POLYMER CONCRETE OVERLAY ON BEULAH ROAD BRIDGE

Interim Report No. 1 — Installation and
Initial Condition of Overlay

by

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Virginia Highway and Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia
Department of Highways & Transportation and
the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

February 1982
VHTRC 83-R28

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SUMMARY

The installation of a thin polymer concrete overlay on the Beulah Road bridge demonstrates that an overlay of low permeability and high skid resistance can be successfully installed by maintenance forces with a minimum of disruption to traffic, approximately 8 hr. per lane, and at about half the cost of alternative service-life-extending measures. Subsequent laboratory tests have indicated that thermal stress at the bond interface can cause the formation of cracks in the overlay, the bond interface or the base concrete. The problem could be minimized by the application of a more flexible PC overlay.

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INTRODUCTION

Thin polymer* concrete (PC) overlays have been installed on portland cement concrete bridge decks in several states during the past four years.(1) This type of overlay was developed by the Brookhaven National Laboratory for the Implementation Division of the Office of Development of the Federal Highway Administration as a protective system for bridge decks.(2) It consists of four layers of resin and clean, dry, angular-grained silica sand applied to the top of a portland cement concrete deck to provide a 0.5 in. (1.3 cm) thick, relatively impermeable, skid resistant wearing surface. Typically, the initiated and promoted resin is sprayed uniformly over the surface of the deck and, before it gels, is covered by find aggregate broadcast over it as shown in Figures 1 and 2. Following polymerization, the excess aggregate is removed with a vacuum device prior to the placement of a subsequent layer. The principal advantage of the overlay over other protective systems is that it is a reasonably priced system that can be installed by state forces or a contractor without the removal of a large amount of concrete and with minimal disruption to traffic, approximately 8 hr. per lane for a 250-ft. (76-m) bridge — 4 hr. for deck preparation and 1 hr. per layer to install the polymer.

This report has resulted from an agreement between the Federal Highway Administration (FHWA) Demonstration Projects Division and Implementation Division, and the Virginia Department of Highways and Transportation (VDHT), and the Federal Aviation Administration (FAA), to construct and evaluate a PC overlay on bridge No. 6232 on State Route 675,

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* Definition of terms shown in Appendix

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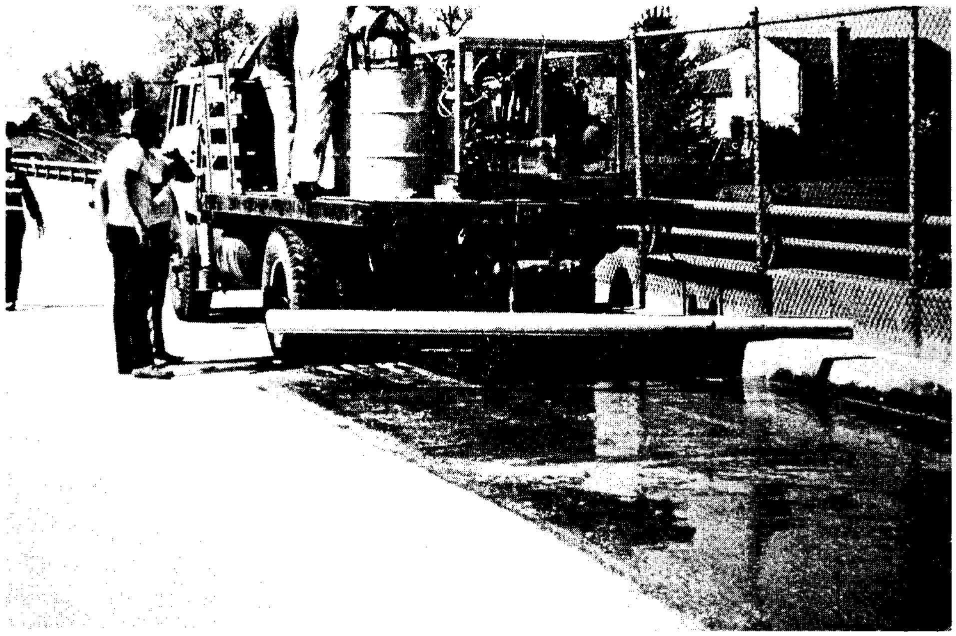

Figure 1. Resin is sprayed over deck surface.

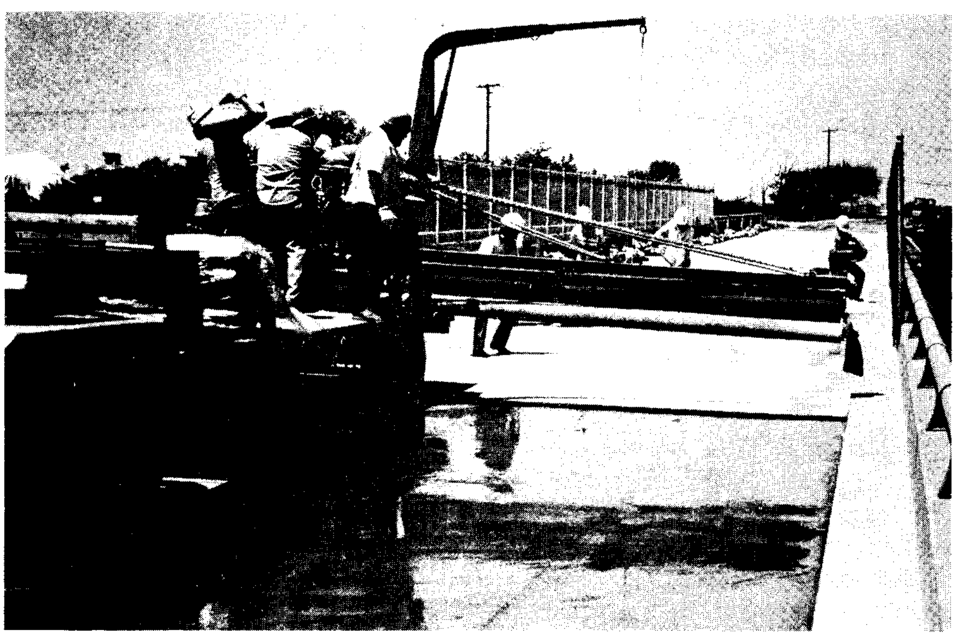

Figure 2. Silica sand is broadcast over resin with wing spreader.

Beulah Road, over the Dulles International Airport Access Highway in Fairfax County, Virginia. The project was conducted under FHWA Demonstration Project No. 51, Bridge Deck Repair and Maintenance, which is directed to the extension of the service life of bridge decks.(3)

OBJECTIVES

The objectives of this report are to describe the construction of the PC overlay and the condition of the bridge deck before and after installation of the overlay, and to present data on the thermal compatibility of the two PC materials used in the overlay.

INSTALLATION OF PC OVERLAY

Materials

The following information on materials was taken from a VDHT special provision for PC overlays which accurately describes the materials used in the construction of the overlay on the Beulah Road bridge.(4)

Monomers-Polyester Resin

The resins used were clear, low viscosity, highly resilient, general purpose, unsaturated polyester resins with a viscosity of 100 to 150 cP (0.1 to 0.15 Pa·s) at 77°F (25°C) and a density of 9.08 lb./gal. (1088 kg/m^3). They were designed for applications requiring resistance to wear and high impacts. U. S. S. Chemical's blend LB183-13 was used on the northbound lane and Reichhold Chemical's blend Polylite 90-570 was used on the southbound lane. The first course contained 1% of Union Carbide A-174 coupling agent and 1% of Surfynol S440 wetting agent to enhance the bond strength and reduce surface tension. The second, third, and fourth courses contained 0.5% of Union Carbide A-174 coupling agent and 0.5% of Surfynol S440 wetting agent.

Initiator

The initiator was 60% methyl ethyl ketone peroxide (MEKP) $C_4H_8O_2$ in dimethyl phthalate with approximately 9% active oxygen and a specific gravity of 1.15 at 77°F (25°C). It was in a liquid state with a water white color, a flash point (Cleveland open cup) of about 180°F (82°C), and a mildly thermal decomposition point (rapid rise) at 320°F (160°C).

Promoter

The promoter was approximately 6% active cobalt in naphtha (CoN). In a liquid state it is bluish red and has a flash point at or above 121°F (49°C) and a density of 7.5 lb./gal. (899 kg/m^3).

Coupling Agent

The coupling agent was gama-methacryloxypropyltrimethoxysilane equal to Union Carbide's formulation A-174.

Wetting Agent

The wetting agent was Surfynol S440 manufactured by Air Products and Chemicals, Inc.

Aggregate

The aggregate was a clean, dry (less than 1% moisture), angular-grained silica sand free of dirt, clay, asphalt and other organic materials, and having a gradation as reported in Table 1.

Table 1

Gradation of Sand Based on a Sample from Two 100-lb. (444 N) Bags, Percent Passing Indicated U. S. Sieve

Grading	Layers	8	12	16	20	30
A (Morie #2)	3 & 4	99.9	59.3	12.1	2.1	0.9
D (Morie #1)	1 & 2	100.0	98.5	58.8	6.9	0.6

Equipment

The polymer distribution equipment and aggregate spreader were built for the Implementation Division of the FHWA by the Brookhaven National Laboratory. A brief demonstration test was conducted in the yard of VDHT's Camp 30 on May 4, 1982, to ensure that these apparatus were functioning properly prior to moving them to the bridge.

Distribution Equipment

The resin distribution equipment was mounted on skids which allowed it to be placed on a flatbed truck provided by the FAA. It consisted of a generator, air compressor, two water-cooled pumps, a kenex static mixer, a spray bar, and the necessary piping to allow for the simultaneous movement of resin from two 55-gal. (0.21-m^3) drums to the spray bar (see Figure 1). Polyester resin containing CoN was pumped from one drum at the same rate that polyester resin containing MEKP was pumped from the other one. The resin from the two drums was mixed in a static mixer before it entered the spray bar.

The resin mixture was sprayed over a 12 ft. wide (3.7 m) lane. The truck was moved forward at a speed calculated to provide an application of 2.00 lb./$yd.^2$ (1.1 kg/m^2) for the first course and 2.75 lb./$yd.^2$ (1.5 kg/m^2) for the subsequent courses. Four drums of resin were required to cover one lane of the 450-ft. (137 m) bridge with one layer of resin. Therefore, it was necessary to stop the application at midspan and replace the two empty drums with two full ones.

A few days prior to placement of the overlay, the coupling agent and wetting agent were added to the drums and the CoN was added to half of the drums. The MEKP was added to the other half of the drums minutes before the resin was to be applied to the bridge deck. Before the drums were moved onto the bridge deck, the ingredients in each were mixed for 15 minutes.

Aggregate Spreader

The aggregate spreader is shown in Figure 2. It consists of a truck connected to a flatbed trailer upon which has been mounted a hopper, motor, and application wing. The wing consists of a trough, an auger to move the aggregate from the hopper into the trough, and a rotating drum that dispenses the aggregate from the bottom of the trough and deposits it over a maximum width of 12 ft. (3.7 m). The auger and drum moved at a constant speed, so it was necessary to establish a forward motion of the truck that would provide an aggregate application rate of 17 lb./$yd.^2$ (9.2 kg/m^2).

