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FINAL REPORT

EVALUATION OF DECK DURABILITY ON CONTINUOUS BEAM HIGHWAY BRIDGES

by

Wallace T. McKeel, Jr.
Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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

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

Charlottesville, Virginia

April 1985
VHTRC 85-R32

2498

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SUMMARY

In an effort to determine the extent of deck cracking on continuous steel beam bridges and the effect of the cracking on deck durability, 137 structures were visually inspected and 5 of these were selected for detailed evaluation. The general survey disclosed widespread transverse cracking throughout the lengths of the continuous beam sections in both the positive and negative moment areas. The cracking appeared to propagate, as the spans vibrated, from short pattern cracking probably caused by differential subsidence of the plastic concrete over the reinforcing steel and plastic shrinkage of the slab. Detailed deck evaluations, which includeed half-cell potential measurements and chloride content determinations, disclosed that chlorides were present in the cracks to a significantly greater degree than in adjacent uncracked concrete. However, sealing the cracks with a low viscosity, low modulus epoxy compound appeared to be effective in limiting the entry of chlorides. In spite of the widespread cracking noted and the presence of chlorides in the cracks, corrosion-induced deck distress was not found to be a widespread problem on continuous span bridges.

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SI CONVERSION FACTORS

To Convert From	To	Multiply By
Length:		
in	cm	2.54
in	m	0.025 4
ft	m	0.304 8
yd	m	0.914 4
mi	km	1 . 609 344
Area:		
in^2	cm^2	6.451 600 E+00
ft^2	m^2	9.290 304 E-02
yd^2	m^2	8.361 274 E-01
mi^2	Hectares	2.589 988 E+02
acre (a)	Hectares	4.046 856 E-01
Volume:		
oz	m^3	2.957 353 E-05
pt	m^3	4.731 765 E-04
qt	m^3	9.463 529 E-04
gal	m^3	3.785 412 E-03
in^3	m^3	1.638 706 E-05
ft^3	m^3	2.831 685 E-02
yd^3	m^3	7.645 549 E-01

NOTE: $1m^3$ = 1,000 L

To Convert From	To	Multiply By
Volume per Unit Time:		
ft^3/min	m^3/sec	4.719 474 E-04
ft^3/s	m^3/sec	2.831 685 E-02
in^3/min	m^3/sec	2.731 177 E-07
yd^3/min	m^3/sec	1.274 258 E-02
gal/min	m^3/sec	6.309 020 E-05
Mass:		
oz	kg	2.834 952 E-02
dwt	kg	1.555 174 E-03
lb	kg	4.535 924 E-01
ton (2000 lb)	kg	9.071 847 E+02
Mass per Unit Volume:		
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lb/in^3	kg/m^3	2.767 990 E+04
lb/ft^3	kg/m^3	1.601 846 E+01
lb/yd^3	kg/m^3	5.932 764 E-01
Degrees	Radians	1.745×10^{-2}

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EVALUATION OF DECK DURABILITY ON CONTINUOUS BEAM HIGHWAY BRIDGES

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INTRODUCTION

Continuous beam highway bridges are widely used throughout the United States. They offer economy in the use of materials and minimize the number of troublesome expansion joints in the deck. One expected disadvantage is transverse cracking of the concrete deck in the negative moment areas over interior supports.

The construction of continuous beam bridges was not common in Virginia prior to 1960, probably because of concern over high maintenance costs due to the deck cracking. Early experience, at least with some structures, strengthened this concern. However, during the last 20 years the number of continuous beam bridges constructed has increased as both the Virginia Department of Highways and Transportation and the Federal Highway Administration have recognized the advantages of eliminating expansion joints over the interior supports. Safety considerations that required the positioning of piers at greater setbacks from the roadway also encouraged the use of continuous spans.

Transverse cracking of the slab remains a concern, however, particularly to field engineers. Cracking often occurs before the structure is accepted from the contractor, and in some instances cracks have progressed through the full depth of the slab. In addition to the anticipated cracks in the negative moment regions, transverse cracks have been noted in the areas of positive bending moment of some bridges.

Virginia usually attempts to minimize cracking in the negative moment regions by specifying deck placement sequences in which the concrete is placed over the supports last, after concrete has been placed in the center portions of adjacent spans. More extraordinary measures to limit cracking, such as by externally loading the positive moment areas of the deck before the placement of concrete in the negative moment areas to induce a compressive force in the slab over the supports, have been proposed. However, it was believed that before such measures were implemented, the extent of the deck cracking and its effect on the durability of the decks of existing continuous span bridges should be determined. The effectiveness of the presently used concrete placement procedures, crack-sealing techniques, and epoxy coated reinforcing steel would also be investigated. Accordingly, the subject field survey of continuous beam bridges was proposed.

