Thin Polymer Concrete Overlays for Bridge Deck Protection

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ABSTRACT

The installation of thin polymer concrete (PC) overlays on portland cement concrete bridge decks during the past 3 years has demonstrated that overlays of low permeability and high skid resistance can be successfully installed with a minimum of disruption to traffic. The initial condition of the overlays has been excellent from the standpoint of permeability, skid resistance, and bond, although some overlays have been better than others. In this paper the potential of thin PC overlays for extending the service life of bridge decks is discussed. The bond achieved between the overlay and the deck concrete, the protection provided by the overlay, and the tensile properties of the resins and how they affect the performance of the overlays are described. The cost of a PC overlay is compared with that of a more conventional, latex-modified concrete overlay, and insight is provided about when to specify a PC overlay based on considerations of service life, traffic volume, discount rate, and the value of driving time.

Thin polymer concrete (PC) overlays have been installed on portland cement concrete bridge decks in Virginia and several other states during the past 6 years (1-5). The experimental overlay 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.-thick, relatively impermeable, skid resistant wearing surface (6). Typically the initiated and promoted resin is sprayed uniformly over the surface of the deck (Figure 1), and before it gels (10 to 20 minutes) the resin is covered to excess with broadcast fine aggregate (Figure 2). Usually, within the first hour a layer cures sufficiently to permit vacuuming the excess aggregate in preparation for placing a subsequent layer. Approximately 12 hours are required to place an overlay on one lane of a 350-ft bridge. Five to 8 hours are required to shotblast the deck and 5 to 6 hours to install the four layers of polymer--1 hr per layer plus 1 hr for curing before opening the lane to traffic. When a lane cannot be closed for 12 hours, the overlay can be placed on part of the lane, or the entire deck can be shotblasted and one layer of resin and aggregate applied one day and the subsequent layers on the next day.

The installation of PC overlays on five bridges on Interstate 64 near Williamsburg, Virginia, in 1981; a sixth bridge near Vienna, Virginia (Beulah Road bridge), in 1982; and a seventh bridge near Columbia, Tennessee (Big Swan Creek bridge), in 1983, has demonstrated that an overlay of low permeability and high skid resistance can be successfully installed by a contractor or by a state or federal force labor with a minimum of disruption to traffic and at a reasonable cost. The initial permeability, skid resistance, and bond condition of the overlays was observed to be excellent, but some overlays were better than others.

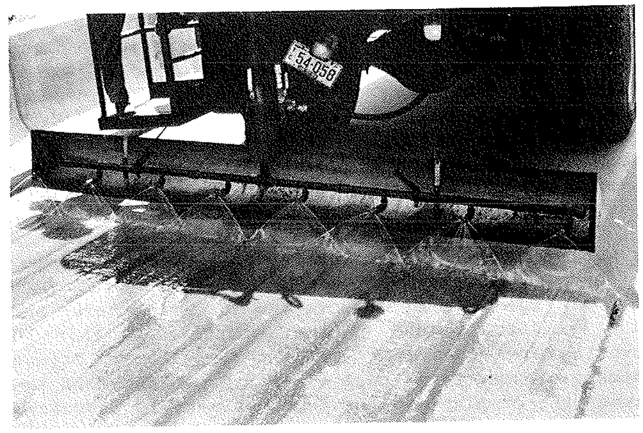


FIGURE 1 Polyester resin sprayed over deck surface.

FIGURE 2 Silica aggregate broadcast over resin.

The resins used were clear, low-viscosity, highly resilient, general-purpose, unsaturated polyester resins designed for applications requiring resistance to wear and high impacts. U.S.S. Chemical blend LB183 was used on bridges near Williamsburg and on the northbound lane of the Beulah Road bridge; Reichhold Chemical blend Polylite 90-570 was used on the southbound lane of the Beulah Road bridge; and Dural International blend 317 was used on the Big Swan Creek bridge. The first course contained 1 percent Union Carbide A-174 coupling agent and 1 percent Surfynol S440 wetting agent to enhance bond strength and reduce surface tension. The second, third, and fourth courses contained 0.5 percent Union Carbide A-174 coupling agent and 0.5 percent Surfynol S440 wetting agent.

Two initiators were used. One was 60 percent methylethylketone peroxide [MEKP $(C_4H_8O_2)$] in dimethyl phthalate and the other was 40 percent benzoyl peroxide dispersion (BPO-40) equal to Reichhold Chemical's formulation 46-742. Two promoters were also used. One was approximately 6 percent active cobalt in naphtha (CoN), and the second was N, N, dimethyl aniline [DMA $(C_6H_4N(CH_3)_2)$].

Before placement of the first layer of polymer and after all major spalls had been repaired, the deck was shotblasted with a machine equipped with a dust collector. 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. The equipment cleans the deck at a rate of 100 to 150 yd² per hour depending on the size of the unit (2,3,5). It does not fracture the aggregate or paste as is common when jackhammers or scarification equipment are used (7), and it cleans more efficiently and completely than does sandblasting equipment.