Since the hopper would hold only 2,500 lb. (11.1 kN) of sand, it was necessary to carry about seventy-five 100-lb. (444 N) bags of sand on the front of the trailer so as to have enough to cover to excess the 12 ft. (3.7 m) by 450 ft. (137 m) lane. It was found, however, that the spreader could not apply sufficient sand to cover the resin to excess over the 450-ft. (137-m) length before the resin gelled. Therefore, the truck was moved forward at a faster rate than was desirable and additional sand was applied by hand.

Shotblaster

Prior to placement of the first layer of polymer, and after all major spalls had been repaired, the deck surface was shotblasted with a Model 1-20D blasting machine and Model 20-40 dust collector supplied by Wheelabrator Frye, Inc. (see Figure 3).[5] The equipment recycles the steel shot, collects concrete cuttings, and rapidly provides, at low cost and with little or no environmental impact, a completely cleaned deck surface.

The equipment was used to clean the northbound lane on May 4 prior to placement of the first layer of LB183 resin and the southbound lane on May 5 prior to placement of the first two layers of 90-570 resin. The equipment was observed to clean at a rate of 118 yd.^{2}/hr. (98.7 m^2/hr.) the first day and 153 yd.^{2}/hr. (128 m^2/hr.) the second day. It is believed that the slower rate produced better results. The first layer of resin was placed within 4 hours after the cleaning was begun.

Roller

A VDHT pneumatic-tire roller from Camp 30 was used to roll the sand into the first layer of resin mixture placed on each lane. The roller was self-propelled and applied 200 lb. (350 N/cm) of rolling width. It was not used on subsequent layers because it was impossible to roll the entire lane before the resin and sand mixture began to gel. It was the consensus of those present that the heretofore specified rolling operation was not necessary and could cause damage to the overlay if the rolling was done after the resin mixture began to gel.

Vacuum

A VDHT self-propelled, sweeperbroom type vacuum truck from Camp 30 was used to remove excess sand from the surface approximately 1 hour after the resin mixture had gelled.

Labor

The labor force consisted of personnel from each of the three parties involved in the cooperative agreement, with the exception that the shotblast equipment was operated by personnel from Wheelabrator Frye, Inc., who provided it at a reduced cost to demonstrate it on an FHWA demonstration project.

The resin distribution equipment was operated by a driver from the FAA, two pump operators from FHWA, and a man on foot with a stopwatch from the VDHT to assist in maintaining a proper forward motion.

The aggregate spreader was operated by a driver from the FHWA, a spreader operator and several men from the VDHT and the FHWA who emptied 100-lb. (444 N) bags of sand into the hopper. Other men from the VDHT, FHWA and FAA applied sand by hand.

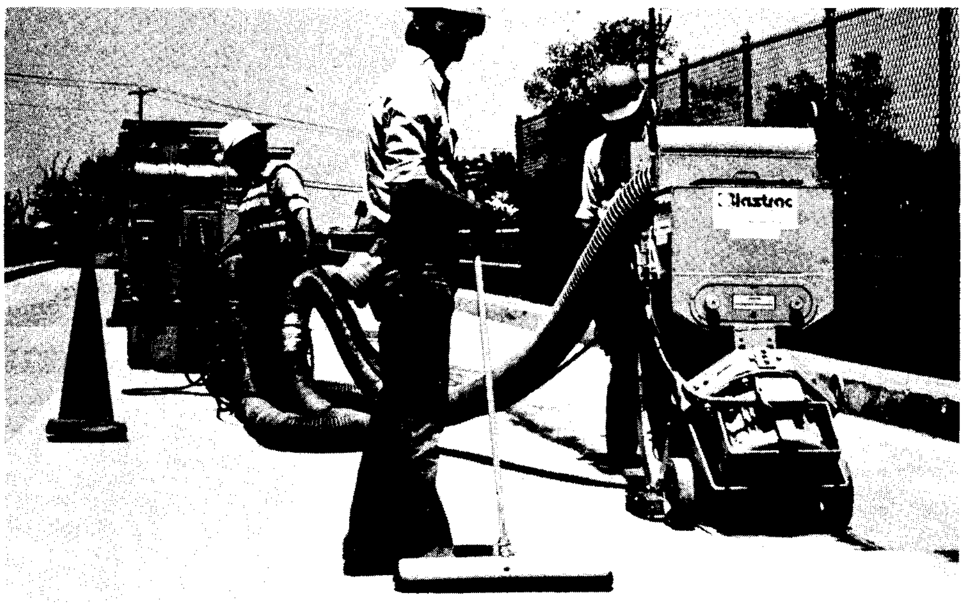

Figure 3. Deck surface is prepared with shot-blasting equipment.

One VDHT man secured a 1.7-oz. (50 ml) sample of resin from the spray bar for each of the six bridge spans and measured the gel time.

One VDHT man operated the vacuum truck.

Two VDHT men maintained two 1-yd.^{2} (0.84 m^2) sampling devices at the end of each application to provide an indication of the rate at which the resin and sand were being applied. Another indication was obtained by measuring resin in the drums and counting the bags of sand before and after a layer was applied.

Composition of the Overlay

Information collected during and subsequent to the 4 days during which the overlay was installed is shown in Tables 2 and 3. Table 2 shows that the average resin application rate was close to the anticipated total of 10.25 lb./yd.^{2} (5.56 kg/m^2) for the four layers. The samples indicated that, typically, the resin application at the end of the lane was light. The bag count data indicated that the sand application was lighter than the anticipated total of 68 lb./yd.^{2} (37 kg/m^2) for four layers, and the samples indicated that the rate was lighter at the end of the lane. The cores shown in Figure 4 verify that the application of resin and sand was lighter at the ends of the lanes, Span A for LB183 and Span F for 90-570. Fortunately, a sand-to-resin ratio by weight in excess of 4 was maintained over most of the deck.

Gel times ranged from 12 to 22 minutes, with averages of 16 minutes for the LB183 and 18 minutes for the 90-570. Deck surface temperatures ranged from 63°F (17°C) to 86°F (30°C) during the eight applications, with averages of 77°F (25°C) for LB183 and 81°F (27°C) for 90-570.

Because of the 450 ft. (137 m) length of application, in some instances the resin had begun to gel before the sand was applied. Table 3 shows spans and layers where some polymer contained no sand based on cores removed from the deck. The LB183 resin was applied from F to A and the 90-570 from A to F. Generally, the problem occurred in the end spans, A for LB183 and F for 90-570, but layer 1 of LB183 received no sand on several spans because the insufficient application by the spreader was not properly compensated for by additional hand application. Cores containing layers of polymer with no aggregate (light color) are shown in Figure 4.

Table 2

Composition of Overlay

Product	Layer	Resin lb./yd.^{2}		Sand, lb./yd.^{2}		Sand/Resin		Temp., $^{\circ}$F.	Gel Time, min.
		Stick	Samples	Bag Count	Samples	Bag/ Stick	Samples		
LB183	1	2.6	3.0	12.2	6.0	4.7	2.0	74	15
"	2	3.0	2.2	13.9	9.2	4.6	4.2	63	22
"	3	3.0	2.3	13.9	10.9	4.6	4.8	83	14
"	4	2.9	2.5	15.2	10.5	5.2	4.2	86	12
"	All	11.5	9.9	55.1	36.6	4.8	3.8	77	16
90-570	1	2.3	1.1	13.1	7.1	5.7	6.5	81	18
"	2	2.7	1.3	13.9	5.7	5.2	4.6	81	19
"	3	2.9	3.2	16.6	11.8	5.7	3.7	74	20
"	4	2.8	2.8	14.7	14.4	5.3	5.2	86	14
"	All	10.7	8.3	58.2	39.0	5.4	5.0	81	18

0.54 kg/m^2 = 1 lb./yd.^{2}

$^{\circ}C = (^{\circ}F - 32)/1.8$

Table 3

Layers That Contained No Sand

Span	A	B	C	F
Layer	1, 3, 4	1, 3	1	1, 2
Resin	LB183	LB183	LB183	90-570

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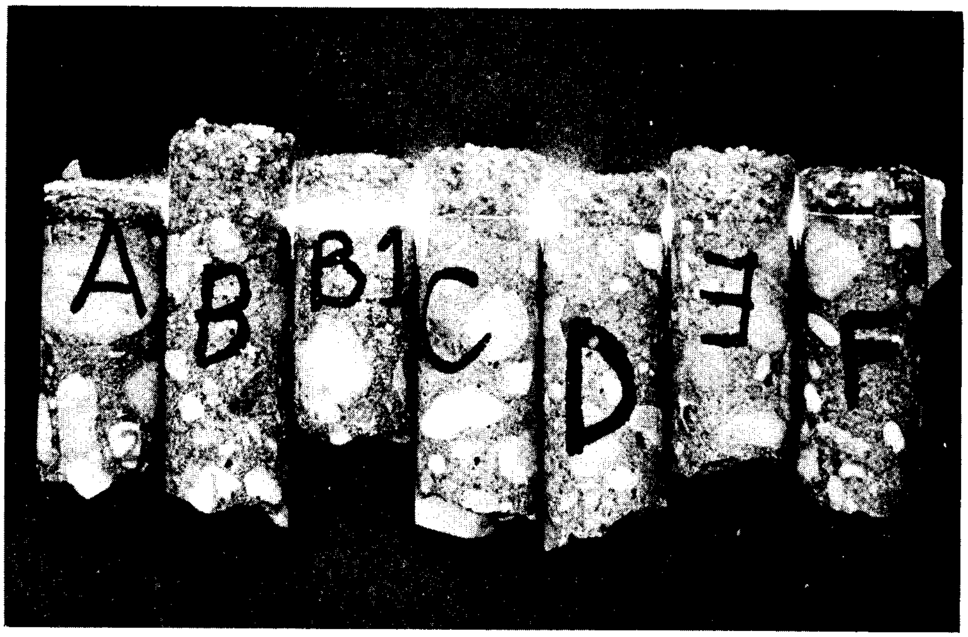

Figure 4. Cores taken from each of six spans show thickness of overlay and layers without sand.

Assessment of Installation

Overall the installation of both resin systems was successful. The resin distribution equipment worked extremely well, and with more experience the resin could be uniformly applied throughout the length of a lane. The sand application equipment is not adequate, except for short applications. The equipment should be modified to apply sand at a faster rate. The deck surface sloped downward about 4% from west to east and caused the resin to flow toward the east curb. This problem could be eliminated on bridges by applying lighter applications of resin, particularly on the first layer, and by providing a sand spreader that can place sand on the resin before it has a chance to flow.

