

Field Performance of Experimental Bridge Deck Membrane Systems in Vermont

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ABSTRACT

The Vermont Agency of Transportation Bridge Deck Membrane Evaluation Program begun in 1971 is reviewed, and the field performance of 33 membrane systems over exposure periods of up to 11 years is discussed. Applications of deicing chemicals (sodium chloride) during the evaluation period have averaged 29.5 tons per two-lane mile per year, with accumulations totaling up to 123 lb of chloride (Cl^-) per linear foot of structure. Performance results are based on the presence or absence of Cl^- above base levels as determined by chemical analysis of more than 1,600 recovered concrete samples. The results indicate that, almost without exception, the experimental systems have outperformed the Agency's original standard treatment of tar emulsion. When grouped by general type, the best performance has been provided by the standard preformed sheet membranes and thermoplastic systems. Although somewhat less successful, satisfactory performance has been provided by the polyurethanes, the NCHRP Project 12-11 recommended systems, and miscellaneous preformed systems. In general, the epoxy and tar emulsion systems were not considered successful, although they have allowed only an average of 0.35 lb of Cl^- per cubic yard of concrete more than base levels in the top inch of concrete as compared to an average of 6.97 lb/yd³ on exposed bridge decks over a similar evaluation period. Chloride contamination was detected in one sample or less on 33 percent of the 63 bridge decks under evaluation. Projections based on performance results to date suggest a significant number of the membrane systems will provide protection from serious Cl^- contamination for 50 years or longer.

Before the period in the early 1970s when bridge deck deterioration was recognized as a serious problem, a number of Snow Belt states commonly treated concrete bridge decks with a seal or membrane system and covered it with a bituminous pavement. The most common systems consisted of coal tar emulsions and roofing grade asphalts often used in conjunction with woven cloth or glass fabric designed to reinforce the system.

In the late 1950s the Vermont Agency of Transportation placed bituminous pavements over several portland cement concrete decks without first attempting to seal the concrete surface with a waterproofing system. In subsequent years inspections of such structures disclosed the presence of severe concrete deterioration beneath the pavement. The condition was always most prevalent along curb lines and adjacent to expansion dams where ponding action increased the level of chloride (Cl^-) contamination.

In a number of cases the concrete was removed to a point below the top mat of reinforcing steel with hand shovels or low pressure water. Often the rebars were found to be completely free of corrosion. Such conditions suggest that the severe concrete deterioration was the result of high Cl^- contamination, numerous freeze-thaw cycles, and the retention of high moisture levels in the concrete caused by the presence of the bituminous overlay. This supposition is supported by studies (1,2) that point out the potential for damage to concrete because of salt crystal growth.

During the period 1960-1971 Vermont specified two coats of tar emulsion and two 1-in. courses of bituminous pavement as the standard treatment for bridge decks. In the late 1960s, Agency personnel recognized that the tar emulsion was not able to prevent Cl^- contamination and the subsequent concrete deterioration and rebar corrosion that was occurring along poorly drained areas. Faced with such information, the Agency chose to participate in the FHWA-sponsored National Experimental and Evaluation Program No. 12: Bridge Deck Protective Systems.

The program was established to encourage the states to try various new products and construction techniques designed to extend the service life of bridge decks. Vermont's participation took the form of a membrane evaluation program that began in 1971 with the application of two experimental systems on four new bridge decks. From that point to 1978, 33 different systems were applied in the field on 69 new concrete bridge decks. The products included 15 preformed systems, 7 epoxies, 5 thermoplastic materials, 4 polyurethanes, and 2 tar emulsion systems. Because the membrane systems were considered experimental, the applications were closely monitored and documented with reports. The information in the reports included background data on deck construction, concrete test results, condition of the decks, membrane product data, laboratory test results, observations made during the membrane applications, cost information, preliminary field test results, and discussions on the applications. Summaries of each membrane system were concluded with recommendations on further use.

The information presented in this paper summarizes the performance of the various membrane systems based on field samples taken through the period 1971-1982.

FIELD EVALUATION PROCEDURE

Follow-up field evaluations of the membrane systems began in 1975 on products that were exposed to a minimum of two winters of deicing chemical applications. Field testing in 1976, 1977, and 1978 included 37, 34, and 47 structures, respectively. Through the current date, field performance results have been obtained on all 33 experimental systems.

Field testing the first 2 years included electrical resistivity readings, electrical half-cell potential readings, and the recovery of concrete samples for the determination of Cl^- content by wet chemical analysis. Comparisons were made between the

resistivity readings and the Cl^- levels detected at specific resistivity test locations. When correlation between the two test methods was found to be less than 60 percent, resistivity testing was deleted from the evaluation program in the following years.