The purpose of this paper is to report on the condition of the PC overlays after 1 year of service life--particularly the overlay on the Beulah Road bridge, which is representative of the others--and the knowledge gained of the potential of thin PC overlays for extending the service life of bridge decks. In the first part of this paper the bond between the overlay and the deck concrete is discussed and attempts are made to answer the question, "How long will the overlay stay down?" In the second part the protection provided by the overlay, which is intended to prevent the infiltration of water and salt and thereby prevent corrosion of the reinforcing steel, is examined. In the third part the tensile properties of the resins are compared and how these properties affect the performance of the PC overlays is noted. In the fourth part the cost of a PC overlay is compared to that of a more conventional, latex-modified concrete overlay and insight is given about when to specify a PC overlay based on considerations of service life, traffic volume, discount rate, and the value of driving time.

STRENGTH OF BONDS

Shear Strength

To obtain an indication of the shear strength of the bond at the interface between the PC overlay and the base and the shear strength of the portland cement concrete base, cores were subjected to two tests. For the former, the shear force was directed through the bond interface; for the second it was directed through the concrete approximately 2.5 inches below the interface. The load was applied at 10,000 lb per minute with the apparatus shown in Figure 3.

Table 1 gives the shear strength and the types of failures for cores taken from the Beulah Road bridge in 1982, 2 weeks after the overlay was placed, and in 1983, 47 weeks after the installation. Although the cores taken in 1982 were 2.75 in. in diameter and those taken in 1983 were 4.0 in. in diameter there is no evidence that the difference in size affected the results. As can be seen from the table, there was no significant difference between the shear strengths of the two sets of cores for the portland cement concrete, but the 1983 strengths for the bond interface were lower than those for 1982. Of particular significance is the deterioration in strength of the bond of LB183 resin during the first year. Whereas the strength of this bond was greater than that of the base concrete in 1982, in 1983 it had decreased an average of 56 percent to a value only 52 percent that of the base concrete. For the 90-570 resin there was a 25 percent loss in the strength of the bond during the first year, but the strength was still 89 percent that of the base concrete. The loss in shear strength may be attributed to the creep and thermal stress that occurred during the year in service and that can be expected to continue (8).

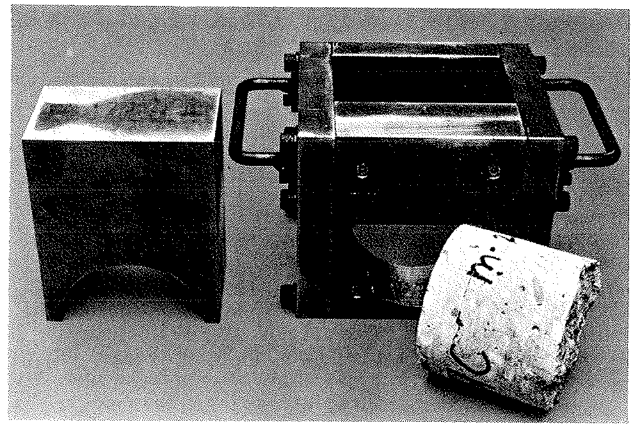


FIGURE 3 Apparatus used to subject cores to shear.

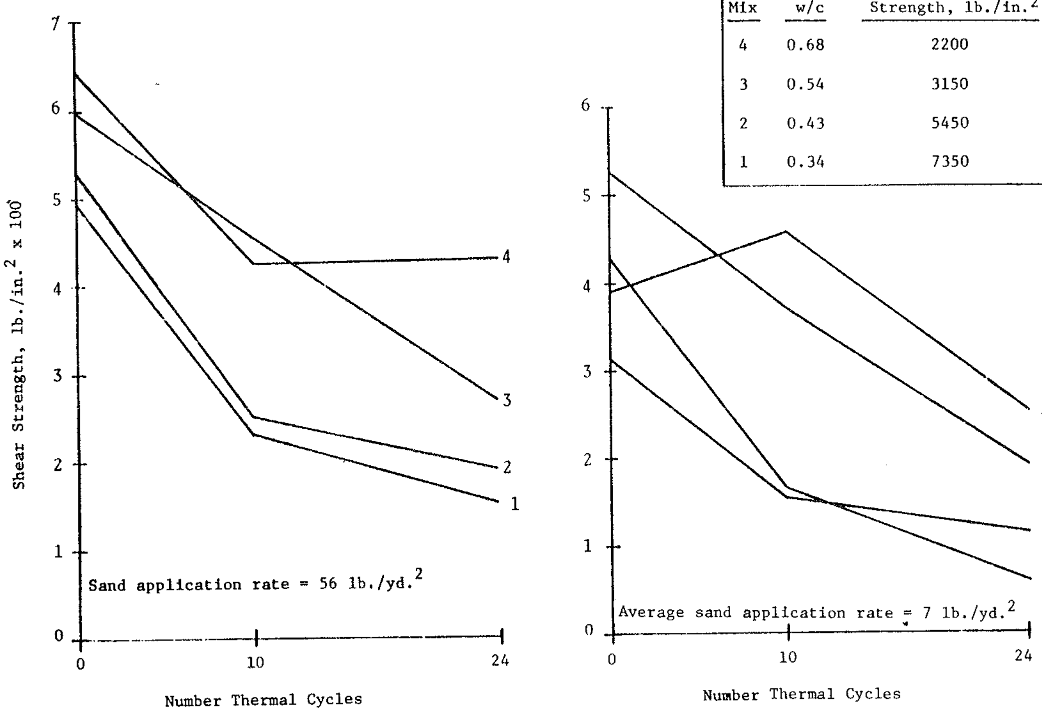
The modes in which the cores failed in the shear tests also provided evidence that the strength of the bond deteriorated during the first year. In 1982 the only failures were in the base concrete; in 1983 failures were noted in the bond interface, in the base concrete, and sometimes in both.