CONDITION OF DECK BEFORE AND AFTER INSTALLATION OF PC OVERLAY

Chloride Ion Content

A chloride ion content in excess of 1.3 lb./yd.^{3} (0.77 kg/m^3) can cause the steel in a concrete bridge deck to corrode. Table 4 shows the results of chloride ion determinations on 13 samples taken from four locations on the Beulah Road bridge. Since the top mat of steel has 2.5 in. (6.4 cm) of concrete cover, it is reasonable to conclude from these data that there is insufficient chloride at the level of the steel to cause corrosion. There was no evidence of corrosion-induced spalling.

The data suggest that small amounts of additional chloride could initiate corrosion, but it is anticipated that the installation of the PC overlay will prevent infiltration of additional chloride and thereby extend the service life of the bridge.

Table 4

Chloride Content at Indicated Depth, lb./yd.^{3}

Span	Location	Depth, in. 0-1/2	1/2-1	1-1 1/2	1 1/2-2
A	Curb, NBL	--	1.02	0.83	0.82
A	LWP, NBL	2.11	1.59	1.36	0.97
B	LWP, NBL	--	2.92	2.43	1.39
F	RWP, SBL	--	1.96	1.11	0.23

0.59 kg/m^3 = 1 lb./yd.^{3}
2.54 cm = 1 in.

Half-Cell Potentials

Copper sulfate half-cell potentials (ASTM C876-77) were measured at grid points spaced 4 ft. apart over the entire deck surface on March 1 and 2, 1982, and the results are shown in Table 5. The half-cell data support the chloride ion data since 99.8% of the measurements are less negative than -0.20 volt, which implies that there is a 90% probability that no corrosion is occurring in 99.8% of the steel.

Delamination

A delam-tech was used to find areas of delamination in the Beulah Road bridge. No delaminations were found prior to placing the overlay, 2 weeks after the overlay was installed, nor 24 weeks after the installation.

Rutting in Wheel Paths

A 12-ft. (3.7-m) straightedge was used to measure rutting in the wheel paths. Measurements were made at 10-ft. (3.1-m) intervals along the length of the bridge in both lanes and the averages are reported in Table 6. The worst rutting was noted in the right wheel path of the southbound lane prior to placement of the overlay and after the installation. The overlay tended to fill low areas, so the rutting was less after it was placed. High areas were found in the left wheel paths of both lanes after the overlays were installed. The purpose of the rutting measurements are to detect wear of the overlay, and the data should become more meaningful when measurements are made after one or more years of service life.

Skid Numbers

Skid numbers were determined in tests at 40 mph (64 km/hr.) in each lane before and after the PC overlay was installed and the results are reported in Table 7. The concrete surface exhibited high numbers prior to the overlay, and the numbers were even higher afterwards. The low reading found for the LB183 resin after 4 weeks of service life were caused by asphalt tracked onto the lane from an approach area that had received a new surface the same week.

Table 5

Electrical Half-Cell Potentials, Percentage of Total Number of Readings

Range (-Volts CSE)		
<0.20	0.20 to 0.35	>0.35
99.8	0.2	0

Table 6

Rutting in Wheel Paths, in.

	SBL		NBL	
Time	Right Wheel Path	Left Wheel Path	Right Wheel Path	Left Wheel Path
3/01/82	0.111	(0.028)*	0.010	0.037
5/18/82	0.048	(0.075)	(0.024)	0.030

* (High Area)

2.54 cm = 1 in.

Table 7

Skid Numbers for 40 mph (64 km/hr.) Tests

	Treaded Tire		Bald Tire	
Age, wk	LB183	90-570	LB183	90-570
- 3*	52	51	39	36
4	44**	57	36**	51
13	53	55	47	49

* 3 Weeks before PC overlay placed.

** Asphalt had been tracked onto bridge.

Electrical Resistivity

Two weeks after the overlay was installed electrical resistivity measurements (ASTM D3633-77) were made at grid points located 4 ft. (1.2 m) apart in the transverse direction and 5 ft. (1.5 m) apart in the longitudinal direction, and again at half of the locations after 24 weeks of service life. The results are reported in Table 8. Both materials were exhibiting similar but good to excellent resistivity 2 weeks after they were installed. The resistivity of LB183 had decreased to fair after 24 weeks of service life, but the resistivity of the 90-570 was still good to excellent.

Permeability

A rapid permeability test recently developed by the Portland Cement Association for the FHWA was used to determine the permeability to chloride ion of 4 in. (10 cm) diameter cores removed from the Beulah Road bridge.(6) The results are shown in Table 9. A permeability of 2,214 coulombs was determined for the base concrete. After 2 weeks of service life the permeability of the base concrete with a PC overlay was almost zero, 2.9 coulombs for LB183 and 0.9 for 90-570. After 24 weeks of service life, additional cores were taken. Cores containing the LB183 overlay showed an increase in permeability but the permeability of the cores with the 90-570 overlay was about the same as when the overlays were installed. The permeability data support the electrical resistivity data in that both indicate a deterioration in the waterproofing characteristics of the LB183 material after 24 weeks of service life. Since the overlay had not been subjected to freezing temperatures after 24 weeks, the breakdown must have been related to shrinkage or to reflective cracking. Prior to placement of the overlays, a greater number of transverse cracks was observed in the lane to be overlaid with LB183 than was observed in the other lane. Also the LB183 would be more susceptible to cracking since it can elongate 7% as compared to 9% for 90-570*. The 24-hour shrinkage of LB183 was observed to be 0.2%, or twice the 0.1% observed for 90-570.

Because it was recognized that low temperatures could produce contraction cracks in the overlay, the test specimens representing 2 weeks of service life were subjected to 125 cycles of temperature change in air in which the temperature fluctuated from 10°F (-12°C) to 100°F (38°C) at a rate of 3 cycles per day. The effects of the thermal cycles are shown in Figure 5. After 77 cycles the permeability increased to 23 coulombs for LB183 and 31 for 90-570 and after 125 cycles it had increased to 72 and 221 coulombs, respectively.

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* Personal communication with Jack Fontana of Brookhaven National Laboratory, New York, 11/19/1982.

Table 8

Electrical Resistivity Measurements, Percentage of Total Number of Readings

		Range of Electrical Resistivity, Ohms/Ft.^{2}			
Age, wk.	Product	Poor $<10^4$	Fair 10^4 to $<10^6$	Good 10^6 to 10^8	Excellent $>10^8$
2	LB183	0	6	15	79
2	90-570	1	2	13	84
24	LB183	2	88	9	1
24	90-570	0	1	41	58

10.8 Ohm/m^2 = 1.Ohm/ft.^{2}

Table 9

Permeability Data, Coulombs

Date		3/01/82	5/18/82	10/20/82	5/18/82	10/20/82
Age, wk.		-9	2	24	2	24
Material		Base Concrete	LB183	LB183	90-570	90-570
↑	A	2308	0.5	52	--	--
	B	--	0.7	--	0.5	0.3
Span	C	--	3.7	248	--	--
	D	--	--	--	2.2	0.0
	E	--	53	447	--	--
↓	F	2124	--	--	0.7	0.7
Log. Avg.		2214	2.9	179	0.9	0.1

In the summer of 1981, a contractor placed PC overlays on five bridges on I-64 near Williamsburg.[7] As is shown in Figure 5, the four overlays constructed with the LB183 resin exhibited a higher permeability than the overlay on Buelah Road. The permeability of the fifth overlay, which was prepared with a methyl methacrylate (MMA) resin, was even higher. It is believed that a lower permeability was achieved with LB183 on the Beulah Road bridge than on the bridges at Williamsburg because in the former (1) the average placement temperature was lower, (2) only the first layer was compacted with a pneumatic-tire roller, (3) there was a two-day delay between the placement of the first and the placement of subsequent layers, which allowed the first layer to shrink before the subsequent layers were placed, and (4) the permeability of the base concrete, which makes up 1.5 in. (3.8 cm) of the 2.0 in. (5.1 cm) thickness of the test specimen, was lower.

Although thermal stress, shrinkage, and reflective cracking can cause an increase in the permeability of the PC overlay, it must be recognized, as is shown in Figure 5, that the overlays exhibit a much lower permeability than the base concrete or a protective system consisting of a 1.25 in. (3.2 cm) thick layer of latex modified concrete.

Shear Strength

To obtain an indication of the shear strength of the portland cement concrete and PC overlay composites, cores were subjected to two tests. For the first test the shear force was directed through the bond interface; for the second it was directed through the concrete approximately 2.5 in. (6.4 cm) below the bond interface, which provided an indication of the shear strength of the portland cement concrete. Prior to the tests, the cores were subjected to from 0 to 200 thermal cycles applied at a rate of 3 per day under a range in air temperature of from 10°F (-12°C) to 100°F (38°C).

A plot of the shear strength of the cores as a function of the number of thermal cycles is shown in Figure 6 for twenty-two 2.75-in. (7.0 cm) diameter cores removed from the Beulah Road bridge 2 weeks after it was overlaid and thirty-four 4.0 in. (10 cm) diameter cores removed from five bridges in Virginia considered as candidates for polymer concrete overlays. The top surfaces of the 4.0-in. (10-cm) cores were sandblasted and LB183 resin overlays were placed on them in the laboratory at the Research Council. The deck of the Beulah Road bridge had been shotblasted before the LB183 and 90-570 overlays were installed.