For the past 7 years (1977-1983), the performance of the various membrane systems has been considered only in relation to the presence or absence of Cl^- more than base levels as determined by chemical analysis of recovered concrete samples. Such samples were taken at points 1, 5, and 15 ft off the curb line. The 1-ft offset was selected because of the potential for leakage at the curb line area, whereas the 15-ft offset establishes membrane performance in the wheel path area that is subject to aggregate puncture under continuous traffic. The 5-ft offset is located in the breakdown lane, where satisfactory performance would be expected if the membrane was not damaged during paving or lateral leakage did not occur. In most cases the test areas were located on the low end of the decks where Cl^- concentrations would be heaviest. Where superelevations resulted in drainage away from the breakdown lane, concrete samples were obtained from the opposite curb line. The pulverized concrete samples were obtained from 0- to 1-in. and 1- to 2-in. depths with the aid of a rotary hammer and a 3/4-in. carbide-tipped twist drill. The overlying bituminous pavement was removed by the same procedure followed by cleaning with compressed air. A depth gauge attached to the drill was used to obtain the proper depth. Sample holes were patched with a quick-set cement.

Before 1982 total Cl^- content in the recovered concrete samples was analyzed following California Test Method 404-C (1972). The method involved an indirect Volhard titration. In 1982 total Cl^- content was analyzed by using a colorimetric procedure based on American Public Health Association Standard Methods for the Examination of Water and Wastewater, Method 602 (1975). The results were randomly checked with a specific ion electrode by using AASHTO test method T 260-82.

FIELD CONDITIONS

Approximately 80 percent of the experimental membrane systems are located on Interstate 91 in the northeastern portion of Vermont where the annual freezing index averages 1,400, 80 to 115 freeze-thaw cycles occur, and snowfall ranges up to 140 in. With the exception of two installations in central Vermont, the remaining systems are located in southwestern areas, where the annual freezing index ranges from 950 to 1,100, 75 to 115 freeze-thaw cycles occur, and snowfall ranges from 70 to 100 in.

Through the spring of 1982 the test sites had been exposed to an average of eight winters of deicing chemical applications. The applications of road salt have been continuously monitored by the Agency's Maintenance Division, and the records indicate that yearly applications ranged from 8.5 to

38.3 tons per two-lane mile, with an average of 29.5 tons. During the evaluation period, the applications have totaled up to a maximum of 123 lb of Cl^- per linear foot of structure, or approximately 3 lb/ft² of deck surface.

Average daily traffic (ADT) volumes on the experimental systems have ranged from 370 to 1,990 vehicles. Total vehicle passes average 3,336,000 passes per structure. The average total passes are equivalent to approximately 3,000 18-kip equivalent axle loads (EALs).

MEMBRANE PERFORMANCE

In this study membrane performance results are considered in regard to the percent of contaminated samples and the level of Cl^- contamination. Chloride contents are expressed in parts per million (ppm) chloride ion by weight of concrete. For a simple and approximate conversion of ppm to pounds of Cl^- per cubic yard of concrete, divide by 250.

For the purpose of the study, concrete samples are considered contaminated when the Cl^- content is 50 ppm more than the base Cl^- levels recorded on the specific bridge decks following construction. Several important facts should be kept in mind as contamination results are reviewed. The presence of Cl^- contamination does not mean a complete failure has occurred. It does indicate the membrane is not 100 percent effective, and the level of contamination must be considered to determine the seriousness of the failure. With regard to rebar corrosion, Cl^- contamination does not become a serious threat until the Cl^- migrates down to the level of the reinforcing steel and the build-up at that level approaches or exceeds 325 ppm or approximately 1.3 lb/yd³ of concrete (3,4). The level of Cl^- contamination that results in severe deterioration to concrete has not been established. However, it is believed that the critical level is much higher than the 325-ppm level that will initiate corrosion of the reinforcing steel.

The following subsections describe the performance of the seven general groups or types of membrane treatment under evaluation, plus information on six exposed bridge decks for comparison purposes. The data in Tables 1-8 provide performance data on individual products and the averages for each group. The Cl^- values recorded in Tables 1-8 and Table 10 include base Cl^- levels. The average Cl^- content of all samples and a summary of membrane performance is given in Tables 9 and 10. The location of Cl^- contamination is given in Table 11, a summary of membrane characteristics and performance is given in Table 12, and proprietary products may be identified by referring to Table 13.

