masonry, brick arches, or even steel structures themselves might be considered.

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Latex-Modified Concrete Bridge Deck Overlays: Field Performance Analysis

ALFRED G. BISHARA

Data on field performance of 132 bridge decks overlaid with latex mortar or concrete in Ohio, Michigan, Kentucky, and West Virginia, as well as some data from Minnesota and Vermont, were collected. Common durability distress features and the factors that might influence them were identified. Statistical analysis was performed to determine the set of variables that best explains the variation in the surface distress features among the different overlay projects investigated and to quantify the relationship between overlay condition and the pertinent variables through the formulation of regression models. Further assessment of available performance data was conducted to connect the obtained relationships with the limited data on effectiveness of latex overlays in providing corrosion protection to the deck rebars and to develop hypotheses on the formation and development of the durability deficiency features of latex overlays. The results obtained and the conclusions drawn explain, quantify, and delineate the interrelationship among such factors as years of service, average daily traffic, trafficked versus untrafficked decks during placement, continuous versus simply supported decks, thickness of overlay, and skid number on the durability and corrosion-protection capability of the overlay.

This study was initiated to provide administrators and bridge designers in the state of Ohio with an analysis of available data on field performance of latex-modified concrete and mortar overlays. Since, at the time the study started, only a score of such overlaid bridges were in service in Ohio, it was decided to extend the survey to the neighboring states of Michigan, Kentucky, and West Virginia, where a larger number of such decks existed. As the study progressed, some data from Vermont and Minnesota also became available.

The total number of latex overlay projects investigated was 132; 47 were in Ohio, 57 in Michigan, 17 in Kentucky, and 11 in West Virginia. Most of the latex overlays used before 1972 were of the mortar type, 19-25 mm (0.75-1.0 in) thick. Since 1972, the majority of the latex overlays have been of the concrete type, 25-44 mm (1.0-1.75 in) thick. The actual thickness, however, may be larger in rehabilitation jobs in which the scarified concrete thickness causes the above-mentioned values to be increased. Only 21 of the projects investigated were new two-course construction; the remaining 111 were rehabilitation projects on old decks. Twelve of the new construction projects had mortar overlays, and 9 had concrete overlays. Twenty-one of the rehabilitation projects had mortar overlays, and 90 had concrete overlays. Almost all of the latex overlays investigated used Dow latex modifier A. However, 20 used Dow modifier B.

Performance of latex-modified concrete bridge deck overlays relates to their durability, antiskid quality, and effectiveness in resisting chloride ingress and preventing corrosion of the rebars. Deficiencies in durability are usually manifested by the existence of one or more of the following physical expressions.

DEFICIENCIES IN DURABILITY

Overlay Distress

Overlay distress can be characterized by one or more of the following features:

1. Random cracks (RC): These cracks are usually random in direction, spaced 300-350 mm (12-14 in) apart; their width may vary from 0.13 to 1.0 mm (0.005-0.04 in). Most of these cracks appear within a short time after curing of the overlay and, when they first appear, do not extend through the full thickness of the overlay. Some measurements have shown them to extend from 6 to 13 mm (0.25-0.5 in) initially. After repetitive winter exposures, they may extend to the full depth of the overlay.
2. Transverse cracks (TC): These cracks are usually spaced 0.9-1.5 m (3-5 ft) apart, and their direction is perpendicular to the bridge center line. Their widths vary from 0.13 to 1.3 mm (0.005-0.05 in). Transverse cracks usually penetrate through the full depth of the overlay and the substrate. Hence, they are also referred to as reflective cracks.
3. Debonding: Debonding is the separation without actual observed failure of the overlay from the overlaid concrete. It is usually detected by the occurrence of a relatively hollow sound when a steel chain is dragged over the surface, when the surface is tapped with a hammer, or when the Delamtect detector is used.
4. Stripping: Stripping is the actual observed separation at the interface of the overlay from the underlying deck concrete.
5. Spalling: Spalling is the separation of the overlay and the underlying concrete cover to the top reinforcement. Examples of Dow latex overlay loss by stripping and spalling are shown in Figure 1.
6. Other deterioration features: These may be failures at transverse or longitudinal joints (see Figure 1) or deficiencies in surface texture, such as scaling.

Antiskid Quality Distress

The antiskid quality is usually measured by the skid number (SN) according to the American Society for Testing and Materials (ASTM) specifications. This number varies according to the intensity of traffic and the speed of vehicles. In this paper, for comparison purposes, only the SN at 74 km/h (40 miles/h) as measured in the driving lane is considered.

