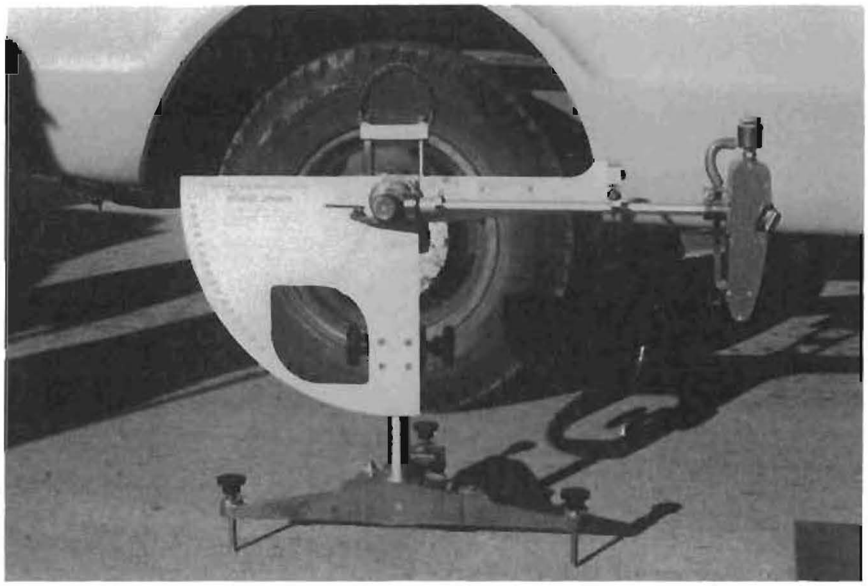


Fig. 3.8. British Portable Skid Tester.

CHAPTER 4

RESULTS OF DURABILITY EVALUATION

4.1 Bond Stress Test

A good bond between PC overlay and concrete is one of the basic requirements for a successful PC overlay. Obtaining an adequate bond strength is complicated by several factors, including the need for a dry concrete surface and the correct monomer system. Several monomer systems were tried in this study, as shown in Table 2.2. Initially, the monomer system used for the first monomer application (PCOL-2 through PCOL-11) was tried without an accelerator (Section 2.4.2). However, an accelerator was added to the more-reactive, second, monomer application. The resulting bond stress of PCOL-11, as shown in Table 4.1, was less than that of PCOL-12, in which a 1/4 percent DMPT was added in the first monomer application. For tests PCOL-13 through PCOL-20, another cross-linking agent, TMPTA, was used. A comparison of the bond stress of PCOL-12 and PCOL-13 showed that TMPTA did not produce as high bond strengths as TMPTMA. Therefore, in the subsequent tests, TMPTA was eliminated and an accelerator was added in the first monomer application.

Table 4.1. Bond Stress Between PC Overlay and Concrete Slab.

Test No.	Ave. Bond Stress, psi	No. of Specimens	Bonded Area[a]	Concrete Cracked[b]	Monomer Odor[c]	Method of Drying	Test Type[d]
PCOL-8	523	5	1/9			Oven	A
PCOL-9	383	5	1/5			Oven	A
PCOL-11	529	2	1/2			Oven	A
PCOL-12	817	2	1/3			Oven	A
PCOL-13	330	2	0			Oven	A
PCOL-14	314	2	0			Oven	A
PCOL-15	260	2	1/10			Oven	A
PCOL-16	277	2	0			Oven	A
PCOL-17	646	3	2/3	Yes		Oven	A
PCOL-18	379	3	1/3			Oven	A
PCOL-19	237	2	2/3	Yes		Air	A
PCOL-20	84	2	0			Oven	A
PCOL-21	624	2	4/5	Yes	No	Oven	B
PCOL-22	510	2	4/5	Yes	Yes	Oven	B
PCOL-23	445	2	4/5	Yes	Yes	Oven	B
PCOL-24	270	2	1/4	Yes	Yes	Air	B
PCOL-25	320	6	1/4	Yes	No	Air	C
PCOL-26	475	2	2/3	Yes	Strong	Oven	C
PCOL-27	443	4	1/3	Yes	Strong	Oven	C
PCOL-28	371	4	1/3	Yes	No	Air	C
PCOL-29	156	4	0	No	Strong	Air	C
PCOL-30	408	4	3/4	Yes	Strong	Oven	C
PCOL-31	448	4	9/10	Yes	Yes	Oven	C
PCOL-32	144	4	0	No	Strong	Air	C
PCOL-33	550	4	3/4	Yes	Strong	Oven	C
PCOL-35	483	4	9/10	Yes	Strong	Oven	C
PCOL-36	84	4	0	No	Yes	Air	C
PCOL-37	133	4	0	No	Yes	Air	C
PCOL-38	36	4	0	No	Strong	Air	C
PCOL-39	170	4	0	No	Yes	Air	C

Table 4.1 (Continued)

Test No.	Ave. Bond Stress, psi	No. of Specimens	Bonded Area[a]	Concrete Cracked[b]	Monomer Odor[c]	Method of Drying	Test Type[d]
PCOL-40	192	4	0	No	Yes	Air	C
PCOL-41	245	4	1/10	Yes	Yes	Air	C
PCOL-42	196	4	0	No	Strong	Air	C
PCOL-43	447	4	1/3	Yes	Yes	Oven	C
PCOL-49	83	4	0	No	Yes	Air	C
PCOL-52	0						
PCOL-54	69	2	0	No	Strong	Air	C
PCOL-56	255	2	0	No	Yes	Oven	C
PCOL-57	220	2	0	No	Yes	Air	C
PCOL-58	526	4	1/3	Yes	Little	Air[e]	C
PCOL-59	520	3	2/3	Yes	Little	Oven	C
PCOL-60	365	3	1/3	Yes	Little	Air[f]	C
PCOL-61	435	3	1/2	Yes	Little	Air	C
PCOL-62	483	4	1/1	Yes	Yes	Oven	C
PCOL-63	300	4	1/1	Yes	No	Air[e]	C

A - Two-sided bond test

B - One-sided bond test with lateral support

C - One-sided bond test without lateral support

a - Ratio of area of concrete bonded to PC overlay after shearing test to total overlay area

b - Cracks occurred in concrete after shearing test

c - Monomer odor detected after shearing test which indicate incomplete polymerization

d - Test types

e - Dried 30 min. in oven

f - Dried 10 min. in oven

Test PCOL-52, as shown in Table 4.1, was performed by applying only the viscous second monomer application, i.e., without first applying the less viscous, first, monomer application. The result showed no bond strength at all between the PC overlay and concrete. Little penetration of the second monomer application through the sand layer was found. Several specimens (PCOL-50 and 51), in which some fine sand or cement (10 percent by weight) was mixed with the concrete sand, were tried. This resulted in little bond strength between PC overlay and concrete. Therefore, it was evident that for PC overlays, the bond strength between overlay and concrete was primarily governed by the penetration of the less viscous first monomer application. It is also believed that a monomer system with a correct percentage of initiator and accelerator will produce a sound polymer concrete with a strong bond strength. Many monomer systems were tried with different percentages of initiator and accelerator at different ambient temperatures (Section 2.4.2). The bond stresses of specimens with the tentatively recommended percentages of initiator and accelerator (Fig. 2.2) showed satisfactory results. After the shearing bond test, cracks were observed in the concrete, as shown in Fig. 4.1.

The bond stress of an oven-dried specimen was found to be higher than that of an air-dried slab. From the test results (Table 4.1) of several specimens, e.g., PCOL-18 and 19, 23 and 24, 27 and 28, the bond stress of an oven-dried slab averaged 100 percent higher than for an air-dried. An interesting result was obtained from PCOL-58 and PCOL-59. The concrete slab of PCOL-59 was oven-dried at $210^{\circ}F$

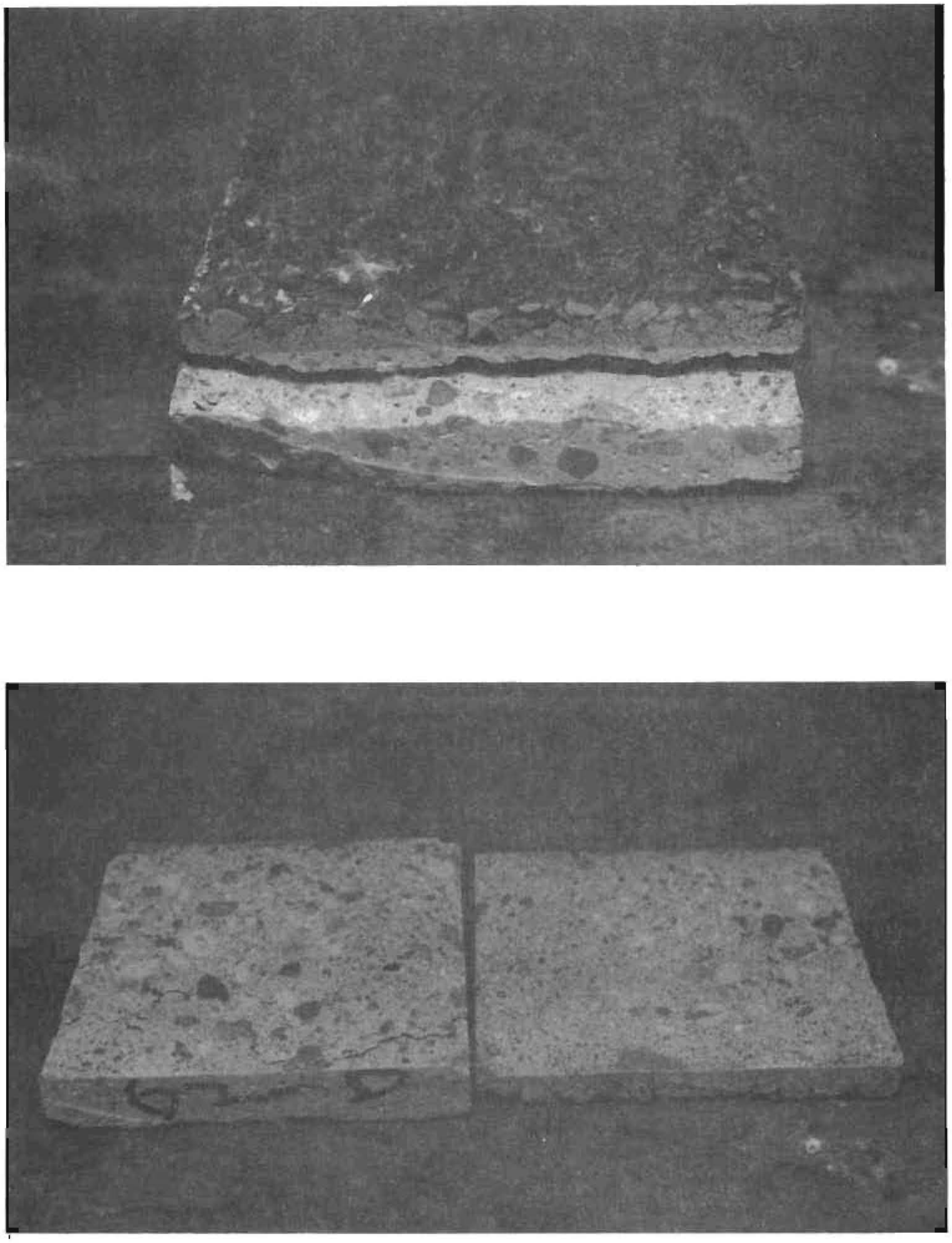


Fig. 4.1. Cracks in Concrete after Shearing Test.

for more than seven days, while the slab of PCOL-58 was air-dried except for being oven-dried at 210°F for 30 minutes prior to the application of the PC overlay. Both PC overlays were performed in a control room at 50°F. The bond stress was found to be about the same (520 psi). This indicated that a 30-min. drying might be sufficient to obtain adequate bond strength.

4.2 Freeze-Thaw Test

The freeze-thaw test is one of the most severe durability tests for concrete slabs. There are two possible mechanisms which contribute to the failure of specimens. First, if the PC overlay is unable to maintain its resistance to the penetration of water into the concrete during freezing and thawing, the water ponded on the surface greatly accelerates the deterioration because of the expansion caused by the formation of ice. The typical failure mechanism of ice expansion would likely produce scaling and/or spalling of the concrete (9). The other possible failure mechanism is the result of thermal volume change incompatibility. The coefficient of thermal expansion of polymethyl methacrylate is approximately ten times that of concrete, although the coefficient of expansion of polymer concrete is not so high. It has been theorized that delamination might occur at the interface of PC overlay and concrete because of the resulting shear caused by differential expansion (2).

Table 4.2 gives the monomer system used for both PCOL-27 and PCOL-28. The only difference between these two overlays was that the

Table 4.2. Monomer Systems for PCOL-27 and 28.

First Monomer Application, % by weight		Second Monomer Application, % by weight	
MMA	90%	MMA	36%
TMPTMA	10%	MMA Syrup	54%
BP	1.125%	TMPTMA	10%
DMPT	0.375%	BP	0.75%
		DMPT	0.125%

sand, pea gravel, and concrete slabs for PCOL-28 were air-dried outdoors for a minimum of seven consecutive sunny days with a high temperature in the 90s ^{o}F every day. The concrete slabs for control specimens and PCOL-27 were oven-dried at 210^{o}F for seven days and then cooled to room temperature ($\sim$ 75^{o}F) before the PC overlays were applied. Two specimens were made for each treatment. Test data were taken from the average of two specimens.

Figure 4.2 shows a control specimen before testing and at 38 cycles, when it no longer held the ponded water within the steel ring; the other control specimen failed at 36 cycles. Cracks were found at the bottom and sides of the specimens. Concrete spalled on the surface where water was ponded and could be easily removed by hand.

Figure 4.3 shows PCOL-27 before testing and after 100 cycles of freeze-thaw exposure. Water began to leak at 100 cycles, and the test was terminated. One or two pieces of pea gravel were found loose on the overlay surface. Fine cracks were found on the bottoms and sides of the concrete slabs, as shown in Fig. 4.4, while no appreciable cracks were detected on the overlay surfaces or at the interfaces between overlays and concrete slabs. The failure was in the concrete rather than in the overlay. This type of failure has been common in partial-depth polymer-impregnated concrete specimens. Apparently some moisture remains in the concrete after drying, and the expansion during freeze-thaw causes cracking.

Figure 4.5 shows PCOL-28 before testing and after 100 cycles of freeze-thaw exposure. Water was held within the steel ring

Fig. 4.2. Control Specimen at Zero and 38 Cycles of Freeze-Thaw Testing.