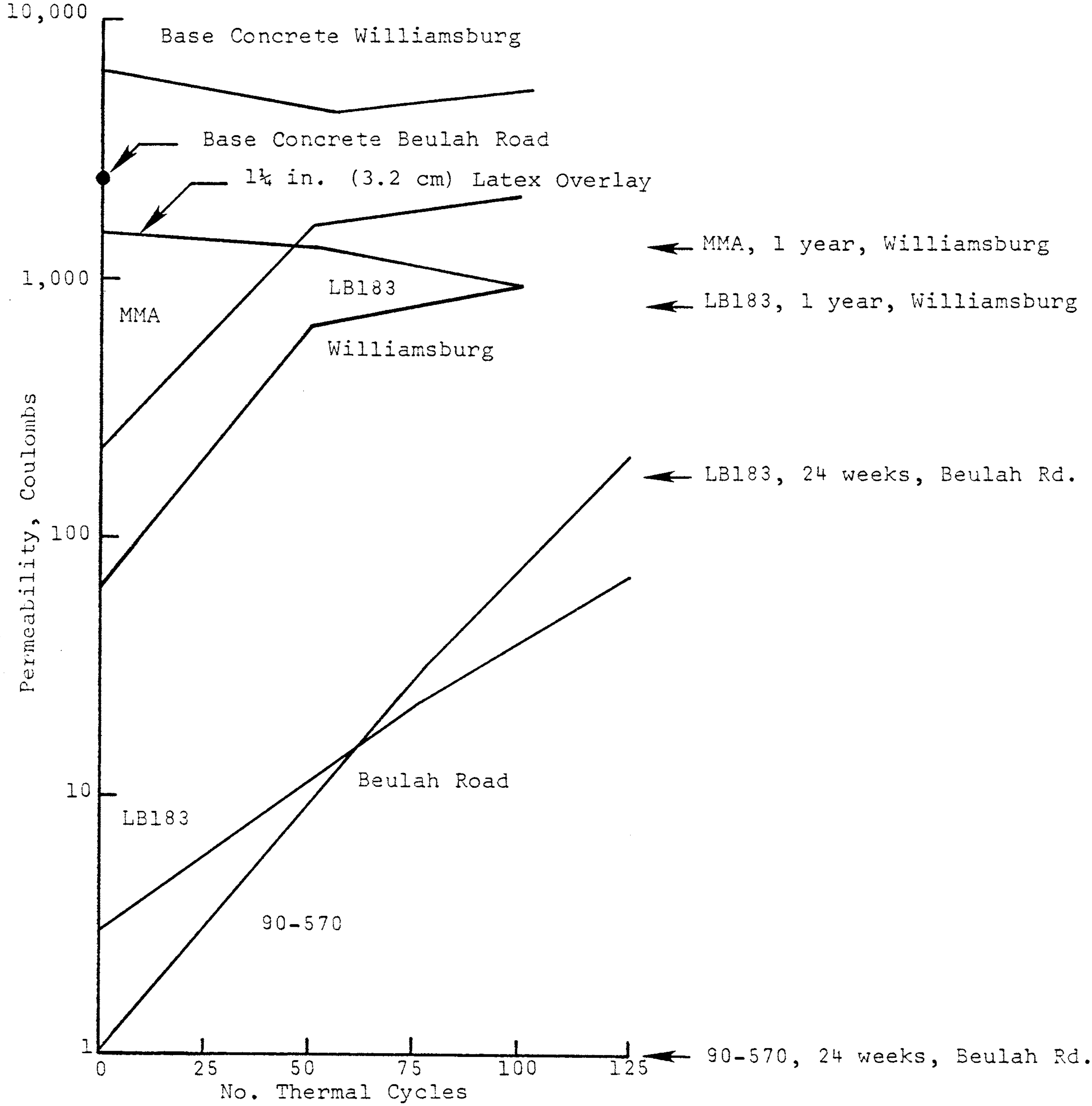

Figure 5. Permeability to chloride ion of PC overlays as a function of number of thermal cycles.

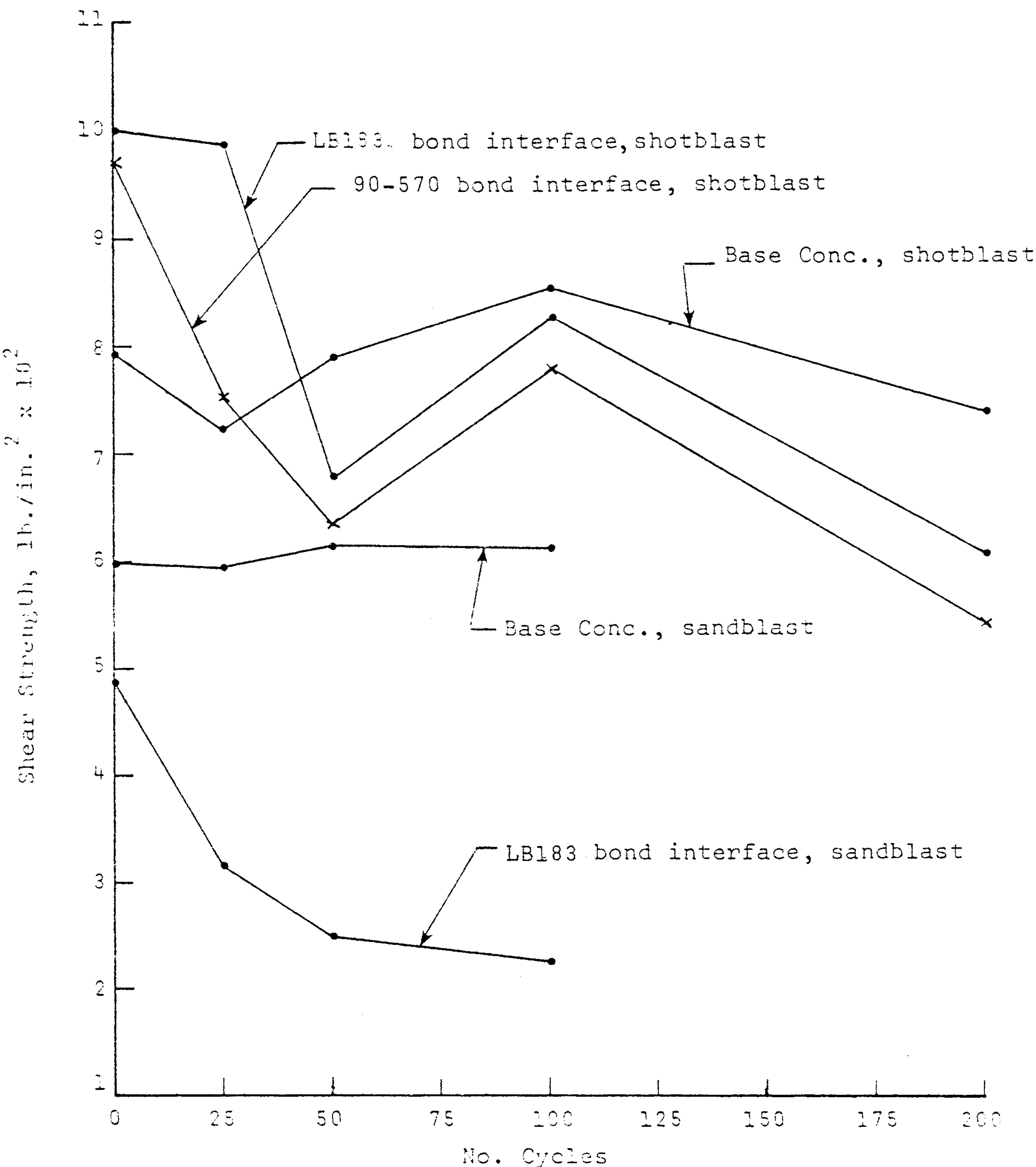

Figure 6. Shear strength as a function of number of thermal cycles. (6.89 kPa = 1 psi)

It can be seen that the shear strength of the portland cement concrete did not change as a result of the thermal loading. On the other hand, the shear strength of the bond interface decreased as the number of thermal cycles increased. For the shotblasted deck, the shear strength of the bond interface was higher than that of the base concrete at zero thermal cycles whereas for the sandblasted cores it was lower. Also, it can be seen that the shear strength of the bond interface was consistently higher for LB183 than for 90-570, but this may have been due to factors external to these products. It was the author's judgement that the shotblasting removed more concrete from the surface that received the LB183 than from the surface with the 90-570 resin. For the sandblasted cores, the low strength of the bond interface at zero cycles may be attributed to a poor job of preparing the concrete surface prior to placing the overlay. Evidently, sandblasting cannot be depended upon to adequately prepare the surface and shotblasting is considerably more dependable.

The type of failures which occurred during the shear tests provided further evidence that the strength of the bond interface deteriorated when subjected to cycles of temperature change. Table 10 shows that for the shotblasted surfaces, at zero thermal cycles all of the shear failures involved only the base concrete, whereas with the sandblasted surface many of the failures involved the bond interface. At 25 or more thermal cycles, all of the failures for both types of surfaces involved the bond interface and none involved only the base concrete.

The delamination of polyester resin overlays placed in Georgia in 1979 and New Mexico in 1980 provides field evidence that thermal stress deteriorates the bond interface and that sandblasting is not an adequate surface preparation technique.

Tensile Strength

Twenty-one 1-in. (2.5 cm) diameter cores were removed from the Beulah Road bridge and subjected to a tensile test as shown in Figure 7. Prior to the test, 8 of the specimens were subjected to 50 thermal cycles. The tensile strength data for 0 cycles and 50 cycles are shown in Table 11. On the average, a 26% to 38% reduction in the strength of the composite resulted from the 50 thermal cycles.

A bond failure occurred only 15% of the time for 0 cycles, whereas after 50 cycles half of the failures were in the bond. At 0 cycles the tensile strength was primarily a function of the strength of the aggregate and concrete, whereas after 50 thermal

Table 10

Number of Shear Failures at Indicated Locations

No. Thermal Cycles	Shotblasted Surface Bond	Shotblasted Surface Concrete	Shotblasted Surface Both	Sandblasted Surface Bond	Sandblasted Surface Concrete	Sandblasted Surface Both
0	0	8	0	1	5	8
25	1	0	2	4	0	2
50	2	0	2	6	0	4
100	3	0	2	2	0	2
200	2	0	0			

Table 11

Tensile Test Data

	Cycles	0		50	
	Product	LB183	90-570	LB183	90-570
	Strength, lb./in.^{2}	337	268	210	198
No. Failures at Indicated Locations	Polymer	0	0	0	0
	Bond	2	0	3	1
	Concrete or aggregate	7	4	1	3

6.89 kPa = 1 psi

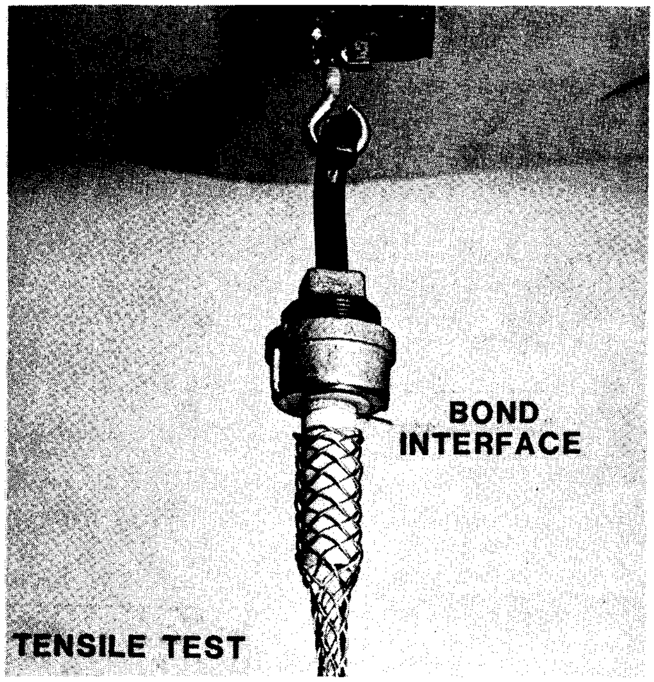

Figure 7. Arrangement for tensile test showing overlay bonded to metal cap and metal fingers surrounding concrete base.

cycles the bond had been weakened to the point that it was of about the same strength as the concrete and aggregate. The reduction in the tensile strength of the bond interface with thermal cycles was similar to the reduction in shear strength.

Assessment of Condition of Overlays

Prior to the installation of the PC overlay the deck was in sound condition, the steel was not corroding and there was no delamination. Chloride contents were moderate, but below levels that would cause corrosion.