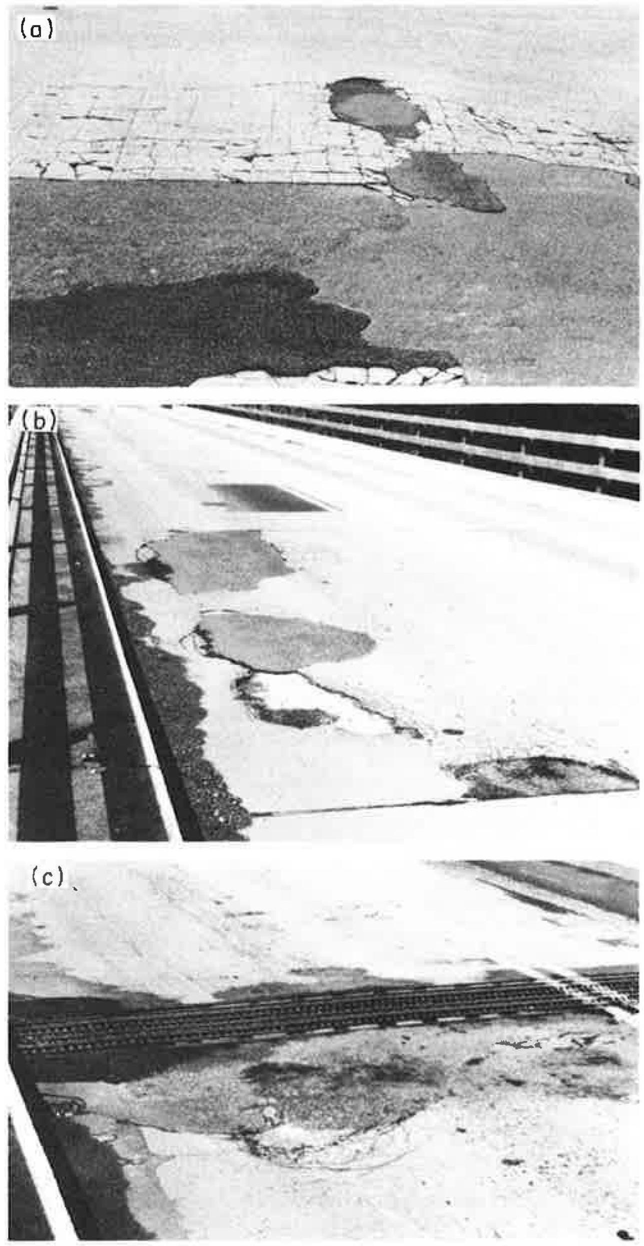
Protective Quality Distress

The effectiveness of an overlay in corrosion protection to the deck rebars is currently done through measurement of

1. The amount of chloride ion $C\bar{L}$ per cubic yard of concrete, absorbed at different depths from the surface [this amount gives an indication of the degree of chloride contamination conducive to active corrosion; at present, if 1.16 kg of $C\bar{L}/m^3$ (2 lb of $C\bar{L}/yd^3$) or more exist at the level of the top reinforcement, then active corrosion is considered possible] and
2. Copper-copper sulfate half-cell potential (this value, in volts, gives an indication of whether active corrosion is taking place; at present the limits of -0.20 V for no corrosion activity and -0.35 V for active corrosion are widely recognized).

Data on overlay distress and antiskid quality for each bridge were classified as shown in Table 1. The details of these data are available in Bishara (1). Data that deal with the effectiveness of the latex-modified concrete overlays in corrosion protection were available for only a limited number of the bridges investigated. Since it is the evolution of the chloride content values and/or the copper-copper sulfate half-cell potential values over time for each bridge that shows whether the overlays have been effective in providing corrosion protection, the data available are discussed separately for each bridge.

Figure 1. Typical examples of Dow latex overlay loss (a) within a span, (b) near a longitudinal joint, and (c) near a transverse joint.



STATISTICAL ANALYSIS OF AVAILABLE DATA ON OVERLAY DISTRESS AND ANTISKID QUALITY

A statistical analysis of the different variables that are thought to affect the durability of latex bridge overlays was conducted. The objective of this analysis is twofold: (a) to determine the set of variables that best explains the variation in overlay distress and (b) to quantify the relationship between overlay condition and the pertinent variables through the formulation of regression models.

Table 1 gives a list of variables and codes used

Table 1. List of variables, codes, levels, and assigned values.

Code	Variable	Assigned Value
X_1	Project identification number	
	Ohio	101-147
	Kentucky	201-217
	West Virginia	301-311
	Michigan	401-457
X_2	Bridge deck type[a]	
	SBC, SMSC	1
	SMS	2
	SMGC	3
	SMG	4
	STT, ST	5
	SGF	6
	CS	7
	CTB	8
X_3	Continuity	
	Continuous	1
	Simple	0
X_4	Age of original deck (years)	From collected data (1)
X_5	Condition of original deck before overlay	
	New	4
	Medium	3
	Poor	2
	Very poor	1
X_6	Type of overlay	
	Concrete	1
	Mortar	0
X_7	Thickness of overlay (in)	From collected data (1)
X_8	Average unidirectional daily traffic in 1975 (vehicles/day)	From collected data (1)
X_9	Bridge operation during placement of overlay	
	Closed	1
	Open	0
X_{10}	Number of winter exposures of overlay when inspected (years)	From collected data (1)
X_{11}	Length of service when SN was measured (years)	From collected data (1)
	Percentage of total area affected by overlay distress	
Y_{12}	Spalling	From collected data (1)
Y_{13}	Stripping	From collected data (1)
Y_{14}	Debonding	From collected data (1)
Y_{15}	Random cracks	From collected data (1)
Y_{16}	Transverse cracks	From collected data (1)
Y_{17}	Skid number	From collected data (1)
Y_{18}	Surface Distress Index (SDI)	Generated[b]
Y_{19}	Percentage of total cracks (2)	Generated[c]

[a]Values are assigned according to relative flexural rigidity. SMS = steel multi-stringer (noncomposite); SMSC = steel multi-stringer composite; SMG = steel multi-girder (noncomposite); SMGC = steel multi-girder composite; CTB = concrete T-beam; CS = concrete slab; SBC = steel beam composite; STT = steel through truss; ST = steel truss; and SGF = steel girder and floor beam.

[b]The surface distress index was generated as a weighted average of all surface distress features as follows: $Y_{18} = (Y_{15} + 2Y_{16} + 4Y_{14} + 8Y_{13} + 10Y_{12})/25$.

[c]$Y_{19} = (Y_{15} + 2Y_{16})/3$.

in the statistical analysis. Binary codes (1,0) as well as numerical weights are included to account for nonnumerical variables. The statistical package used in the analysis is OMNITAB II (2).