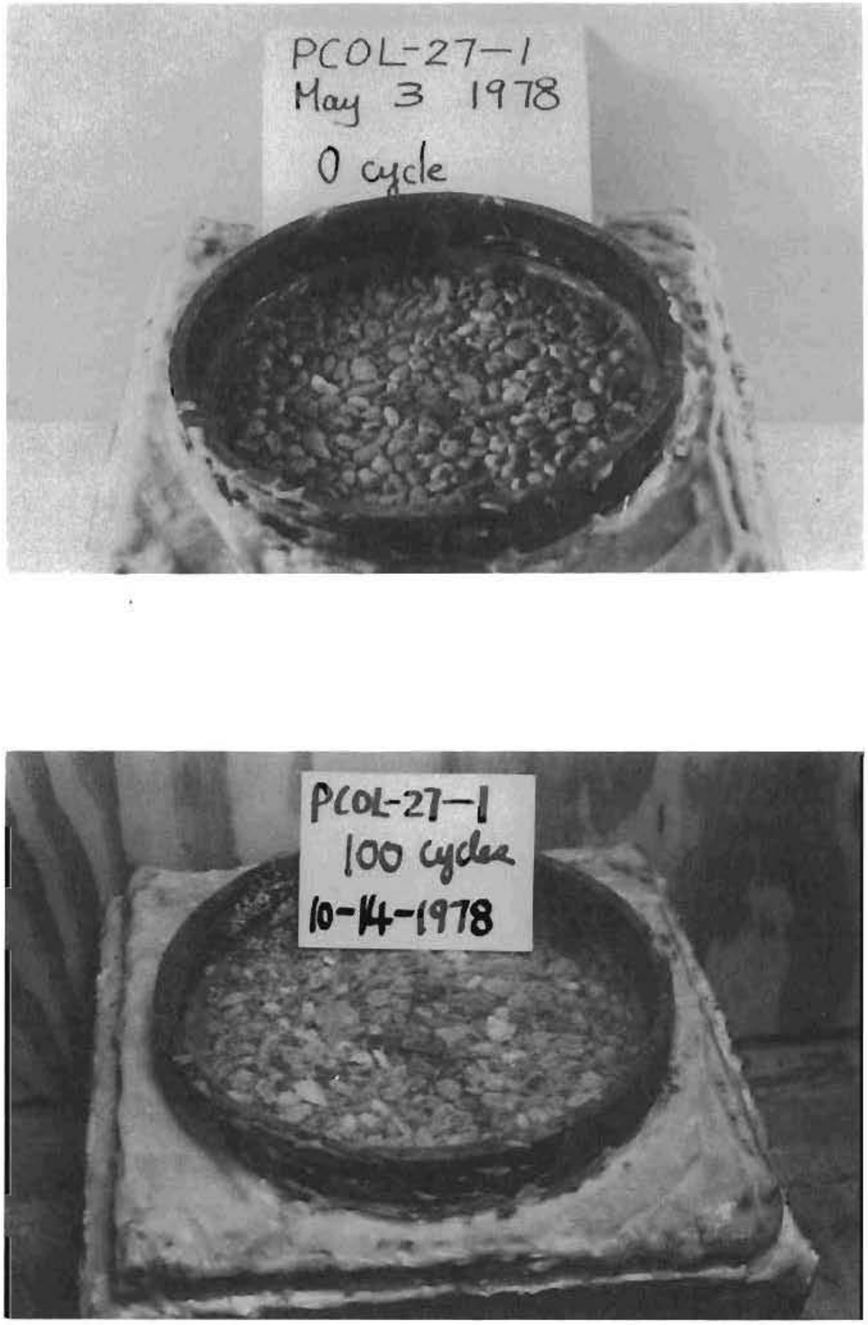


Fig. 4.3. PC Overlay-27 at Zero and 100 Cycles of Freeze-Thaw Testing.

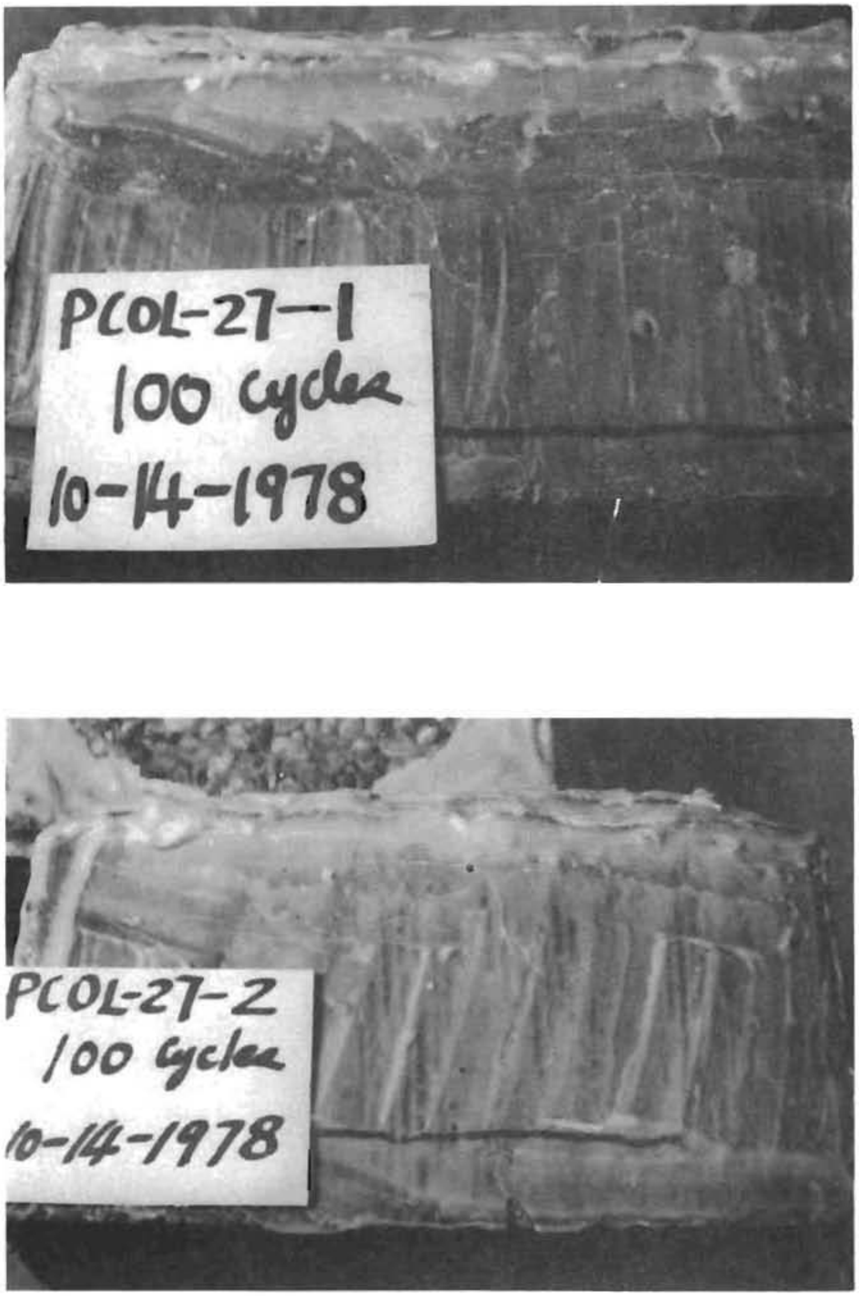


Fig. 4.4. Fine Cracks on the Sides of PC Overlay-27 Specimens.

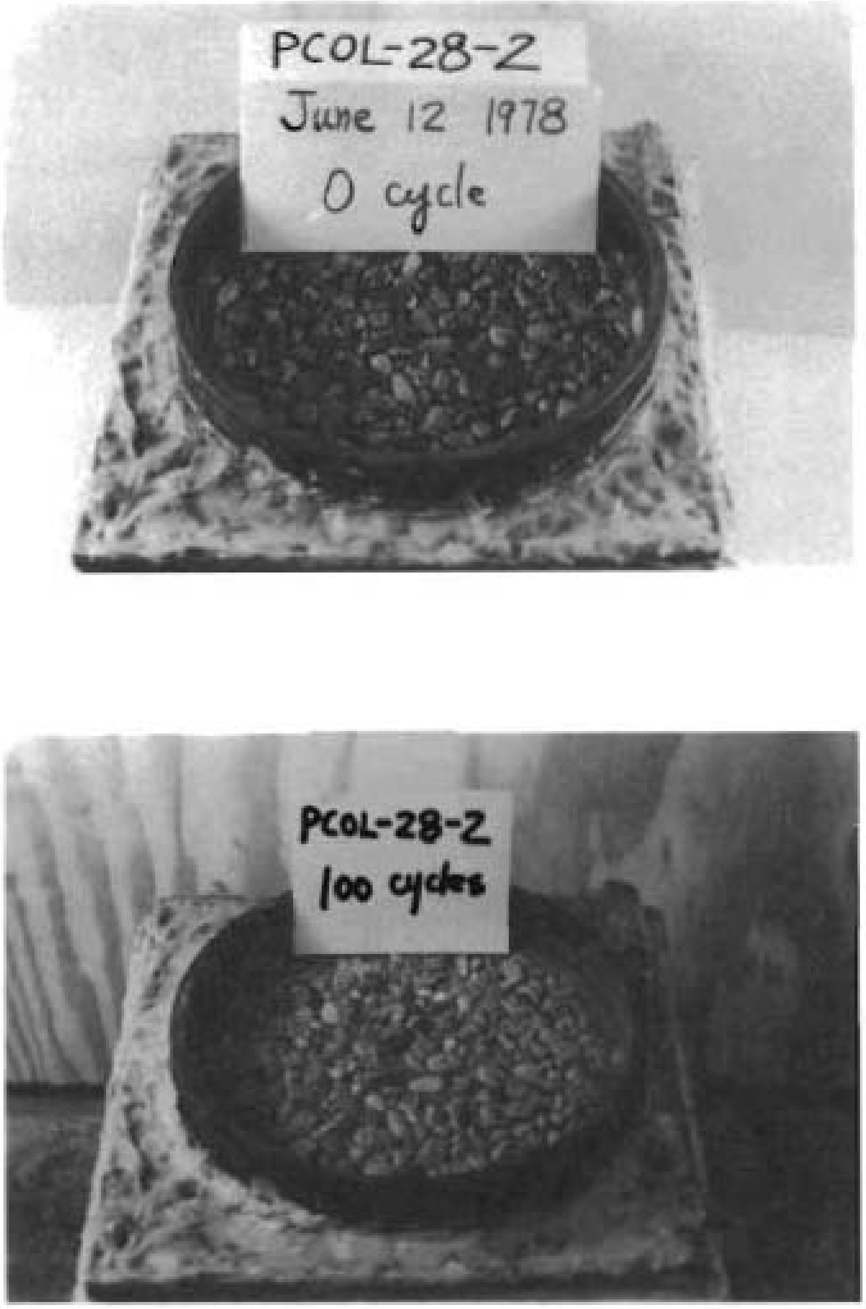


Fig. 4.5. PCOL-28 at Zero and 100 Cycles of Freeze-Thaw Testing.

throughout the test. Both specimens were in excellent condition. No appreciable scaling or cracking was detected. Apparently, PCOL-28 provided an effective waterproof surface for the concrete slab.

Figure 4.6 is a plot of strains measured near the top of specimens. The graph gives an indication of the volumetric stability of the specimens. The PCOL-27 specimens indicated fairly stable behavior, although not to the degree of PCOL-28. The absolute value of strains began to increase at approximately 64 cycles of freeze-thaw exposure. Temperature in the test chamber was reduced from 0°F to -20°F at 69 cycles to determine if it would accelerate the freeze-thaw deterioration. Apparently, this lower temperature did accelerate the volumetric instability of PCOL-27. However, both PCOL-28 specimens were volumetrically stable throughout the test. The control specimens of this test first contracted, then began to expand rapidly to about 4000 in./in. at about 15 cycles. The ponded water was lost at about 37 cycles.

No delamination was detected at the interface between the PC overlay and concrete for either set of PC overlay specimens. Apparently, the presence of PC overlay did provide a waterproof surface for the concrete slab. A properly designed monomer system is one of the major factors contributing to the durability of PC overlays, more than the dryness of the concrete slab. A PC overlay placed on an air-dried concrete slab which was dried for seven consecutive hot sunny days can perform as well as an overlay applied on a slab oven-dried at elevated temperatures for several days.

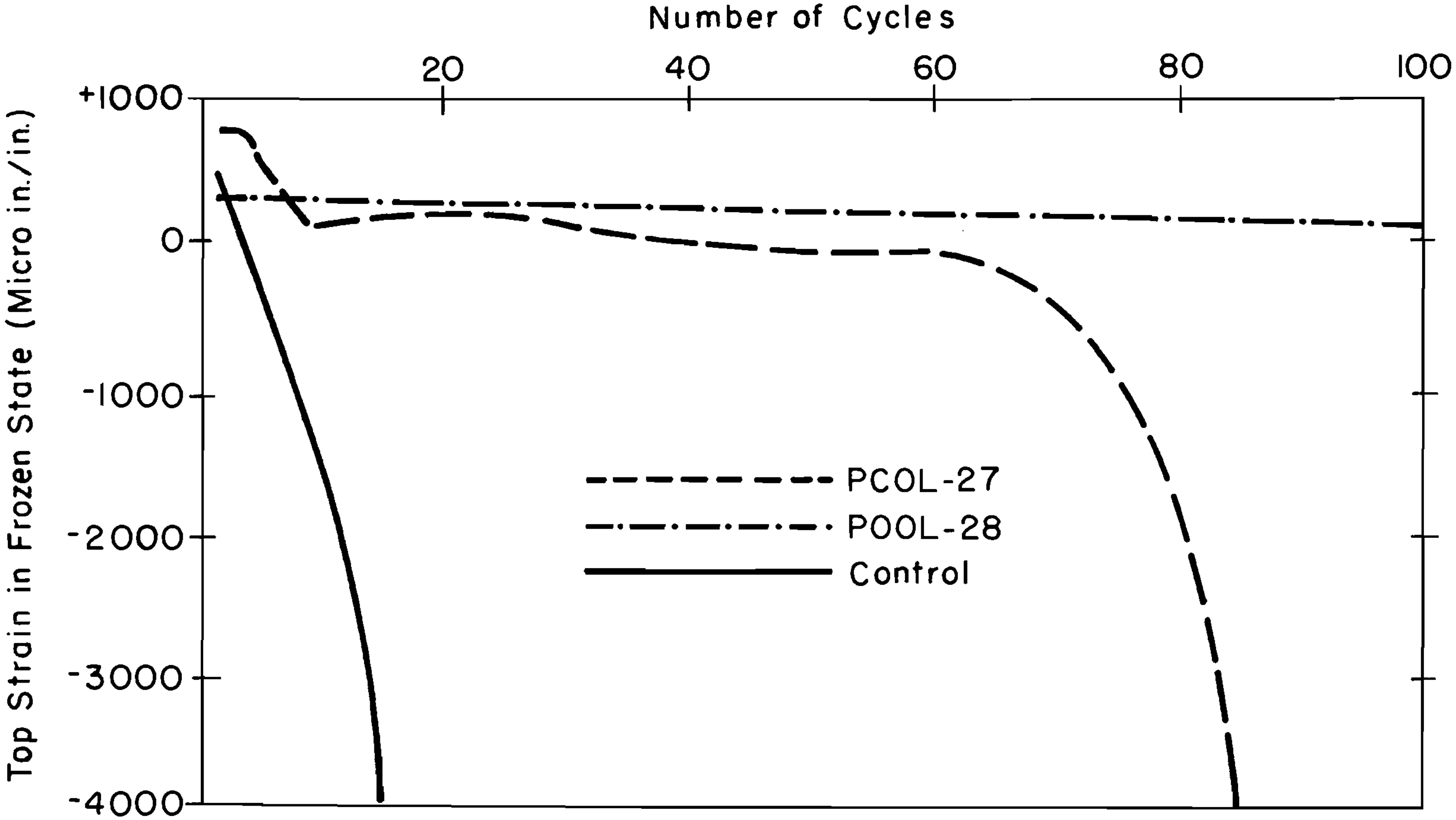


Fig. 4.6. Effect of Freeze-Thaw Cycles on Volumetric Stability.

PCOL-56 and PCOL-57, oven- and air-dried slabs, respectively, are still under test. The monomer system, given in Table 4.3, was chosen from the tentatively optimum combination of BP and DMPT, as shown in Fig. 2.2 (8). This test will be continued until failure. At the date of this writing (January 26, 1979), the specimens have undergone 91 cycles.

4.3 Water Tightness

The water tightness test is a rapid durability test for concrete slabs. It is used because so many problems associated with the concrete deterioration are associated with water intrusion into concrete. In a sense, the freeze-thaw test tests water tightness test; however, the water tightness test provides a measurable index of water penetration. It was theorized that PC overlays, which are capable of providing an effective seal against water penetration, could minimize deterioration problems of concrete, such as sealing, cracking, and corrosion of the reinforcing steel.

Two specimens for each overlay and two control specimens were subjected to the water tightness test, described in Section 3.4, before and after the freeze-thaw testing. A specimen immersed in the soaking vessel is shown in Fig. 4.7, and a split specimen with depth of penetration marked is shown in Fig. 4.8.

The results of the water tightness are summarized in Fig. 4.9. The bar graph includes the results of tests performed before and after the freeze-thaw testing. The specimens should be compared in three

Table 4.3. Monomer Systems for PCOL-56 and 57.