The deck surface was properly prepared and the overlay was soundly bonded to the concrete. The overlay is providing a wearing surface of low permeability and high skid resistance following 24 weeks of service life. The LB183 appears to be cracking more rapidly than the 90-570, and it will be interesting to monitor the performance of these materials over the coming years as they are subjected to wear, reflective cracking, and thermally-induced stress.

THERMAL COMPATIBILITY OF POLYMER CONCRETE OVERLAYS

Theory

When two materials of different properties are bonded together a shearing stress develops when the composite is subjected to a change in temperature. Van Vlack's equation for this stress is

$$S = \frac{(C_p - C_c)\, E_p E_c\, \Delta T}{E_p + E_c}$$

where

S = shearing stress, lb./in.^{2} (Pa);

C_p = coefficient of thermal expansion for PC overlay, in./in./deg. F. (cm/cm/deg. C);

C_c = coefficient of thermal expansion for portland cement concrete, in./in./deg. F. (cm/cm/deg. C);

E_p = modulus of elasticity of PC overlay, lb./in.^{2} (Pa);

E_c = modulus of elasticity of portland cement concrete, lb./in.^{2} (Pa); and

ΔT = temperature change, deg. F (C) (8)

The shearing stress is a function of the temperature change and the coefficient of thermal expansion and moduli of elasticity of the two materials. A shear failure in the vicinity of the interface can be expected if the shear stress exceeds the shear strength of either of the materials or the strength of the bond. The objective of the testing program discussed below was to gain an indication of the thermal compatibility of PC overlays and the portland cement concrete bridge deck. The conclusions are based on a comparison of the theoretical shear stress as reflected by the Van Vlack equation and the measured strength and observed performance of specimens subjected to cycles of temperature change.

Testing Program

Thirty-six specimens of the PC overlay materials 3 in. (7.6 cm) wide by 11 in. (28 cm) long by 0.30 to 0.6 in. (0.8 to 1.5 cm) thick were prepared for determinations of density, moduli of elasticity, and coefficient of thermal expansion (unbonded specimens). In an additional 6 specimens, prepared for the same purpose, the PC overlay was placed on portland cement concrete without sandblasting the concrete surface (bonded specimens). Prior to any measurements, the 6 bonded overlays were removed from the base concrete by subjecting the composite to a freeze-thaw test in accordance with Procedure A of ASTM C666. In addition, PC overlays were placed on the sandblasted tops and bottoms of eighteen 3 in. x 4 in. x 16 in. (7.6 cm x 10.2 cm x 40.6 cm) portland cement concrete specimens that were then subjected to cycles of temperature change. The portland cement concrete had a plastic density of 145 lb./ft.^{3} (2323 kg/m^3), a 28-day compressive strength of 5,150 lb./in.^{2} (35.5 MPa), and a shear strength of 612 lb./in.^{2} (4.22 MPa), which are reasonbly typical of values for bridge deck concrete. The PC overlays were prepared in four layers according to the currently recommended practice that requires 2.0 lb./yd.^{2} (1.1 kg/m^2) of resin for the first layer and 2.75 lb./yd.^{2} (1.5 kg/m^2) for subsequent layers. The overlays were prepared at a temperature of 74°F (23°C). The sand application rate was varied from 0 to 21 lb./yd.^{2} (11 kg/m^2) per layer (0 to 84 lb./yd.^{2} (46 kg/m^2) for 4 layers) to study the effect of the rate on performance.

Results

Density of PC Overlays

Figure 8 shows the density of the PC overlays based on the weights of the specimens and the volumes of water displaced as a function of the sand application rate for four layers. As would be expected, the density increased with increases in the rate at which the sand was applied. In addition to the 42 overlays fabricated in layers, 16 cylindrical specimens having a volume of 1.7 in.^{3} (28 cm^3) each were made. It can be seen from Figure 8 that for the higher sand application rates, the densities of the four-layer PC overlays were less than those of the cylindrical specimens prepared as a single mixture. This is because in the layered system the excess sand was removed after each layer was prepared, while for the single mixture the ingredients were combined in a mold. Also, the densities of the bonded specimens were less than those of the unbonded specimens, probably because there was less shrinkage in the former. Sand was omitted from one layer of each of 3 unbonded specimens and two layers of each of 3 other unbonded specimens prepared with each of the two polyester resins. It can be seen that the omission of the sand, particularly from two layers, produced a density less than that found when one-fourth of the total amount of sand was applied to each of four layers.

Dynamic Moduli of Elasticity

Figure 9 shows the dynamic moduli of elasticity (E_p) of the PC overlays based on ASTM C215-60 as a function of the sand application rate. It can be seen that as the rate increased, the E_p increased up to a maximum for a rate of 52 lb./yd.^{2} (28 kg/m^2) and then tended to level off or decrease. Also, the E_p for LB183 appeared to be higher than that for 90-570 for the unbonded specimens. Except when no sand was applied, the lowest E_p for a given sand application was found for the bonded LB183 overlays. The reader is cautioned to remember that the bonded LB183 overlays were fabricated in bond to concrete but were not bonded when the moduli were measured. Because the specimens prepared with no sand were very thin and flexible, it was difficult to accurately determine their E_p. The omission of sand from one or two layers produced moduli less than found when one-fourth of the total amount of sand was applied to each of four layers.

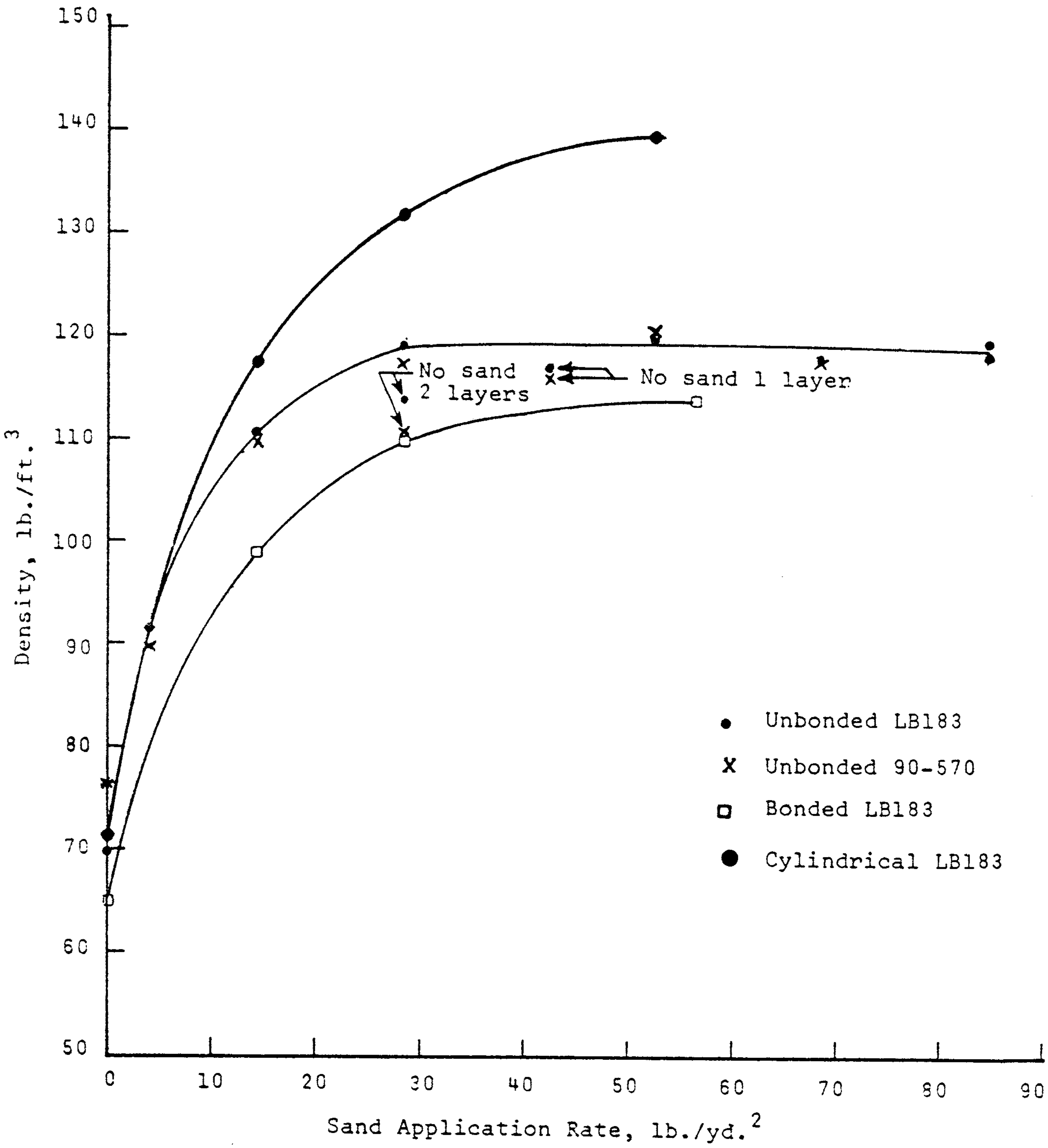

Figure 8. Density as a function of sand application rate. (16 kg/m^3 = 1 lb./ft.^{3}; 0.54 kg/m^2)