Before any modeling (i.e., formulation of regression equations) was attempted, initial plots were made to search for any visual trend in the input data. Since some of the variables in the initial data base were missing, it was necessary to work with different subsets, each of which contained a complete listing of some, but not all, variables. Plots between surface distress index (SDI) (Y_{18}) and X_2 through X_{10} were obtained through a plotting routine. Except for overlay thickness (X_7) and years of service (X_{10}), no visual trend was observable for the subset of 117 data points. It was therefore decided to proceed with the modeling phase: The main objective at this stage was to rank the variables by degree of contribution to the regression equation.

First a regression analysis was conducted for the three dependent variables Y_{15} (random cracks), Y_{16} (transverse cracks), and Y_{19} (total cracks) with the five dependent variables X_2, X_3, X_6, X_7, and X_9, using 117 data points available. This analysis showed that it is necessary to search for another variable (or set of variables) to improve the degree of association between the Y's and X's investigated.

A second regression analysis was therefore conducted that involved Y_{18} versus X_3, X_7, and X_{10}. The variable X_7 was selected because it showed the largest contribution among the first subset variables. X_{10} was also selected as a result of the initial plot observations, and X_3 was selected to test the effect of deck continuity. From this analysis, it was concluded that variable X_{10} (number of winter exposures of the overlay) had the greatest impact on the amount of surface distress. Other variables tested either did not influence or were overshadowed by this variable.

It was then decided to limit the modeling process to that variable and superimpose (a) the effect of deck continuity (X_3) and (b) bridge operation (open or closed) during placement (X_9). This was accomplished in the third regression analysis, which involved Y_{15}, Y_{16}, Y_{18}, and Y_{19} versus X_{10}, X_3, and X_9.

This analysis showed that

1. Bridge continuity has a detrimental effect on random cracks, although it is not statistically significant;
2. Bridge continuity has a detrimental effect on transverse cracks, although it is not statistically significant (see Figure 2);
3. Bridge continuity has a detrimental effect on total cracks, although it is not statistically significant;
4. Bridge continuity has a detrimental effect on SDI, but its effect is not statistically significant;
5. Bridges open to traffic during overlay placement exhibit larger, although not statistically significantly larger, areas that have random cracks;
6. Bridges open to traffic during overlay placement exhibit larger, although not statistically significantly larger, areas that have transverse cracks (see Figure 3);
7. Bridges open to traffic during overlay placement exhibit larger, although not statistically significantly larger, total areas of cracks; and
8. Bridges open to traffic during overlay placement exhibit larger, although not statistically significantly larger, areas of general surface distress of one type or another.

The regression analysis for antiskid quality was limited to 44 projects for which SNs were available; only 28 of these bridges had traffic volume data on average daily traffic (ADT) as well. Therefore, the following result of this analysis--that there is a mild, although not significant, detrimental effect of years of service on the SNs--should be viewed cautiously because of the small sample size. The average SN in the driving lane dropped from 45 to 41 in five years.

ANALYSIS OF AVAILABLE DATA ON EFFECTIVENESS IN CORROSION PROTECTION

Ohio Bridges

Table 2 presents copper-copper sulfate half-cell potential data from eight Ohio bridges. The points at which readings were taken were uniformly spaced over the deck area. In one bridge (WAY-021-0089R), readings were also taken before the existing deteriorated surface was scarified in order to place the overlay. In another bridge (OTT-590-0799), although the readings were usually taken at

Figure 2. Percentage of areas that have transverse cracks versus years of service for continuous and simply supported bridge decks.

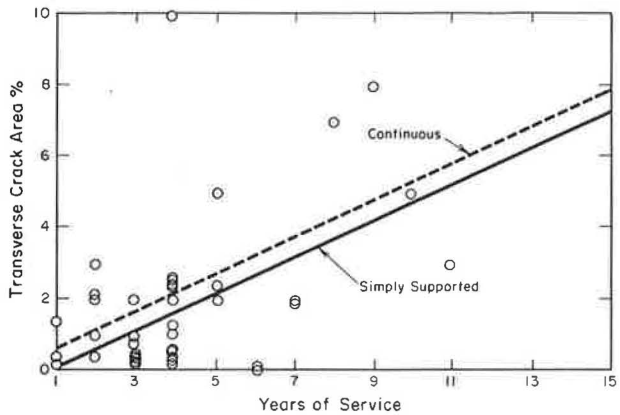


Figure 3. Percentage of areas that have transverse cracks versus years of service for bridge decks open or closed during overlay.

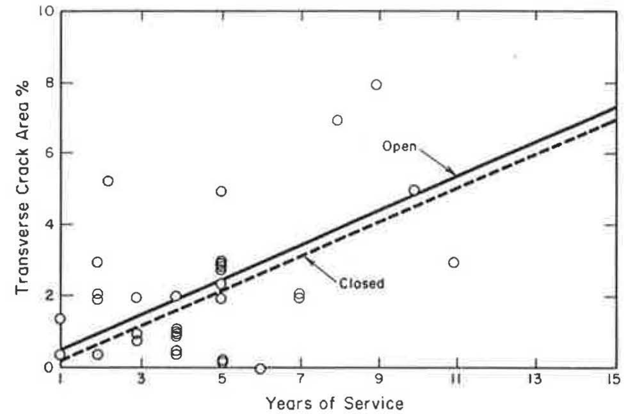


Table 2. Copper-copper sulfate half-cell potentials from some Ohio Down latex overlays.

