Rapid Techniques for the Repair and Protection of Bridge Decks

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Bridges that are candidates for rapid repair techniques have peak-hour traffic volumes that are so high it is not practical to close a lane to repair the deck or to install a deck protection system except during off-peak traffic periods. Results of the first 25 months of a 55-month project (Task 4 of Strategic Highway Research Program Project C103) to investigate rapid techniques for the protection, rehabilitation, and replacement of bridge decks are summarized. A review of the literature and responses to questionnaires sent to state departments of transportation (DOTs), Canadian provinces, selected turnpike and thruway authorities, technology transfer centers, and material suppliers was conducted. Techniques being used by the DOTs are identified and compared from the standpoint of frequency of use, performance characteristics, time demands, service life, maintenance, initial cost, and life cycle cost.

The Strategic Highway Research Program (SHRP) awarded contract SHRP C103 to Virginia Polytechnic Institute and State University on September 22, 1988, to conduct a 55-month study entitled *Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques* (*1*). The objective of Task 4 of SHRP C103 was to develop technically and economically feasible methods of deck protection, rehabilitation, and replacement that could be used where contruction must be rapid. The objective would be accomplished by a progression through six activities. The state-of-the-art review, data reduction and analysis, and comparison of alternatives (Activities 1 and 2) are summarized herein. This paper is based on reviews of the literature and of the responses to three questionnaires. Additional details can be found in Interim Report 1 (*2*). Rapid repair techniques are compared from the perspective of frequency of use, performance characteristics, time demands, service life, and cost.

CRITERIA FOR RAPID REPAIR TECHNIQUES

For this study, rapid repair is not defined in terms of repair rate, such as surface area per unit of time, because repair rate is a function of manpower and equipment. Rates at which repairs are done can best be controlled by contract requirements with incentives and penalties to promote rapid rates of repair. Contractors can then invest in additional manpower and equipment to accelerate the rate of repair.

For this study, rapid repair is defined in terms of suitability for stage construction. To be considered a rapid-repair technique, the repair system must be suitable for installation during off-peak traffic periods and suitable for traffic during peak traffic periods.

A flow diagram for rapid repair techniques for bridge decks is shown in Figure 1. Lane closure and surface preparation are necessary first steps for any rapid technique. Lane closure can be accomplished using cones or other temporary portable barriers. All unsound concrete must be removed in preparation for new repair materials.

If there is insufficient time to install and cure a protection system or repair material, temporary materials should be placed to maintain a traffic-bearing surface. Otherwise, the repair should continue with the installation of a protection system, a rapid-curing concrete repair material, or a precast replacement section. The materials are allowed to cure to the required strength to receive traffic. After necessary temporary materials are installed, the lane is opened to traffic. If needed, a rapid deck protection system is installed following deck replacement or rehabilitation.

A bridge deck that must be repaired using a rapid-repair technique will usually have one of four maximum lane closure time conditions that require the use of one of four rapid-repair techniques as follows:

- <56 hr—semirapid (e.g., Friday at 9:00 p.m. to Monday at 5:00 a.m.);
- <21 hr—rapid (e.g., 6:30 p.m. to 3:30 p.m.);
- <12 hr—very rapid (e.g., 6:00 p.m. to 6:00 a.m.); and
- <8 hr—most rapid (e.g., 9:00 p.m. to 5:00 a.m.).

A repair system must follow the flow diagram (see Figure 1) within the lane closure constraints of <56, <21, <12, or <8 hr to qualify as part of a rapid-repair technique.

QUESTIONNAIRE RESPONSE

Three questionnaires on rapid-repair techniques for bridge decks were prepared and distributed in 1989 to obtain state-of-the-art information. Questionnaire 1 was sent to state department of transportation (DOT) coordinators, SHRP Canadian provincial coordinators, and selected turnpike and thruway authorities. Questionnaire 2, a condensed 1-page version of Questionnaire 1, was sent to the directors of the technology transfer centers for publication in their newsletters. Questionnaire 3, an expanded 14-page version of Questionnaire 1, was designed to obtain detailed data on the properties

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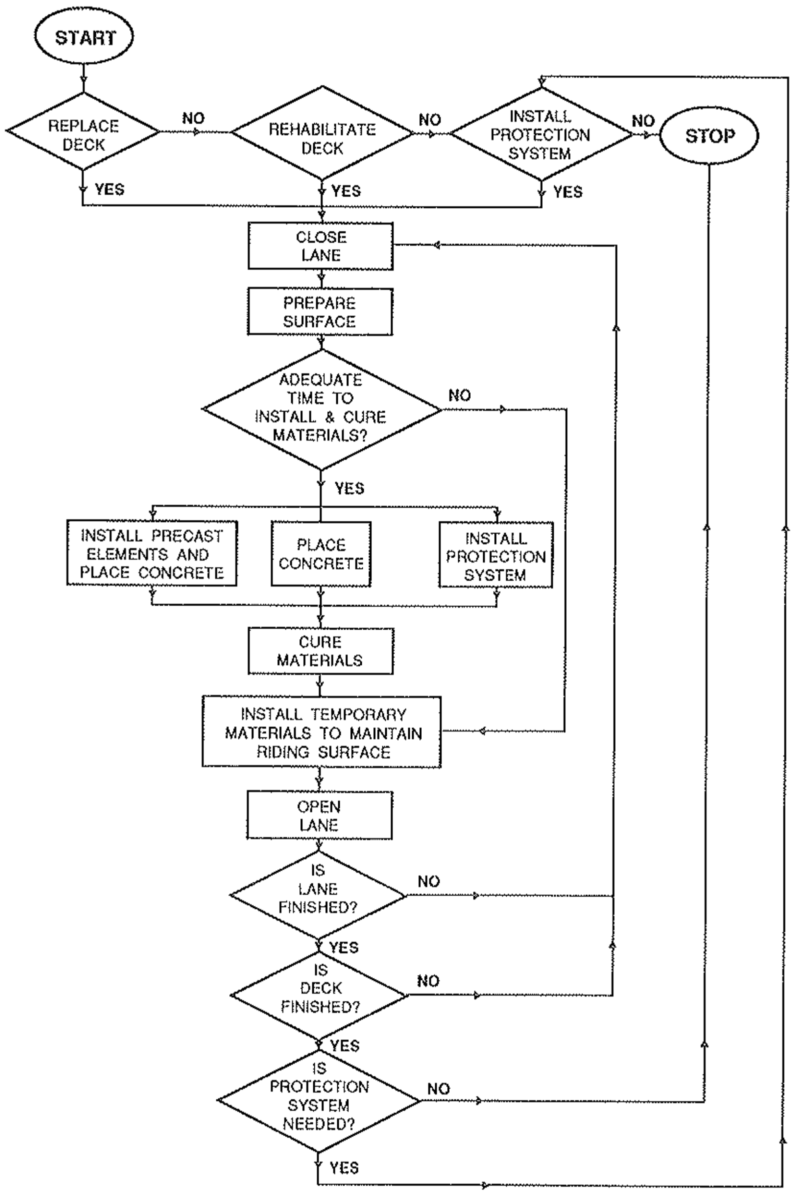