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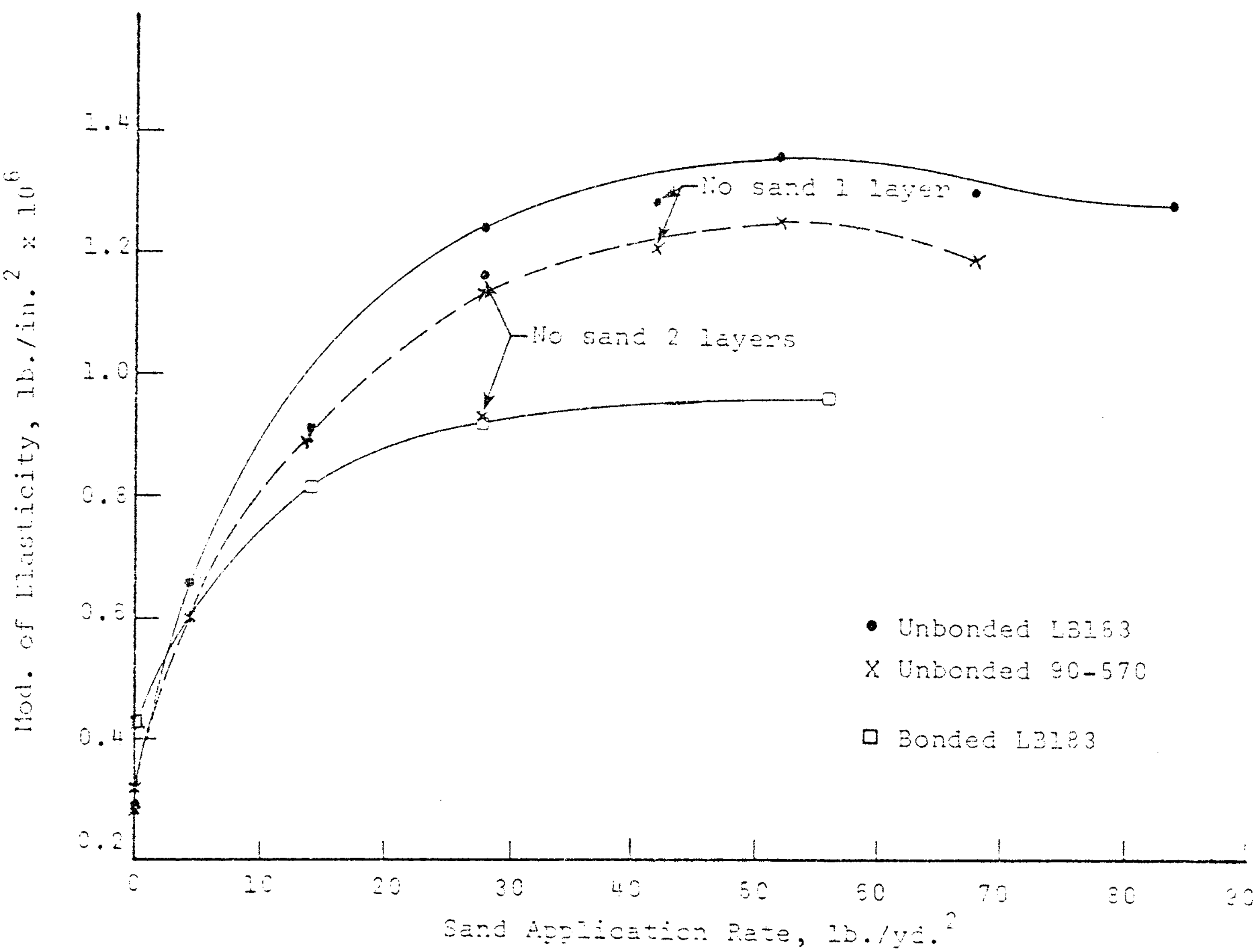

Figure 9. Modulus of elasticity as a function of sand application rate. (6.89 kPa = 1 lb./in.^{2}; 0.54 kg/m^2 = 1 lb./yd.^{2}.)

Coefficient of Thermal Expansion

Metal studs were installed in the ends of the 42 specimens of PC overlay and the 6 specimens of base concrete to allow a determination of the length of the specimens at a given temperature. The length of each specimen was determined three times at each of three temperatures: at $0^{o}F$ ($-17.8^{o}C$) as provided by a freezer, at $74^{o}F$ ($23^{o}C$) as provided by the laboratory atmosphere, and at $140^{o}F$ ($60^{o}C$) as provided by a water bath. Plastic bags were used to keep the specimens from absorbing moisture when placed in the bath. Based on the length measurements, the coefficients of thermal expansion were determined for the $74^{o}F$ ($23^{o}C$) base temperature.

Figure 10 shows the coefficient of thermal expansion (C_p) as a function of the sand application rate for four layers. The C_p decreased as the rate increased up to a minimum value for a rate of about 52 lb./yd.^{2} (28 kg/m^2), then tended to level off. The two products didn't appear to have significantly different values, although the C_p for the 90-570 was slightly lower at a sand application rate of 52 lb./yd.^{2} (28 kg/m^2) or more. The lowest C_p's were found for the bonded LB183 specimens. The omission of sand from two layers produced C_p's only slightly higher than that found when one-fourth of the total weight of sand was applied to each of four layers. The portland cement concrete specimens had a coefficient of thermal expansion of 5.7×10^{-6} in./in./^{o}F (10.3×10^{-6} mm/mm/^{o}C).

Theoretical Shear Stress

Figure 11 shows the theoretical shear stress in the vicinity of the bond interface as a function of the sand application rate based on the Van Vlack equation and the values of moduli of elasticity and coefficients of thermal expansion determined for the base concrete and the PC overlays. A value of 4.2×10^6 lb./in.^{2} (28.9 GPa) as determined by ASTM C215 was used for the modulus of elasticity of the base concrete. The use of other values which might be found for bridge deck concrete would not have a significant effect on the theoretical shear stress.

It can be seen from Figure 11 that the theoretical shear stress for a $1^{o}F$ ($0.56^{o}C$) change in temperature decreased as the sand application rate increased beyond 7 lb./yd.^{2} (4 kg/m^2). The highest stress occurred for a sand application rate of 4 to 7 lb./yd.^{2} (2 to 4 kg/m^2), depending on the product. The theoretical shear stress for the unbonded specimens prepared with no sand was low because the E_p was low. The theoretical shear stress was less for the 90-570 than for the LB183 for the 52 lb./yd.^{2} (28 kg/m^2) sand application rate. The lowest theoretical shear stress was found using values of E_p and C_p found for the bonded LB183. The

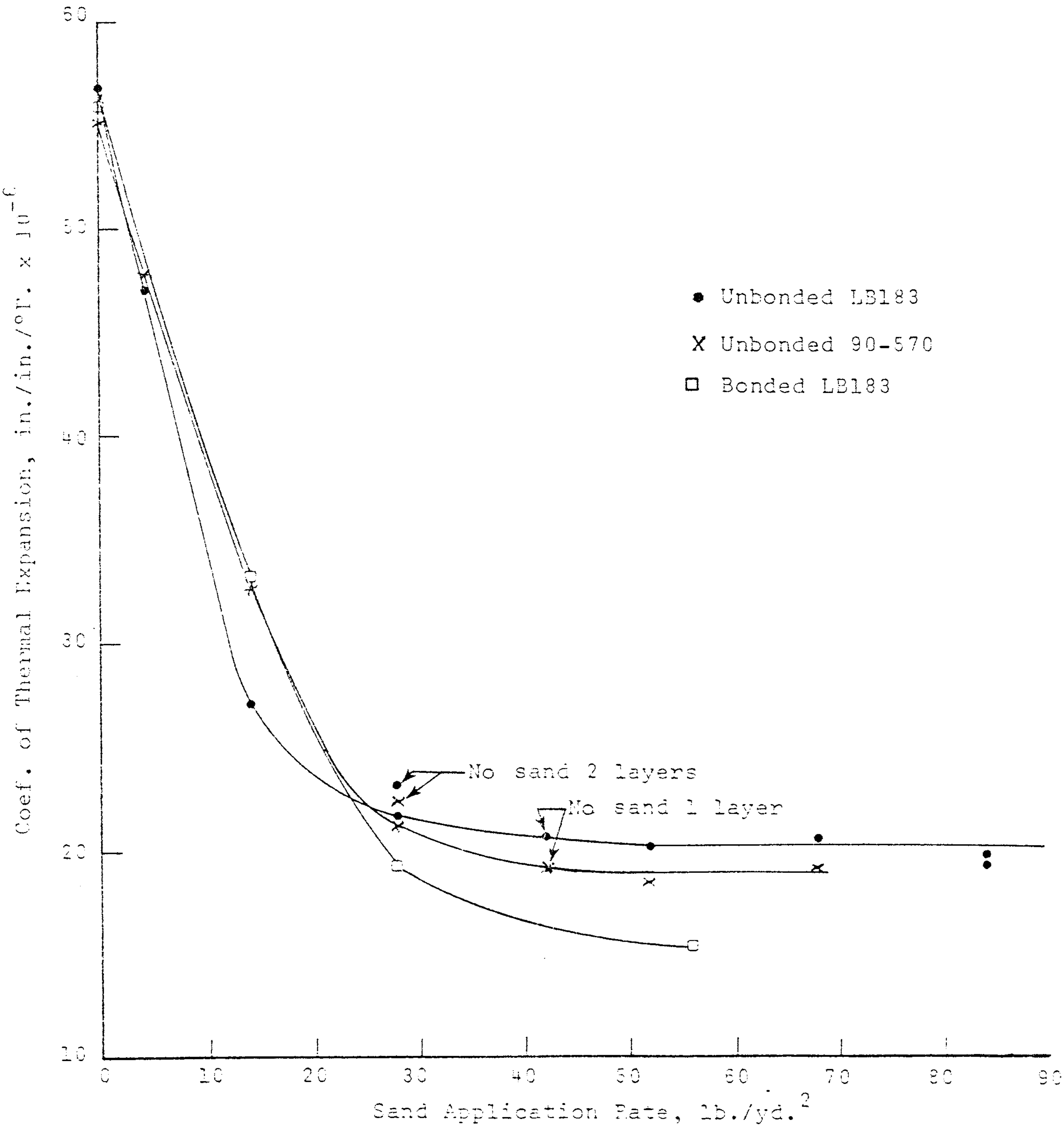

Figure 10. Coefficient of thermal expansion as a function of sand application rate. (2.54 cm = 1 in.; $^{o}C = (^{o}F-32)/1.8$; 9.54 kg/m^2 = 1 lb./yd.^{2})