Standard Preformed Sheet Systems: Status--3 Systems on 21 Bridges Averaging 7 Winters of Exposure

The standard preformed sheet membrane systems have

TABLE 1 Field Performance of Standard Preformed Systems

System	No. of Bridges	Avg Winters Salted	Samples Contaminated (%)		Avg Cl^- in Contaminated Samples (ppm)	
			0-1 in.	1-2 in.	0-1 in.	1-2 in.
70-mil preformed sheet	7	8.1	14	4	111	80
65-mil preformed sheet	5	8.4	19	12	111	79
75-mil preformed sheet	9	6.1	25	5	140	103
Class averages		7.3	19	7	125	86

TABLE 2 Field Performance of Thermoplastic Systems

System	No. of Bridges	Avg Winters Salted	Samples Contaminated (%)		Avg Cl ⁻ in Contaminated Samples (ppm)	
			0-1 in.	1-2 in.	0-1 in.	1-2 in.
Rubberized asphalt	2	11	9	0	73	0
Polypropylene fabric and asphalt concrete (AC)	1	6	11	0	70	0
Polyvinyl chloride (PVC) polymer	2	7	12	12	393	128
Hot asphalt and glass fabric	2	9	28	14	208	131
Class averages		8.6	17	8	209	130

TABLE 3 Field Performance of Polyurethane Systems

System	No. of Bridges	Avg Winters Salted	Samples Contaminated (%)		Avg Cl ⁻ in Contaminated Samples (ppm)	
			0-1 in.	1-2 in.	0-1 in.	1-2 in.
100 percent solids (69 mils)	1	8	0	0	0	0
Asphalt modified (100 mils)	1	6	0	0	0	0
Asphalt modified (38 mils)	2	9.5	31	22	88	69
Tar modified (39 mils)	1	10	50	28	77	70
Class averages		8.6	26	17	83	70

TABLE 4 Field Performance of NCHRP Project 12-11 Preformed Systems

System	No. of Bridges	Avg Winters Salted	Samples Contaminated (%)		Avg Cl ⁻ in Contaminated Samples (ppm)	
			0-1 in.	1-2 in.	0-1 in.	1-2 in.
Pitch and PVC polymer	1	8	7	7	298	150
Neoprene rubber	1	8	27	13	180	84
Butyl rubber	1	8	27	27	114	89
Ethylene-propylene-diene monomer (EPDM) rubber	1	8	33	7	82	72
Butyl rubber and felt	1	8	47	20	90	150
Class averages		8	28	15	120	109

TABLE 5 Field Performance of Miscellaneous Preformed Systems

System	No. of Bridges	Avg Winters Salted	Samples Contaminated (%)		Avg Cl ⁻ in Contaminated Samples (ppm)	
			0-1 in.	1-2 in.	0-1 in.	1-2 in.
165-mil panel	1	4	0	0	0	0
60-mil tar resin	1	4	0	0	0	0
PVC-butyl rubber	1	6	11	0	68	0
75-mil vented	2	4.5	27	20	118	82
Hydrocarbon rubber	1	8	40	20	77	68
60-mil vented	2	4.5	40	13	108	98
Butyl-neoprene	2	4.5	47	20	193	111
Class averages		4.9	30	12	125	91

TABLE 6 Field Performance of Epoxy Systems

System	No. of Bridges	Avg Winters Salted	Samples Contaminated (%)		Avg Cl ⁻ in Contaminated Samples (ppm)	
			0-1 in.	1-2 in.	0-1 in.	1-2 in.
90-mil 100 percent solids	1	8	0	0	0	0
13-mil polyamide	1	8	44	17	70	58
Coal tar modified	2	9.5	47	31	100	74
12-mil polyamide	1	8	60	13	108	67
48-mil 100 percent solids	1	9	61	17	138	68
52-mil 100 percent solids	1	9	67	17	100	54
12-mil solvent cut	1	10	89	67	201	69
Class averages		8.9	50	22	116	68

TABLE 7 Field Performance of Tar Emulsion Systems

System	No. of Bridges	Avg Winters Salted	Samples Contaminated (%)		Avg Cl ⁻ in Contaminated Samples (ppm)	
			0-1 in.	1-2 in.	0-1 in.	1-2 in.
Tar emulsion and glass fabric, 7-layer system	5	9.8	58	31	111	84
Tar emulsion, 2 coats	2	11	64	44	270	182
Class averages		10.1	60	35	163	122