FIGURE 1 Flow diagram for rapid repair techniques for bridge decks.

of materials. It was sent to selected material suppliers. The questionnaires were distributed and returned as follows:

No.	*Sent to*	*Date Mailed*	*No. Mailed*	*No. Returned*
1	SHRP state DOT coordinators	March 8	55	49
1	CSHRP provincial coordinators	March 8	12	10
1	Selected turnpike and thruway authorities	May 30	44	9
2	Directors of technology transfer centers	April 26	58	8
3	Selected material suppliers	June 7	276	31

FREQUENCY OF USE

Table 1 presents the frequency of use of rapid-repair systems on the basis of the responses to Questionnaires 1 and 2. The respondents were requested to list the three most frequently used techniques for the rapid protection, rehabilitation, and replacement of bridge decks. The rehabilitation of a deck usually requires crack repair, joint repair, patching, and the application of a protective system. In order to simplify the reporting of data, protective systems are not recorded as part of rehabilitation systems. The systems most often used are the bituminous concrete overlay for rapid protection (35 responses), the high-early-strength portland cement concrete patch for rapid rehabilitation (30 responses), and no rapid replacement technique (43 responses).

PERFORMANCE CHARACTERISTICS

The most important performance characteristics of rapid protection and rehabilitation systems for bridge decks are the condition of the temporary surfaces, minimum curing time,

TABLE 1 FREQUENCY OF USE OF RAPID REPAIR SYSTEMS

Protection System	No. Users	Rehabilitation System	No. Users	Replacement System	No. Users
Bituminous Concrete Overlay	35	Crack Repair and Sealing	3	Precast Concrete Slab Span	0
Coating	3	Joint Repair	0	Precast Concrete Box Beam	0
Portland Cement Concrete Overlay	9	Bituminous Concrete Patch	11	Precast Concrete Channel and Tee Beam	0
Penetrating Sealer	9	Portland Cement Concrete Patch	30	Precast Concrete Deck Panel	5
Polymer Overlay	13	Polymer Concrete Patch	3	Permanent Forms with Site Cast Concrete	0
Other Hydraulic Concrete Overlay	1	Other Hydraulic Concrete Patch	11	Site Cast Portland Cement Concrete	9
None	33	Steel Plate over Concrete	3	Site Cast Polymer Concrete	0
No Reply	13	None	31	Other Site Cast Hydraulic Concrete	3
		No Reply	10	None	43
				No Reply	20

bond strength, permeability to chloride ion, skid resistance, and wear. With two exceptions, the same performance characteristics apply to rapid-replacement systems. Bond strength is not important unless a protective overlay will be applied, and permeability to chloride ion is less important because the rebar in new decks is usually coated with epoxy.

Temporary Surfaces

A major requirement for a rapid-repair system is a temporary surface that is suitable for traffic during peak-hour traffic periods. The temporary surface is the disturbed surface between the original surface of the deck and the completed surface. For bridges whose entire deck surface can be repaired during one off-peak traffic period, there is no temporary surface. The surface should provide a satisfactory ride when the lane is open to traffic. Typical surface elevations for the rapid protection systems are presented in Table 2 and shown in Figure 2. When patching, bituminous concrete, steel plates, or timber plank can be used to provide a temporary riding surface if the patching materials cannot be placed and cured properly before opening the surface to traffic.

Minimum Curing Time

One of the most important properties of a rapid protection, rehabilitation, or replacement system is the strength of the materials at the time they are first subjected to traffic. Materials that do not have adequate strength can be damaged by traffic and fail prematurely as a result of a failure of the matrix or the bond interface. Obviously, a material must be relatively free of cracks and must be adequately bonded to the substrate to protect the deck and provide skid resistance. With the exception of bituminous concrete, sealers, and coat-

TABLE 2 TYPICAL SURFACE ELEVATIONS FOR RAPID PROTECTION SYSTEMS

Protection System	System Thickness (in)	Surface Preparation Depth (in)	Change in Elevation (in)	Effect on Ride Quality
Bituminous Concrete Overlay on Membrane	≥1.6	≤0.1	>1.6	Major
Coating	≤0.1	≤0.1	≤0.1	Negligible
Portland Cement Concrete Overlay	≥1.3	≥0.5	≥0.8	Medium
" "	≥2.0	≥0.5	≥1.5	Major
Penetrating Sealer	≤0.1	≤0.1	≤0.1	Negligible
Polymer Overlay	≥0.3	≤0.2	≥0.1	Negligible
" "	≥0.5	≤0.2	≥0.3	Minor
Other Hydraulic Concrete Overlay	≥1.3	≥0.5	≥0.8	Medium
" "	≥2.0	≥0.5	≥1.5	Major