Bridge Identification	Latex Type	Date Measurements Taken	No. of Winters of Exposure	No. of Readings	Avg Voltage (V)	Percentage ⩽ -0.35 V	Maximum Voltage (V)
MAR-231-0343	Dow A	1976	1	228	-0.20	0.4	-0.37
		1977	2	140	-0.12	0.0	-0.22
		1978	3	138	-0.15	0.0	-0.33
AUG-198-0153	Dow A	1975	1	330	-0.09	0.0	-0.28
		1976	2	360	-0.07	0.0	-0.21
		1977	3	270	-0.10	0.0	-0.20
		1978	4	158	-0.06	0.0	-0.14
MED-083-0053	Dow A	1976	2	160	-0.14	0.6	-0.36
		1977	3	170	-0.10	0.0	-0.32
		1978	4	101	-0.11	0.0	-0.31
WAY-301-0389	Dow A	1976	2	177	-0.24	2.8	-0.40
		1977	3	164	-0.12	0.0	-0.24
		1978	4	114	-0.11	0.0	-0.26
OTT-590-0799	Dow B	1973	0	77	-0.37	58.0	-0.55
		1974	1	77	-0.22	5.2	-0.45
		1975	2	77	-0.24	15.6	-0.40
		1976	3	91	-0.13	1.1	-0.38
		1977	4	91	-0.10	0.0	-0.22
		1978	5	91	-0.16	0.0	-0.32
		1979	6	91	-0.11	0.0	-0.33
WAY-021-0089R	Dow A	1973	Original deck	155	-0.39	69.0	-0.55
		1973	1	155	-0.37	73.0	-0.50
		1974	2	155	-0.18	5.2	-0.35
		1975	3	155	-0.24	15.5	-0.45
		1976	4	156	-0.14	2.6	-0.39
		1977	5	94	-0.10	0.0	-0.30
		1978	6	91	-0.09	0.0	-0.23
CRA-602-0600	Dow A	1976	1	206	-0.18	0.0	-0.31
		1977	2	154	-0.14	0.0	-0.24
		1978	3	154	-0.16	0.0	-0.24
PRE CR 36	Dow A	1977	3	105	-0.13	0.0	-0.24
		1979	5	78	-0.35	51.3	-0.51

locations away from deck cracks, 31 additional readings in 1979 were taken at crack locations. Their average was -0.27 V, 6.5 percent of the readings were ≤ -0.35 V, and the maximum reading was -0.39 V, compared with -0.11 V and none of the readings at -0.33 V when the readings were taken at off-crack locations. This difference may be attributed to lack of proper wetting of off-crack locations during half-cell potential measurements.

Although the data presented in Table 1 seem to indicate a marked reduction with time in the areas where half-cell potential readings are ≤ -0.35 V, this should not be construed as an indication of cessation of corrosion activities in contaminated substrates (as more correctly demonstrated by high half-cell readings at crack locations).

Chloride analyses data for four Ohio latex overlay projects are discussed here. For one of them (AUG-198-0153), a new two-course construction completed August 23, 1974, that has a 25-mm (1-in) latex overlay (Dow A), chloride data are available (before salt applications) after one, two, and four consecutive winter exposures. For another one (WAY-021-0089R), a rehabilitation project that has a 38-mm (1.5-in) latex overlay placed June 13, 1973, chloride data are available after four and six winter exposures. For the other two rehabilitation projects (CRA-602-0600 and MAR-231-0343), only one set of data is available after four winter exposures. Table 3 gives average chloride values for these bridges, drawn from three to five samples obtained by pulverization from the center line of the median lanes and 3 m (10 ft) from the curb lines. The chloride contents were obtained by using wet analysis based on concrete that weighed 2200 kg/m^3 (3800 lbs/yd^3) and are given for different

Table 3. Variation of chloride content with depth and winter exposures for four Ohio bridges.

	Chloride Content (kg of CL^-/m^3)							
	AUG-198-0153 (ADT = 6380)				WAY-021-0089R (ADT = 4500)		CRA-602-0600 (ADT = 1230)	MAR-231-0343 (ADT = 810)
Depth from Surface (mm)	December 1974 (0 winters)	May 1976 (1 winter)	April 1977 (2 winters)	April 1979 (4 winters)	April 1977 (4 winters)	April 1979 (6 winters)	April 1979 (4 winters)	April 1979 (4 winters)
13	0.39	3.40	2.34	4.15	3.39	4.32	2.84	3.57
25	0.42	1.26	-	1.46	-	1.58	1.05	0.96
38	-	-	0.85	-	0.61	-	-	-
51	0.38	0.90	0.81	0.97	0.34	0.85	0.59	0.50
64	-	-	0.93	-	0.37	-	-	-

Note: 1 mm = 0.039 in.

Figure 4. Chloride content versus depth and winter exposures for a new Ohio bridge (AUG-198-0153) that has a 25-mm (1-in) concrete Dow A overlay.

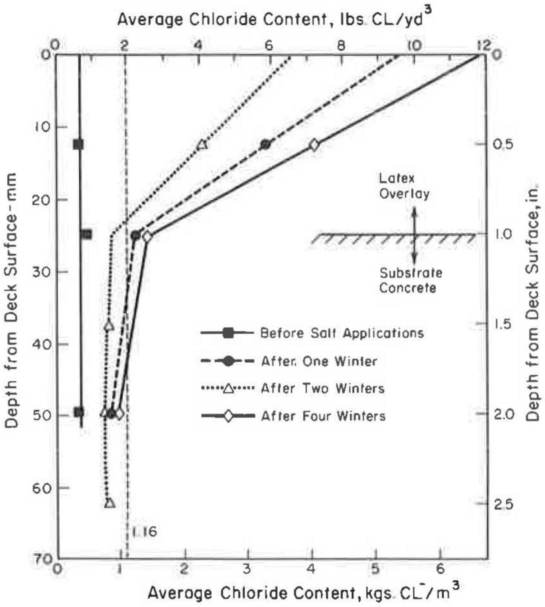
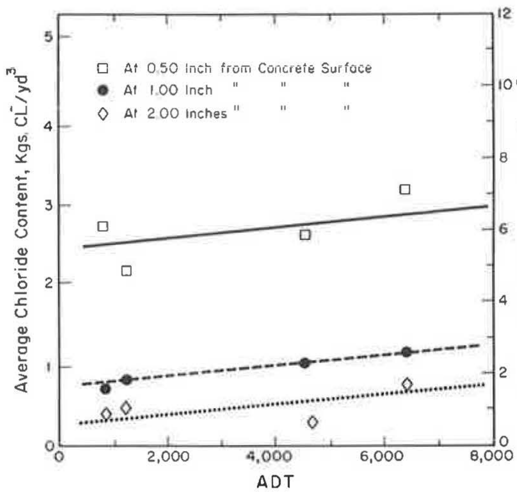


Figure 5. Chloride content versus ADT after four years of service for four Ohio bridges.



depths from the overlay surface and dates of extraction.