First Monomer Application, % by weight		Second Monomer Application, % by weight	
MMA	95%	MMA	48%
TMPTMA	5%	MMA Syrup	32%
BzP	0.925%	TMPTMA	2.5%
DMPT	0.46%	BA	17.5%
		BzP	0.8%
		DMPT	0.4%

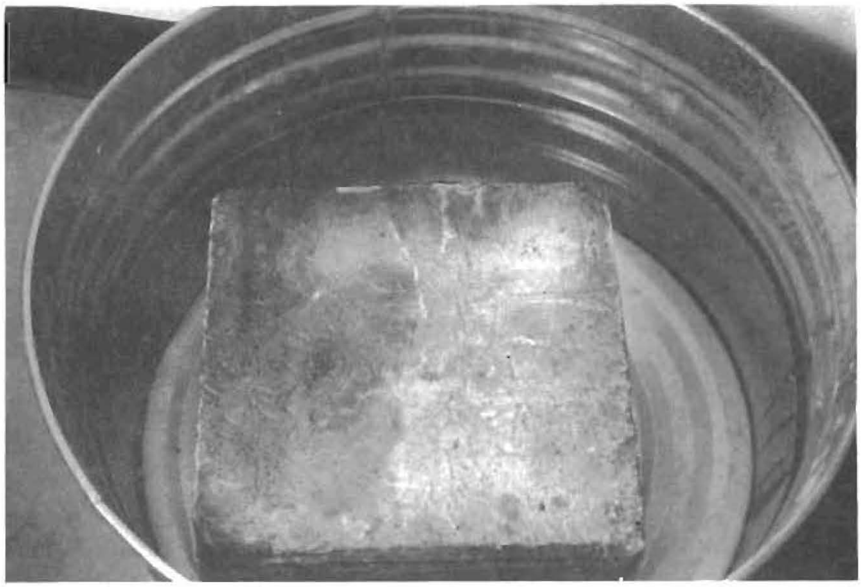


Fig. 4.7. Tank for Water Tightness Test.

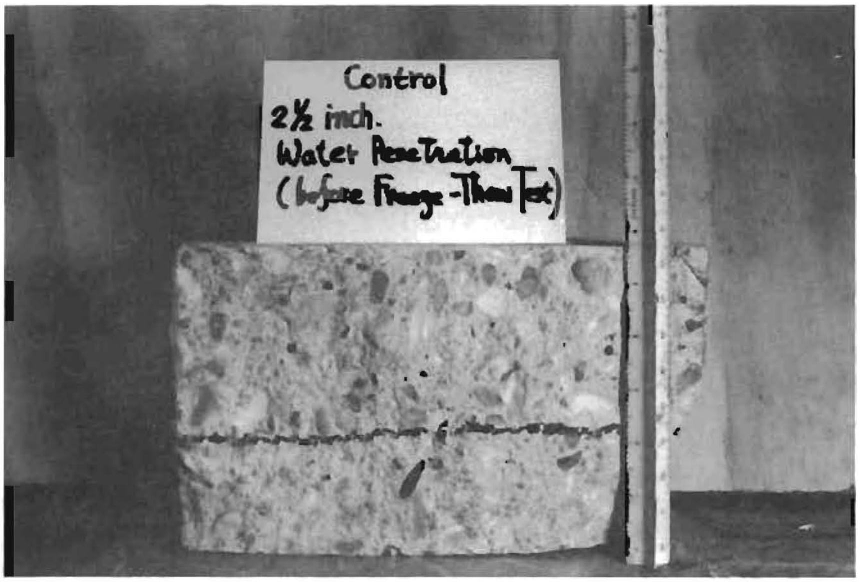


Fig. 4.8. Water Penetration from Water Tightness Test.

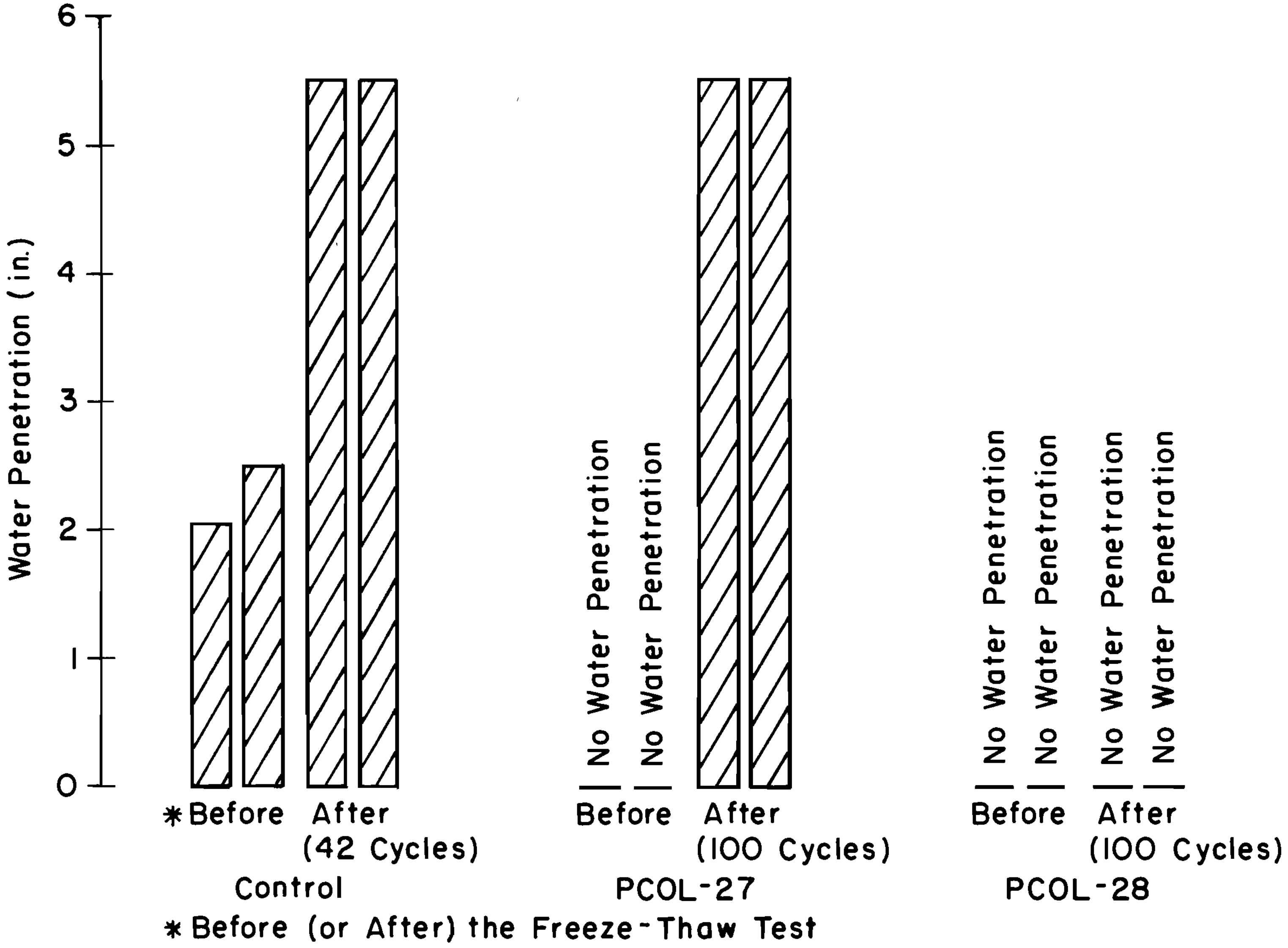


Fig. 4.9. Effect of Freeze-Thaw Exposure on Water Tightness.

ways: first, the overlay specimens with the control specimens; second, the specimens before and after the freeze-thaw tests; and third, the overall effectiveness of the PC overlays.

The treated specimens were more water tight than the control specimens, as expected. Before the freeze-thaw testing, water penetrated into the control specimens to an average depth of 2.28-in. with a 5-in. head. However, no water penetration was detected for PCOL-27 and PCOL-28. The PC overlay sealed the concrete effectively.

During the 42 cycles of freeze-thaw testing, both of the control specimens began to lose the ponded water; cracks were found on the bottom and side faces. The water tightness test showed complete water penetration through the specimens (5-1/2-in.). Both of the PCOL-27 specimens failed to hold the ponded water after 100 cycles of freeze-thaw. The PC overlay looked good, but water penetrated through the cracks on the side faces during the water tightness test. However, it was found that both PCOL-28 specimens, in which the concrete slabs were air-dried, were completely water tight after 100 cycles of freeze-thaw exposure. No water penetration was detected. Although this limited data do not permit any definite conclusions to be drawn, they do indicate that generally the PC overlay treatments displayed a promising consistency in regard to water tightness. A PC overlay specimen with an air-dried slab can work as well as one with an oven-dried slab. The most important factor is the proper selection of monomer system, especially the proper combination of initiator and accelerator, which is based on ambient temperature.

4.4 Sandblast Abrasion

All specimens subjected to the water tightness test were also evaluated by the sandblast abrasion test. Specimens were cut from the surface of the broken halves after water tightness testing. The sandblast abrasion test was selected to simulate the action of abrasive materials under traffic and to provide a laboratory evaluation of the relative resistance of the surface to abrasion.

The results of the sandblast abrasion study are summarized in Fig. 4.10. The values plotted are the weight losses due to abrasion. The exact measured values are not as significant as the relative values for slab to another slab. The values should also be compared in the same manner as for the water tightness test results.

The treated specimens showed improved durability over the controls, as expected. Before the freeze-thaw testing, the abrasion losses of the controls averaged 86 percent higher than those of the overlays. The abrasion losses of PCOL-27 and PCOL-28 were almost the same; i.e., 0.67-gm. and 0.64-gm., respectively. After the freeze-thaw testing, the abrasion losses of the controls were 528 percent higher than those of the treated. After 100 cycles of freeze-thaw exposure, the abrasion losses of PCOL-27 (Fig. 4.11) and PCOL-28 were only 21 percent and 50 percent higher, respectively, than the values before freeze-thaw exposure. However, for the controls (Fig. 4.12), the abrasion losses after 42 cycles of freeze-thaw exposure, when the specimens failed, were 356 percent times higher than the original values. Although this limited data do not permit definitive

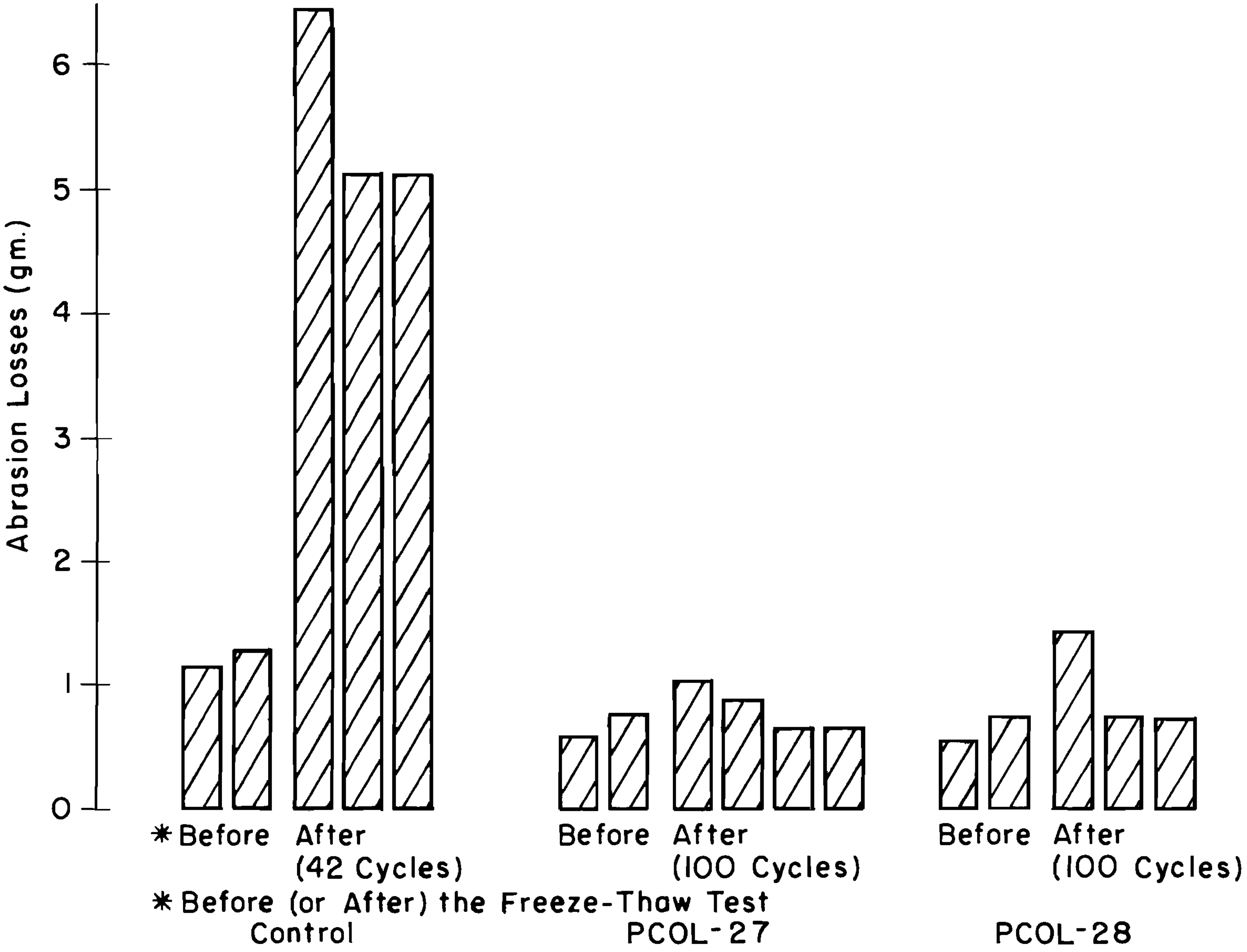


Fig. 4.10. Effect of Freeze-Thaw Exposure on Sandblast Abrasion Resistance.

Fig. 4.11. Sandblast Abrasion Specimen of PC Overlay-27 After 100 Cycles of Freezing and Thawing.

Fig. 4.12. Sandblast Abrasion Specimen of Control Concrete After 100 Cycles of Freezing and Thawing.

conclusions to be drawn, they indicate that the PC overlay treatment improves the abrasion resistance of the concrete slab even after 100 cycles of freeze-thaw exposure. Two important factors that will influence the success of abrasion resistance are the monomer system and aggregate. A proper monomer system will produce a sound polymer concrete and strong bond strength to hold the aggregate. Sound crushed rock and hard pea gravel will provide better abrasion and skid resistance than round and weak aggregate.

4.5 Skid Resistance

In addition to sealing a bridge deck against water penetration, the PC overlay may be used to provide better skid resistance, because of the surface formed by using the coarse aggregate. Table 4.4 gives the skid numbers taken from different surfaces on the bridge deck in Henrietta, Texas, on which a full-scale field PC overlay was performed (Section 5.4). Before the PC overlay was applied, the concrete surface of the bridge deck, which was about seven years old, had a skid number of 67. A higher value of skid resistance, 80, was obtained after the PC overlay application. A test area of overlay, which was applied one month earlier than the rest of the overlay, still showed a value of 75. A skid test performed on the asphalt pavement near the bridge deck showed a value of 55. Small, isolated slick spots, which were due to excess monomer, (Fig. 4.13), developed a skid value of 58. Generally, the application of PC overlay gave an improved skid resistance.

Table 4.4. Skid Numbers of Polymer Overlay.