TABLE 8 Chloride Contamination Levels on Exposed Bridge Decks

System	No. of Bridges	Avg Winters Salted	Samples Contaminated (%)		Avg Cl ⁻ in Contaminated Samples (ppm)	
			0-1 in.	1-2 in.	0-1 in.	1-2 in.
No treatment	3	7.3	95	65	1,559	791
Linseed oil and mineral spirits	3	11.7	100	98	1,855	945
Class averages		9.5	97	82	1,743	887

TABLE 9 Average Cl⁻ Content of All Samples

System	No. of Decks	Avg Winters Salted	No. of Samples	Avg Base Cl ⁻ Level (ppm)	Avg Cl ⁻ Content Above Base Levels (ppm)	
					0-1 in.	1-2 in.
Standard preformed	21	7	458	47	38	15
Thermoplastic	7	9	208	39	53	25
Polyurethane	5	9	155	47	32	18
NCHRP Project 12-11 preformed	5	8	150	65	39	15
Miscellaneous preformed	10	5	162	53	46	20
Epoxy	8	9	258	34	70	31
Tar emulsion	7	10	234	30	108	58
Avg, all systems	9	8	226	45	55	26

TABLE 10 Summary of Membrane Performance by Type

System	Samples Contaminated (%)		Avg Cl ⁻ in Contaminated Samples (ppm)	
	0-1 in.	1-2 in.	0-1 in.	1-2 in.
Standard preformed	19	7	125	86
Thermoplastic	17	8	209	130
Polyurethane	26	17	83	70
NCHRP Project 12-11 preformed	28	15	120	109
Miscellaneous preformed	30	12	125	91
Epoxy	50	22	116	68
Tar emulsion	60	35	163	122
Exposed bridge decks	97	82	1,743	887

TABLE 11 Location of Cl^- Contamination and Percent of Samples Over Corrosion Threshold Level of 325 ppm

System	Samples Contaminated (%)						Samples Greater Than 325 ppm (%)					
	1 ft Offset		5 ft Offset		Wheel Path		1 ft Offset		5 ft Offset		Wheel Path	
	0-1 in.	1-2 in.	0-1 in.	1-2 in.	0-1 in.	1-2 in.	0-1 in.	1-2 in.	0-1 in.	1-2 in.	0-1 in.	1-2 in.
Standard preformed	34	10	14	5	15	4	3	0	1	0	0	0
Thermoplastic	18	9	17	6	17	9	3	0	6	3	3	0
Polyurethane	31	27	15	8	31	16	0	0	0	0	0	0
NCHRP Project 12-11 preformed	52	32	16	8	16	4	8	0	0	0	4	0
Miscellaneous preformed	37	11	26	11	26	15	0	0	0	0	7	0
Epoxy	71	32	41	18	41	16	0	0	4	0	2	0
Tar emulsion	82	64	51	18	46	21	15	3	0	0	3	0
Avg, all systems	46	25	26	10	26	11	4	0	2	1	2	0

TABLE 12 Summary of Membrane Characteristics and Performance

System	Ease of Application	Flexibility	Bond and Seal at Curb	Blister Pinholes		Bond Between		Problems with Pavement Application	Applied Cost ^a per yd ² (\$)	Overall Performance	Recommendation
						Membrane and Concrete	Pavement and Membrane				
Standard preformed	Easy	Good	Fair	Yes	No	Fair	Good	Occasionally	4.50	Good	Continue use
Thermoplastic	Hard	Poor to good	Fair	No	Yes	Good	Good	Occasionally	6.00	Good	Consider selective use
Polyurethane	Easy	Good	Excellent	No	Yes	Good	Poor	Occasionally	5.25	Fair to good	Consider selective use
NCHRP Project 12-11 preformed	Hard	Very good	Fair	Yes	No	Good	Good with protection boards	Yes	10.65	Fair to good	Not recommended; application too difficult
Miscellaneous preformed	Easy	Good	Poor	Yes	No	Fair	Fair	Yes	5.00	Fair to good	Consider selective use
Epoxy	Easy	Poor	Fair	No	Yes	Good	Poor	No	9.50	Poor	Not recommended for use
Tar emulsion	Very easy	Poor	Poor	No	No	Good	Good	No	1.35-3.50	Poor	Not recommended for use

^aCost covers period 1971-1978. Cost does not include bituminous overlay. Estimate \$3.00/yd² for 2-in. overlay when bituminous mix is bid at \$27/ton in-place.