Figure 4 illustrates the variation of chloride content penetration profiles according to the number of winter exposures for the AUG-198-0153 bridge. After one year, Figure 4 shows a steady increase in chloride content in the overlay and at the bond interface as a function of winter exposures. However, even after six years of exposure, as in the case of the WAY-021-0089R bridge, the chloride content in the vicinity of the top rebars remains below the active corrosion limit of 1.16 kg of CL^-/m^3 (2.0 lb/yd^3). Since only a maximum of five samples was taken from each bridge deck for chloride analysis, it is possible that, at some of the crack locations, chloride contents may exceed 1.16 kg/m^3, indicating localized active corrosion.

The data in Table 2, illustrated in Figure 4 and as demonstrated by Clear (3), indicate that the rate of decrease of chloride content is much higher in the latex concrete than in the substrate concrete. As to whether the bond surface between the overlay and the substrate constitutes an actual barrier to chloride penetration, as postulated by some, it is clear from the data in Table 2 and Figure 4 that chloride content in the vicinity of the bond surface had been increasing steadily with years of service; hence, there seems to be no substantiation for that hypothesis.

To see whether the intensity of traffic as represented by ADT (which has a direct bearing on the frequency of salt applications and hence on the rate of its penetration through the overlay) affects chloride contents, Figure 5 was plotted. Figure 5 shows the average chloride contents versus ADT for the four bridges in Table 3 after four years of service at 13, 25, and 51 mm (0.5, 1, and 2 in) from the surface. Figure 5 seems to show a slight increase of the chloride content as the ADT increases, other factors being equal. This topic was also statistically analyzed above.

Michigan Bridges

The following copper-copper sulfate half-cell potential and chloride content data are those made available to me for two spans of the same bridge (Buchanan Street overpass of I-96 in Detroit). Of this bridge's four simply supported spans, only span 3 had a 25-mm (1-in) latex mortar overlay applied in October 1969, right after correction of an elevation problem. This brought the cover of the top reinforcing bars to 76 mm (3 in) in span 3, compared with 51 mm (2 in) in the other spans. The overlay was placed before the bridge was opened to traffic or had had any salt applications. The readings were taken in 1972, 1974, and 1977 after three, five, and eight years of winter exposure, respectively.

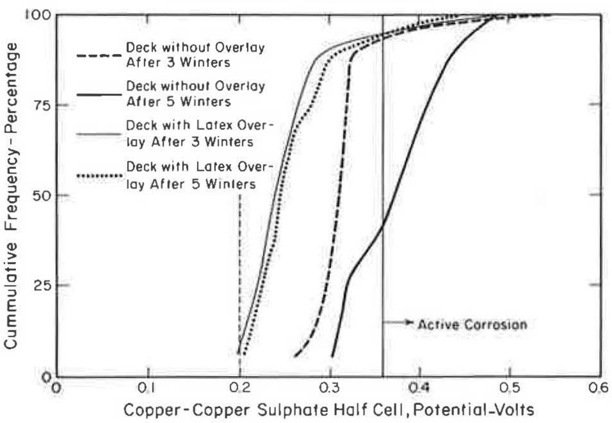
The half-cell potential readings were run on a 1.525-m (5-ft) grid pattern along lines 0.30, 1.83, and 3.35 m (1, 6, and 11 ft) from the curb lines in the outside traffic lane in both directions of spans 2 and 3. Table 4 presents a summary of these data.

Table 4. Summary of half-cell potential readings from a Michigan bridge.

			Span 2			Span 3		
Location from Curb (m)	Winter Exposures	No. of Readings	Average Voltage (V)	Percentage ≤-0.35 V	Maximum Voltage (V)	Average Voltage (V)	Percentage ≤-0.35 V	Maximum Voltage (V)
0.30	3	34	-0.35	50	-0.58	-0.27	15	-0.54
	5	34	-0.42	76	-0.57	-0.45	20	-0.51
	8	34	-0.40	70	-0.58	-0.39	40	-0.60
1.83 and 3.35	3	68	-0.31	12	-0.54	-0.24	12	-0.53
	5	68	-0.35	46	-0.52	-0.25	13	-0.51
	8	68	-0.47	63	-0.48	-0.47	50	-0.70

Note: 1 m = 0.3 ft.

Figure 6. Cumulative frequency-distribution curves of half-cell potentials after three and five winter exposures for a Michigan bridge.