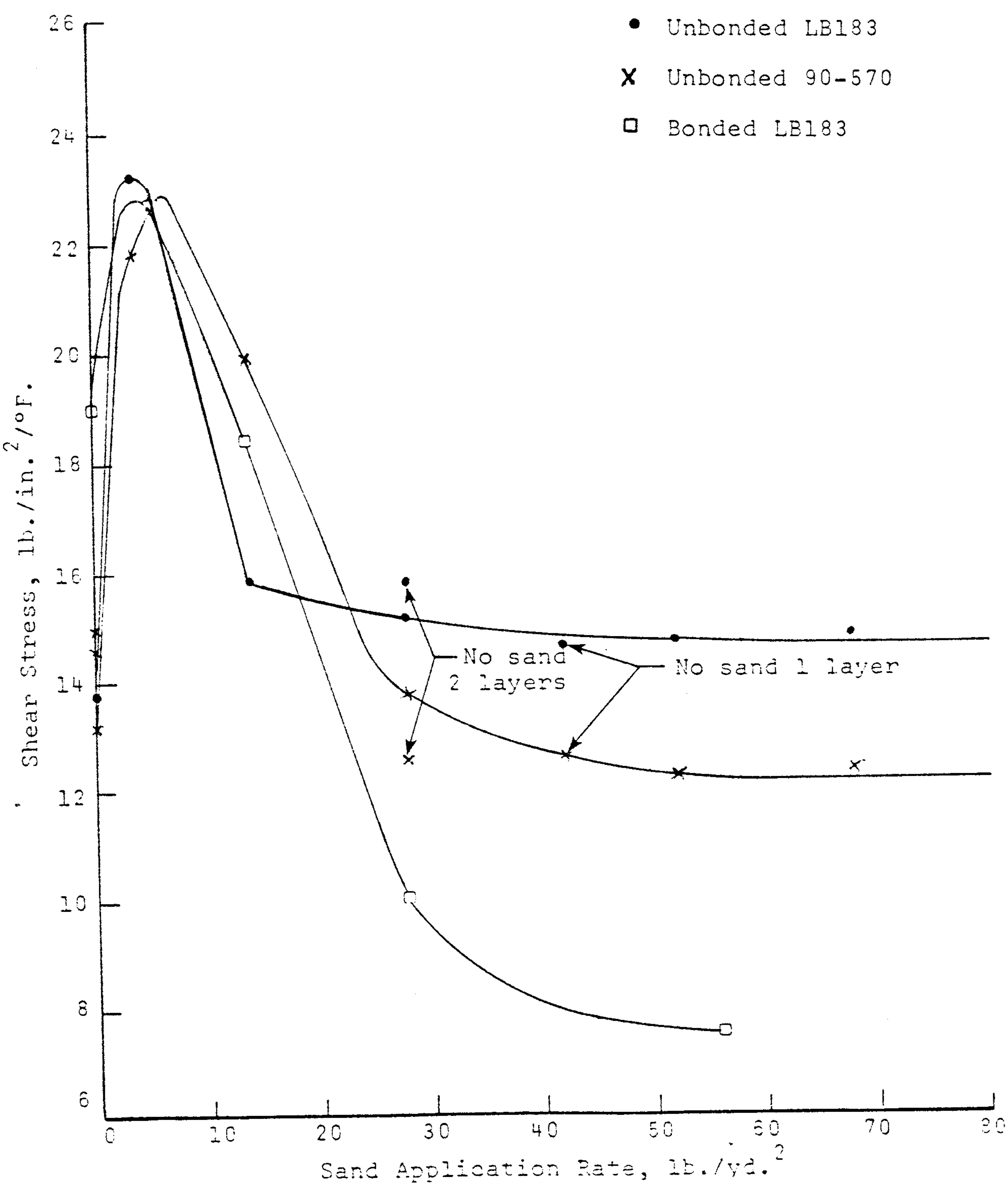

Figure 11. Shear stress per degree F. as a function of sand application rate. (6.89 kPa = 1 lb./in.^{2}; °C = (°F-32)/1.8; 0.54 kg/m^2 = 1 lb./yd.^{2}

fabrication of the bonded overlays or the fatigue resulting from the freeze-thaw test used to remove the overlay caused the E_p and the C_p to be lower than those found for the unbonded specimens. The E_p and the C_p appear to have changed as a result of the overlay being placed on the concrete, and therefore to have taken on properties more compatible with those of the base concrete and properties that provide for less shear stress for a given temperature change. Although E_p decreased and C_p increased, on the average, the omission of sand from one or two layers of the unbonded specimens prepared with a sand application rate of 14 lb./yd.^{2} (7.6 kg/m^2) per layer did not produce a theoretical shear stress significantly different than that produced when one-fourth of the total amount of sand was applied to each of four layers.

Delamination

To gain an indication of the amount of cracking that would occur at the bond interface as a result of thermal loading, PC overlays were placed on specimens having a surface area of 3 in. (7.6 cm) by 16 in. (41 cm). The surfaces were sandblasted prior to placing the overlays. Figure 12 shows the percentage of the perimeter of the bond interface that was shown by a visual inspection to contain cracks as a function of the number of thermal cycles. It is obvious from the figure that thermal loading initiated cracks at the bond interface in all the specimens. The percentage of delamination as indicated by the length of the cracks increased with an increase in the number of thermal cycles. More delamination occurred with the LB183 resin than with the 90-570 for the same number of cycles and the same sand application rate. This difference may have resulted from a difference in stress (Figure 11), or it may be related to the condition of the surface of the portland cement concrete. The LB183 overlay was placed on the screeded tops of the specimens and the 90-570 overlay on the molded bottoms. Either the bottoms of the specimens received a better cleaning than the tops, or the tops needed more cleaning than the bottoms. The data in Figure 12 support the need to remove unsound or weak concrete prior to placing the overlays.

More importantly, the data in Figure 12 show the effect of the sand application rate on the amount of delamination. It can be seen that for application rates of 0 to 14 lb./yd.^{2} (7.6 kg/m^2), PC overlays approached complete delamination in 27 cycles or less. At an application rate of 28 lb./yd.^{2} (15 kg/m2) the amount of delamination was reduced significantly, and rates in excess of 28 lb./yd.^{2} (15 kg/m^2) generally resulted in the least amount of delamination. It's interesting to note that for overlays

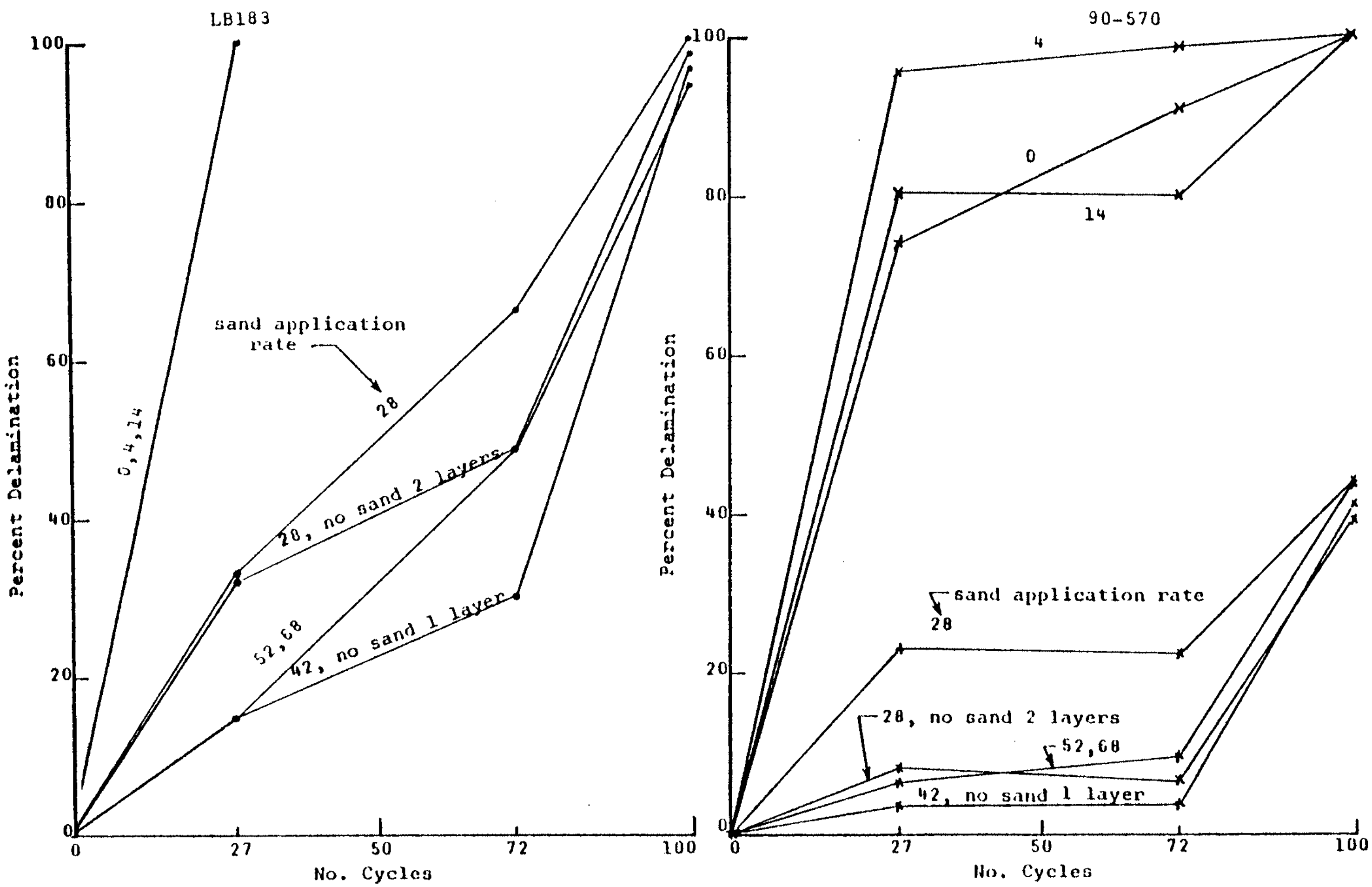

Figure 12. Delamination vs. number of thermal cycles for different sand application rates (lb./yd.^{2}). (0.54 kg/m^2 = 1 lb./yd.^{2})

prepared with an application rate of 14 lb./yd.^{2} (7.6 kg/m^2) per layer, the omission of sand from one or two layers did not have a significant effect on the amount of delamination, which would be expected based on the shear stress data in Figure 11. The delamination data in Figure 12 are evidence that the theoretical shear stress data reported in Figure 11 are reasonable, particularly the curve for the bonded specimens. The data in Figure 12 also indicate that even at the higher sand application rates, when the base concrete is sandblasted a major amount of delamination can be expected after 100 cycles.

Failure of PC Overlays

The data clearly indicate that the temperature changes to which the Beulah Road bridge will be subjected are sufficient to cause a level of stress that can lead to the deterioration and eventual failure of the PC overlay. Cycles of temperature change can deteriorate the bond interface by reducing the shear strength as was shown in Figure 6 and Table 10 and the tensile strength as was shown in Table 11, and eventually can cause delamination as was shown in Figure 12. They can also cause an increase in the permeability of the overlay as was shown in Figure 5. The failures can be grouped into one or more of three basic types as follows:

1. The formation of vertical cracks through the thickness of the overlay. (Figure 13)

2. The shearing of the portland cement concrete below the bond line. (Figure 14)

3. The deterioration of the bond between the PC overlay and the base concrete.

The formation of vertical cracks increases the permeability of the overlay and reduces its effectiveness in preventing the infiltration of chlorides. It will be the predominate mode of failure on bridges where the shear strength of the base concrete and the bond strength are high, or where the modulus of elasticity of the overlay is high or the tensile strength low. The failure will likely occur after a few cycles of temperature change. The overlay will likely remain bonded to the base concrete until freezing and thawing action causes delamination.