TABLE 13 Description of Systems Applied

Fifteen preformed systems on 38 bridges	
Heavy-duty bituthene:	65-mil reinforced rubberized asphalt
Protecto Wrap M 400:	70-mil reinforced tar and synthetic resin modified
Royston No. 10:	75-mil reinforced bituminous
Royston No. 10 P.V.:	75-mil pre-vented reinforced bituminous
Royston No. 15:	60-mil pre-vented reinforced bituminous
Nordel:	65-mil reinforced noncured hydrocarbon rubber
Hyload 125:	125-mil pitch and PVC polymer
Gacoflex N-35:	0.0625-in. cured and buffed neoprene rubber
Sure-Seal Butyl:	65-mil vulcanized butyl rubber
Sure-Seal EPDM:	65-mil cured EPDM rubber
Butylfelt:	60-mil butyl rubber and felt laminate
Hydro-Ban RVN-45:	45-mil reinforced PVC and butyl rubber
Tri-Ply:	62-mil butyl neoprene rubber
Polyguard 860:	60-mil reinforced tar resin
Melnar 8:	165-mil reinforced rubberized asphalt in 4 x 8-ft panels
Five thermoplastic systems on 9 bridges	
Uniroyal 6125:	195-mil hot-applied rubberized asphalt
Hot asphalt and glass fabric:	5-layer built-up system
NEA 4000:	90-mil single component PVC polymer
Petromat:	nonwoven polypropylene fabric and asphalt cement
Gussaphalt:	2-in. mastic-type paving mixture
Four polyurethane systems on 7 bridges	
Polytak 165:	asphalt-modified polyurethane, 38-mil application
Bon-Lastic Membrane:	tar-modified polyurethane, 39-mil application
Duraseal 3100:	100 percent solids polyurethane, 69-mil application
Chevron Bridge Membrane:	asphalt-modified polyurethane, 100-mil application
Seven epoxy systems on 8 bridges	
Duralkote 304:	solvent-cut epoxy, 12-mil application
Duralkote 306:	coal tar modified, 46- and 65-mil applications
Duralbond 102:	100 percent solids, 48-mil application
Rambond 620-S:	100 percent solids, 52-mil application
Rambond 223:	100 percent solids, 90-mil application
Ramcoat Epoxy Paint:	polyamide, 12-mil application
Polyastics:	polyamide epoxy, 13-mil application
Two tar emulsion systems on 7 bridges	
Tar emulsion:	2 coats at 0.1-0.2 gal per coat
Tar emulsion and glass fabric:	7-layer built-up system

provided the best overall performance to date, with only 7 percent of the samples revealing contamination at the 1- to 2-in. depth and total Cl⁻ levels averaging 86 ppm in contaminated samples (Tables 1 and 10). All three products feature controlled membrane thickness, satisfactory cold temperature flexibility, and relatively easy application. The materials have been used on nearly all nonexperimental bridges in Vermont since 1973, when a specification was written that allowed the contractor the option of selecting one of the three proprietary systems.

Two potential problems recognized with the use of preformed membranes are the curb line seal and the formation of blisters in the pavement-membrane system. It is believed that the curb seal problem has been alleviated by modifying the specification to include the use of a compatible liquid polyurethane sealant along the membrane perimeter and the vertical curb face.

The problem of blister formations remains to be solved. Blisters that occur in the bituminous mix during paving are often caused by concentrations of air that were trapped beneath the membrane during installation. In many cases such blister formations can be prevented by puncturing the larger air bubbles and then bonding the membrane to the deck after the air has been forced out the vent hole. Blisters are also caused by small concentrations of moisture that collect beneath the membrane because of outgassing of moisture vapor from the concrete. Such moisture may subsequently turn to a vapor when exposed to the high temperature of the bituminous overlay. The blistering can often be reduced by requiring that the overlay be placed shortly after the membrane application is completed.

Post-construction blistering is also believed to be the result of moisture vapor pressures outgassing from the concrete. The occurrence of such blisters can be reduced by improving membrane adhesion to the concrete and by increasing the thickness of the bituminous overlay. Initial and post-construction blistering has been noted on a number of preformed membrane installations made in Vermont, but the occurrences have never become serious problems. In most cases the blisters have been noted only after the pavement has become slightly polished by snow-plow wear on the high spots.

Thermoplastic Systems: Status--4 Systems on 7 Bridges Averaging 9 Winters of Exposure

Performance of the thermoplastic systems has also been satisfactory, with 8 percent of the samples revealing contamination at the 1- to 2- in. depth and total Cl⁻ levels averaging 130 ppm in contaminated samples (Tables 2 and 10). Test results suggest that at least two of the systems could be recommended for further use. The best performance has been obtained from a hot rubberized asphalt, although it should be noted that the system is not recommended for structures on grades or superelevations in excess of 3 percent because of the potential for membrane-pavement stability problems under traffic. Protection boards were not included on the two decks under evaluation, but would be specified on any future applications of the system.