Specimen	Skid Number
PC overlay	80
PC overlay after 1 month	75
Concrete surface before overlay application	67
PC overlay with slick surface	58
Old asphalt pavement	55

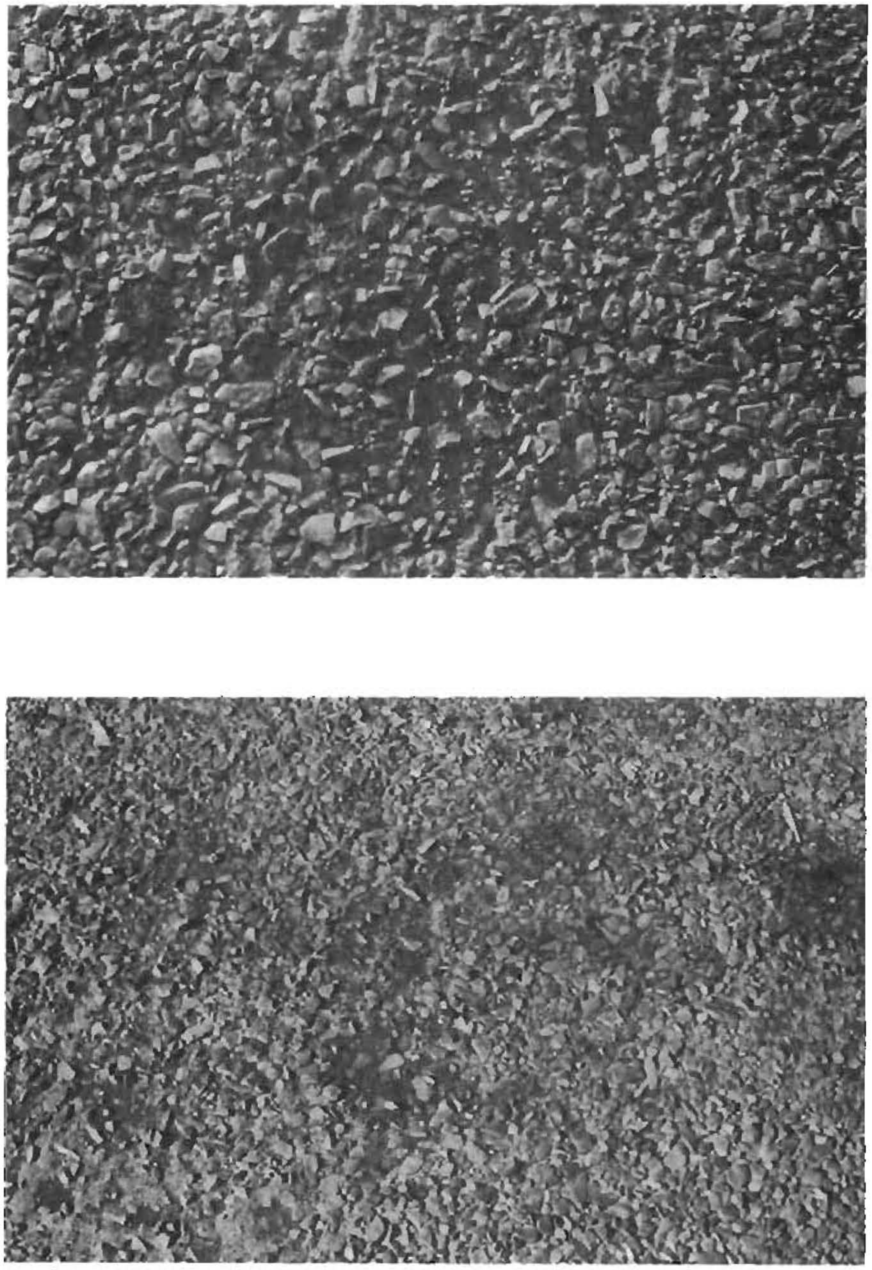


Fig. 4.13. PC Overlay with Slick Spots.

As a comparison, Table 4.5 shows the results of skid resistance tests performed on polymer-impregnated concrete surfaces in previous research (9). The monomer formulation and application procedure are given in reference 9.

Table 4.5. Skid Numbers of Polymer-Impregnated Concrete Surfaces (9).

Specimen No.	Skid Number at 0 Revolution	Skid Number at 70,000 Revolution
MMA (3a,b)	78	59
MMA LWAT (4a,b,c)	85	60
IBMA (6b,c)	73	59
IDMA (7a,b)	71	59
50% MMA 50% IDMA (8b,c)	76	61
MMA (5a,b)	86	60
MMA LWAT (9a,b,c)	81	64
IBMA (10b)	83	58
IDMA (11a,b)	75	58
CONTROL	75	57

CHAPTER 5

FIELD TESTS

5.1 Introduction

The main objective of this research was to develop a feasible and economical PC overlay to increase the durability of bridge decks. This chapter describes the development of PC overlays from simulated to actual field applications. The safety and storage of monomer as well as handling precautions are also discussed.

5.2 Safety, Storage, and Handling Precautions

Most monomers used to produce polymer concrete are volatile, flammable, and toxic liquids. The training of workmen in safe storage and handling procedures is of great importance. The manufacturers' instructions and safety procedures should be carefully followed (11). Generally, the initiator and accelerator are added to the monomer separately just prior to use, and they should never be mixed directly together because an explosive reaction could occur. Care should be exercised during handling of certain chemicals since excessive contact or breathing can cause ill effects. It is better to be equipped with respirators with chemical filters, safety eye glasses, and impervious gloves and aprons while handling and mixing monomers. Mixing should occur in a shaded, well-ventilated area free of ignition sources.

Stirring should be accomplished by using wooden paddles or bubbling with an air hose. Metal stirring rods should not be used in metal containers because of the danger of sparking. Equipment made of copper or copper alloys must not be used because of the possibility of chemical reaction which may cause accidental bulk polymerization. Once a solution is mixed, it should be used as quickly as possible. Any improper delay would cause the monomer to first gel and then solidify in the mixing can. Excess monomer containing both initiator and accelerator should be placed in open-top containers partially filled with aggregate. Loose-fitting plastic sheets should be draped over the top of the container during polymerization. After polymerization, the polymer can be disposed like any other material.

Monomer should be stored in the container in which it is shipped by the manufacturer. The storage temperature should not exceed 100^{o}F; perferably it should be 80^{o}F or lower. Ventilation should be provided to prevent buildup of monomer vapor concentrations in the storage room. In no case, should initiators and accelerators be stored in the same area. Dry chemical extinguishers should be kept near the storage area.

5.3 Simulated Field Application

5.3.1 Introduction

Following the promising results from laboratory tests, PC overlay applications were performed outdoors under sunlight to simulate an actual field condition. In order to decrease the loss due to evaporation (Section 2.3.3) and prevent premature polymerization due to high temperature and ultraviolet light in the summer, tests were performed either in the late afternoon, usually at 6 PM, or in the morning. The late afternoon was preferable because then the concrete slab had been solar-dried for almost 12 hours.

It was found that the amount of monomer required for outdoor tests without polyethylene film cover was almost 50 percent more than that for indoor tests (400-cc/sq. ft). Only 25 percent more was required of the overlay which was covered with a membrane during monomer soaking and curing.

Initially, the overlay tests were conducted on slabs 12-in. x 12-in. and 40-in. x 43-in. Later, tests on larger areas, 5-ft x 10-ft and 10-ft x 10-ft were performed on slabs on grade at the Balcones Research Center of The University of Texas at Austin.

5.3.2 Monomer System and Preparation

Monomers were mixed in a clean 10-gal. can and stirred with a wooden paddle. The initiator (BP) and accelerator (DMPT) were added just prior to monomer application. Two 1-gal. sprinkler cans were used to spread the monomer. Tests were performed around 6 PM. The monomer systems used in the field tests are shown in Table 5.1. Initially, the monomer system used for PCOL-32 was tried for the 5-ft x 10-ft area. The monomer system was satisfactory for the field test except for the approximately 2-hr curing time required. Therefore, an increase in the concentration of accelerator for both the first

Table 5.1. Monomer Systems Used in Field Tests.

	First Treatment Monomer System					Second Treatment Monomer System					
Test No.	MMA, %	TMP TMA, %	BP, %	DMPT, %	Soak Time (Min.)	MMA, %	MMA Syrup, %	TMP TMA, %	BA, %	BP, %	DMPT, %
PCOL-32	90	10	1.0	0.125	30	16	64	2-1/2	17-1/2	0.75	0.125
PCOL-39	90	10	1.0	0.25	30	16	64	2-1/2	17-1/2	0.75	0.25
PCOL-42	95	5	0.8	0.32	30	16	64	2-1/2	17-1/2	0.75	0.188
PCOL-55	95	5	1.0	0.5	30	48	32	2-1/2	17-1/2	0.8	0.4

All percentages are based upon weight. The initiator (BP) and accelerator (DMPT) are based upon 100% of the monomer.

and second monomer systems was used on a larger area, 10-ft x 10-ft (PCOL-39). Probably due to the large amount of monomer in the mixing can and delay in the sprinkling process, the second monomer began to gel in the container before the monomer application was finished. Also, the second monomer system was too viscous to flow adequately. The ratio between MMA and MMA syrup was changed to 3:2 after this test. From the laboratory tests, a tentatively optimum monomer system of 95 percent MMA and 5 percent TMPTMA for the first monomer application and of 48 percent MMA, 32 percent MMA syrup, 2-1/2 percent TMPTMA, and 17-1/2 percent BA for the second monomer application was tried in PCOL-55. The percentages of initiator and accelerator were 1.0 percent BP and 0.5 percent DMPT for the first monomer application and 0.8 percent BP and 0.4 percent DMPT for the second monomer application (Table 5.1).

5.3.3 Application Procedure

One of the major problems encountered in the field application of PC overlays is drying the slab decks. A hot, dry climate is much more suitable for field application since surface moisture could reduce the bond between the PC overlay and the concrete deck. Several consecutive hot, dry summer days would probably be adequate drying for most surface treatments. However, neither the maximum moisture content nor a suitable method for measuring the moisture has yet been established. Similar to those developed in the laboratory tests (Section 2.4.3), the field application procedures are described as follows:

1. The surface of the concrete was cleaned by brooming. Oil, grease, and other contaminants should be removed with solvent or, preferably, by sandblasting.
2. Screed guides, consisting of 1/2-in. x 1/2-in. wood strips, were bonded to the slab around the perimeter of the test area with latex caulking to confine the monomer (Fig. 5.2).
3. Approximately 2 psf of clear, well-graded concrete sand was spread on the slab and screeded to a thickness of approximately 1/4-in. (Fig. 5.1, 5.2).
4. Approximately 1.8 psf of pea gravel was applied to the top of sand to provide a total thickness of 3/8-in. to 1/2-in. (Fig. 5.3).
5. The overlay was compacted with a 6-in.-diameter by 20-in.-long concrete cylinder (Fig. 5.4) to embed the gravel into the sand layer (Section 2.3.6).
6. The first monomer application was sprinkled on the aggregate. The area was covered with a sheet of polyethylene film to minimize the evaporation and kept saturated with monomer, as required for 30 min.
7. The second monomer application was made with a sprinkler (Section 2.3.7). The area was recovered with polyethylene during polymerization.

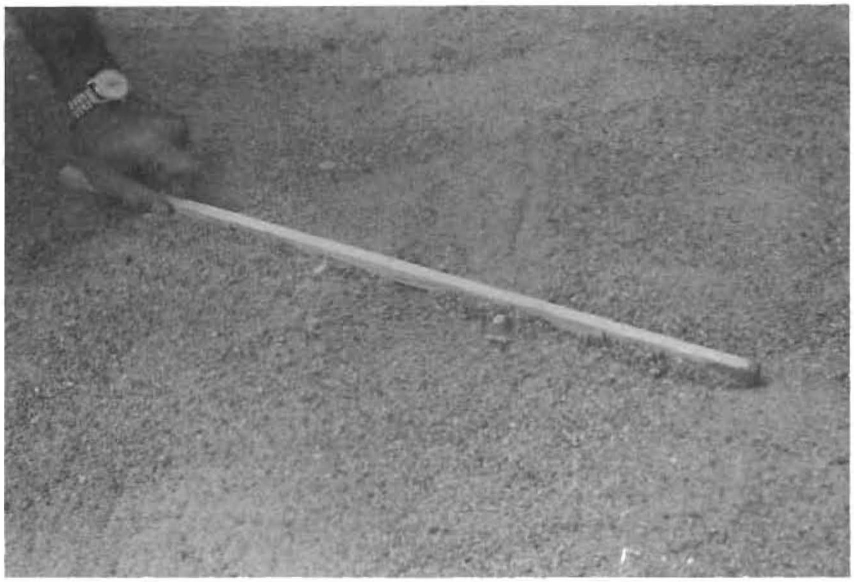


Fig. 5.1. Screeding Sand to 1/4-in. Thick.

Fig. 5.2. 1/4-in. Sand and 1/2-in. Wood Strip.

Fig. 5.3. Applying 1.8 psf of Pea Gravel to the Top of Sand.

Fig. 5.4. Compacting with 6-in. Diameter Concrete Cylinder.

5.3.4 Results

The main purpose of the outdoor field tests at the Balcones Research Center was to evaluate the procedure developed in the laboratory. The first field test (PCOL-32), which had an area of 5-ft x 10-ft, indicated a good correspondence between laboratory and field work. A larger area of 10-ft x 10-ft was tried in the next test. In the second field test (PCOL-39), which required twice as much monomer and more time to apply it, the second monomer application began to gel in the mixing can before it was all applied. Also, the second monomer application proved to be too viscous to completely fill the voids between aggregate and formed a glossy polymer on the surface (Fig. 5.5). As a result of this test, the ratio of MMA and MMA syrup was changed to 3:2. This test also showed that once the monomer was mixed, it should be applied as soon as possible. For large-scale application, the monomer should be mixed in-line at the nozzle to eliminate the danger of premature polymerization.

The pot life of a monomer is defined as the length of time when the monomer, initiator, and accelerator are mixed together to the peak exotherm temperature. A gel begins to form at about one-third to one-half of the pot life. A pot life of 30 minutes was usually preferred for overlays. This gives 10 to 15 minutes of working time for the second monomer application. Usually, the pot life of monomer in polymer concrete is about 1.5 to 2 times longer than that of pure monomer due to the absorption of heat by the aggregate, especially for the large surface-to-volume ratio of thin PC overlays.

Fig. 5.5. PC Overlay after Polymerization.

Overall, the small-scale field tests showed satisfactory results and led to the planning of a full-scale overlay on a bridge deck at Henrietta, Texas.

5.4 Field Work in Henrietta, Texas

5.4.1 Introduction

The Center for Highway Research at The University of Texas at Austin in conjunction with the Texas State Department of Highways and Public Transportation has conducted numerous field repairs throughout the state of Texas with polymer-concrete materials. This section discusses the implementation of a polymer-concrete overlay on a portland cement concrete bridge deck near the intersection of U.S. 287 and Texas 148 in Henrietta, Texas. Figure 5.6 shows the location of the bridge, which is about 40-ft wide and 120-ft long with a transverse slope of 1/8-in. per ft (Fig. 5.7) and is level longitudinally. The bridge was chosen for the PC overlay test since it is on an exit road from U.S. 287 to the junction of Texas 148. Many heavy trucks use this exit to reach a nearby truck stop, as shown in Fig. 5.8. Also, this bridge is located in the northern part of the state, where subfreezing weather occurs regularly throughout the winter. The PC overlay was applied to the bridge to provide improved skid resistance and durability.