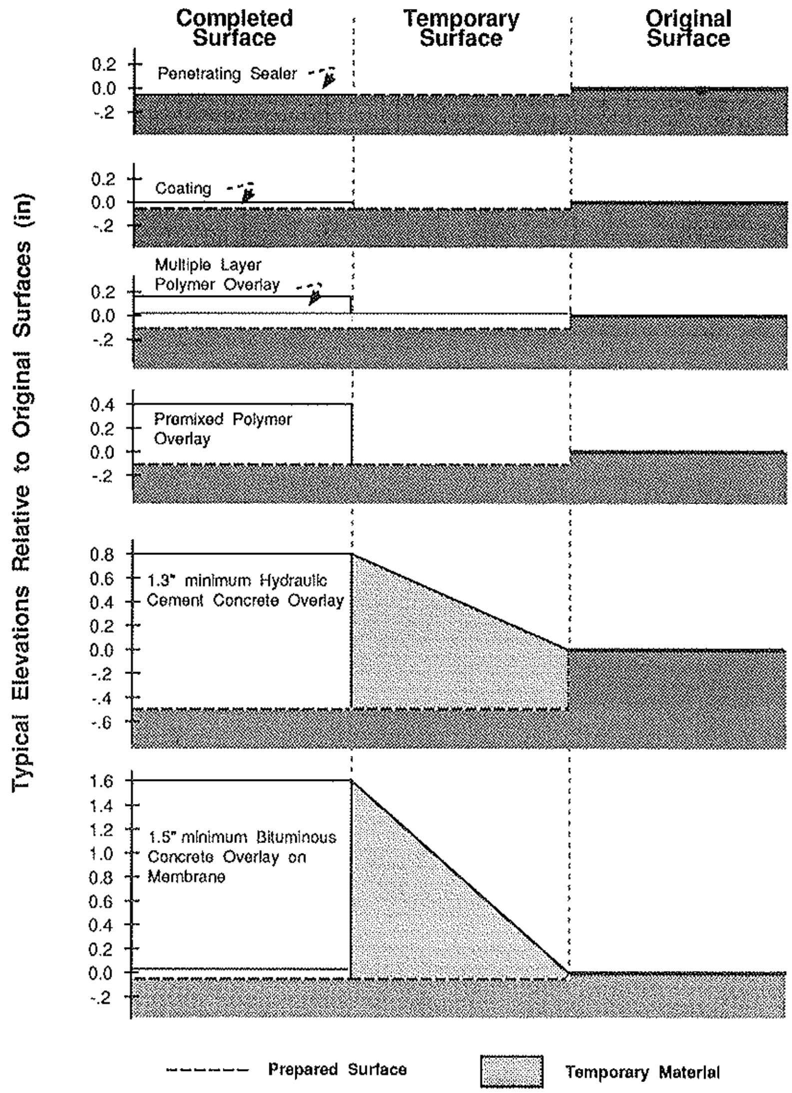

FIGURE 2 Typical surface elevations for rapid protection systems.

ings, the most convenient indicators of strength are the compressive strengths of 4 × 8-in. cylinders of concrete and 2-in. cubes of mortar. Hydraulic cement concretes and polymer concretes are usually required to have a compressive strength of 2,500 to 4,000 psi before being subjected to traffic (*3*). Guillotine shear bone strengths of at least 200 to 400 psi are usually obtained at these compressive strengths when concrete substrates are properly prepared (*4,5*). Tensile adhesion strengths greater than 100 psi are also indicative of satisfactory performance (*6,7*). Coatings and sealers must be tack-free at the time they are subjected to traffic. Membranes must be tack-free before being overlaid with bituminous concrete, which is then allowed to cool to 150°F before being opened to traffic (*3*). Patches that can be protected with a steel plate can be opened to traffic once the plate is in place. Minimum curing times do not apply to precast members because they have adequate strength when installed. However, site-cast materials used to connect the members must have adequate strength. Site-cast concrete used for deck replacement should have a minimum compressive strength of 4,000 psi when subjected to traffic (*3*).

Table 3 presents estimates of the minimum curing times needed before subjecting protective systems to traffic without causing major damage to them. The estimates are based on compressive and bond strength data, tack-free times, and cooling rate data for bituminous concrete obtained from the literature and the responses to the questionnaire sent to the materials suppliers (*3,7–13*). Curing time is a function of the curing temperature of the material, which is a function of the mixture proportions, mass, air and substrate temperature, and degree to which the material is insulated. The values in Table 3 are reported as a function of air temperature for typical installations. Minimum curing times can be reduced by increasing the rate of reactions by adjusting the mixture proportions, applying insulation, and increasing the mass of the application. Bituminous concrete cools more rapidly when placed in thin lifts, and sealers become tack-free sooner when the application rate is reduced.

TABLE 3 MINIMUM CURING TIMES OF RAPID PROTECTION SYSTEMS (HOURS)

System	Installation Temperature (°F)				References
	40	55	75	90	
Bituminous Concrete Overlay on Membrane	NA	2	2	2	3, 8
Coating	NA	9	3	1	7, 9
Portland Cement Concrete Overlay	8	6	4	4	10, 11
Penetrating Sealer	4	3	2	1	7
Polymer Overlay	2*	6	3	2	7, 12
Other Hydraulic Cement Concrete Overlay	1*	1*	1	1	10, 13

NA: Not applicable since materials are not usually placed at indicated temperature.
* Special cold weather formulation used.

Permeability to Chloride Ion

A rapid permeability test (AASHTO T277) can be used to measure the permeability to chloride ion of 4-in.-diameter by 2-in.-thick specimens prepared in the laboratory or 4-in.-diameter by 2-in.-thick slices of cores obtained from bridge decks. The results are usually reported in coulombs, which have the relationship to permeability indicated in the footnote to Table 4.

Table 4 presents the permeability to chloride ion of cores taken from decks to which rapid protection systems had been applied and of specimens prepared in the laboratory (*5,7,9,14–17*). Results for specimens tested at early and later ages are reported where data are available to provide an indication of how the permeability changes with age. To properly rank the protective systems, the permeability over the life of the systems needs to be considered. Typically, unprotected bridge deck concretes have a moderate-to-high permeability. The materials used to rehabilitate a deck should have a low permeability to chloride ion unless a protective system will be placed following the crack repair or patching.

Skid Resistance and Wear

To be used on traffic-bearing surfaces, a protection system must have an adequate skid resistance. Corrective action is required when smooth tire numbers (ASTM E524) are <20 and treaded tire numbers (ASTM E501) are <37. Table 5 presents skid numbers for the protection systems at <1 year of age and at 5 years of age to provide an indication of how the skid resistance changes with age (*5,7,14,18*). As indicated by Table 5, unacceptable skid numbers can be obtained when coatings and some penetrating sealers are applied to screeded concrete surfaces. Coatings and sealers can usually be applied to tined and grooved surfaces as long as the material does not fill the grooves. Freshly placed hydraulic cement concretes can be tined and grooves can be sawcut in the hardened concrete to ensure proper skid resistance. Silica aggregate can be broadcast onto polymer materials to provide good skid numbers.