An application of Gussaphalt, a mastic-type paving mixture commonly used in Europe, resulted in a failure that required removal of the system after

330 linear feet of full-depth cracks occurred during the second winter. The failure was believed due to stresses caused by rapid temperature changes.

Polyurethane Systems: Status--4 Systems on 5 Bridges Averaging 9 Winters of Exposure

The polyurethane systems rate third with regard to the percent of contaminated samples, but the level of contamination is the lowest of all classes of material, averaging only 83 ppm total Cl^- in the top inch and 70 ppm at the 1- to 2-in. depth (Tables 3 and 10). The permeability may be caused by the development of pinholes and bubbles in the liquid-applied materials during application. The problems, caused by outgassing of moisture vapors from the concrete, can be alleviated by applying the polyurethane after midday when air temperatures are declining and by applying multiple coats. Advantages offered by the polyurethanes include ease of application, satisfactory cold temperature flexibility, and excellent bond and seal along curb lines. The systems should include protection boards or roll roofing to ensure adequate bond between membrane and pavement. Two of the individual polyurethane systems have remained free of detectible Cl^- contamination for up to 8 years of exposure.

NCHRP Project 12-11 Preformed Systems: Status--5 Systems on 5 Bridges Averaging 8 Winters of Exposure

The five vulcanized, cured, or cross-linked preformed elastomer systems selected as the most promising membrane materials under Phase I of NCHRP Project 12-11 were well-designed and displayed excellent physical characteristics. However, the application of the systems in Vermont under Phase II of the project was difficult, thus making it appear doubtful that the systems could be placed properly under typical field conditions. The overall performance of the systems has been satisfactory (Tables 4 and 10), except for curb line areas where 52 percent of the samples have been contaminated (Table 12). A pitch and polyvinyl chloride (PVC) polymer system has performed best, with Cl^- contamination limited to a single sample.

Miscellaneous Preformed Systems: Status--7 Systems on 10 Bridges Averaging 5 Winters of Exposure

Most of the systems included in this group are similar to the three standard preformed sheet systems but have had less widespread use. Four of the systems have performed well, including two products that have remained free of detectible Cl^- contamination (Table 5). Two of the products were manufactured with 0.0625-in. prepunched vent holes designed to prevent initial and post-construction blistering by allowing vapors to escape from beneath the membrane following installation. Both products were basically successful in reducing the amount of air entrapped beneath the materials, but Cl^- contamination found in 27 to 40 percent of the field samples suggests that some of the holes did not reseal on application of heat and pressure during the paving operation.

Epoxy Systems: Status--7 Systems on 8 Bridges Averaging 9 Winters of Exposure

With the exception of one product, the epoxy systems have performed poorly when compared with the other

experimental membranes (Tables 6 and 10). Exactly 50 percent of the samples revealed Cl^- contamination at the 0 to 1-in. depth, although the levels are still low, averaging less than 0.5 lb/yd³ over base Cl^- levels.

Advantages of the epoxy systems include relative ease of application, generally satisfactory bond to the concrete, and avoidance of problems with pavement applications. Disadvantages include unsatisfactory cold temperature flexibility and a tendency to pinhole or bubble during application.

Tar Emulsion: Status--2 Systems on 7 Bridges Averaging 10 Winters of Exposure

Test results indicate that both the two-coat standard treatment and the glass fabric reinforced system performed poorly when compared with all other classes of material. Contamination was identified in 60 percent of the samples taken at the 0 to 1-in. depth (Table 7). Based on all samples taken, the tar emulsion systems have allowed an average of 0.43 lb/yd³ of Cl^- contamination above base levels in the top inch of concrete. When such contamination levels are compared with the average of 6.97 lb/yd³ of Cl^- recorded on exposed concrete decks (Table 8), the results suggest that tar emulsion does offer a substantial level of protection to the concrete. The highest levels of Cl^- contamination were recorded on two 11-year-old structures treated with two coats of tar emulsion. Copper-copper sulfate half-cell potential measurements taken on the two structures in 1982 indicated the presence of active corrosion on 1 percent of the deck areas.

Exposed Bridge Decks: Status--6 Bridges Averaging 10 Winters of Exposure

For comparison purposes, three exposed bridge decks and three decks treated with an initial application of linseed oil and mineral spirits have been monitored for Cl^- contamination levels over a similar evaluation period. The results reveal Cl^- contamination in all samples taken from the top inch of concrete, with levels averaging 1,743 ppm or 6.97 lb/yd³ (Table 8). Contamination was found in 98 percent of the samples from the 1- to 2-in. depth, with levels averaging 887 ppm or 3.55 lb/yd³. In general, the decks appear to be in satisfactory condition; however, the most recent copper-copper sulfate half-cell potential measurements indicate the presence of active corrosion on an average of 30 percent of the deck areas. Concrete delamination was noted on one structure where it totaled 13 percent of the deck surface.