In order to familiarize the highway crew with the application procedure, a demonstration 9.3-ft x 40-ft PC overlay was put down on October 18, 1978. The weather was clear and sunny with a 10 mph wind and temperatures in the mid 80s (^{o}F). The rest of the bridge, about

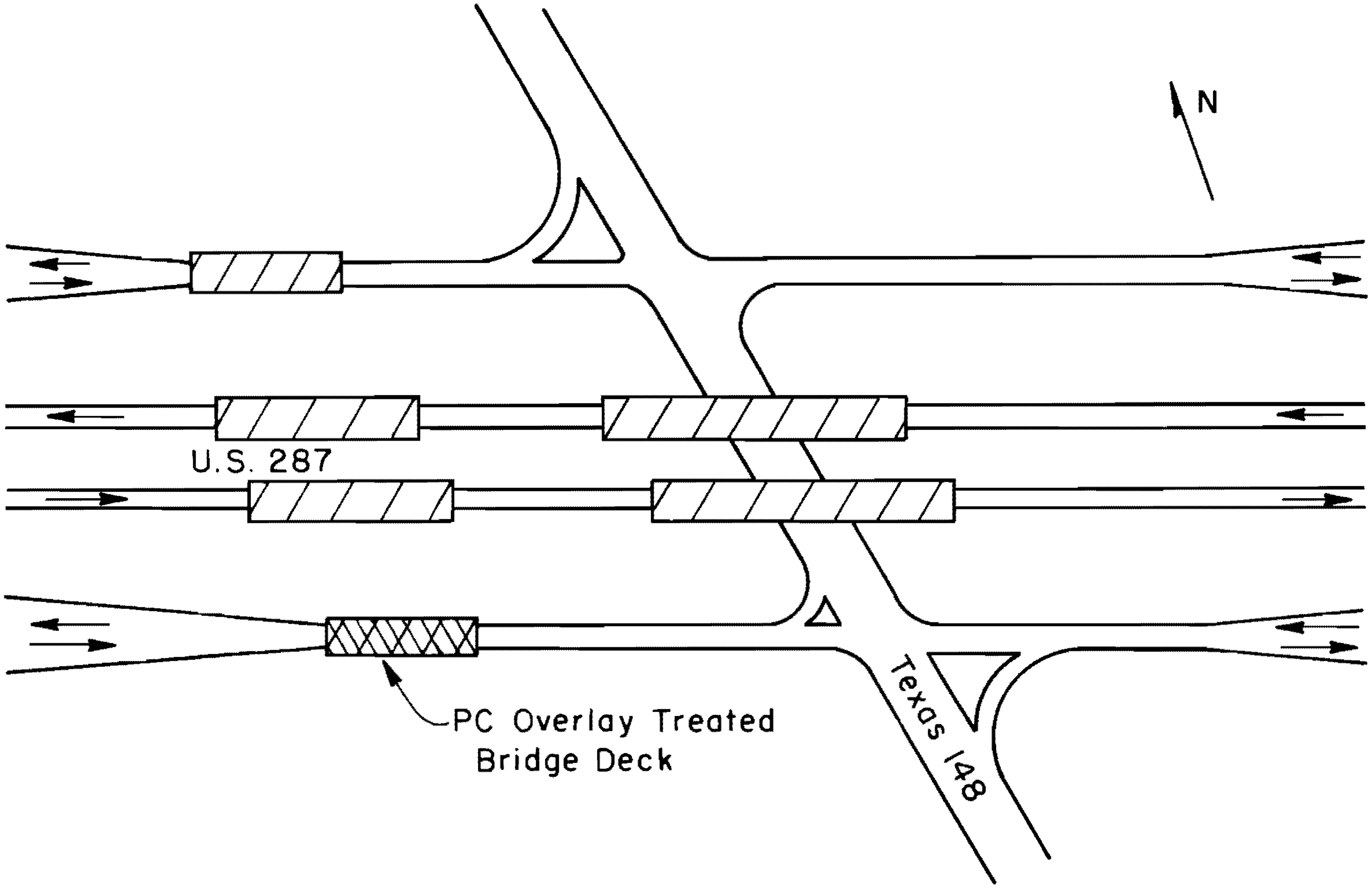


Fig. 5.6. Location of the Treated Bridge.

Fig. 5.7. Transverse Slope of 1/8-in. per ft.

Fig. 5.8. A View of the Bridge from U.S. 287.

4127-sq. ft, was overlaid November 27 to December 1, 1978. The weather was clear and sunny with a 10 to 25 mph wind and temperatures in the mid 50s (^{o}F).

5.4.2 Application Procedure

Localized surface contamination was cleaned with gasoline (Fig. 5.9), and the bridge deck was swept clean. An 8-ft x 4-ft butane-fired infra-red heater (Fig. 5.10) was pulled slowly back and forth over the area to dry the surface of the concrete deck for about 30 min. After the concrete cooled to the ambient temperature, concrete sand was spread on the deck. The sand was wet, and it was dried with the heater (Fig. 5.11). The sand was removed to the side and the concrete deck was redried. A 1/2-in.-thick screed guide, to which latex caulking compound had been applied (Figs. 5.12, 5.13), was nailed (Fig. 5.14) around the perimeter to confine the monomer from leaking. The dry concrete sand was re-spread on the deck (Fig. 5.15) and screeded to a depth of approximately 1/4-in. with a steel bar (Fig. 5.16). Approximately 1.8 psf of dry, crushed aggregate was spread on top of the sand (Fig. 5.17) to produce a total thickness of 3/8-in. to 1/2-in. The gradations of the sand and coarse aggregate used are shown in Table 5.2. A 6-in.-diameter concrete cylinder was rolled over the area to embed the coarse aggregate into the sand (Fig. 5.18).

At 3:00 PM, the first monomer application was applied on the aggregate with a sprinkling bar (Fig. 5.19). The amount of monomer

Fig. 5.9. Surface Contamination Cleaned Off.

Fig. 5.10. Concrete Deck Dried by Blackwall Infra-Red Asphalt Patcher IR-96.

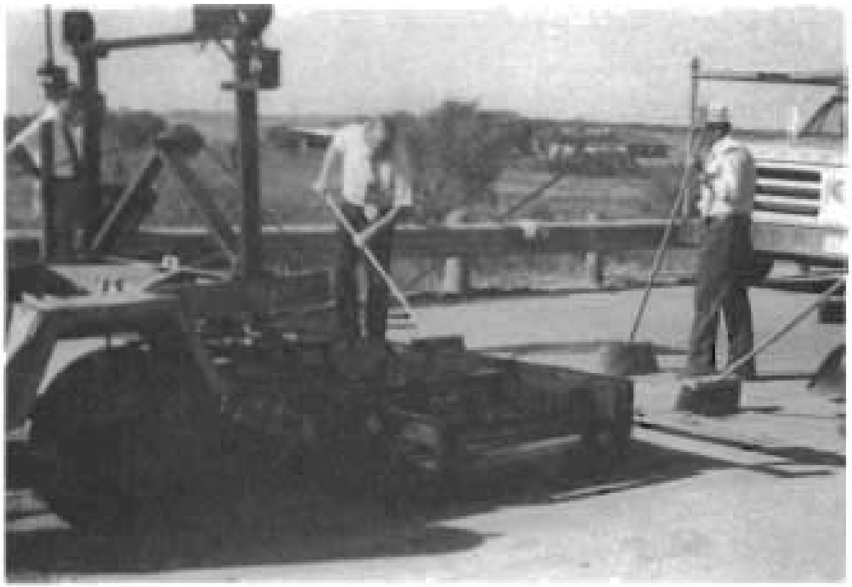


Fig. 5.11. Concrete Sand Dried by Blackwall Infra-Red Asphalt Patches IR-96

Fig. 5.12. 1/2 in. Thick Wood Strip Caulked with Latex.

Fig. 5.13. Bonding Wood Strip to the Deck.

Fig. 5.14. Nailing the Wood Strip.

Fig. 5.15. Spreading the Concrete Sand.

Fig. 5.16. Screeding the Sand to 1/4-in. Thickness.

Fig. 5.17. Spreading the Coarse Aggregate.

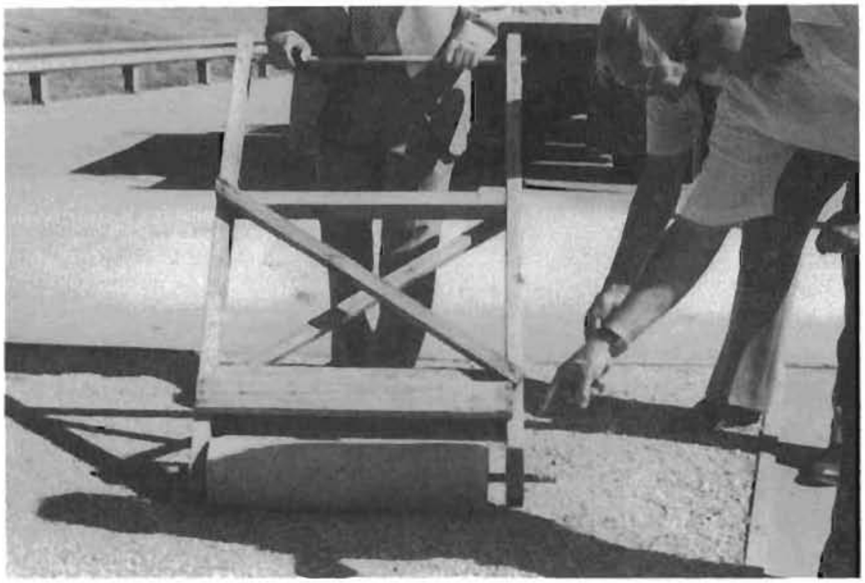


Fig. 5.18. Rolling the Aggregate with Concrete Cylinder (Appendix).

Table 5.2. Gradation

Sieve Size	Sand From Colorado River Bottom, % Passed by Weight	Sand from Henrietta, Texas % Passed by Weight
No. 4	99	90
No. 8	91	79
No. 16	77	67
No. 30	54	50
No. 50	22	17
No. 100	4	3

Sieve Size	Pea Gravel from Colorado River Bottom, % Passed by Weight	Crushed Pea Gravel from Henrietta, Texas, % Passed by Weight
3/4-in.	100	100
3/8-in.	80	66
1/4-in.	9	20
1/8-in.	2	3

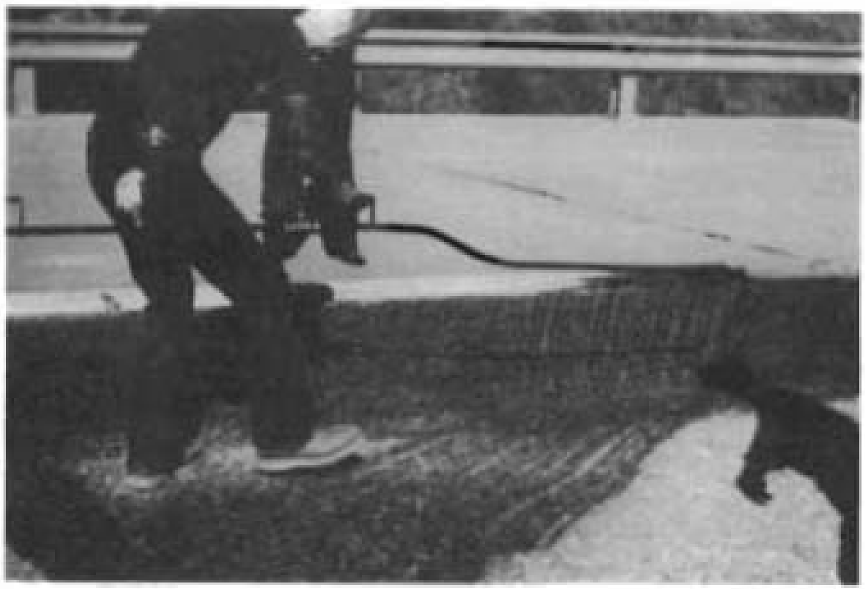


Fig. 5.19. Monomer Applied with Sprinkling Bar (Appendix).

was pre-calculated and mixed in a 55-gal. drum placed on a truck about 5-ft above the bridge deck (Fig. 5.20). This produced a pressure head sufficient to sprinkle the monomer by gravity. The initiator and accelerator were added into the mixing drum just prior to use. The volume of monomer prepared in the mixing drum was determined by the flow rate of the spray bar. Once the initiator and accelerator were added to the monomer, it was necessary to apply the monomer solution as soon as possible. In this test, the total monomer solution required for the first monomer application, 38.8 gal., was divided into two equal parts in two drums. After emptying the first drum, initiator and accelerator were added to the monomer in the second drum. It took about 5 minutes to make the first monomer application. The area was covered with polyethylene during soaking (Fig. 5.21). After 30 minutes of soaking with the first monomer application, the second monomer application was made. It took about 3 minutes to apply the 9.8-gal. second monomer application, which was prepared in a 55-gal. drum. The area was again covered with polyethylene during curing. At 5:30 PM, or 2.5 hours after the first monomer application was made, the PC overlay was opened to traffic (Fig. 5.22).

The rest of the overlay was applied from November 27 to December 1, 1978. An improved monomer spray bar with wheels was used (Fig. 5.23). It gave a more uniform monomer loading. Also, the polyethylene cover was framed as shown in Fig. 5.24. Figure 5.25

Fig. 5.20. Monomer Mixed in 55-gal. Drums Loaded on a Truck (Appendix).

Fig. 5.21. PC Overlay Covered with Polyethylene Film While Soaking and Curing.

Fig. 5.22. Open to Traffic After 2-1/2 Hours.

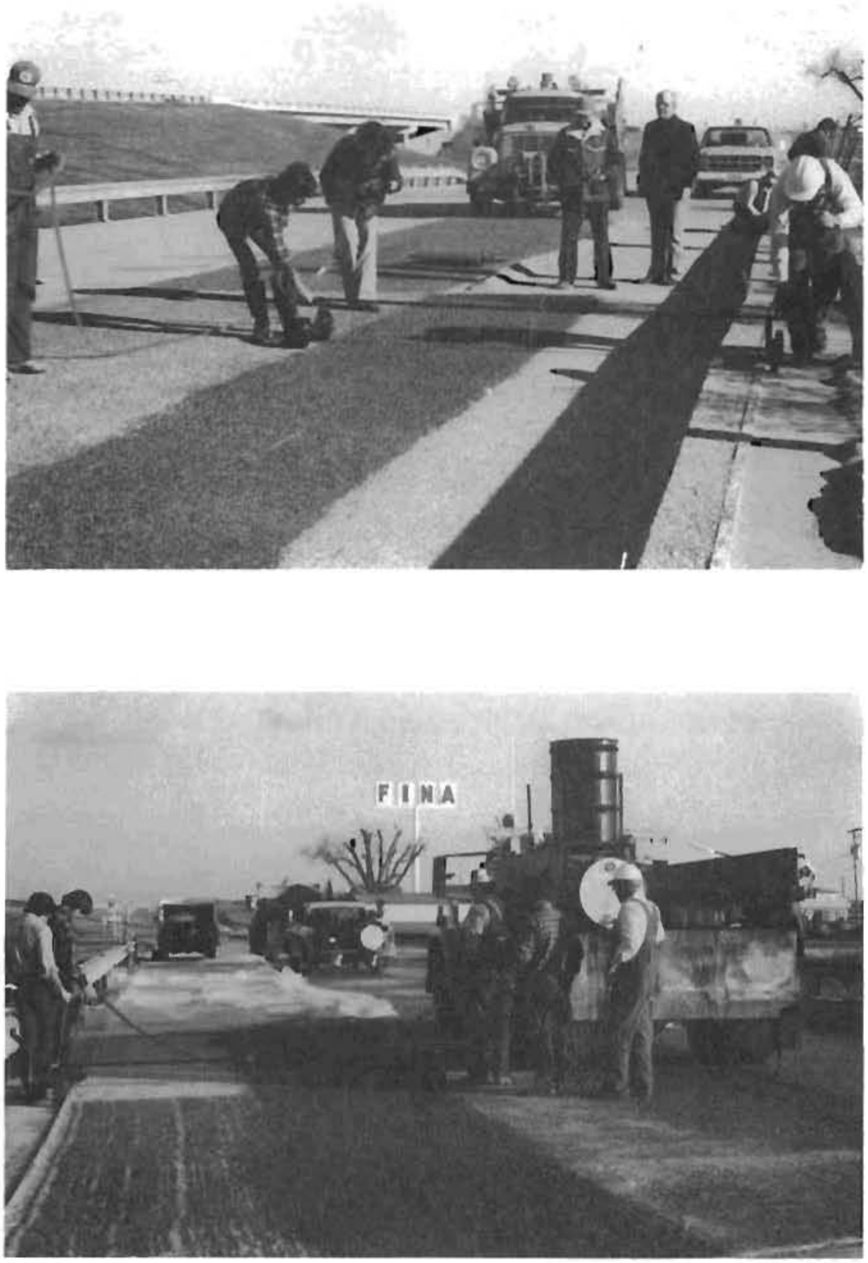


Fig. 5.23. Spray Bar with Wheels (Appendix).

Fig. 5.24. Wood-Framed Polyethylene Film Cover.