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PROCEDURE AND SCOPE

The objectives of this study were accomplished through field inspections of existing continuous span bridges across Virginia. Two levels of detail were used in the surveys: a general survey encompassing a large number of bridges and detailed deck evaluations on selected structures.

In the general survey, the decks of 137 steel beam bridges from the June 1982 population of continuous span structures were inspected visually. The sample represented 26% of the 521 such bridges in the inventory listing. They were chosen essentially at random, except that an effort was made to include old structures that were believed most likely to exhibit severe deck distress. Bridges were selected from all of the state's 9 construction districts, though not in equal numbers.

The structures in the general survey ranged in age from 2 to 54 years at the time of inspection. As shown in Table 1, the preponderance of the structures were 10 years or less in age, reflecting the recent increased usage of the continuous span design in Virginia.

TABLE 1

Ages of Bridges in General Survey

Age at Time of Inspection (years)	Number of Bridges
0 - 5	61
6 - 10	33
11 - 15	18
16 - 20	8
21 - 25	5
26 - 30	1
31 - 35	2
36 - 40	2
41 - 45	2
46 - 50	3
51 - 55	1
Undetermined	1
TOTAL	137

In order to include a relatively large number of bridges, the general survey was conducted without closure of the roadways. Thus, it was generally limited to visual inspections of the decks in which the locations and types of cracks, their spacings and widths, and any noticeable deck distress were recorded along with pertinent bridge characteristics such as framing details, skew angle, and deck placement sequence. Other structural information such as span lengths and date of construction were provided by the printout. Occasional soundings were made with a chain drag in deck areas that appeared to have possible delaminations and a pachometer was used to check the depth of cover over the reinforcing steel on some bridges.

The general survey proved too gross an evaluation technique to allow the consideration of the effects of structural details such as shear connector spacings and amount of longitudinal reinforcement. Little use was made of bridge plans and project records, and no analytical procedures were applied to the structures. However, the general survey did provide valuable information on the nature of cracking in the decks, the pattern of formation and propagation of the cracks, and the extent of the cracking problem.

Detailed surveys were conducted on 5 bridges to answer questions that arose during the general survey. Specifically, answers to the following questions were sought:

1. What role does cracking play in general deck deterioration?
2. To what extent do cracks provide entry for chlorides?
3. Is the routing and sealing of cracks effective in preventing the entry of chlorides?
4. How effective is epoxy coated reinforcing steel in protecting a continuous span deck?

Detailed deck evaluations included visual inspections, half-cell potential measurements, chloride content determinations, and sounding with chain drags. Traffic control was required during this phase of the study. The size of the deck area evaluated varied, depending upon the nature of the information required.

RESULTS

The General Survey

Incidence of Deck Cracking

Cracking of the concrete decks was noted in all but 12 of the 137 bridges in the general survey. All of the decks on which no cracking was noted had been in service 5 years or less. Most were on overpasses or local road bridges with relatively low traffic volumes, low vehicle speeds, and fewer trucks than on main-line bridges. Some of the newer bridges also had the currently specified harsh surface texture with transverse grooves that may mask the appearance of cracking in its early stages.

Transverse, longitudinal, and diagonal cracks were noted on the bridges. Of these, the transverse cracking, which was by far the most extensive, clearly presented the most serious problem. Longitudinal cracks were noted on a number of bridges, usually in the more heavily traveled traffic lane. The lengths of longitudinal cracks were often extensive, but there were never a large number on a single structure. The longitudinal cracks were fine, and there were no instances of distress being associated with them. The relatively few instances of diagonal cracking were invariably found on bridges with sharp skew angles approaching 45 degrees. The cracks ran approximately perpendicular to construction joints on the skew, usually in the acute corners and at the ends of continuous span sections. The major research effort was concentrated on an evaluation of the effect of the widespread transverse cracking on the durability of the deck slabs.

The presence of cracking in the decks of continuous span bridges is not, itself, surprising, as cracking normally occurs in the negative moment areas over the internal supports. However, the general survey disclosed widespread cracking in the positive moment regions in the central portions of continuous spans. Cracking in these areas was often of equal severity, in terms of width and spacing, to that found over the supports. It was obvious that these cracks were not caused by the primary flexure of the spans due to heavy vehicles crossing the bridge. It was noted in several cases, however, that the passage of a heavy vehicle caused sustained vibration of the continuous spans. Discussions with research personnel at other agencies indicate that similar transverse cracking related to span vibration has been noted elsewhere.

Formation and Propagation of Transverse Cracks

Fine pattern cracking, shown in Figure 1, was noted in the great majority of the decks in the general survey. The cracking, which was usually very fine, often covered substantial areas of the decks. Its cause appears to be differential consolidation, as the top reinforcing steel obstructs the subsidence of the concrete, along with some contribution by plastic shrinkage of the concrete mass.(1) The effect has long been recognized.