Further evidence of the breakdown in shear strength with cycles of temperature change is shown in Figure 4, which shows the results of shear tests on specimens prepared in the laboratory of the Virginia Highway and Transportation Research Council. The concrete base of each specimen consisted of a section 4 in. in diameter and 2.25 in. thick cut from a 4-in. x 8-in. cylinder. The base concretes were fabricated to have four different 28-day com-

TABLE 1 Shear Strength of Cores from Beulah Road

	LB183 Resin					90-570 Resin				
	Shear Strength (lb/in.²)		No. Failures at Indicated Location			Shear Strength (lb/in.²)		No. Failures at Indicated Location		
Year	Concrete	Bond Interface	Bond	Concrete	Both	Concrete	Bond Interface	Bond	Concrete	Both
1982	Avg 776 SD 76	1,001 229	0	4	0	Avg 824 SD 164	972 175	0	3	0
1983	Avg 838 SD 38	436 140	1	1	1	Avg 823 AD 165	730 108	0	0	4

Note: SD = standard deviation.



Physical Properties of Base Concrete

Mix	w/c	28-day Compressive Strength, lb./in.^{2}	Shear Strength, lb./in.^{2}
4	0.68	2200	877
3	0.54	3150	894
2	0.43	5450	1235
1	0.34	7350	1543

FIGURE 4 Shear strength of bond interface as function of number of thermal cycles for different base concrete strengths.

pressive strengths as shown in Figure 4. Following a 2-week period of moist curing and a 6-week period of air curing, a PC overlay constructed with 90-570 resin was placed on one sawn concrete surface of each specimen. Fine aggregate was applied to the overlays in an excessive amount (approximately 56 pounds per square yard) and at rates of 0 and 14 lb per square yard. The curves are based on the averages of tests on two specimens of concrete representing each level of design strength and subjected to either 0, 10, or 24 thermal cycles. The cycles were applied at the rate of 1 per day with the temperature changing from 0°F to 100°F. The overlays were 1 week old at the time the first thermal cycle was applied and 2 months old at the time the shear tests were conducted.

Figure 4 shows that, regardless of the strength of the base concrete, the shear strength of the bond interface decreased as the number of thermal cycles increased. Also, the highest shear strengths in the bond interface were achieved with the base concrete having the lowest design strength. This implies that the more permeable low-strength base concrete absorbed more resin, provided more mechanical bond, and yielded more under stress thereby subjecting the bond interface to less stress. Finally, Figure 4 shows that when an excess of aggregate (56 lb per square yard) was used in the overlay, the shear strengths at 0, 10, and 24 cycles were higher than when an average of 7 lb per square yard was used because the thermal and shrinkage stresses are less when an excess of aggregate is used in the overlay (8).

The mode of failure for the specimens prepared in the laboratory was similar to that of the cores taken from the Beulah Road bridge. At 0 cycles, which can be compared with the data for the cores taken in 1982 (Table 1), most failures were in the base concrete or involved the base concrete. At 10 and 24 cycles, which can be compared with the data for the cores taken in 1983, most failures were in the bond interface, and the few failures that involved the base concrete were in the two lower strength concretes.

Of additional interest is the fact that the shear strength of the bond interface at 0 cycles was lower for all specimens prepared in the laboratory than for the cores from the bridge. There are three possible explanations: First, the A174 coupling agent that is added to the resin helps bond the resin to the silica in the aggregate and this effect would be less pronounced for the siliceous gneiss coarse aggregate used in the laboratory specimens, which contain less silica, than for the chert aggregate used in the Beulah Road bridge. Second, the shear strengths of the base concrete in the laboratory specimens were generally higher than those of the base concrete in the bridge. Third, more surface contact was achieved with the shotblasted surface of the cores than with the sawn surface of the laboratory specimens.

Of particular importance is the fact that, despite the loss in bond strength that occurred with both resins as a result of thermal and shrinkage stresses, a second set of specimens identical to those that had been subjected to the shear tests and constructed with 90-570 resin and 56 lb per square yard of aggregate (Figure 5, right) withstood 300 thermal cycles without becoming debonded. The remaining specimens in the second set prepared with 0 and 14 lb per square yard of aggregate (Figure 5, left) delaminated in the vicinity of the bond interface. Based on the performance of these specimens, it is reasonable to expect that a PC overlay properly constructed with 90-570 resin will stay bonded for approximately 10 years.

Tensile Strength of Bond

One-inch-diameter cores were removed from the Beulah

FIGURE 5 Condition of test specimens after 300 thermal cycles.

Road bridge in 1982 and again in 1983 and tested in tension in an attempt to pull the overlay from the base concrete. The average tensile strength of the composite and the mode of failure are given in Table 2. Note that the tensile strength of the cores with the LB183 overlay decreased an average of 28 percent during the first year but the tensile strength of the cores with the 90-570 resin did not change, which suggests that a longer service life can be expected for the 90-570 resin. The results of the tensile tests agree in pattern with those of the shear tests.

Delamination

As determined with the Delamtech, after 47 weeks of service life, 1.4 percent of the LB183 overlay on the Beulah Road bridge was delaminated whereas no delaminations were detected in the 90-570 overlay. Inspections of the delaminated area revealed that insuffcent aggregate was placed on that portion of the overlay. The lower aggregate content resulted in an increase in shrinkage and in thermal stress during the first winter and thereby led to premature failures in the bond and in the base concrete. After 2 years of service life delaminations have not been observed in the LB183 overlays near Williamsburg.