Subjective Rating

Subjective ratings of the most rapid protection systems based on performance characteristics, as presented in Table 6, can be used to select the optimum system. As indicated by Table 6, typically the best most rapid protection system (lowest total) is the polymer overlay, and the least desirable system (highest total) is the high-early-strength portland cement concrete overlay. Although the results presented in Table 6 would not necessarily be applicable to every situation, the application of a polymer overlay or penetrating sealer is typically

TABLE 4 PERMEABILITY TO CHLORIDE IONS OF RAPID PROTECTION SYSTEMS

System	Laboratory Specimens	Cores at Indicated Age			References
		≤1 yr	5 yr	10 yr	
Bituminous Concrete Overlay on Membrane	—	N	—	—	14
Coating	—	L	—	—	7,9
Portland Cement Concrete Overlay	L	L	VL	VL	5, 15, 16, 17
Penetrating Sealer	—	L, M	L, M	—	7
Polymer Overlay	N	N	VL, L	VL, L	7, 14
Other Hydraulic Cement Concrete Overlay	VL	—	—	—	15

Permeability		Coulombs
H = High =	>	4,000
M = Moderate =		2,000 – 4,000
L = Low =		1,000 – 2,000
VL = Very Low =		100 – 1,000
N = Negligible =	<	100

TABLE 5 SKID NUMBERS AT 40 mph FOR RAPID PROTECTION SYSTEMS

System	Texture	Smooth Tire		Treaded Tire		References
		≤1 yr	5 yr	≤1 yr	5 yr	
Bituminous Concrete Overlay on Membrane	Compacted	26	28	46	41	14
Coating	Screeded	7	—	7	—	
	Tined	36	—	47	—	7, 9
Portland Cement Concrete Overlay	Screeded	—	28	61	51	
	Tined	41	—	44	—	5, 18
Penetrating Sealer	Screeded	23	34	36	51	
	Tined	45	45	46	45	7
Polymer Overlay	Tined	38	45	45	48	
	Sand broadcast	63	36	64	45	7, 14

desirable because acceptable skid resistance and permeability to chloride ion can be obtained with negligible effect on ride quality and with short curing times. Also, in situations where traffic begins to back up, these protective systems can be open to traffic in short times to relieve conjestion. On the other hand, bituminous overlays and high-early-strength portland cement concrete overlays do not lend themselves to use where the most rapid repairs are desired because of the major effect on ride quality and the effort required to remove installation equipment and apply temporary materials to prepare the surface for traffic. Bituminous overlays and portland cement concrete overlays become more desirable as longer times are allowed for lane closure. These systems are much better suited for rapid installations and are particularly well suited for semirapid installations.

TECHNIQUE TIME DEMANDS

The responses to Questionnaires 1 and 2 concerning the time required to set up and remove traffic control, prepare the surface, and place and cure materials are presented in Table 7 along with the average deck area (in square yards) for which the time estimates were made.

The technique time demands for three of the most used rapid protection systems and three of the most used rapid patching systems are shown in Figures 3 and 4, respectively. Figures 3 and 4 and the data in Table 7 should be useful to bridge engineers when planning rapid repairs for bridge decks.

No time requirement data for precast concrete slab spans, box beams, and channel and tee beams were obtained from the responses to the questionnaires. However, these members can be used for rapid deck replacement when the spans are shorter than 100 ft (*19*).

SERVICE LIFE AND MAINTENANCE

The responses to Questionnaires 1 and 2 provided sufficient information to estimate the service life of most of the rapid repair systems (see Table 8). The times until minor repairs (maintenance) are required are also presented in Table 8. Service life data obtained from a review of the literature are presented in Table 9 (*7,14,20–34*). Site-cast portland cement concrete decks can be constructed to last 50 years with maintenance in the form of an overlay applied at 25 years of age (*35*). The maintenance and service life estimates were used to determine the life cycle cost for each repair system. It is anticipated that in SHRP Contract Year 4, the influence of rate of corrosion on repair life and the influence of a repair on the service life of a deck will be determined so that more accurate life cycle costs can be computed in Contract Year 5.

TABLE 6 SUBJECTIVE RATING OF MOST RAPID PROTECTION SYSTEMS

System	Temporary Surfaces	Minimum Curing Time	Permeability	Skid No.	Total	Rank
Bituminous Concrete Overlay on Membrane	4	2	1	3	10	#5
Coating	1	2	3	3	9	#4
High Early Strength Portland Cement Concrete Overlay	3	3	2.5	2	10.5	#6
Penetrating Sealer	1	1	3.5	2	7.5	#2
Polymer Overlay	1	2	2	1	6	#1
Other Hydraulic Cement Concrete Overlay	3	1	2	2	8	#3

1 – excellent
2 – very good
3 – good
4 – fair

TABLE 7 TECHNIQUE REQUIREMENTS

System	Average Area, (yd^2)	Average Time Requirements (hr)				Number of Responses Indicating Total Time		
		Traffic Control	Surface Preparation	Placing and Curing	Total	≤ 8 hr	> 8 ≤ 12 hr	> 12 hr ≤ 21 hr
Bituminous Concrete Overlay on Membrane	587	2.5	3.7	6.5	12.7	5	8	12
Coating	519	2.0	1.8	5.7	9.5	0	3	0
Portland Cement Concrete Overlay	1181	0.9	2.3	5.6	8.8	2	3	0
Penetrating Sealer	673	1.5	2.2	3.4	7.1	6	1	0
Polymer Overlay	481	1.2	4.0	4.7	9.9	3	8	1
Other Hydraulic Concrete Overlay	452	0.9	4.0	3.1	8.0	1	0	0
Crack Repair and Sealing	700[a]	2.0	1.3	4.0	7.3	1	1	0
Bituminous Concrete Patch	5	0.9	0.4	0.7	2.0	6	0	0
Portland Cement Concrete Patch	9	1.7	3.3	2.6	7.6	14	9	0
Polymer Concrete Patch	202	2.1	1.9	5.2	9.2	1	2	0
Other Hydraulic Concrete Patch	43	1.5	2.2	3.1	6.8	6	4	0
Steel Plate over Concrete	2	0.8	1.7	2.2	4.7	1	1	0
Precast Concrete Deck Panel	1291	1.4	4.6	5.1	11.1	1	2	1
Site-Cast Portland Cement Concrete	4	3.2	2.6	5.6	11.4	0	3	0
Other Site-Cast Hydraulic Concrete	3	1.9	2.5	3.9	8.3	2	1	0

[a] Linear feet.