DISCUSSION OF PERFORMANCE

The test results given in Tables 1-7 disclose that 12 of the decks under evaluation were free of Cl^- contamination. Contamination was limited to a single sample on nine additional decks. The combined decks treated with 15 different membrane systems make up 33 percent of the decks under evaluation.

A number of the membrane systems did not provide adequate provisions for preventing Cl^- penetration along curb lines. As shown in Table 11, 46 percent of the curb line samples were contaminated at the 0 to 1-in. depth. Furthermore, such samples made up 47 percent of all the contaminated samples recorded in the top inch of concrete. The data in Table 11 also disclose that the number of Cl^- contaminated samples found at the 5-ft offset from the curb line and

in the wheel path were approximately equal. Such results suggest aggregate puncture under traffic loading is probably not a significant factor contributing to membrane permeability in Vermont.

Attempts to project future performance of the membrane systems may be seen in Figures 1 and 2. All projections are based on a statistical analysis by using the method of least squares.

Figure 1 shows the number of samples contaminated with Cl^- is increasing at a rate of 1.3 percent per year. If the present rate continues, the top inch of concrete will become contaminated with Cl^- after 64 years of service. All samples at the 1- to

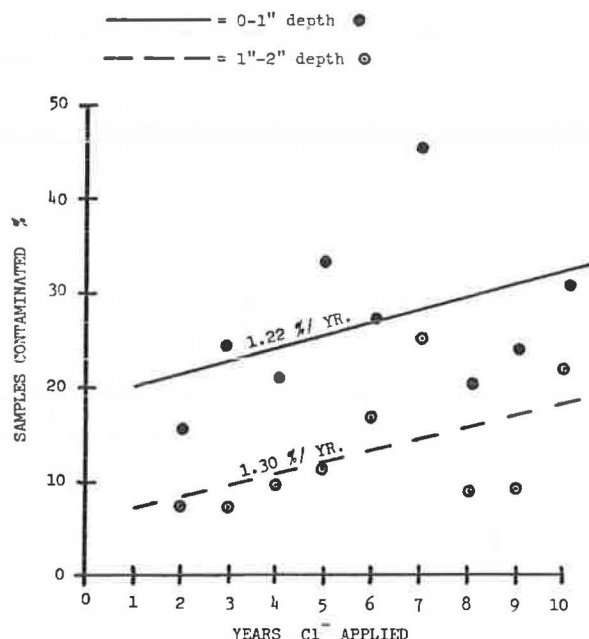


FIGURE 1 Rate of increase in percentage of samples contaminated with Cl^- .

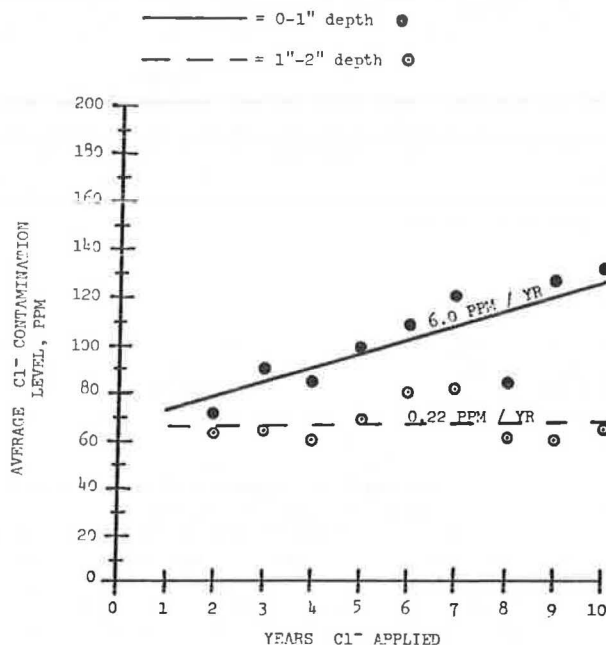


FIGURE 2 Rate of increase in Cl^- contamination levels.

2-in. depth will be contaminated after 73 years of service.