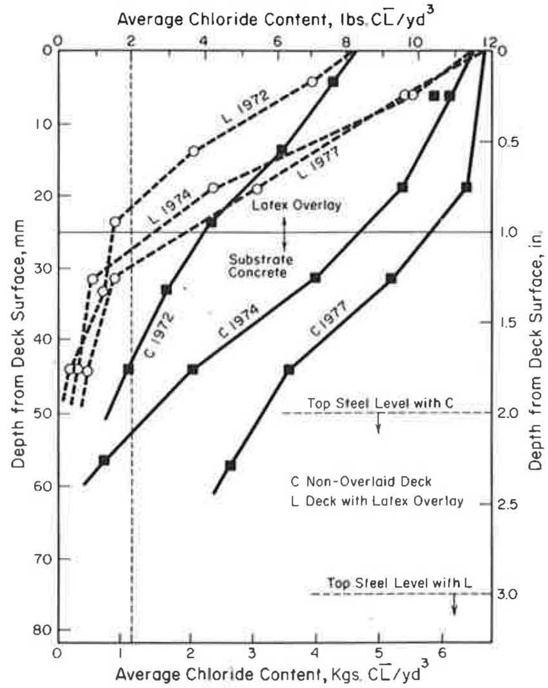
As customary, relatively higher readings usually occurred close to the expansion joints and the curb lines. This may be attributed to the presence of exposed steel dams at the expansion joints and the tendency of salt brines to be more concentrated near the curb lines. In addition, relatively lower chloride content values and half-cell potential readings were usually obtained at locations where the latex overlay was 38 mm (1.5 in) thick than at locations where it was only 25 mm (1 in) thick.

Figure 6 represents the same array of half-cell potential data obtained in 1972 and 1974 in cumulative frequency-distribution curves. A shift to the right of the cumulative frequency curve indicates an overall increase in the half-cell potentials; a shift to the left means a decrease in the half-cell potentials.

In contrast to the Ohio data presented in Table 1, the number of half-cell potential readings ≤ -0.35 V seems to continue to increase with years of service in decks that have and that lack latex overlays under the same exposure and traffic conditions. The comparison of actual percentages of areas in which the half-cell potential readings are ≤ -0.35 V in the two types of decks (that is, overlaid versus nonoverlaid) should be taken with some reservation since the cover to the top rebars was not the same in the two cases, as mentioned earlier.

Chloride content data were obtained from 100-mm (4-in) cores located 1.17-1.67 m (3.83-5.5 ft) from the curb lines and 1.55-5.36 m (5.08-17.83 ft) from the expansion joints. Three or four cores were taken each time. Each core was sliced; each slice was dried and pulverized. The chloride content was extracted by using a dilute nitric acid. The 1972 cores were sliced 10, 19, 28, 38, and 51 mm (0.375, 0.75, 1.125, 1.5, and 2 in) from the deck surface. Thus, their readings represented the average chloride content 5, 9.5, 14, 19, and 25 mm (0.1875, 0.375, 0.562, 0.75, and 1 in), respectively, from the deck surface. The 1974 and 1977 cores were sliced at intervals of 13, 25, 38, 51, and 63 mm (0.5, 1.0, 1.5, 2.0, and 2.5 in) from the surface. Thus, they gave the average chloride content at 6, 13, 19, 25, and 32 mm (0.25, 0.5, 0.75, 1, and 1.25 in), respectively, from the surface of the deck. Although the coefficient of variation between individual sample chloride content results varied from 32 percent to more than 100 percent, the sample's mean was used in plotting the chloride penetration diagrams in Figure 7.

Figure 7. Chloride content versus depth for different winter exposures for a Michigan bridge that had an overlay placed in 1969.



These diagrams indicate that chloride contents at the same depth from the surface were much lower in the deck that had a latex overlay than in the deck that did not have an overlay under the same exposure and traffic conditions.

Actual observations after eight years of service show that, in the deck that did not have a latex overlay, 2 percent of its area either was spalled or sounded hollow (i.e., indicated imminent spalling), compared with only 0.5 percent in the deck that had a latex overlay. Since both decks had similar percentages of surface area in which the half-cell potential readings were ≤ -0.35 V, whereas chloride contents in the vicinity of the top rebars were much higher in the deck that did not have an overlay, it seems that chloride contents in the vicinity of top rebars give a better indication of expected deck surface distress than do half-cell potential readings.

In addition, the chloride penetration profiles in Figure 7 show that the rate of decrease of chloride content with depth is much higher in the latex overlays than in the nonoverlaid concrete and that the chloride content at the bond interface between the overlay and the substrate increases steadily with years of service, which indicates that the interface does not constitute a barrier to chloride penetration.

OVERALL ASSESSMENT OF AVAILABLE PERFORMANCE DATA

The purpose of this section is (a) to tie the relationships between overlay condition and the pertinent variables obtained through regression analysis to the limited data on effectiveness of latex overlays in corrosion protection and (b) to develop hypotheses on the formation and development of various deficiency features of latex overlays based on their relationships to the pertinent variables.

Relationship Between Cracking and Other Distress Features

In contrast to stripping and spalling, cracking of bridge deck overlays does not constitute in itself an imminent distress problem that demands immediate maintenance attention. However, cracking contributes to other distress features. Since the primary function of the latex overlay is to act as a barrier to chloride ion penetration into substrate concrete, a flaw in this barrier would facilitate chloride ingress. It is also noteworthy to distinguish between the role of random cracks and transverse cracks in that connection. Since transverse cracks usually extend through the substrate, chloride brine penetration through them goes closer to the vicinity of the top rebars and causes imminent corrosion activity that may end by producing spalling. Random crack depths, on the other hand, usually do not exceed the overlay thickness, and chloride ingress through them would still have to penetrate through the substrate concrete in order to reach the top rebars.

On the other hand, accumulation of moisture in random cracks can lead (after sufficient cycles of freezing and thawing) to debonding and/or stripping of the overlays. In the case of transverse cracks, the same procedure can lead to spalling as well.

Effect of Placement of the Overlay Under Open Traffic

Most states allow traffic on one or more lanes of a bridge deck when latex-modified concrete or high-density, low-slump concrete is being placed and cured in an adjacent lane as a part of a deck restoration project, essentially because of the high cost of rerouting (sometimes equivalent to the cost of restoration itself). Precautions are sometimes taken, however, to minimize possible negative effects of traffic vibrations. These precautions can include imposing restrictions on speed, placing concrete at night or at other times when traffic volume is low, and stiffening the deck.