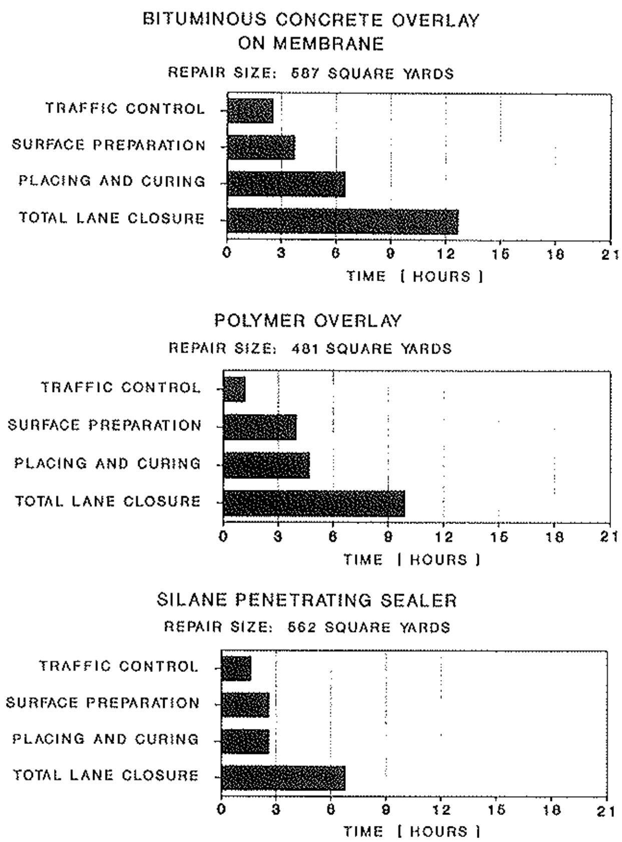

FIGURE 3 Technique time requirements for the three most frequently used rapid protection systems.

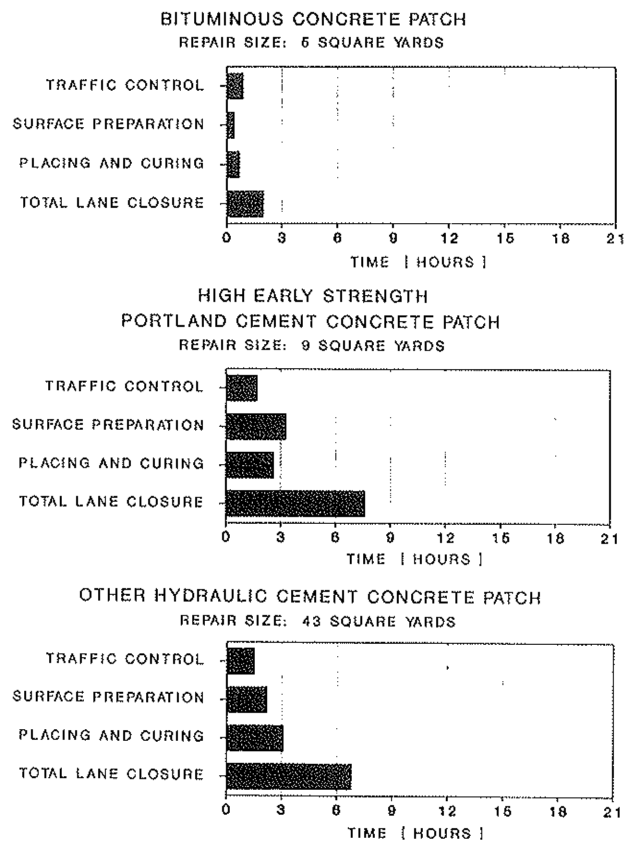

FIGURE 4 Technique time requirements for the three most frequently used rapid patching systems.

TABLE 8 SERVICE LIFE AND MAINTENANCE ON THE BASIS OF QUESTIONNAIRE RESPONSE (YEARS)

System	Time until Maintenance			Service Life		
	Average	Low	High	Average	Low	High
Bituminous Concrete Overlay on Membrane	5.1	1.0	10.0	11.8	4.5	20.0
Coating	5.2	2.8	10.3	10.3	5.5	20.0
Portland Cement Concrete Overlay	8.3	5.3	11.9	15.5	10.0	22.5
Penetrating Sealer	6.8	4.0	10.1	16.5	10.0	25.0
Polymer Overlay	6.4	3.0	10.0	12.7	6.0	25.0
Crack Repair and Sealing[a]	7.5	5.0	10.0	15.0	10.0	20.0
Bituminous Concrete Patch	0.3	0.1	0.8	1.7	1.0	3.0
Portland Cement Concrete Patch	2.8	0.3	7.0	5.9	1.8	10.0
Polymer Concrete Patch	10.0	—	—	20.0	15.0	25.0
Other Hydraulic Concrete Patch	6.3	1.0	10.0	11.9	2.0	20.0
Steel Plate over Concrete	10.0	—	—	15.0	—	—
Precast Concrete Deck Panel	20.0	12.5	30.0	38.8	30.0	50.0
Site-Cast Portland Cement Concrete	6.2	4.0	8.0	11.7	7.5	15.0
Other Site-Cast Hydraulic Concrete	2.0	—	—	5.5	5.0	6.0

[a]($/linear foot).