The level of contamination is an important factor that must be considered when attempting to project the service life of the membrane systems and the service life of the bridge decks. Figure 2 projects the rate of increase in contamination levels at approximately 6 ppm per year in the top inch of concrete. If the 6-ppm rate of increase continues, the contamination will reach the 325-ppm corrosion threshold level in the top inch of concrete after 43 years of service. The rate of increase in contamination levels at the 1- to 2-in. depth is less than 1 ppm per year. Although all projections point toward a long service life, it is recognized that at some point in time the various membrane materials will begin to deteriorate and the performance life will decrease accordingly.

Currently, only 25 of 1,625 samples tested have Cl^- contamination greater than the corrosion threshold level of 325 ppm (Table 11). When the tar emulsion and epoxy-treated decks are not included, the number drops to 13, or 1 percent of the samples, with all but 1 occurring in the top inch of concrete. When all samples are taken into consideration, the average Cl^- content greater than base levels is 55 ppm in the top inch and 26 ppm at the 1- to 2-in. depth (Table 9). Because the decks were constructed with 2 in. of concrete cover, additional corrosion-free life can be expected before the 325-ppm Cl^- level is reached at the 2- to 3-in. depth.

The test results indicate that most of the membrane systems have performed well for up to 11 years of exposure. Based on the experiences gained during the membrane installations, it is believed that overall membrane performance would have been even better if the following conditions had been met:

1. Systems not well suited for the intended purpose had been eliminated through better preliminary laboratory testing;
2. Difficulties with certain facets of some applications had been anticipated and avoided; this would be possible with future applications of the same materials;
3. Certain construction procedures had been modified to suit the particular needs of a system;
4. Additional safeguards had been taken to prevent leakage along curb line areas;
5. Protection board had been placed over some membrane systems to improve stability during the paving process and under continuous traffic;
6. Construction traffic had not been allowed to travel on the membrane and first course of pavement; and
7. Pavement overlay thickness was increased to 2.5 in., with a minimum of 2 in. maintained.

CONCLUSIONS

Many conditions such as weather, winter maintenance practices, traffic volumes, and design and construction practices are known to vary in different regions. Accordingly, it is recognized that membrane systems that extend the service life of bridge decks in Vermont may not necessarily perform with the same results at other locations. Nevertheless, based on performance data obtained to date, the following conclusions are considered significant.

1. Performance results based on more than 1,600 field samples indicate that, almost without exception, the experimental membrane systems have outperformed the Agency's original standard treatment of tar emulsion.

2. When grouped by general type, the best performance has been provided by the standard preformed sheet membranes and thermoplastic systems, closely followed by the polyurethanes, the NCHRP Project 12-11 recommended systems, and miscellaneous preformed systems.

3. In general, the epoxy and tar emulsion systems were not considered successful, although they have allowed only an average of 0.35 lb of Cl^- per cubic yard of concrete more than base levels in the top inch of concrete as compared with an average of 6.97 lb/yd³ on exposed bridge decks during a similar evaluation period.

4. Chloride contamination was detected in one sample or less on 33 percent of the 63 bridge decks under evaluation. Protective systems on the 21 decks included 15 of the 33 different membrane systems tried.

5. Less than 2 percent of the more than 1,600 field samples disclosed Cl^- levels greater than 325 ppm, the level considered sufficient to initiate corrosion of the reinforcing steel. All but three of the greater than 325-ppm samples were located in the top inch of concrete.

6. Although curb line samples made up only 33 percent of those taken, they accounted for 47 percent of all contaminated samples, pointing out the difficulty of sealing that area of the bridge deck.

7. The number of Cl^- contaminated samples found at the 5-ft offset from the curb line and in the wheel path (± 15 -ft offset) were approximately equal. Such results suggest aggregate puncture under traffic loading is probably not a major contributor to membrane permeability.

8. Projections based on performance results to date suggest that a significant number of the membrane systems will provide protection from serious Cl^- contamination for 50 years or longer.

RECOMMENDATIONS

1. Before initiating action to replace deteriorated bituminous pavements on membrane-treated bridge decks, field testing for Cl^- contamination should be undertaken on the respective structures. If the performance survey results indicate a membrane system is still providing the desired protection, only the upper ± 75 percent of the bituminous pavement should be removed with cold planing equipment, thereby retaining the functional membrane system.

2. Long-term field performance results indicate that a variety of membrane systems can be made to work if adequate time and effort are spent in selection, design, and installation. However, the potential for improper placement and other related

problems with individual applications should be sufficient to discourage membrane use in areas where a lack of sufficient care and attention might be anticipated.

3. Promising new membrane systems that have become available in the past 5 years or so should be applied in the field in a new test program to determine their effectiveness in relation to current acceptable materials.

4. This research project should be continued as planned for a minimum of 3 additional years through fiscal year 1987.

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