In summary, overlays constructed with both resins were soundly bonded to the base concrete initially and after 1 year of service life. An area of the LB183 overlay on the south end of the Beulah Road bridge debonded during the first year because insufficient aggregate had been placed on that portion of the overlay. The bond strength of the LB183 overlay is decreasing more rapidly than that of the 90-570 overlay. Whereas it is anticipated that the properly constructed portion of the LB183 overlay will remain bonded at least 5 years (2), the 90-570 overlay should remain bonded a much longer time.

PROTECTION PROVIDED BY OVERLAY

Electrical Resistivity

Two weeks and 47 weeks after the overlay was installed on the Beulah Road bridge, electrical resistivity measurements (ASTM D3633-77) were made at grid points located 4 ft apart in the transverse direction and 5 ft apart in the longitudinal direction. Measurements were also made at half of these locations after 24 weeks of service life. The results are given in Table 3. Both materials exhibited good to excellent resistivity 2 weeks after they were installed. The resistivity of the LB183 overlay decreased to fair after 24 weeks of service life, but that of the 90-570 overlay was still good to excellent after 24 weeks and good after 47 weeks. The resistivity of the LB183 overlays placed near Williamsburg was fair to poor after 1 year of service life.

The test provides a good indication of the extent of cracking in an overlay. A low reading is indicative of a crack at the test location. The crack allows water to penetrate the overlay and lower the resistance in the electrical circuit. The 90-570 overlay is more flexible than the LB183 and therefore is less prone to cracking to relieve the stress caused by temperature changes, shrinkage, reflective cracking, and creep.

Permeability

A rapid test (9) recently developed by the Portland Cement Association for the FHWA was used to determine the permeability to chloride ion of 4-in.-diameter cores removed from the Beulah Road bridge, and the results are given in Table 4. A permeability of 2214 coulombs was determined for the base concrete. After 2 weeks of service life the permeability of the base concrete with a PC overlay was 2.9 coulombs for LB183 and 0.9 coulombs for 90-570. After 24 and 47 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 only 24 weeks of service life. The deterioration was probably caused by a combination of shrinkage and thermal stresses.

Cores taken from the LB183 overlay after 47 weeks of service life showed a greater permeability than ones taken at 24 weeks, which suggests that the thermal stress to which the overlay was subjected during the first winter caused additional cracking. Of greatest significance is the fact that the cores taken from the 90-570 overlay exhibited a permeability of only 1 coulomb after 47 weeks of service.

TABLE 2 Tensile Strength of Cores from Beulah Road

	LB183 Resin				90-570 Resin			
	Tensile Strength (lb/in.^{2})	No. Failures at Indicated Location			Tensile Strength (lb/in.^{2})	No. Failures at Indicated Location		
Year		Polymer	Bond	Concrete		Polymer	Bond	Concrete
1982	Avg 337 SD 78	0	2	5	Avg 268 SD 93	0	0	6
1983	Avg 241 SD 48	0	2	4	Avg 266 SD 53	0	1	5

Note: SD = standard deviation.

TABLE 3 Electrical Resistivity Measurements, Percentage of Total Number of Readings

		Range of Electrical Resistivity (ohms/ft²)			
Age (weeks)	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
	90-570	1	2	13	84
24	LB183	2	88	9	1
	90-570	0	1	41	58
47	LB183	2	80	17	1
	90-570	0	11	78	11

Clearly, this represents the best 1-year performance of any thin PC overlay placed in Virginia.

To further examine the permeability of the 90-570 resin, laboratory-prepared specimens identical to the ones subjected to the shear tests were subjected to 300 cycles of temperature change at the rate of 3 cycles per day, and permeability tests were conducted at 0, 10, 50, 100, 200, and 300 cycles. The results, which are based on the average of tests of two or more specimens at each number of test cycles, are shown in Figure 6. Also shown in this figure are the results of tests on cores removed from the Beulah Road bridge, the bridges in Williamsburg (3), and a bridge with a latex overlay. Recent tests of cores removed from 12 bridges with latex overlays ranging in age from 1 to 9 years have exhibited permeabilities in the range of 130 to 1298 coulombs with an average of 773 coulombs for an overlay thickness of 1.25 in.

It is not obvious that the 90-570 overlay is significantly better than the LB183 overlay from the standpoint of permeability (Figure 6). However, it must be remembered that the base concrete prepared in the laboratory had an average permeability of 7400 coulombs, a value significantly higher than that of the base concrete in the Beulah Road bridge. Test results for the overlay are affected by the

TABLE 4 Permeability Data, Coulombs

	Date of Sample and Age (weeks)						
	3/01/82 (-9)	5/18/82 (2)	10/20/82 (24)	3/29/83 (47)	5/18/82 (2)	10/20/82 (24)	3/29/83 (47)
	Material						
Span	Concrete	LB183	LB183	LB183	90-570	90-570	90-570
A	2308	0.5	52	809	–	–	–
B	–	0.7	–	–	0.5	0.3	2.2
C	–	3.7	248	859	–	–	–
D	–	–	–	–	2.2	0.0	5.1
E	–	53.0	447	521	–	–	–
F	2124	–	–	–	0.7	0.7	0.1
Log. Avg	2214	2.9	179	713	0.9	0.1	1.0

Note: Dash = no samples taken.