TABLE 9 SERVICE LIFE AND INITIAL COST OF RAPID REPAIR SYSTEMS ON THE BASIS OF LITERATURE REVIEW

System	Service Life (yrs.)			Initial Cost ($/yd^2)			References
	Average	Low	High	Average	Low	High	High
Bituminous Concrete Overlay on Membrane	9.7	3.7	15.0	50.84	15.53	135.44	7, 20, 21, 22, 23
Coating	—	—	—	—	—	—	—
Portland Cement Concrete Overlay	17.9	13.6	25.0	83.21	11.19	287.75	20, 21, 22, 23, 24, 25, 26
Penetrating Sealer	5.0	—	—	5.45	2.58	9.84	7, 23, 27, 28, 29
Polymer Overlay	10.0	—	—	43.55	7.03	100.08	7, 14, 23, 24, 25, 30, 31, 32
Other Hydraulic Concrete Overlay	—	—	—	6.08	—	—	24
Crack Repair and Sealing[a]	10.0	—	—	—	—	—	23
Joint Repair[a]	3.7	3.5	3.9	78.23	77.73	78.72	21
Bituminous Concrete Patch	0.6	0.1	1.0	40.57	20.01	72.24	21, 23, 33, 34
Portland Cement Concrete Patch	14.8	4.3	35.0	202.17	164.71	239.63	20, 21, 23
Polymer Concrete Patch	5.5	—	—	247.07	—	—	21
Other Hydraulic Concrete Patch	3.8	—	—	235.16	—	—	21
Steel Plate over Concrete	—	—	—	—	—	—	—
Precast Concrete Box Beam	44.1	—	—	967.44	—	—	21
Precast Concrete Channel and Tee Beam	—	—	—	—	—	—	—
Precast Concrete Deck Panel	25.3	24.5	26.1	852.35	822.58	882.11	21
Site Cast Portland Cement Concrete	34.8	29.6	40.0	482.39	468.84	495.93	20, 21
Other Site Cast Hydraulic Concrete	12.5	—	—	686.64	—	—	21

[a]($/linear foot).

INITIAL COST AND LIFE CYCLE COST

The responses to Questionnaires 1 and 2 provided initial costs for traffic control, surface preparation, placing and curing materials, and other items as presented in Table 10. It was assumed that the cost data were accurate for 1988. Costs obtained from a review of the literature were inflated at the rate of 5 percent per year to provide reasonable values for 1988 (see Table 9).

The information in Tables 8 and 10 was used to estimate the initial cost and life cycle costs for the rapid repair systems presented in Table 11. In order to compute the life cycle costs presented in Table 11, it was assumed that maintenance and system replacement occurred at the time intervals presented in Table 8. The data from Table 9 were used to estimate the life cycle costs presented in Table 12. Because maintenance intervals were not obtained from the literature review, maintenance costs were not included in the life cycle costs presented in Table 12. Present values were calculated for a period of 50 years because present value data based on a 50-year period are available for new decks, and present values calculated for longer than 50 years are not much higher (*35*). Present values were also calculated for a 25-year period because a deck with a high rate of corrosion would not likely be repairable for more than 25 years. In Figure 5, present-value life cycle costs of repair systems based on the surveyed literature are compared with averaged questionnaire responses. Several systems shown in Figure 5 have a present-value life cycle cost based only on one source. It is anticipated that, in SHRP Contract Year 4, more accurate values and precise conclusions will be available as the result of more studies of repair materials and techniques are added to the data base.

INTERIM CONCLUSIONS

1. Most transportation agencies do not use rapid-repair techniques.
2. The most-used rapid-protection systems are bituminous concrete overlays on membranes, polymer overlays, high-early-strength portland cement concrete overlays, and penetrating sealers.
3. The most-used rapid-patching systems are high-early-strength portland cement concrete patches, bituminous concrete patches, and other hydraulic cement concrete patches.
4. The most-used rapid deck replacement systems are site-cast high-early-strength portland cement concrete and precast concrete deck panels.
5. Most of the rapid-repair techniques can be done with lane closures of 8 hr or less.
6. On the basis of the life cycle cost analysis, the most cost-effective protection system is the application of a penetrating sealer. The most cost-effective patching system is patching

TABLE 10 INITIAL COST OF RAPID REPAIR SYSTEMS ON THE BASIS OF QUESTIONNAIRE RESPONSE (DOLLARS PER SQUARE YARD)

System	Traffic Control	Surface Preparation	Placing and Curing	Other	Average Total	Low Total	High Total
Bituminous Concrete Overlay on Membrane	3.73	3.09	15.28	2.52	24.62	1.95	44.00
Coating	0.11	4.39	11.95	0.00	16.45	6.95	24.41
Portland Cement Concrete Overlay	19.31	21.39	38.02	8.73	87.45	77.28	95.60
Penetrating Sealer	0.67	0.46	1.57	0.07	2.77	1.36	4.55
Polymer Overlay	0.73	5.68	31.35	0.64	38.40	4.00	92.99
Other Hydraulic Concrete Overlay	0.36	46.80	53.30	0.00	100.46	—	—
Crack Repair and Sealing	0.15	5.28	4.05	0.00	9.48	6.95	12.00
Bituminous Concrete Patch	63.42	7.54	39.57	0.63	111.16	7.00	250.00
Portland Cement Concrete Patch	30.93	108.34	119.74	7.12	266.13	15.00	611.43
Polymer Concrete Patch	0.11	18.00	48.75	0.00	66.86	—	—
Other Hydraulic Concrete Patch	32.84	31.26	102.92	14.30	181.32	3.96	527.47
Steel Plate over Concrete	9.00	6.00	9.00	60.00	84.00	—	—
Precast Concrete Deck Panel	149.37	176.29	288.55	162.44	776.65	741.94	800.00
Site-Cast Portland Cement Concrete	33.14	33.77	74.65	0.00	141.56	34.32	249.00
Other Site-Cast Hydraulic Concrete	271.67	94.33	297.33	0.00	663.33	249.00	980.00

[a]($/linear foot).