The effect of traffic-induced vibrations on setting and curing of a latex concrete or mortar overlay may bear on the overlay's mechanical properties, its interface bond to substrate concrete, incidence of transverse and random cracking, and overall durability. However, there is no reason to believe that material strength properties of the overlay are adversely affected, since a considerable body of research at the Portland Cement Association has shown that concrete strength properties are not harmed (and sometimes are enhanced) by agitation or vibration, even for extended periods during the setting time.

With regard to interface bond, results of tests by Furr and Ingram (4) in which a 51-mm (2-in) overlay was cast on a vibrating beam show that concrete overlays will adhere firmly to base concrete when bonded with a portland cement grout.

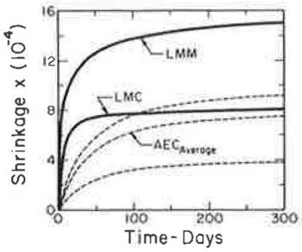
With regard to the effect on random and transverse cracking, the possibility that there is a higher incidence of transverse cracking where latex overlays were placed under traffic seems to be recognized by some states (e.g., Michigan, Minnesota, Kansas, and Oklahoma). This is not hard to understand since vehicle loading on trafficked lanes also deflects the construction lane, whose flexural rigidity has been weakened by scarifying its surface. Particularly in continuous decks, existing tension transverse cracks in the substrate in the vicinity of intermediate supports are likely to be intermittently widened by vehicle-induced flexing and vibration, thus imparting to the setting and hardening overlay certain tensile strains at those crack locations that it cannot resist. Hence the propagation of those cracks through the overlay forms transverse cracks. Random cracks in the vicinity of intermediate supports may also be enlarged by the tensile strains caused by negative moments induced by passing vehicles on adjacent lanes during the setting of the overlay. This is illustrated in the regression analysis, which shows a higher incidence of random and transverse cracking in the decks open to traffic during placement of the overlay. However, the final effect on the SDI, which combines all distress features, seems to be negligible in spite of consistently slightly higher values in the case of decks open to traffic; thus, the additional expense incurred in detouring the traffic is not warranted.

A Hypothesis on Crack Formation in Latex Overlays

A latex overlay is a relatively thin layer [nominal thickness of 19-39 mm (0.75-1.5 in)] that is placed on a reinforced bridge deck 150-300 mm (6-12 in) thick. The difference between shrinkage strains in the overlay and the substrate concrete (differential shrinkage) is a primary cause of cracking of the overlay. The fact that specifications require wetting of the substrate surface and application of a grout-bond coat before the overlay is placed does not eliminate differential shrinkage. The wetting of the surface of a concrete bridge deck can hardly saturate more than 13 mm (0.5 in) of the deck thickness unless the deck itself, after scarification, is of very poor quality, which is highly unlikely.

Studies by Bishara, Rose, and Youssef (5) have shown that the final free shrinkage of latex-modified mortar (LMM) is of the order of 0.0015 mm/mm, which is almost double that of ordinary bridge deck air-entrained concrete, as well as latex-modified concrete (LMC). In addition, the rate of shrinkage of LMM and LMC is much higher, in the first two to three weeks, than that of air-entrained normal-weight concrete, as shown in Figure 8. If the shrinkage of the substrate concrete is to be considered as virtually complete

Figure 8. Shrinkage versus time curves of Dow latex-modified mortar or concrete compared with that of air-entrained normal-weight concrete (5).



before placement of the latex overlay, a larger differential shrinkage strain will have to take place. Its value would be close to the difference between the free shrinkages of the overlay and the substrate, that is, about 0.001 mm/mm from LMM and 0.0005 mm/mm for LMC. However, if the overlay is placed a short time after the substrate is placed, as in new two-course construction jobs, the above differential shrinkage values may be substantially reduced.

Since shrinkage is greatly dependent on such factors as the water/cement ratio, surface/volume ratio, ambient temperature during placement, wind velocity during placement, and humidity conditions, thin latex-mortar overlays would shrink more than would thicker concrete overlays, other things being equal.

Bishara and Tantayanondkul (6) have shown that the tensile strain capacity of latex mortar or concrete is of the order of 0.0003 mm/mm, compared with about 0.0002 mm/mm for normal-weight air-entrained concrete used in bridge decks. The differential shrinkage between the overlay and the substrate may produce tensile strains in the overlay that exceed its tensile strain capacity and hence may cause random or pattern cracking.

The formation of random cracks is enhanced by surface plastic shrinkage that takes place before hardening, particularly when the weather is windy, the ambient temperature is high [> 27°C (80°F)], and the mixture has a relatively high water/cement ratio (> 0.50).

Random cracks may be detected shortly after the overlay has been placed during hot windy weather conditions and may take several years to become fully visible. The spacing of random cracks is usually 300-350 mm (12-14 in). When first observed, the cracks look like hairlines of pigment darker than the surrounding concrete. Their depth may start out being on the order of 13 mm (0.5 in) or less, but with time these cracks widen by the effect of freeze-thaw cycles and end by penetrating the full thickness of the overlay.

Transverse cracks are also caused by differential shrinkage; however, they occur at locations where cracks existed in the original deck. They thus usually extend the full width of the deck and run perpendicular to the bridge axis. In general, such cracks may have been caused in the parent deck slab by restraint to free contraction and expansion or by excessive tensile stresses caused by negative moments in the vicinity of the piers in continuous decks. This is quite common in continuous concrete slab bridges and in heavy concrete T-beam decks when the webs are cast ahead of the deck itself.