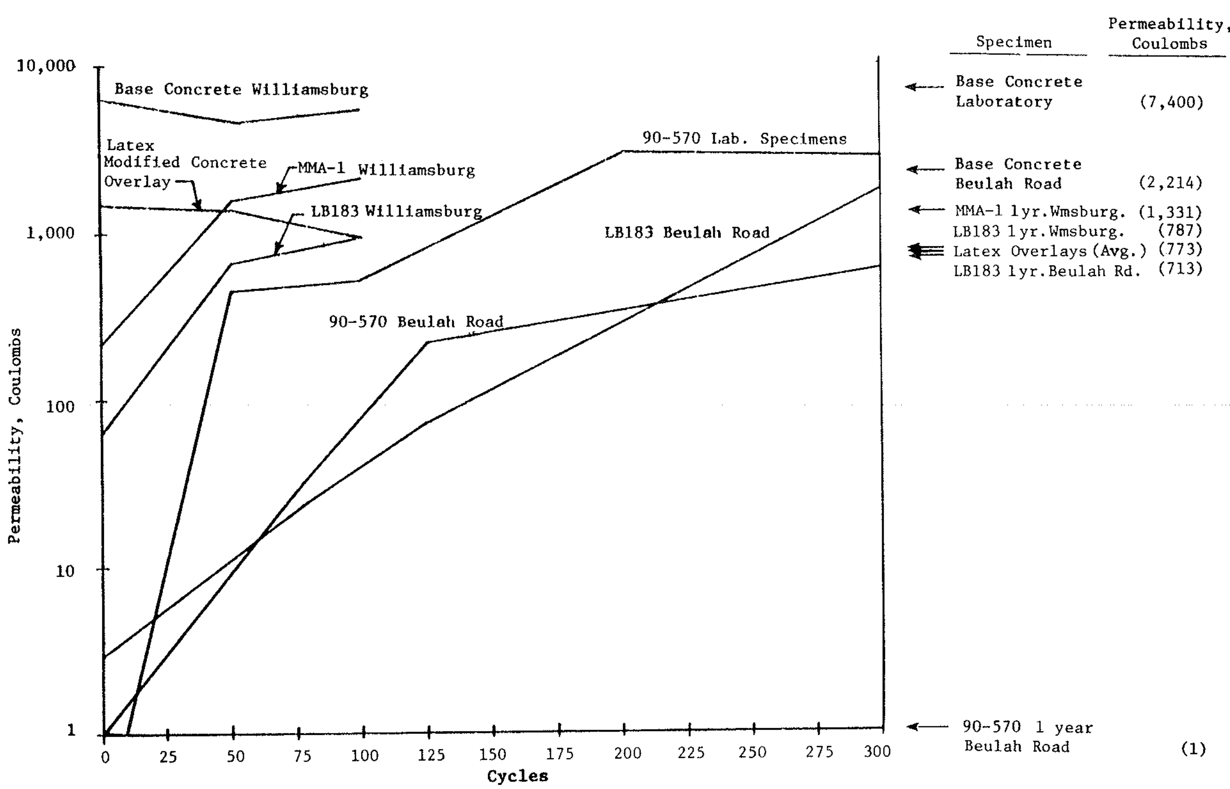


FIGURE 6 Permeability to chloride ion of PC overlays as a function of number of thermal cycles.

permeability of the base concrete because the 0.5-in.-thick PC overlay accounts for only 25 percent of the 2-in. thickness of the test specimen.

Based on the data shown in Figure 6, it can be concluded that both resins experienced an increase in permeability when subjected to cycles of temperature change. Also, if the results obtained with the laboratory specimens and the cores removed from the Beulah Road bridge are averaged, it can be concluded that after 300 cycles the permeability of a 0.5-in.-thick layer of 90-570 resin and aggregate was about equal to that of a 1.25-in.-thick overlay of latex-modified concrete. If it can be assumed that 1 year in service is equivalent to 50 thermal cycles, the 90-570 and the LB183 overlays should provide a permeability less than or equal to that of a 1.25-in.-thick latex overlay for at least 6 years. The performance of the overlays must be observed for a number of years to allow a more accurate projection of the permeability to be expected after 6 years.

Shrinkage

It was believed that the LB183 resin cracked more than 90-570 resin because it exhibited a higher shrinkage. However, recent measurements indicated no major differences among the shrinkages of the two resins and resin 317. The measurements indicated that a shrinkage of approximately 2 percent can be expected when no aggregate is used and a shrinkage of 0.2 percent is typical when the aggregate-to-resin ratio by weight is 4 to 1. It is obvious that the principal way to minimize shrinkage is to load the resin to excess with aggregate. Because the LB183 resin does not shrink significantly more than the other resins, one must conclude that it cracks more as a result of shrinkage-induced stress because it is less flexible and therefore less able to strain to accommodate stress.

Half-Cell Potential

Copper sulfate half-cell potentials (ASTM C876-77) were measured before, immediately after, and approximately 1 year after the installation of the PC overlays. The results of the measurements imply that there was a high probability that no corrosion was occurring before and approximately 1 year after the installation of the overlays. Values could not be determined immediately after the installation of the overlays because there were no cracks in the overlays to allow the completion of the electrical circuit.