The shearing of the concrete below the bond line causes the PC overlay to delaminate with concrete remaining bonded to its underside as shown in Figure 14. The failure is most likely to occur when the shear strength of the base concrete is low and

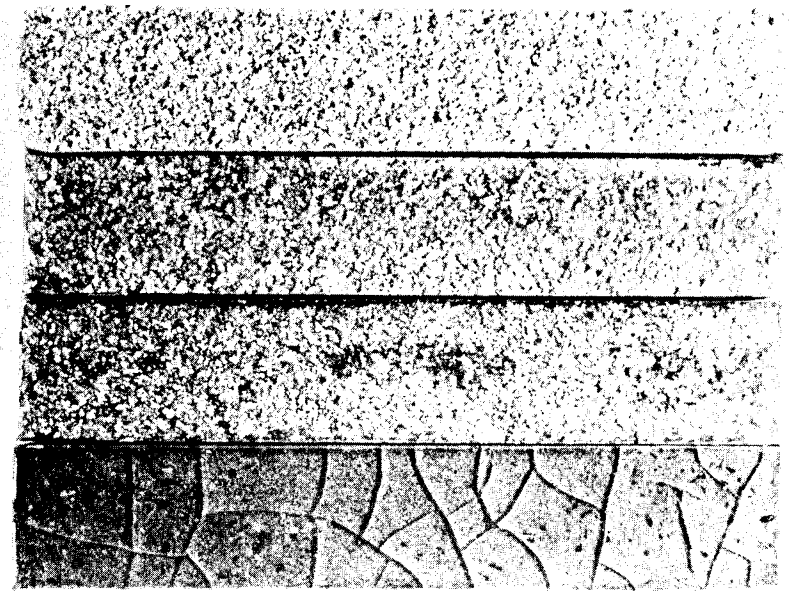

Figure 13. Top view of bonded PC overlay prepared with methy methacrylate resin and sand application rates of 0, 14, 28 and 56 lb./yd.^{2}, from bottom to top of figure. Cracks in the specimen with no sand are obvious after 1 thermal cycle. (0.54 kg/m^2 = 1 lb./yd.^{2})

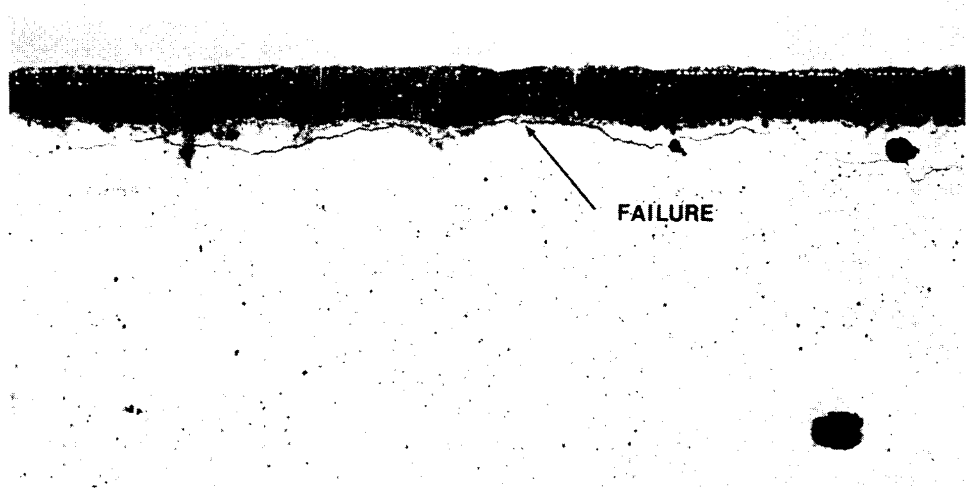

Figure 14. Shear stress failure of the portland cement concrete below the bond interface.

the bond is good and the tensile strength of the PC overlay is high. The failure will likely occur after a few cycles of temperature change and result in the delamination of the PC overlay.

The deterioration of the bond between the PC overlay and the base concrete causes the overlay to delaminate with no concrete remaining on the underside. The failure is likely to occur when the surface preparation prior to the installation of the overlay is poor or when the shear strength of the base concrete and the tensile strength of the PC overlay are high. Where the initial bond is poor, the failure will likely occur after a few cycles of temperature change (less than 100). Where the initial bond is good, a significant number of thermal cycles (more than 250) may be required to complete the failure.

COST AND SERVICE LIFE

Based on data compiled in May 1982 for the Beulah Road bridge, the cost of PC overlays is estimated to be between \$20 and \$25/yd.^{2} (\$24 and \$30/m^2). The cost of the materials is approximately \$11/yd.^{2} (\$13/m^2) and that for shotblasting approximately \$4/yd.^{2} (\$5/m^2), depending on the size of the job (see Table 12). Although overlays were installed under contract on four bridges in Virginia in 1981 at a cost of \$41/yd.^{2} (\$49/m^2), it is believed that with more competition, or with the use of state force labor, the cost of labor can be held to from \$5/yd.^{2} (\$6/m^2) to \$10/yd.^{2} (\$12/m^2). The cost of traffic control is negligible.

The cost of an alternative type of deck repair requiring the scarification and removal of the top 0.5 in. (1.3 cm) of old concrete and the installation of a 1.25 in. (3.2 cm) thick overlay of low permeability portland cement containing a latex modifier is estimated to be between \$34 and \$54/yd.^{2} (\$41 and \$65/m^2). These figures assume a cost of \$9/yd.^{2} (\$11/m^2) to remove the old concrete, \$20 to \$25/yd.^{2} (\$24 to \$30/m^2) for the installation of the new overlay, and \$5 to \$20/yd.^{2} (\$6 to \$24/m^2) for traffic control. Clearly, the PC overlay has an obvious cost advantage over a latex modified concrete overlay when traffic control costs are high.

From the information at hand, it is reasonable to estimate that a PC overlay constructed with LB183 or 90-570 will provide a skid resistant wearing surface of low permeability for a period of at least 5 years, depending upon the quality of installation and the characteristics of the weather and traffic to which the overlay is subjected. Where there are high volumes

Table 12

Estimated Materials Costs for Polymer Concrete Overlays (4 Layers) May 1982

	Materials		Percentage of Total
1.	Shotblast - \$4/yd.^{2}	=	27
2.	Sand - 17 lb./layer @ \$39.85/ton = \$1.35/yd.^{2}	=	9
3.	Resin - 10.25 lb./yd.^{2} @ \$0.75/lb. = \$7.69/yd.^{2}	=	51
4.	Additives: (\$1.95/yd.^{2})	=	13
	a) MEKP @ 1.20% 0.12 lb./yd.^{2} @ \$3.02/lb. = \$0.37/yd.^{2}		
	b) CoN @ 0.50% 0.05 lb./yd.^{2} @ \$10.67/lb.= \$0.55/yd.^{2}		
	c) S440 @ 0.63% 0.06 lb./yd.^{2} @ \$3.40/lb. = \$0.22/yd.^{2}		
	d) A174 @ 0.63% 0.06 lb./yd.^{2} @ \$12.56/lb.= \$0.81/yd.^{2}		
5.	Total (14.99/yd.^{2})	=	100

0.84 m^2 = 1 yd.^{2}; 4.45 N = 1 lb.; 8.9 kN = 1 ton; 0.54 kg/m^2 = 1 lb./yd.^{2}

of traffic that make it difficult, if not impossible, to close a lane except for short periods of time, it is quite possible that a service life of only 5 years or less can be economical, particularly when one considers that the overlay can be installed for about 50% of the cost for an alternative installation. Once the overlay fails, another could be installed. Where a lane can be closed for an extended period of time, a service life of 5 years or more might be unacceptable, since alternative and more permanent repairs such as full-depth concrete replacement or the removal of the top 0.5 in. (1.3 cm) to 2.0 in. (5.1 cm) of concrete and the installation of a portland cement concrete overlay of low permeability, which will last for 20 years, could be more cost-effective.

The engineer must make a decision as to whether or not to specify a PC overlay based on the characteristics of the bridge being repaired. The longest achievable service life for a specified environment of temperature change would be expected from a PC overlay installed on properly shotblasted portland cement concrete having a high shear strength, preferably in excess of 600 lb./in.^{2} (4.1 MPa). The overlay must contain sufficient sand, preferably five times the weight of resin, and have a low modulus of elasticity to minimize cracking. Resins are available that are more flexible than LB183 and 90-570.[9] The PC overlays are clearly best suited to extend the service life of bridge decks where traffic volumes are high and where the chloride ion content of the concrete at the level of the reinforcing steel is less than the 1.3 lb./yd.^{3} (0.77 kg/m^3) required to cause corrosion.

CONCLUSIONS

1. Thin PC overlays that provide low permeability and high skid resistance can be successfully installed on bridge decks by maintenance forces with a minimum of disruption to traffic and at about half the cost of alternative service-life-extending measures such as portland cement concrete overlays.

2. Laboratory tests indicate that the temperature changes to which bridge decks in Virginia are typically subjected are sufficient to cause deterioration and eventual failure of the overlays. The deterioration results from the development of shear stress in the vicinity of the bond between the concrete and overlay because of differences in the moduli of elasticity and the coefficients of thermal expansion of the materials. The Van Vlack equation provides a reasonable indication of the magnitude of the stress.

3. The thermally-induced stress can be held to a minimum by placing the overlay at 60° to 70°F (16 to 21°C), by applying an excess of sand to the resin, and by specifying a resin with a low modulus of elasticity and a low coefficient of thermal expansion.

4. Thermally-induced cracks have been noted in the overlay, the base concrete, and the bond interface, a majority of them in the medium least able to withstand the stress. Cracks in the overlay increase its permeability and cracks in the base concrete or the bond interface lead to delamination of the overlays.

5. The base concrete is least likely to fail when its shear strength is high, its surface is prepared by shotblasting, and an excess of sand is applied to the resin.

6. It is estimated that a properly installed overlay prepared with either of the two polyester resins tested in this study will have a useful service life of at least 5 years, which, considering its ease of application, may be acceptable for bridges where it is difficult to close a lane to make a more permanent repair.

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ACKNOWLEDGEMENTS

The author acknowledges the technical contributions made by Darrell Maret of the Demonstration Projects Division of FHWA, John Bartholomew and more recently Thomas Larkin of the Implementation Division of FHWA and Jack Fontanna of Brookhaven National Laboratory. Contributions were also made by the members of the Council's Bridge and Concrete Research Advisory Committees and TRB Committee A3C14, Adhesives and Bonding Agents.

The author acknowledges the support and assistance provided by Culpeper District personnel under Frank Prewoznik, Camp 30 personnel under Thomas Atkins, personnel from the FAA, Richard Steele from the Materials Division of the Virginia Department of Highways & Transportation, and Council technicians, B. Marshall, J. French, C. Giannini and M. Burton.

Arlene Fewell handled the secretarial responsibilities and the Report Section under Harry Craft edited and reproduced the final report.

The study was conducted under the Direction of Howard Newlon, Jr., and with the administrative guidance and support of Harry Brown.

The study was sponsored by the VHTRC in cooperation with the Demonstration Projects Division of FHWA. The opinions, findings, and conclusions expressed in the report are those of the author and not necessarily those of the sponsoring agencies.

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APPENDIX — DEFINITION OF TERMS

Polymer Concrete: (PC)	A composite material consisting of a polyester resin as a binder and a well-graded, high-quality aggregate as a filler.
Resin:	A low viscosity liquid material, sometimes referred to as a monomer, that hardens to a solid plastic.
Polymer:	A hard,glossy,plastic-like material.
Polymerization:	A chemical reaction by which the molecules of a monomer are cross-linked to form a polymer.
Initiator:	A substance added to the resin in small quantities to cause the resin to harden.
Promoter:	A substance added to a resin which, in combination with an initiator, causes polymerization at ambient temperatures.
Cure Time:	Time required for the liquid resin to harden and reach the required strength.
Inhibitor:	A substance added to resin to slow down or prevent curing.
Gel Time:	Length of time the resin may be worked without destroying the cross-linking internal bonds. The gel time is determined by noting the time interval required for a 50-ml sample of resin to exhibit a consistency similar to gelatin following the addition of the initiator and promoter.