TABLE 11 INITIAL COST AND LIFE CYCLE COST ON THE BASIS OF QUESTIONNAIRE RESPONSE (DOLLARS PER SQUARE YARD)

			Present Value Total Cost*	
Code Number	System	Initial Cost	25-Yr Evaluation Period	50-Yr Evaluation Period
IA	Bituminous Concrete Overlay on Membrane	24.62	42.84	55.40
IB	Coating	16.45	31.69	41.03
IC	High-Early-Strength Portland Cement Concrete Overlay	87.45	127.08	160.77
ID	Penetrating Sealer	2.77	3.90	4.90
IE	Polymer Overlay	38.40	63.03	81.53
IF	Other Hydraulic Cement Concrete Overlay	100.46	—	—
IIA	Crack Repair and Sealing**	9.48	14.08	17.86
IIC	Patching with Bituminous Concrete	111.16	1,453.69	1,884.92
IID	Patching with High-Early-Strength Portland Cement Concrete	266.13	815.22	1,057.86
IIE	Patching with Polymer Concrete	66.86	81.36	104.88
IIF	Patching with Other Hydraulic Concrete	181.32	312.20	403.78
IIG	Temporary Steel Plate over Conventional Concrete Patch	84.00	123.77	157.14
IIID	Replacement with Precast Concrete Deck Panel	776.65	724.35	874.72
IIIF	Replacement with Site-Cast High Early Strength Portland Cement Concrete	141.56	247.03	319.35
IIIH	Replacement with Other Site-Cast Hydraulic Concrete	663.33	2,334.08	3,017.19

* Parameters: 10% interest rate; 5% inflation rate; maintenance cost 10% of initial cost.
** ($/linear foot).

TABLE 12 INITIAL COST AND LIFE CYCLE COST ON THE BASIS OF LITERATURE REVIEW (DOLLARS PER SQUARE YARD)

			Present Value Total Cost*	
Code Number	System	Initial Cost	25-Yr Evaluation Period	50-Yr Evaluation Period
IA	Bituminous Concrete Overlay on Membrane	50.84	95.90	123.21
IB	Coating	—	—	—
IC	High-Early-Strength Portland Cement Concrete Overlay	83.21	103.13	130.96
ID	Penetrating Sealer	5.34	17.74	22.98
IE	Polymer Overlay	43.55	80.27	102.96
IF	Other Hydraulic Cement Concrete Overlay	—	—	—
IIA	Crack Repair and Sealing**	—	—	—
IIB	Joint Repair**	78.23	334.16	432.49
IIC	Patching with Bituminous Concrete	40.57	991.02	1,283.63
IID	Patching with High-Early-Strength Portland Cement Concrete	202.17	281.82	360.28
IIE	Patching with Polymer Concrete	247.07	742.20	958.46
IIF	Patching with Other Hydraulic Concrete	235.16	980.81	1,268.66
IIG	Temporary Steel Plate over Conventional Concrete Patch	—	—	—
IIIB	Replacement with Precast Concrete Box Beam	967.44	843.71	1,006.87
IIID	Replacement with Precast Concrete Deck Panel	852.35	849.37	1,098.63
IIIF	Replacement with Site-Cast High Early Strength Portland Cement Concrete	482.39	442.27	547.01
IIIH	Replacement with Other Site-Cast Hydraulic Concrete	686.64	1,059.77	1,372.73

* Parameters: 10% interest rate; 5% inflation rate; maintenance cost 10%of initial cost.
** ($/linear foot).

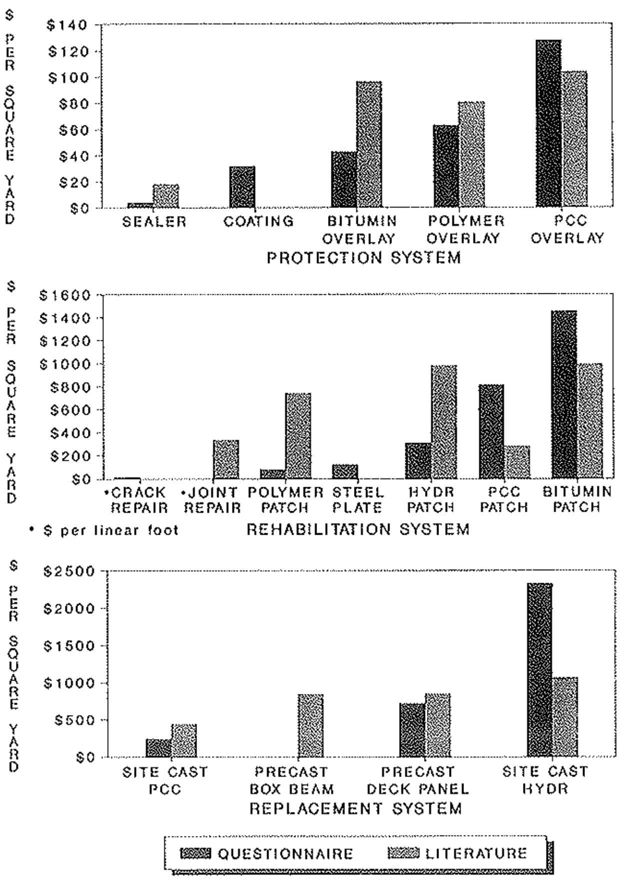

FIGURE 5 Present value life cycle cost on the basis of a 25-year evaluation period.

with polymer concrete (based on the questionnaire responses) and patching with high-early-strength portland cement concrete (based on the literature review). The most cost-effective replacement system is site-cast high-early-strength portland cement concrete. High-early-strength portland cement concrete overlays are the most expensive protection systems, and patching with bituminous concrete is the most expensive patching system. Other site-cast hydraulic concrete is the most expensive replacement system. The analysis of some systems was based on a limited data and results can change as more data become available.

7. Information on the effect of the repairs on the service life of a deck and the effect of the rate of corrosion of the rebar in a deck on repair life is needed to make an accurate assessment of life cycle costs.