Rutting in Wheelpaths

A 12-ft straightedge was used to measure rutting in the wheelpaths. The device has six scales spaced 2 ft apart. Measurements are made by depressing the six scales until they touch the surface of the deck and recording the readings. The rutting in a wheelpath is computed by subtracting the reading on the scale located in the center of the wheelpath from the average of the readings for the two adjacent scales. Measurements were made at 10-ft intervals along the length of the bridges. The amount of wear, computed by subtracting the measurements obtained after 1 year of service life from the measurements obtained immediately after the overlay was installed, was less than 1/32 in. for all the bridges.

Skid Numbers

Skid numbers (ASTM E501-76 and E524-76) were determined in tests at 40 mph in each lane 3 weeks before and 4, 13, and 50 weeks after the PC overlay was installed on the Beulah Road bridge. The results are given in Table 5. The concrete surface exhibited high numbers prior to the overlay and even higher numbers afterwards. The low reading found for the LB183 resin after 4 weeks of service life was caused by asphalt tracked onto the lane from an approach area that had been given a new surface the same week. After 50 weeks of service life the lane with the LB183 resin exhibited slightly higher skid numbers than the lane with 90-570 resin, but the numbers obtained in both lanes were excellent and higher than the ones determined for the base concrete prior to placing the overlays. The skid resistance of the lane with the 90-570 resin should be monitored over the next few years because it is the only overlay of its type in Virginia. After 1 year of service life the LB183 overlays near Williamsburg exhibited an average treaded tire number of 57 and a bald tire number of 44 (3).

TABLE 5 Skid Numbers for 40 mph Tests

		Treaded Tire		Bald Tire	
Date	Age (weeks)	Resin LB183	Resin 90-570	Resin LB183	Resin 90-570
4/15/82	-3[a]	52	51	39	36
6/03/82	4	44[b]	57	36[b]	51
8/02/82	13	53	55	47	49
4/19/83	50	58	56	49	45

[a]Three weeks before PC overlay was placed.
[b]Asphalt had been tracked onto bridge.

TENSILE PROPERTIES

The bond strength and the protection provided by the overlay constructed with the 90-570 resin were better than those of the overlays constructed with LB183 resin. For example, the shear and tensile strengths of the bond interface deteriorated much more for the latter than for the former during the first year of service life. Also, the resistivity of the LB183 overlay decreased and the permeability increased significantly during the first year of service life, whereas the 90-570 overlay exhibited good resistivity and low permeability after 1 year. Because both products are polyester resins, it was thought necessary to determine their physical properties, which explain the superior performance of the 90-570 overlay.

The most obvious differences between the two products were determined using ASTM D 638-80, "Standard Test Method for Tensile Properties of Plastics." The results of tests conducted in accordance with this procedure are given in Table 6 and shown

TABLE 6 Tensile Properties of Resins

	Tensile Strength ($lb/in.^2$)		Elongation at Break (%)		Modulus of Elasticity ($lb/in.^2$)[a]	
Resin	Avg	SD	Avg	SD	Avg	SD
317	2,858	301	23.3	8.1	4.69×10^4	0.99×10^4
LB183	5,089	1,928	8.0	3.8	7.81×10^4	0.91×10^4
90-570	2,836	373	49.2	11.4	3.52×10^4	0.21×10^4
MMA-1[b]	1,427	525	2.3	0.4	6.29×10^4	1.39×10^4
EP5LV	4,797	626	12.5	1.2	6.60×10^4	1.56×10^4
MMA-2[c]	4,821	262	6.7	0.0	7.19×10^4	0.58×10^4

Note: SD = standard deviation.
[a]Calculated at 0.05 in./in. strain except MMA.
[b]63 percent MMA and 37 percent PMMA.
[c]FX822, PMMA unknown.

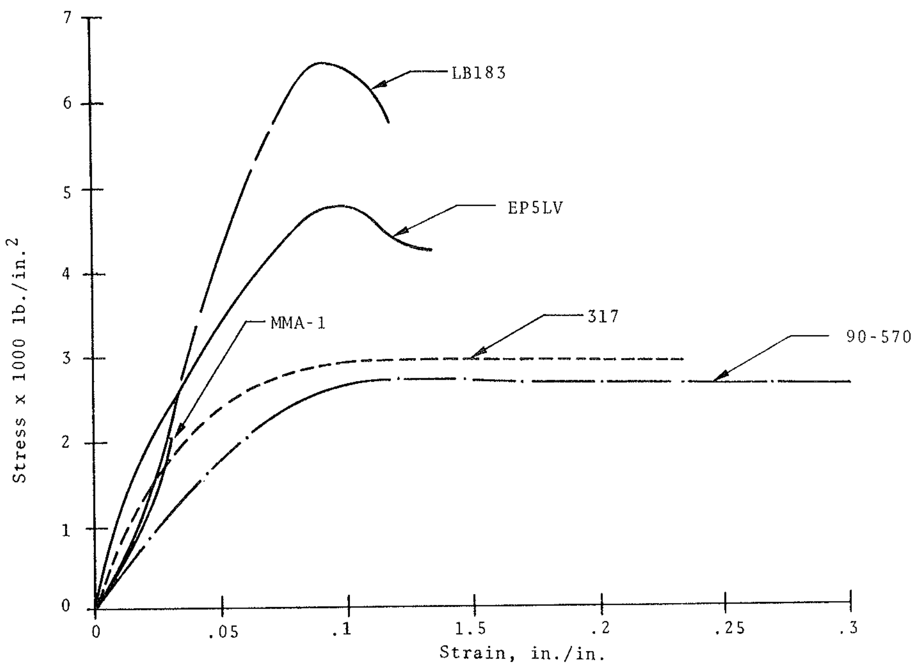


FIGURE 7 Stress-strain data based on average of three specimens of each resin.