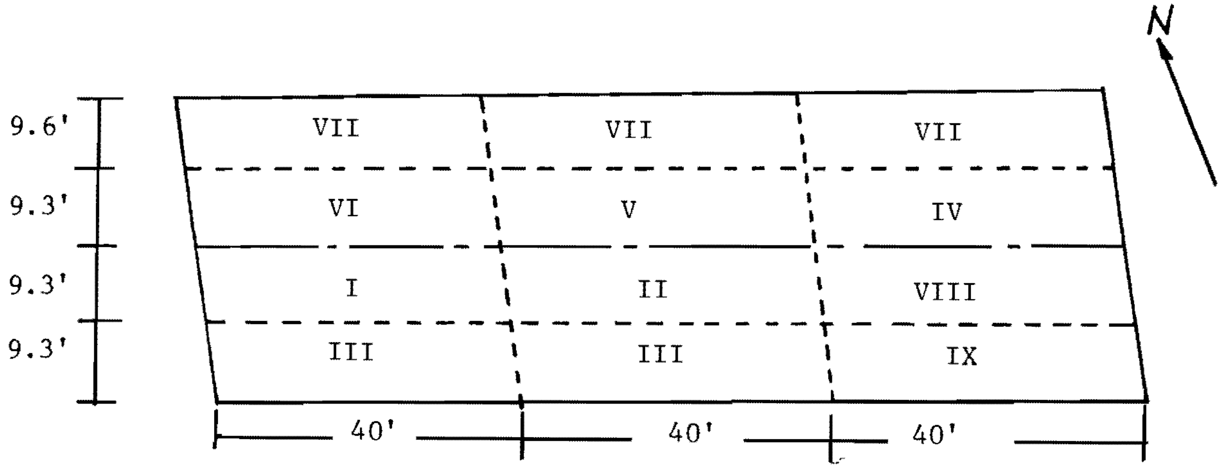


Fig. 5.25. Overlay Sections on Bridge Deck.

shows the 12 areas over where the overlays were applied. Each area was about 9 - ft 3-in. by 40-ft. Tables 5.3 to 5.12 give the monomer systems used in the field test.

5.4.3 Results

In the first overlay test section, the initial estimate, 38.8 gal. for the first monomer application, proved to be about 5 percent more than required. Excess monomer flowed over the wood strip at the low side of the overlay. Dry sand was used to soak up excess monomer and was removed before polymerization. Some small areas over-saturated with monomer were covered with dry aggregate to avoid forming slick spots (Fig. 5.26). A small amount of coarse aggregate was not completely bonded to the overlay and quickly came off after the bridge was opened to traffic.

In the other overlay sections, the first monomer application was reduced to 33.6 gal. and the second monomer application was increased to 12.1 gal. (45.8 gal. total). This proved to be about the right amount required for a 9.3-ft x 40-ft section (i.e., 0.986 lb/sq. ft).

The spray bar proved satisfactory, and the viscosity of the second monomer application appeared to be satisfactory.

The PC overlay was structurally sound and skid-resistant with a thickness of 3/8-in. to 1/2-in., as shown in Fig. 5.27. Several 6-in.-diameter cores were taken from the bridge deck and evaluated by SDHPT D-9 (Ref. 28). The general character and thickness of the PC

Table 5.3. Monomer Systems for Field Work (% by weight).

	First Monomer System Treatment					Second Monomer System Treatment						
Test No.	MMA	TMP TMA	BzP	DMPT	Soak Time (min.)	MMA	MMA Syrup	TMP TMA	BA	BzP	DMPT	Temp. (^oF)
I	95	5	0.95	0.4	30	48	32	2-1/2	17-1/2	0.75	0.375	85
II	95	5	1.27	0.78	30	48	32	2-1/2	17-1/2	1.75	0.95	50
III	95	5	1.6	0.87	30	48	32	2-1/2	17-1/2	1.75	0.95	50
IV	95	5	1.45	0.78	30	48	32	2-1/2	17-1/2	1.35	0.70	65
V	95	5	1.45	0.78	30	48	32	2-1/2	17-1/2	1.60	0.87	55
VI	95	5	1.60	0.87	30	48	32	2-1/2	17-1/2	1.75	0.95	50
VII	95	5	1.60	0.87	30	48	32	2-1/2	17-1/2	1.60	0.87	55
VIII	95	5	1.35	0.70	30	48	32	2-1/2	17-1/2	1.35	0.70	65
IX	95	5	1.35	0.70	30	48	32	2-1/2	17-1/2	1.45	0.78	60

Table 5.4. Monomer System of Section I.

		9.3' x 40'			
		liter	gallon	kg	lb
First Monomer Application	MMA	137.05	36.21	130.2	286.4
	TMPTMA	6.46	1.71	6.85	15.08
	BP	2.86	0.75	3.255	7.161
	DMPT	0.593	0.157	0.548	1.206
	Total 1	147.0	38.8	140.9	309.8
Second Monomer Application	MMA	17.62	4.66	16.74	36.83
	MMA Syrup	10.94	2.89	11.16	24.55
	TMPTMA	0.823	0.217	0.872	1.918
	BA	6.827	1.803	6.103	13.43
	BP	0.574	0.152	0.654	1.439
	DMPT	0.141	0.037	0.131	0.288
	Total 2	36.9	9.8	35.7	78.5
Total 1 + Total 2		183.9	48.6	176.6	388.30

Table 5.5. Monomer System of Section II.

		9.3' x 40'			
		liter	gallon	kg	lb
First Monomer Application	MMA	129.22	34.14	122.76	270.07
	TMPTMA	6.10	1.61	6.46	14.21
	BP	3.60	0.95	4.103	9.03
	DMPT	1.09	0.288	1.01	2.22
	Total 1	140.01	36.99	134.33	295.53
Second Monomer Application	MMA	19.58	5.17	18.60	40.92
	MMA Syrup	12.16	3.21	12.40	27.28
	TMPTMA	0.914	0.241	0.97	2.13
	BA	7.577	2.002	6.781	14.92
	BP	1.487	0.393	1.695	3.73
	DMPT	0.398	0.105	0.368	0.810
	Total 2	42.12	11.12	40.81	89.79
Total 1 + Total 2		182.13	48.11	175.14	385.32

Table 5.6. Monomer System of Section III.

		9.3' x 80'			
		liter	gallon	kg	lb
First Monomer Application	MMA	234.94	62.068	223.20	491.04
	TMPTMA	11.08	2.920	11.74	25.84
	BP	8.24	2.180	9.40	20.68
	DMPT	2.210	0.584	2.04	4.50
	Total 1	256.47	67.75	246.38	542.06
Second Monomer Application	MMA	43.08	11.38	40.92	90.02
	MMA Syrup	26.74	7.06	27.28	60.02
	TMPTMA	2.010	0.54	2.14	4.68
	BA	16.58	4.38	14.92	32.82
	BP	3.272	0.864	3.730	8.206
	DMPT	0.876	0.232	0.810	1.782
	Total 2	92.56	24.46	89.80	197.53
Total 1 + Total 2		349.03	92.21	336.18	739.59

Table 5.7. Monomer System of Section IV.

		9.3' x 40'			
		liter	gallon	kg	lb
First Monomer Application	MMA	117.47	31.034	111.60	245.52
	TMPTMA	5.54	1.46	5.87	12.92
	BP	3.735	0.987	4.258	9.369
	DMPT	0.991	0.262	0.916	2.016
	Total 1	127.74	33.74	122.64	269.83
Second Monomer Application	MMA	21.54	5.69	20.46	45.01
	MMA Syrup	13.37	3.53	13.64	30.01
	TMPTMA	1.005	0.266	1.07	2.34
	BA	8.288	2.190	7.459	16.41
	BP	1.262	0.333	1.439	3.165
	DMPT	0.323	0.085	0.298	0.656
	Total 2	45.79	12.09	44.37	97.59
Total 1 + Total 2		173.53	45.83	167.01	367.42

Table 5.8. Monomer System of Section V.

		9.3' x 40'			
		liter	gallon	kg	lb
First Monomer Application	MMA	117.47	31.034	111.60	245.52
	TMPTMA	5.54	1.46	5.87	12.92
	BP	3.735	0.987	4.258	9.369
	DMPT	0.991	0.262	0.916	2.016
	Total 1	127.74	33.74	122.64	269.83
Second Monomer Application	MMA	21.54	5.69	20.46	45.01
	MMA Syrup	13.37	3.53	13.64	30.01
	TMPTMA	1.005	0.266	1.07	2.34
	BA	8.288	2.190	7.459	16.41
	BP	1.496	0.395	1.705	3.751
	DMPT	0.401	0.106	0.370	0.815
	Total 2	46.10	12.18	44.70	98.34
Total 1 + Total 2		173.84	45.92	167.34	368.17

Table 5.9. Monomer System of Section VI.

		9.3' x 40'			
		liter	gallon	kg	lb
First Monomer Application	MMA	117.47	31.034	111.60	245.52
	TMPTMA	5.541	1.46	5.87	12.92
	BP	4.12	1.09	4.70	10.34
	DMPT	1.105	0.292	1.02	2.25
	Total 1	128.24	33.88	123.19	271.03
Second Monomer Application	MMA	21.54	5.69	20.46	45.01
	MMA Syrup	13.37	3.53	13.64	30.01
	TMPTMA	1.005	0.27	1.07	2.34
	BA	8.29	2.190	7.46	16.41
	BP	1.636	0.432	1.865	4.103
	DMPT	0.438	0.116	0.405	0.891
	Total 2	46.28	12.23	44.90	98.76
Total 1 + Total 2		174.52	46.11	168.09	369.79

Table 5.10. Monomer System of Section VII.

		9.59' x 120'			
		liter	gallon	kg	lb
First Monomer Application	MMA	363.42	95.98	345.24	759.53
	TMPTMA	17.15	4.49	18.18	39.93
	BP	12.77	3.34	14.535	31.99
	DMPT	3.418	0.898	3.165	6.905
	Total 1	396.80	104.72	381.14	838.36
Second Monomer Application	MMA	66.63	17.60	63.29	139.25
	MMA Syrup	41.37	10.93	42.20	92.83
	TMPTMA	3.11	0.082	3.30	7.25
	BA	25.64	6.773	23.076	50.767
	BP	4.627	1.222	5.275	11.604
	DMPT	1.240	0.328	1.147	2.524
	Total 2	139.82	36.94	138.29	304.23
Total 1 + Total 2		536.62	141.66	519.43	1142.59

Table 5.11. Monomer System of Section VIII.

		9.3' x 40'			
		liter	gallon	kg	lb
First Monomer Application	MMA	117.47	31.034	111.60	245.52
	TMPTMA	5.541	1.46	5.87	12.92
	BP	3.478	0.919	3.965	8.722
	DMPT	0.889	0.235	0.822	1.809
	Total 1	127.38	33.65	122.26	268.97
Second Monomer Application	MMA	21.54	5.69	20.46	45.01
	MMA Syrup	13.37	3.53	13.64	30.01
	TMPTMA	1.005	0.266	1.07	2.34
	BA	8.288	2.190	7.459	16.41
	BP	1.262	0.333	1.439	3.165
	DMPT	0.323	0.085	0.298	0.656
	Total 2	45.79	12.09	44.37	97.59
Total 1 + Total 2		173.17	45.74	166.63	366.56

Table 5.12. Monomer System of Section IX.

		9.3' x 40'			
		liter	gallon	kg	lb
First Monomer Application	MMA	117.47	31.034	111.60	245.52
	TMPTMA	5.541	1.46	5.87	12.92
	BP	3.478	0.919	3.965	8.722
	DMPT	0.889	0.235	0.822	1.809
	Total 1	127.38	33.65	122.26	268.97
Second Monomer Application	MMA	21.54	5.69	20.46	45.01
	MMA Syrup	13.37	3.53	13.64	30.01
	TMPTMA	1.005	0.266	1.07	2.34
	BA	8.288	2.190	7.459	16.41
	BP	1.355	0.358	1.546	3.399
	DMPT	0.360	0.095	0.332	0.731
	Total 2	45.92	12.13	44.51	97.90
Total 1 + Total 2		173.30	45.78	166.77	366.87

Fig. 5.26. Dry Aggregate Used to Soak the Excess Monomer.

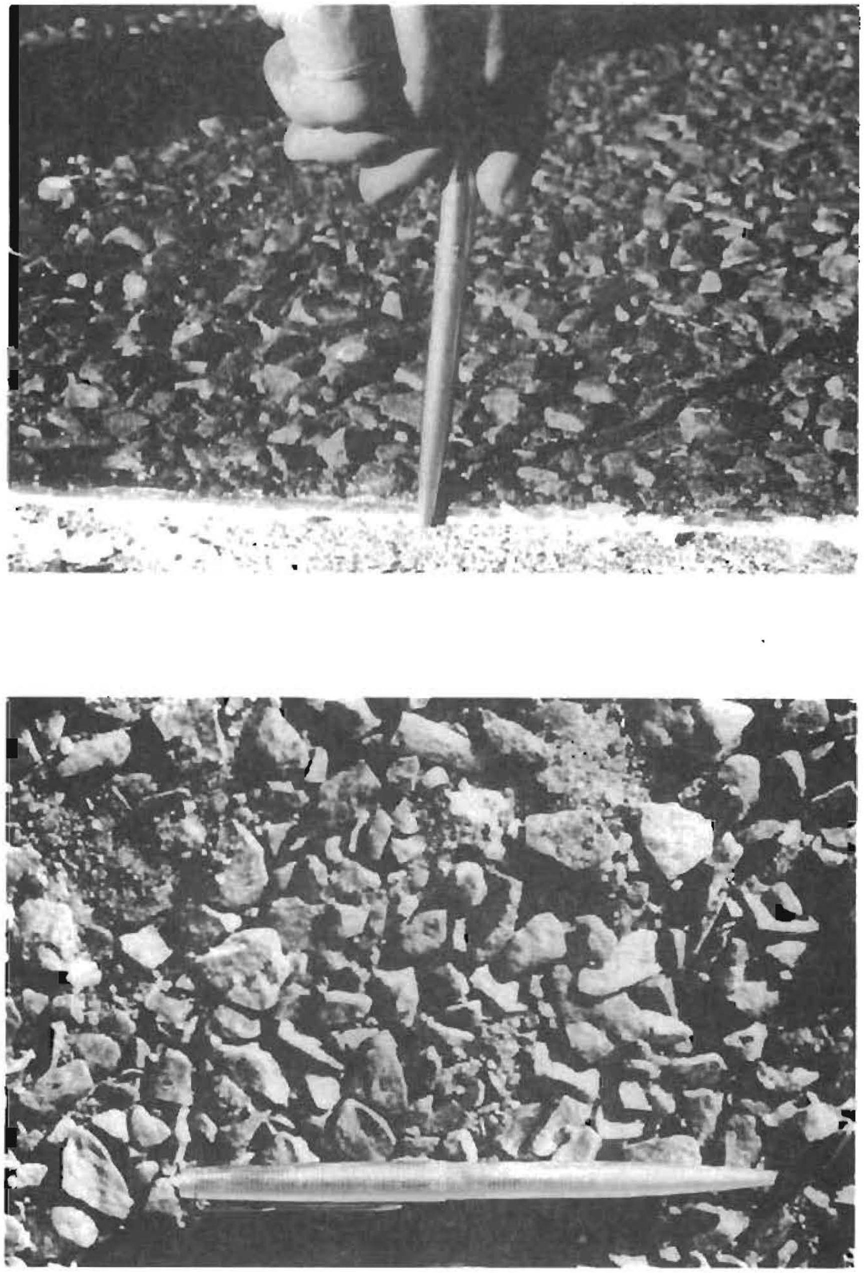


Fig. 5.27. View of PC Overlay.

overlay could be observed from the cores, as shown in Fig. 5.28. Figure 5.29 is a close-up of a polished section showing the boundary between the PC overlay and the concrete. A darker zone below the interface is polymer-impregnated cement paste. The pervasive nature of the polymer is shown in Fig. 5.30. The sand grains are completely surrounded by polymer in the upper part of the photo and a penetration of approximately 1/32-in. of polymer into the concrete is seen in the lower portion of the photo (Ref. 28).

Observations after the 72-hr soak period (Fig. 5.31, 5.32) showed no penetration of the phenolphthalein solution into the polymer system. The polymer apparently provided a satisfactory seal in addition to providing a good bond to the concrete surface (Ref. 28).

The bridge deck, built in 1970, had been subjected to several light chloride applications (6 applications since records were begun several years ago). The usual application rate was 50 lbs NaCl/yd^3 of sand applied over about 1500 sq yds. After the overlay was installed, 3 additional applications were made before coring in the spring of 1979.