REFERENCES

1. R. E. Weyers, N. S. Berke, P. D. Cady, W. P. Chamberlain, J. G. Dillard, P. C. Hoffman, F. Sebba, M. M. Sprinkel, R. E. Swanson, and M. C. Vorster. Proposal, *Strategic Highway Research Program* Contract C103, *Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques*, Virginia Polytechnic Institute and State University, Blacksburg, April 8, 1988, Revised July 29, 1988.
2. M. M. Sprinkel, R. E. Weyers, and R. Sellars. *Rapid Repair Techniques for Bridge Decks*. Interim Report 1, *Virginia Polytechnic Institute and State University*, Blacksburg, Sept. 1990.
3. *Road and Bridge Specifications*. Virginia Department of Transportation, Richmond, Jan. 1987.
4. L. I. Knab, M. M. Sprinkel, and O. J. Lane, Jr. *Preliminary Performance Criteria for the Bond of Portland Cement and Latex-Modified Concrete Overlays*. NISTIR 89-4156, National Institute of Standards and Technology, Gaithersburg, Md., Nov. 1989, p. 97.
5. M. M. Sprinkel. High-Early-Strength Latex-Modified Concrete Overlay. In *Transportation Research Record 1204*, TRB, National Research Council, Washington, D.C., 1988, pp. 42–51.
6. E. J. Felt. Resurfacing and Patching Concrete Pavements with Bonded Concrete, *TRB Proc.*, Vol. 35, 1956, pp. 444–469.
7. M. M. Sprinkel. *Comparative Evaluation of Concrete Sealers and Multiple-Layer Polymer Concrete Overlays*. VTRC 88-R2. Virginia Transportation Research Council, Charlottesville, Sept. 1987.
8. *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 39, Feb. 9–11, 1970.
9. M. M. Sprinkel. *Evaluation of the Use of High-Molecular-Weight Methacrylate Monomers to Seal Cracks in Decks on I-81 over the New River*. VTRC 91-R13, Virginia Transportation Research Council, Charlottesville, Sept. 1990.
10. M. A. Temple, R. D. Ballou, D. W. Fowler, and A. H. Meyer. *Implementation Manual for the Use of Rapid Setting Concrete*. Research Report 311-7F, University of Texas, Austin, Nov. 1984.
11. R. L. Carrasquillo and J. Farbiarz. *Pyrament 505 Program 1 Project Progress Report*, University of Texas, Austin, May 8, 1987.
12. L. Kukacka and J. Fontana. *Polymer Concrete Patching Materials: Vol. II Final Report*. Implementation Package 77-11. FHWA, U.S. Department of Transportation, 1977.
13. S. Popovics and N. Rajendran. Early Age Properties of Magnesium Phosphate-Based Cements Under Various Temperature Conditions, In *Transportation Research Record 1110*, TRB, National Research Council, Washington, D.C., pp. 34–95.
14. M. M. Sprinkel. *Evaluation of the Construction and Performance of Multiple-Layer Polymer Concrete Overlays*. Interim Report 2, VTRC 87-R28, Virginia Transportation Research Council, Charlottesville, May 1987.
15. A. Bradbury. *Laboratory Evaluation of Concrete Patching Materials*. Ministry of Transportation of Ontario, Toronto, Nov. 1987.
16. R. L. Carrasquillo. *Permeabilities and Time to Corrison of Pyrament Blended Cement*. Pyrament, Houston, Tex.,
17. C. Ozyildirim. Experimental Installation of a Concrete Bridge Deck Overlay Containing Silica Fume, In *Transportation Research Record 1204*, TRB, National Research Council, Washington, D.C., 1988, pp. 36–41.
18. S. S. Tyson. *Two-Course Bonded Concrete Bridge Deck Construction—Condition and Performance After Six Years*. VHTRC 81-R50. Virginia Transportation Research Council, Charlottesville, May 1981.
19. M. M. Sprinkel. *NCHRP Synthesis of Highway Practice 119: Prefabricated Bridge Elements and Systems*. TRB, National Research Council, Washington, D.C., Aug. 1985.
20. *Monolithic Bridge Deck Overlay Program*. New York State Department of Transportation Bridge Preservation Board, New York, 1986.
21. R. E. Weyers, P. D. Cady, and J. M. Hunter. *Cost-Effectiveness of Bridge Repair Details and Procedures—Part I: Final Report*. Report FHWA-PA-86-025. Pennsylvania Department of Transportation, Harrisburg, 1987.
22. G. Malasheskie, D. Maurer, D. Mellott, and J. Arellano. *Bridge Deck Protective Systems*. Report FHWA-PA-88-001 + 85-17. Pennsylvania Department of Transportation, Harrisburg, 1988.
23. W. Chamberlin, P. Hoffman, and R. E. Weyers. *Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques, Task 1 Field Survey: First Annual Report*. Virginia Polytechnique Institute and State University, Blacksburg, 1989.
24. P. D. Krauss. *New Materials and Techniques for the Rehabilitation of Portland Cement Concrete*. Report FHWA-CA-TL-85. California Department of Transportation, Office of Transportation Laboratory, Sacramento, 1985.
25. M. M. Sprinkel. *Polymer Concrete Overlay on Beulah Road Bridge: Interim Report 1*. VTRC Report No. 83-R28. Virginia Transportation Research Council, Charlottesville, 1982.

26. D. Bunke. ODOT's Experiences with Silica Fume (Microsilica) Concrete. Presented at 67th Annual Meeting, TRB, National Research Council, Washington, D.C., 1988.
27. D. W. Pfeifer and M. J. Scali. *NCHRP Report 244: Concrete Sealers for Protection of Bridge Structures*. TRB, National Research Council, Washington, D.C., 1981.
28. T. S. Rutkowski. *Evaluation of Penetrating Surface Treatments of Bridge Deck Concretes*. WisDOT Report 81-5. Wisconsin Department of Transportation, Madison, 1988.
29. P. D. Carter and A. J. Forbes. *Comparative Evaluation of the Waterproofing and Durability Performance of Concrete Sealers*. Report ABTR-RD-RR-86-09. Alberta Transportation, Edmonton, 1986.
30. *Technical Report on Flexiolith Epoxy Overlay*. Steinman, Boynton, Gronquist, and Birdsall, New York, 1987.
31. Polymer Concretes Protect Bridge Decks. *Better Roads*, May, 1989, p. 34.
32. P. D. Krauss. Status of Polyester-Styrene Resin Concrete Bridge Deck and Highway Overlays in California. *Proc., 43rd Annual Conference of the Society of the Plastics Industry*, 1988, pp. 1–7.
33. Transportation Research Board. *NCHRP Synthesis of Highway Practice 45: Rapid-Setting Materials for Patching of Concrete*. TRB, National Research Council, Washington, D.C., 1977.
34. *Bituminous Patching*. Report FHWA-TS-78-220. FHWA, U.S. Department of Transportation, 1980.
35. K. Babaei and N. M. Hawkins. *NCHRP Report 297: Evaluation of Bridge Deck Protective Strategies*. TRB, National Research Council, Washington, D.C., Sept. 1987.

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