in Figure 7 (unpublished memoranda from R.E. Steele to M.M. Sprinkel, July 13 and October 17, 1983). Data for resin 317, which was used on the Swan Creek bridge in Tennessee, data for methylmethacrylate (MMA-1) used on one of the bridges near Williamsburg, and data for an EP5LV epoxy currently being placed on several bridges in Virginia are included in the table and figure. The tests were conducted on specimens 0.13 in. thick, 0.50 in. wide, and 8.5 in. long. A 3.0-in. gauge was used, and the test speed was 0.2 in. per minute.

From Table 6 and Figure 7 it is obvious that the LB183 resin has a higher tensile strength and modulus of elasticity and a much lower elongation than the 90-570. Because the LB183 resin elongates only 8.3 percent it is more likely to crack when subjected to shrinkage, reflective cracking, or thermal stress than is the 90-570 resin. The more flexible 90-570 is able to elongate and accommodate the tensile stresses and thereby provide an overlay of high resistivity and low permeability. The 90-570 and 317 resins should be less prone to cracking than LB183, MMA-1, MMA-2, and EP5LV epoxy. Extensive cracking has occurred in overlays constructed with LB183 and MMA-1 (2,3). The EP5LV epoxy overlay system is being studied at this time. Based on the data in Table 6, it is reasonable to conclude that a resin should have a minimum elongation of 20 percent to minimize the formation of cracks and thereby ensure adequate protection. A specification requiring 20 to 40 percent elongation seems reasonable.

Thermal Stress

When two materials of different properties are bonded together, a shear stress develops when the composite is subjected to a change in temperature. The stress is a function of the temperature change and the coefficient of thermal expansion and moduli of elasticity of the 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. A method for computing the theoretical stress is discussed in detail elewhere (2-8).

Reasonable values for the dynamic modulus of elasticity for a polyester resin, as determined by ASTM C215-60, are 0.4×10^6 lb per square inch for an overlay with no aggregate and 1×10^6 lb per square inch for an overlay sanded to excess (2). For the same aggregate application rates, reasonable values for the coefficient of thermal expansion for a polyester resin are 56×10^{-6} in./in./°F and 16×10^{-6} in./in./°F, respectively. Portland cement concrete typical of that used in bridge decks in Virginia has a dynamic modulus of elasticity of 4.2×10^6 lb per square inch and a coefficient of thermal expansion of 5.7×10^{-6} in./in./°F (2). Using these values, the theoretical shear stress at the bond line for a 1°F change in temperature is 18 lb per square inch for an overlay with no aggregate and 8.3 lb per square inch for an overlay with excess aggregate.

If an overlay is placed on concrete at 74°F and later cooled to 0°F, as was the case for the specimens shown in Figures 4 and 5, the bond interface is subjected to a stress of 1,300 lb per square inch if the overlay has no aggregate and 610 lb per square inch if it has an excess of aggregate. When no or a small amount of aggregate is placed in the overlay, the theoretical shear stress exceeds the shear strength of both the bond interface and the base concrete, which explains the failures shown in Figure 5. On the other hand, when an excess of aggregate is placed in the overlay, the theoretical shear stress is about equal to the shear strength of the bond interface and is less than the shear strength of the base concrete, which explains why the specimens shown in Figure 5 with an excess of aggregate in the overlay did not delaminate after 300 thermal cycles. Because the shear stress is great enough to fatigue the bond interface, the strength of the bond decreases with an increase in the number of thermal cycles, as shown in Figure 4.

Because of fatigue due to cycles of thermal stress, the service life of a PC overlay is finite but difficult to predict. A useful service life of 10 years seems reasonable for an overlay constructed with a high-elongation resin and an excess of sand. It will be necessary to continue to monitor the performance of the overlays to make a more accurate projection.

WHEN TO SPECIFY THIN POLYMER CONCRETE OVERLAYS

Three cases are presented to illustrate when the use of a thin PC overlay instead of a more conventional latex-modified concrete overlay is justified. The comparison is based on consideration of the service life of the PC overlay, the volume of traffic, the discount rate, and the value of driving time. For each of the three cases, it is assumed that the following conditions exist.

1. The overlay is to be placed on a two-lane bridge on I-95, 40 ft wide by 350 ft long.
2. It is necessary to increase the skid resistance and curtail the infiltration of additional chloride.
3. It is not feasible to construct a temporary bridge or detour traffic.
4. A 0.5-in.-thick PC overlay can be installed with 12 hr of lane closure time, at a cost of $24 per square yard plus the cost of controlling traffic with cones, and will provide acceptable service for 5 to 15 years.
5. A 1.25-in.-thick latex-modified concrete overlay can be installed with 9 days of lane closure time, at a cost of $30 per square yard plus the cost for controlling traffic with median barriers, and will provide acceptable service for 30 years.
6. Because it is difficult to predict the relationship between interest rate and inflation over a 30-year period, calculations are made for discount rates of 0, 5, and 10 percent, where the discount rate is the annual rate at which money increases in value through investment.