Six 6-in. diameter cores were subjected to the 90-day ponding test (AASHTO T 259) by FHWA and tested for chloride penetration in accordance with AASHTO T 260. Two cores were subjected to the 90-day ponding tests at the Center for Highway Research and tested for chloride penetration by D-9 Materials and Test Division of the SDHPT by a method which determines free chloride. The results of these tests are shown in the Appendix. The FHWA results underated an

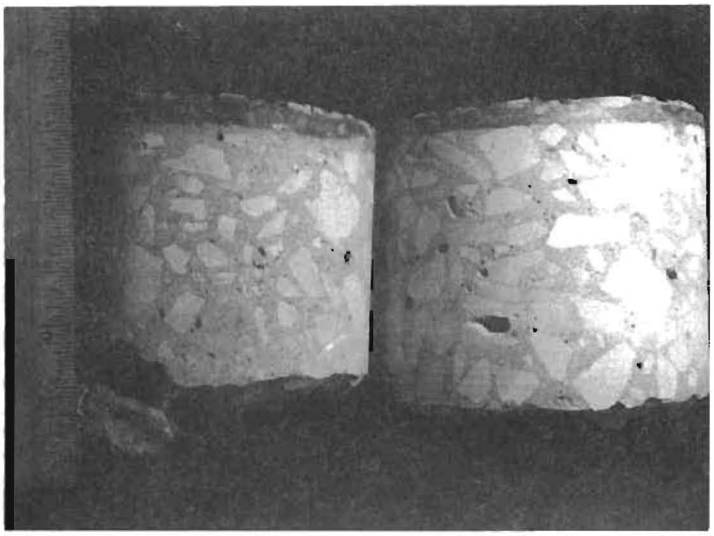


Fig. 5.28. View of cores taken from the bridge deck. (Ref 28)

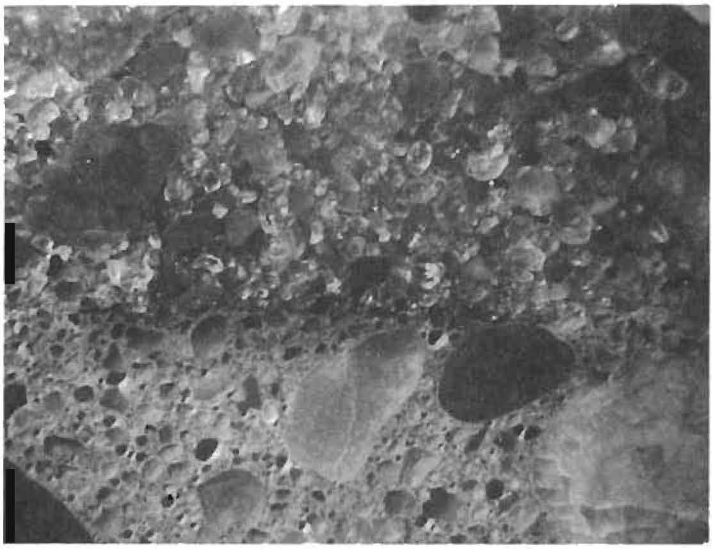


Fig. 5.29. Close-up of polished section showing boundary between overlay and concrete. Darker zone below contact is polymer-impregnated cement paste. (Mag. 7X) (Ref 28)

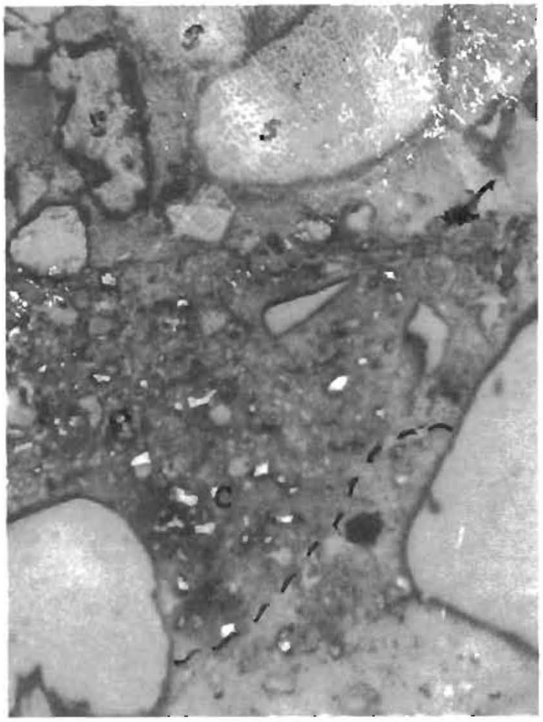


Fig. 5.30. Photomicrograph of contact zone showing polymer-bonded sand grains (s) and top of concrete with impregnated polymer. Limit of polymer penetration is indicated. Relic cement grains (c) are noted. (Vertical illumination, polarized light, Mag. 200X) (Ref 28)

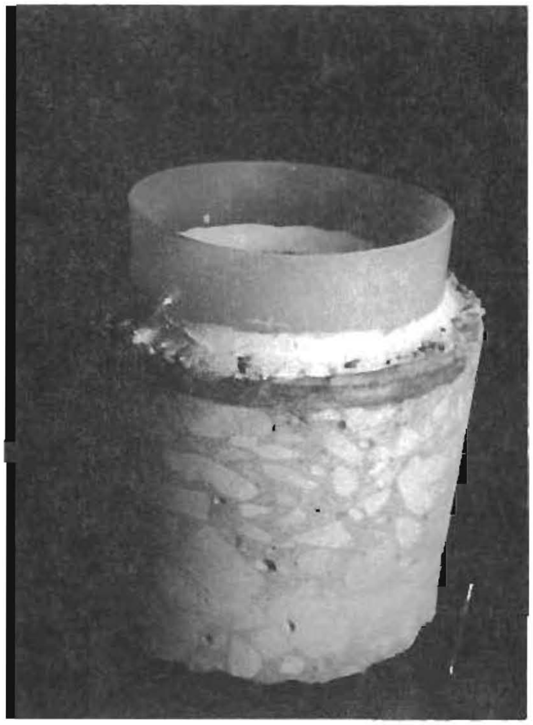


Fig. 5.31. Open Cylinder Sealed to Top Surface Used in 72-Hour Phenolphthalein Soak Test. (Ref 28)

Fig. 5.32. Split core after 72-hour soak test showing polymer seal coat on top surface. No penetration of phenolphthalein through the polymer system was observed. (Ref 28)

average chloride content of 1.6 lbs/yd^3 at a depth of 1/2 to 1 in., which the SDHPT tests gave an average of 0.6 lbs/yd^3. At depths of 1 to 1-1/2 in., FHWA found 0.57 lbs/yd^3 and, at depths of 1-1/2 to 2 in., 0.33 lbs/yd^3. Even with prior salting of the deck, the chloride levels are lower than the corrosion threshold values near the level of the reinforcing steel.

5.4.4 Cost

Table 5.13 shows the total quantities of the chemicals, furnished by the Center for Highway Research, used in the Henrietta overlay and Table 5.14 shows the costs. The cost is approximately \$ 0.71 per sq. ft based on relatively small quantities at 1978 prices. The actual cost to the SDHPT in terms of labor, materials (including lumber, pipe, fittings, and polyethylene), and equipment usage is shown in Table 5.15. It should be noted that due to the experimental nature of the project more workers were assigned to the job than would be required on future overlays. Some of the labor costs and nearly all of the materials costs were for equipment that could be reused, such as spray bars, piping, and evaporation covers.

It is estimated that 5 experienced men could apply 1200 to 2000-sq. ft of overlay per day. For labor costs of \$360 per day, the cost would be \$ 0.18 to \$ 0.30 per sq. ft. Including the cost of chemicals, the total direct costs, excluding equipment rental, overhead, and profit, would be in the range of \$ 0.90 to \$ 1.00 per sq. ft. The development of equipment to spread and roll the

Table 5.13. Total Amounts of Monomers, Initiators, and Accelerators.

		4498.80 sq. ft			
		liter	gallon	kg	lb
First Monomer Application	MMA	1451.98	383.57	1379.38	3034.64
	TMPTMA	68.50	18.09	72.58	159.68
	BP	46.02	12.16	52.45	115.38
	DMPT	12.18	3.22	11.24	24.73
Second Monomer Application	MMA	254.61	67.26	241.85	532.07
	MMA Syrup	158.06	41.76	161.24	354.73
	TMPTMA	11.88	3.14	12.58	27.68
	BA	98.07	25.91	88.18	193.99
	BP	16.97	4.48	19.35	42.56
	DMPT	4.50	1.19	4.16	9.15

Table 5.14. Cost of Chemicals.

Chemical	Quantity, lbs	Cost, lb.	Cost	Percent of Total Cost
MMA	3566.71	$ 0.51	$1819.02	57.07
MMA Syrup	354.73	$ 1.10	390.20	12.24
TMPTMA	187.36	$ 2.50	468.40	14.69
BA	193.99	$ 0.51	98.93	3.10
BP (40% dispersion)	157.94	$ 1.53	241.65	7.58
DMPT	33.88	$ 5.00	169.40	5.31
			$3187.60	100.00

$$\text{Av.} = \frac{\$3187.60}{4498.80 \text{ sq. ft}} = \$\,0.7085/\text{sq. ft}$$

Table 5.15. SDHPT Labor and Material Costs*.

Salaries and Wages	$3149.43
Equipment Usage	263.52
Material	1034.51
Total	$4447.46

* Costs were provided by Mr. Frank Craig of District 3. Some of the labor and most of the materials were for constructing equipment that can be reused. The labor costs do not include two CFHR researchers who assisted in applying the overlay. Chemicals were furnished by the Center for Highway Research and are not included in Table 5.15.

aggregate and to apply the monomer could further reduce the costs. However, one of the advantages of method used at Henrietta is the simplicity of the technique and equipment required.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objective of this investigation was to develop a monomer system and application techniques for a thin polymer-concrete overlay to be applied to the surface of portland cement concrete bridge decks to improve the durability. The following conclusions summarize the investigation.

1. A monomer system of 95 percent MMA and 5 percent TMPTMA for the first monomer application and 48 percent MMA, 32 percent MMA syrup, 2-1/2 percent TMPTMA, 17-1/2 percent BA for the second monomer application has shown promise for PC overlay. The concentrations of the initiator and the accelerator are inversely related to the temperature.
2. The moisture content of the aggregate and concrete should be kept as low as possible to maximize both flexural and bond strengths.
3. Concrete slabs and aggregate which is spread, not piled up, placed outdoors for a minimum of seven consecutive hot sunny days should be sufficiently dry.

4. A 30-min. soaking time for the first monomer application gives up to 1/8-in. penetration, depending on the dryness of the slab.
5. The bond strength between the PC overlay and the concrete slab depends primarily on the monomer system used, especially the concentrations of initiator and accelerator. An average bond stress of 400 psi can be achieved if the concrete is air-dried.
6. The proportion of 48 percent MMA and 32 percent MMA syrup provided an acceptable viscosity to minimize run-off. A significantly lower or higher percentage would cause more monomer evaporation or fail to adequately fill the voids in the coarse aggregate, respectively.
7. Besides embedding the coarse aggregate, the concrete sand used in the PC overlay can both minimize monomer losses due to evaporation and prevent run-off on a sloping concrete deck while monomer is soaking and curing.
8. A sheet of polyethylene film should be used to cover the area after each monomer application is made.
9. PC overlays can effectively seal a concrete surface against water penetration; some specimens succeed even after 100 cycles of freeze-thaw exposure.

10. PC overlays slightly improve the durability of a concrete surface when subjected to the sandblast abrasion test. However, after 100 cycles of freeze-thaw exposure, the PC overlays showed a 528 percent higher abrasion resistance than the control specimens, which failed at about 42 cycles of freeze-thaw exposures.
11. The PC overlay has a greater freeze-thaw durability than the concrete by a factor of at least two. By sealing the surface against water penetration, PC overlay eliminates many of the problems associated with freezing and thawing.
12. The materials cost for PC overlays on bridge decks is approximately \$ 0.71 per sq. ft (1978 prices) when monomer leakage is minimized, and the labor cost is estimated to be \$ .18 to \$ 0.30 per sq. ft.
13. A PC overlay using crushed, rough, and hard pea gravel is preferable to one using round and weak aggregate.
14. A recommended PC overlay application procedure is summarized as follows:
    a. Clean and dry the bridge deck.
    b. Caulk a 1/2-in.-thick wood strip around the perimeter with latex caulking to confine the monomer.
    c. Spread 2 psf of clean, dry, well-graded concrete sand to a 1/4-in. to 1/8-in. thickness.

d. Spread 1.8 psf of crushed 3/8-in. maximum size aggregate to produce a total thickness of 3/8-in. to 1/2-in.

e. Compact the aggregate with low pressure.

f. Make the first monomer application with a sprinkling bar and keep the aggregate saturated and covered with a sheet of polyethylene film for 30 min.

g. Apply the second monomer system and cover it again with the polyethylene film until it has polymerized.

h. If the overlay surface shows lack of monomer in the coarse aggregate, apply more of the second monomer system to fill the voids. Caution should be exercised to prevent any excess monomer remaining on the surface and forming a glossy surface. Sand or coarse aggregate should be applied where this occurs.

6.2 Recommendations

The application of a thin polymer-concrete overlay to the surface of a portland cement concrete bridge deck appears to be an effective and economical means to improve the durability. To assist in the future development and acceptance of this method, the following studies are recommended.

1. Continued field application of PC overlays and observation of these applications to determine the long-term behavior.

2. Continued studies to determine the optimum percentage of initiator and accelerator to be used at any specific ambient temperature for different monomer systems.
3. Investigation of the degree of pre-drying of aggregate and concrete surface necessary to obtain an adequate bond strength.
4. Investigation of optimum procedures to minimize monomer leakage and evaporation losses.
5. Investigation of the optimum procedure for applying PC overlays on sloping surfaces.
6. Determination of the effect of fire on the surface of PC overlays.
7. Development of an automated procedure to produce PC overlays.
8. Investigation of the optimum soaking and curing time for a given monomer system under different environmental conditions.
9. Development of field tests to evaluate PC overlays.