CONCLUSIONS

Analysis of field performance data from 132 latex overlay projects (almost all using Dow modifier A) in Ohio, Michigan, Kentucky, and West Virginia led to the following conclusions:

1. Performance of a latex overlay may be evaluated by (a) degree of deficiencies in its surface durability, as manifested by the percentage of deck area that has random cracks, transverse cracks, debonding, stripping, and spalling, which can be represented by the SDI (defined above); (b) the antiskid quality, as measured by the SN; and (c) its effectiveness in providing corrosion protection to the deck rebars, as judged by copper-copper sulfate half-cell potentials being ≥ -0.20 V and/or absorbed chloride ions in the vicinity of top rebars being ≤ 1.16 kg of $C\bar{L}/m^3$ (2.0 lb of $C\bar{L}/yd^3$).

2. Overlay cracks are caused by the difference between the shrinkage strains of the overlay and the substrate concrete. Transverse cracks are essentially extensions of cracks that existed in the original deck and, as such, they extend through the substrate to and beyond the level of the top rebars. Random cracks exist only in the overlay and have a maximum depth equal to its thickness.

3. The percentage of latex overlay areas that have either random or transverse cracking increases with the number of winter exposures. The rate of increase is rather slow in the first three years and becomes much higher in subsequent years.

4. The percentage of decks that exhibit either random or transverse cracks increases with the number of years service from none when the structure is new to 100 percent after seven years.

5. The cracking of a latex overlay does not in itself constitute a serious maintenance problem. However, cracking contributes to greater incidence of chloride penetration and subsequent corrosion activity. Therefore, transverse cracks, because they usually extend through the substrate to and beyond the level of the top rebars, are more harmful than random cracks. In addition, accumulation of moisture in cracks can lead to stripping and/or spalling after sufficient cycles of freezing and thawing have occurred.

6. Cumulative frequency-distribution curves give a clear representation of half-cell potential readings observed on a bridge deck and their evolution year after year.

7. Half-cell potential readings are much more consistent and easier to obtain than chloride content data, which have an exceptionally high coefficient of variation.

8. Half-cell potential readings at off-crack locations are usually lower than those at crack locations due to lack of proper wetting at off-crack locations when the readings are taken.

9. Latex-modified concrete or mortar overlays are not impermeable to chloride ion ingress, and their absorption of chloride ions increases steadily with years of service.

10. Chloride contents at a given depth from the deck surface are much lower in decks that have latex overlays than in decks that lack such overlays, all other factors being equal.

11. The rate of decrease of chloride content as a function of depth from the surface seems to be higher in the latex overlays than in the nonoverlaid concrete and the substrate concrete.

12. In the rehabilitated and new two-course bridge construction, chloride content at and below the bond interface between the overlay and the substrate increases steadily with years of service, indicating that the bond surface does not constitute a barrier to chloride ion ingress.

13. In new two-course construction, although chloride content within the overlay, in the vicinity of the bond surface, and in the substrate increases steadily as a function of winters of exposure, even after six years of service the resulting chloride content in the vicinity of the top rebars remained

below the active corrosion limit of 1.16 kg of $C\bar{L}/m^3$ (2 lb/yd^3).

14. Relatively high chloride contents and half-cell readings are usually found along curb lines and expansion dams.

15. Other factors being equal, relatively higher ADT seems to be associated with a slight increase in the incidence of chloride ion ingress, which results in slightly higher chloride contents, half-cell potential readings, and SDI. However, statistically this increase is insignificant for the sample investigated.

16. Continuous bridge decks tend to exhibit a higher degree of surface distress than simply supported decks. However, the sample studied shows the difference to be statistically insignificant.

17. Bridges that are open to traffic during placement of a latex overlay generally exhibit a higher degree of surface distress than those that are closed to traffic. Statistically, this increase was found to be insignificant for the sample studied. Thus, it would seem unwarranted to require the closing of decks to traffic during placement of a latex overlay. However, it is certainly beneficial to restrict speed or to place the overlay at night or at other times when traffic volume is low.

18. The thickness of the overlay does not seem to have a statistically significant effect on observed surface distress, as judged from the sample of data available. However, because of the higher rate of reduction in chloride content in latex overlays than in substrate concrete, it is clear that the thicker the overlay, the lower the resulting chloride content at the bond surface and, hence, the chloride content in the vicinity of the top rebar level for a given concrete cover, all other conditions being equal.

19. For the sample of data available, the type of latex overlay, the age of the substrate when it was placed, the deck's original condition, and the type of deck did not seem to affect observed distress features in a statistically significant manner.

20. For the limited set of data of driving lane SNs at 74 km/h (40 miles/h) from 44 bridges, it seems that the SN decreases slightly with years of service (from an average of 45 to an average of 41 after five years of service), and this reduction does not seem to be related, in a statistically significant manner, to the ADT.

21. Since virtually no scaling was observed on the 132 inspected bridge decks, it is safe to say that latex-modified concrete and mortar overlays provide adequate freeze-thaw resistance.

22. Since only a few of the inspected bridge decks had more than 10 years of useful life at the time of inspection, it is difficult to predict with confidence the useful life of latex mortar or concrete overlays. However, the available field performance data of the 111 rehabilitated decks and the 21 two-course new construction decks show that, in spite of some differences in their random and transverse cracking under identical service conditions, both mortar and concrete overlays seem to give essentially the same additional useful life. (Mortar overlays produced less dead load on the deck and cost less to put on.) They both should add a useful life to a rehabilitated deck in excess of 10 years. For new two-course construction, the projected useful life should be more than 15 years. However, if correct construction practices are not adequately observed and if a rehabilitated deck is not properly scarified before the placement of the overlay, the projected useful life mentioned above may be reduced and/or necessary spot repairing of spalled areas may be needed before the end of the projected useful life.

23. Since regression-analysis results are valid only within the range of input data, it is recommended that this analysis be conducted periodically.

24. Chloride contents in the vicinity of top rebars seem to give a better indication of expected deck surface distress than do half-cell potential readings.

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