Case 1

For case 1, the peak-hour volume-to-capacity ratio with both lanes open is 0.30. With one lane closed, the ratio for the open lane is 0.60. Traffic flow will not be impeded by closing one lane for an extended period of time.

The cost for traffic control while the PC overlay is being installed is $1 per square yard and the cost for the latex overlay is $5 per square yard. The present worth of the thin PC overlay at a discount rate of 0 percent and a service life of 10 years is $\$25/yd^2 + \$25/yd^2 + \$25/yd^2 = \$75$ per square yard compared with $35 per square yard for the latex. At a discount rate of 5 percent and a service life of 10 years the present worth of the PC overlay is $25 + (\$25) \div (1.05)^{10} + (\$25) \div (1.05)^{20} = \$50$ per square yard, and at a discount rate of 10 percent it is $38 per square yard. According to the data in Table 7, the latex overlay at $35 per square yard is the most economical alternative in case 1 unless for a service life of 10 years the discount rate exceeds 12.6 percent, which is highly unlikely, or for a service life of 15 years the discount rate exceeds 6.3 percent. It seems reasonable to conclude that for case 1 the latex overlay is the most economical alternative because a service life for the PC overlay in excess of 10 years and a discount rate in excess of 5 percent are not likely at this time.

Case 2

For case 2 the peak-hour volume-to-capacity ratio is 0.6 with both lanes open and 1.0 with one lane closed. The one open lane cannot carry the peak-hour traffic volume, and a major reduction in speed and level of service occurs. The PC overlay is justified because one lane of the bridge cannot be closed during peak-hour traffic, which is necessary for the construction of the latex overlay.

For case 2 the cost of traffic control for the latex is higher than in case 1 because of the higher volume of traffic. A cost of $20 per square yard seems reasonable. The cost of traffic control for the PC overlay would be the same as in case 1. The present worth of the latex overlay for the 30-year service life is $50 per square yard and, as can be seen in Table 7, the present worth of the PC overlay is less if the discount rate exceeds 5 percent for a 10-year service life and exceeds 0 percent for a 15-year service life. For case 2 the use of the PC overlay is justified because one lane cannot be closed during peak-hour traffic to allow the construction of a latex overlay. In addition, the PC overlay can be justified on the basis of present worth when the discount rate exceeds 5 percent for a 10-year service life and 0 percent for a 15-year service life.

TABLE 7 Present Worth ($\$/yd^2$) of Thin PC Overlay as a Function of Discount Rate and Service Life

Service Life (yr)	Discount Rate (%) 0	5	10
5	$150	$89	$62
10	75	50	38
15	50	37	31

Case 3

For case 3 the peak-hour volume-to-capacity ratio with both lanes open is 0.5 and with one lane closed it is 1.0. It is reasonable to assume that an increase in the volume-to-capacity ratio from 0.5 to 1.0 will cause a decrease in the average speed of the motorist from 53 mph to 32 mph (10, p. 140). Assuming the speed reduction affects a 10-mile segment of the average trip, the average time lost per vehicle is 7.4 min. Furthermore, assuming an average wage rate of $1 per hour per vehicle, which is extremely conservative, the cost of reduction in speed to the motorist is 12 cents per trip. Assuming an average hourly traffic flow of 1,300 vehicles, which is reasonable (11, p. 20), the cost to motorists of the reduction in speed is $161 per hour. For the 12 hours of the lane closure required for the installation of the PC overlay the cost is negligible assuming the lane closure occurs during off-peak hours. For the minimum of 9 days required for the installation of the latex overlay, the cost is $15 per square yard assuming the delays associated with the lane closure last for 8 hours each day. The addition of the cost of travel time increases the present worth of the latex overlay to $65 per square yard, and for a service life of 15 years the polymer overlay is more economical. For a service life of 5 or 10 years, the polymer is more economical when the discount rate exceeds 9.2 or 1.5 percent, respectively. For case 3, if the value of travel time is taken into account, the PC overlay is generally the most economical alternative based on present worth.

The costs of accidents and increases in vehicle operating costs that result from a lane closure provide an additional incentive to use a PC overlay. Over a 30-year period the total lane closure time required for the construction of a latex overlay with a 30-year service life is 3, 6, or 9 times greater than that required for the construction of

PC overlays with useful service lives of 5, 10, or 15 years, respectively. It is reasonable to expect that the benefits from a reduction in lane closure time and, therefore, in the number of potential accidents would increase with an increase in the volume of traffic and the useful service life of the PC overlay. Research is needed to quantify these benefits.

CONCLUSIONS

PC overlays can be installed by maintenance forces or by a contractor with a minimum of disruption to traffic.

PC overlays constructed with two polyester resins, 90-570 and LB183, are securely bonded to the base concrete and provide low permeability and high skid resistance after 1 year of service life.

PC overlays constructed with resins 90-570 and 317 are exhibiting the highest bond strength, the least amount of cracking, and the lowest permeability because they have a tensile elongation at break in the range of 20 to 50 percent as determined by ASTM D638-80, which is higher than that of the other resins tested.

The PC overlay becomes more economical relative to a latex overlay with increases in the service life of the PC overlays, the volume of traffic, the discount rate, and the value of driving time. These factors can be used to determine the most economical alternative.

PC overlays are still experimental and should not be used where alternative methods for extending service life are practical. A useful service life of 10 years seems reasonable, but the performance of the overlays should be monitored so that a more accurate projection of service life can be made.

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