APPENDIX

GRADATIONS

Sieve Size	Sand from Colorado River Bottom, % Finer by Weight	Sand from Henrietta, Texas, % Finer by Weight
No. 4	99	90
No. 8	91	79
No. 16	77	67
No. 30	54	50
No. 50	22	17
No. 100	4	3

Sieve Size	Pea Gravel from Colorado River Bottom, % Finer by Weight	Crushed Pea Gravel from Henrietta, Texas % Finer by Weight
3/4-in.	100	100
3/8-in.	80	66
1/4-in.	9	20
1/8-in.	2	3

CONCRETE DESIGN MIX

Specifications

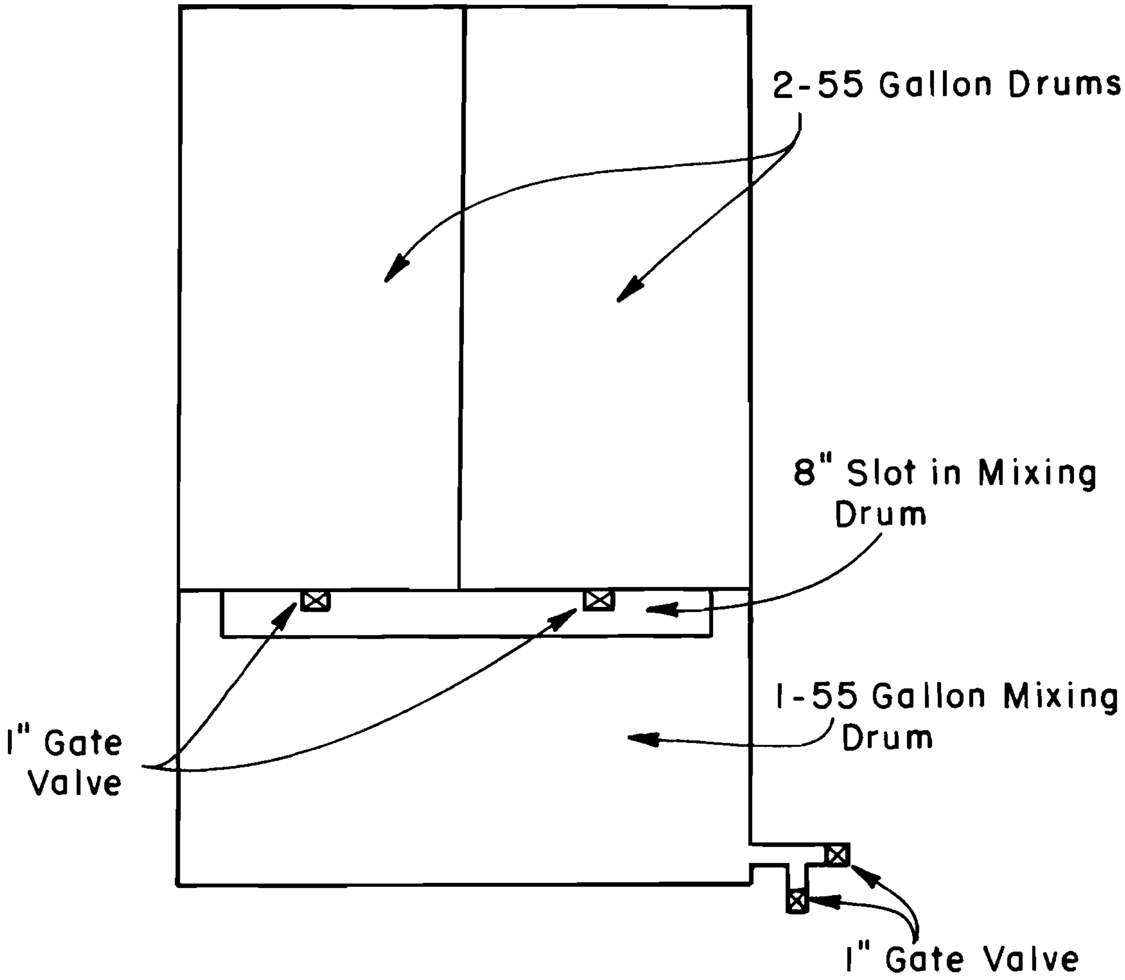
Cement	Type I
Cement Factor	5.6 SK/CY
Water : Cement	6.6 GAL/SK
Slump	5 IN.
Aggregate	Colorado River Bottom

Mix Proportions
(% absolute volume)

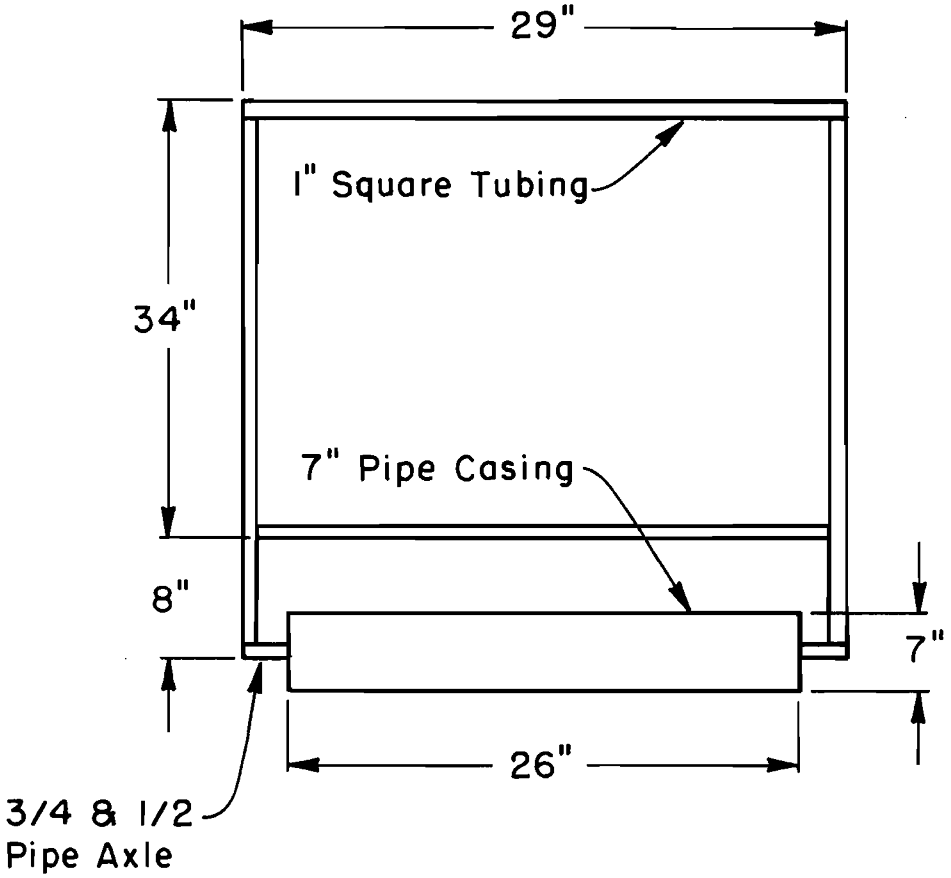
Cement	9.9%
Water	18.2%
Fine Aggr.	33.0%
Coarse Aggr.	37.5%
Air	1.4%

28-Day Test Results
(3 in. x 6 in. cylinder)

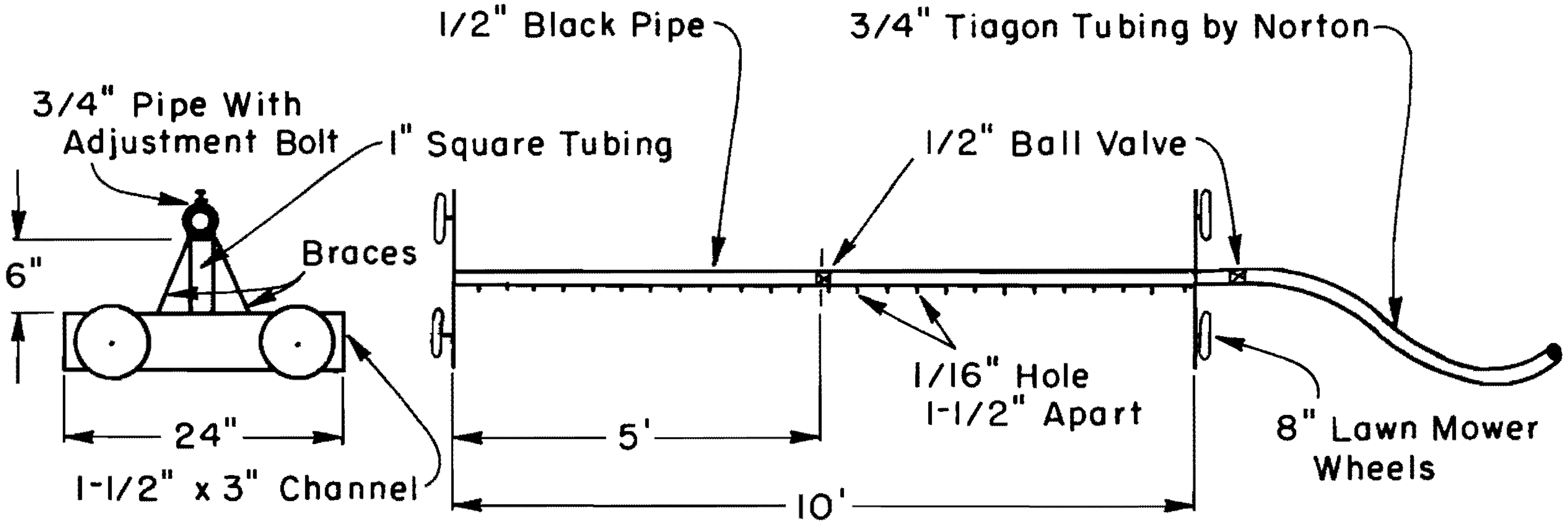
Compression	5500 psi
Split Tensile	540 psi

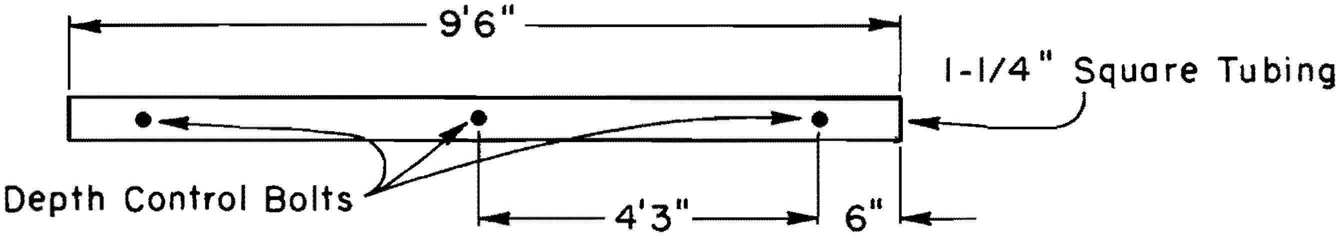


Chemical Drums

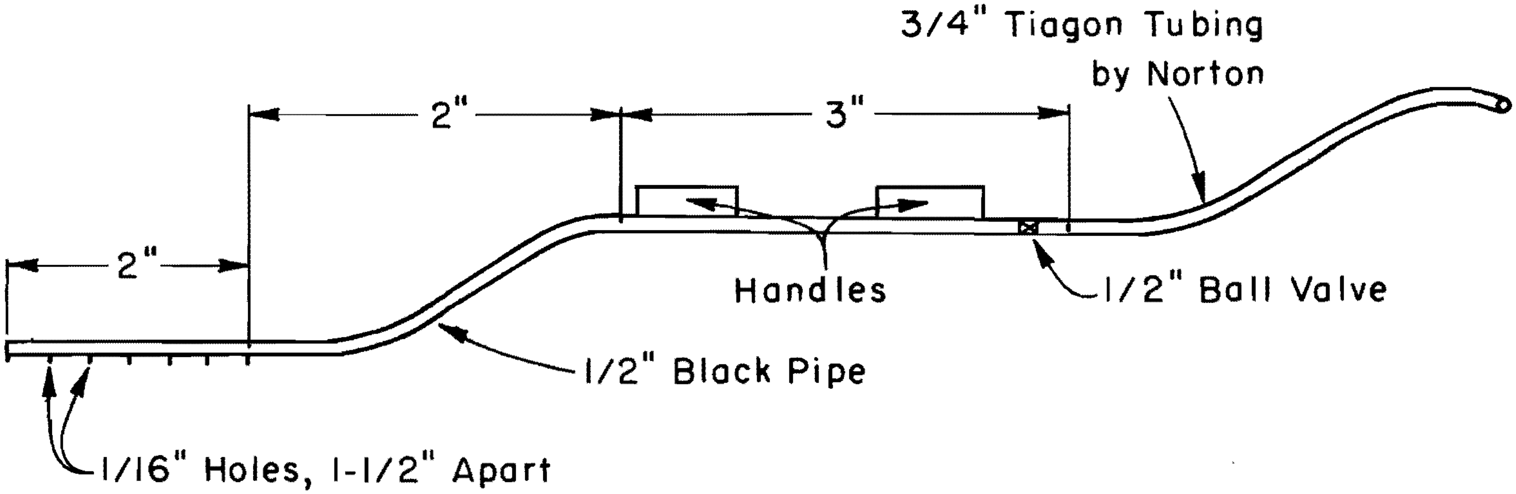


Aggregate Roller


3/4" Pipe With Adjustment Bolt
1" Square Tubing
1/2" Black Pipe
3/4" Tiagon Tubing by Norton
1/2" Ball Valve
Braces
6"
24"
1-1/2" x 3" Channel
5'
10'
1/16" Hole 1-1/2" Apart
8" Lawn Mower Wheels


9'6"
1-1/4" Square Tubing
Depth Control Bolts
4'3"
6"

Sand Screed


3/4" Tiagon Tubing by Norton
2"
3"
2"
Handles
1/2" Ball Valve
1/2" Black Pipe
1/16" Holes, 1-1/2" Apart

CHLORIDE CONTENT IN CORES TAKEN FROM STRUCTURE ON
ACCESS ROAD CONNECTING EASTBOUND US 287 AND SH 148 NEAR HENRIETTA

FHWA ID NO.	Texas I.D. No.	Sample No.	Total Chloride Content, Percent (lb/yd^3) @ Indicated Depth 1/16-1/2-IN.	1/2 to 1-Inch	1 to 1-1/2-INCH	1-1/2 to 2-IN.
6409	Span 1 Pour 2	1	0.0231 (0.90)	0.0372 (1.46)	0.0265 (1.04)	0.0154 (0.60)
		2	0.0499 (1.95)	0.0783 (3.06)	0.0349 (1.37)	0.0173 (0.68)
6410	Span 2 Pour 3	1	0.0781 (3.06)	0.0517 (2.02)	0.0104 (0.41)	0.0052 (0.20)
		2	0.0611 (2.39)	0.0260 (1.02)	0.0062 (0.24)	0.0039 (0.15)
6411	Span 3 Pour 4	1	0.0321 (1.26)	0.0280 (1.10)	0.0055 (0.22)	0.0039 (0.15)
		2	0.0244 (0.95)	0.0242 (0.95)	0.0046 (0.18)	0.0051 (0.20)
AVERAGE		ALL	0.0448 (1.75)	0.0409 (1.60)	0.0147 (0.57)	0.0085 (0.33)

Notes:

1. 90-day ponding test according to AASHTO T 259: total chloride, determined by AASHTO T 260; chlorides given in parenthesis are in lbs/yd^3 assuming a unit weight for concrete of 145 lbs/ft^3.

2. Overlay thicknesses were as follows:
   Core 6409 = 3/8 to 1/2-inch
   Core 6410 = 1/4-inch
   Core 6411 = 1/4 to 3/8-inch

3. The subject bridge deck is located near Henrietta, Texas on an exit ramp (frontage road) from U.S. Route 287 east to State Highway 148. It receives significant truck traffic. The polymer concrete overlay was placed November 27 through December 1, 1978. The original bridge deck was built in 1970 and had received 6 light chloride applications (each application consisted of 50 lbs NaCl mixed with 1 yd^3 of sand and spread over about 1,500 sq. yds) prior to overlaying, and 3 light salt applications after overlaying but prior to coring in the Spring of 1979.

4. Conditioning of cores prior to 90-day ponding included 28 days of air drying at 72°F and 50 percent Rh and a light (1/16-inch) surface sandblast.

2. CHR and SDHPT Tests

Pour No. 2	ppm	Percent by wt	lbs/yd^3*
PC overlay	267	0.03	1.1
Surface of original structure to 1/2 inch depth	341	0.03	1.4
1/2 inch to 1 inch depth	194	0.02	0.8
Pour No. 3			
PC overlay	406	0.04	1.6
Surface of original structure to 1/2 inch depth	387	0.04	1.5
1/2 inch to 1 inch depth	102	0.01	0.4

Notes: 1. 90-day ponding tests by CHR according to AASHTO T 259 except for the following exceptions:

a. The bridge deck was 8 years old when cores were taken.
b. Cores taken from bridge deck were 3 to 5 in. long (> 2 in.).
c. The overlay surfaces were not abraded before ponding.

2. Chloride contents based on assumed weight of 4000 lbs/yd^3 for the concrete and PC overlay.

3. The chloride determination was obtained by SDHPT D-9 according to the following procedure:

Prior to obtaining samples from the cores for chloride determination, the surface of the polymer seal coat was rinsed with deionized water to remove any surface salt. The surface was allowed to dry and then powdered samples of the seal coat, original concrete surface to 1/2 inch depth and 1/2 inch to one inch depth were obtained by drilling with a 3/4 inch diameter concrete bit. Drilled-out material was collected from three holes near the center of each core and combined for each layer. The polymer seal coat was approximately 3/8 inch thick. 10.0000 ± 0.0010 grams of the powdered material from each level was weighed into a 400 ml beaker and 200 ml of deionized water was added. The samples were digested at 180 F for 18 hours with occasional stirring to dissolve any sodium chloride present. The solution was then filtered and the solids washed with additional deionized in a volumetric flask and a 50 ml aliquot titrated with 0.01 normal silver nitrate. The end point was determined potentiometrically using a pH meter equipped with a selective chloride ion and reference electrodes. The end point is based on the greatest change in potential obtained by addition of a given amount of titrant.

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