> If reinforcement is held in a position close to the surface of concrete, the settling material will build upon the rod, but the settlement will continue on either side. As the hydrating cement gradually develops a structure through the concrete, this continuing settlement on either side of a rod will cause a crack over the rod.(2)

> Cracking develops usually over obstructions to uniform settlement, e.g. reinforcement or large aggregate particles, or when a large horizontal area of concrete makes construction in that direction more difficult than vertically; deep cracks of an irregular pattern are then formed.(3)

Figure 1. Fine pattern cracking on bridge deck.

As the bridge vibrates under load the transverse limbs of the pattern cracking connect to form transverse cracks of some length in the roadway, as in Figure 2. Eventually fine transverse cracks may propagate across the width of the deck, as in Figure 3. The spacing of the cracks along the length of the deck was quite close on some of the surveyed structures, Figure 4. Although the crack usually was fine through the thickness of the deck, it widened substantially at its top, Figure 5. The use of a pachometer indicated that the transverse cracks were almost invariably located over a reinforcing bar, and coring indicated that the crack extended to the steel, as in Figure 6. Figure 7, a view of the underside of the deck of one of the oldest bridges in the study, shows cracking that had propagated through the depth of the slab. Note that the cracks were essentially equally spaced along the length of the span, through both the positive and negative moment areas. A view of the deck surface on the structure, a 1932 bridge on the Colonial Parkway, is shown in Figure 8. In spite of severe deck cracking, there was no other distress, probably because of little use of deicing salts on the parkway.

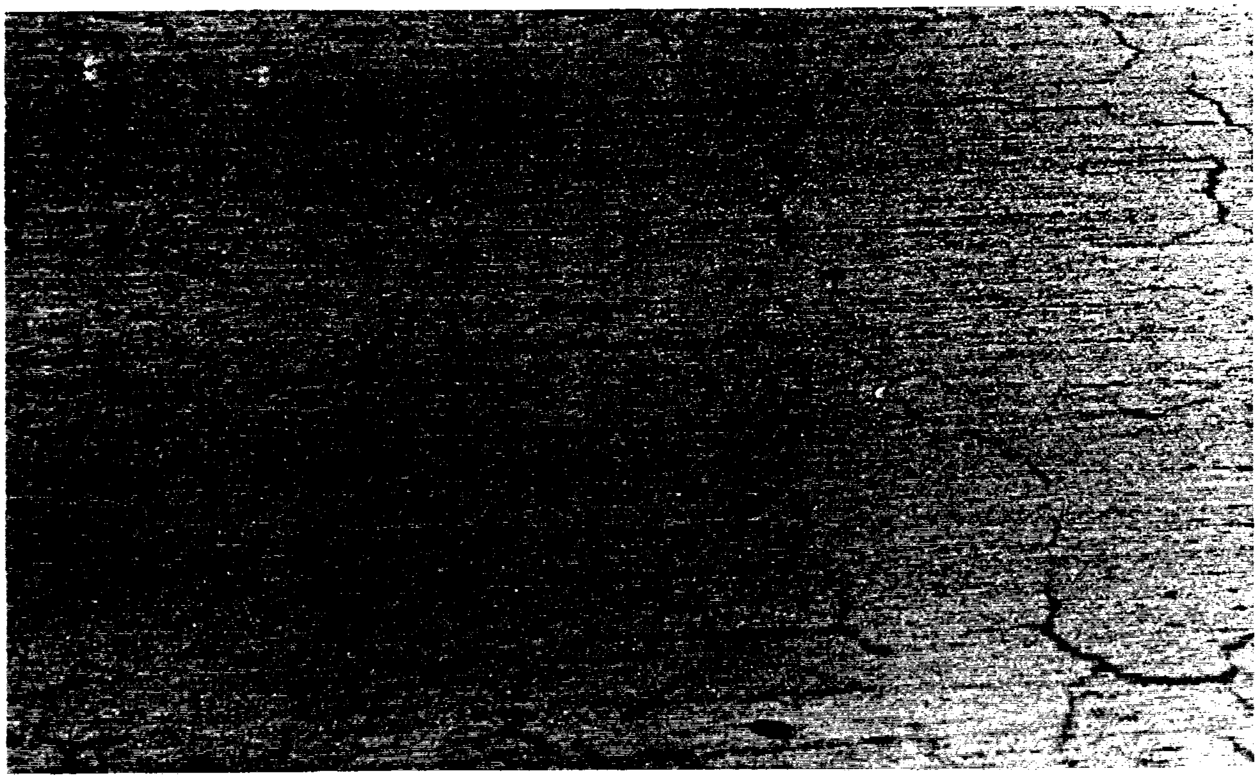

Figure 2. Short transverse segments formed in pattern cracking.

Figure 3. Transverse crack across roadway width.

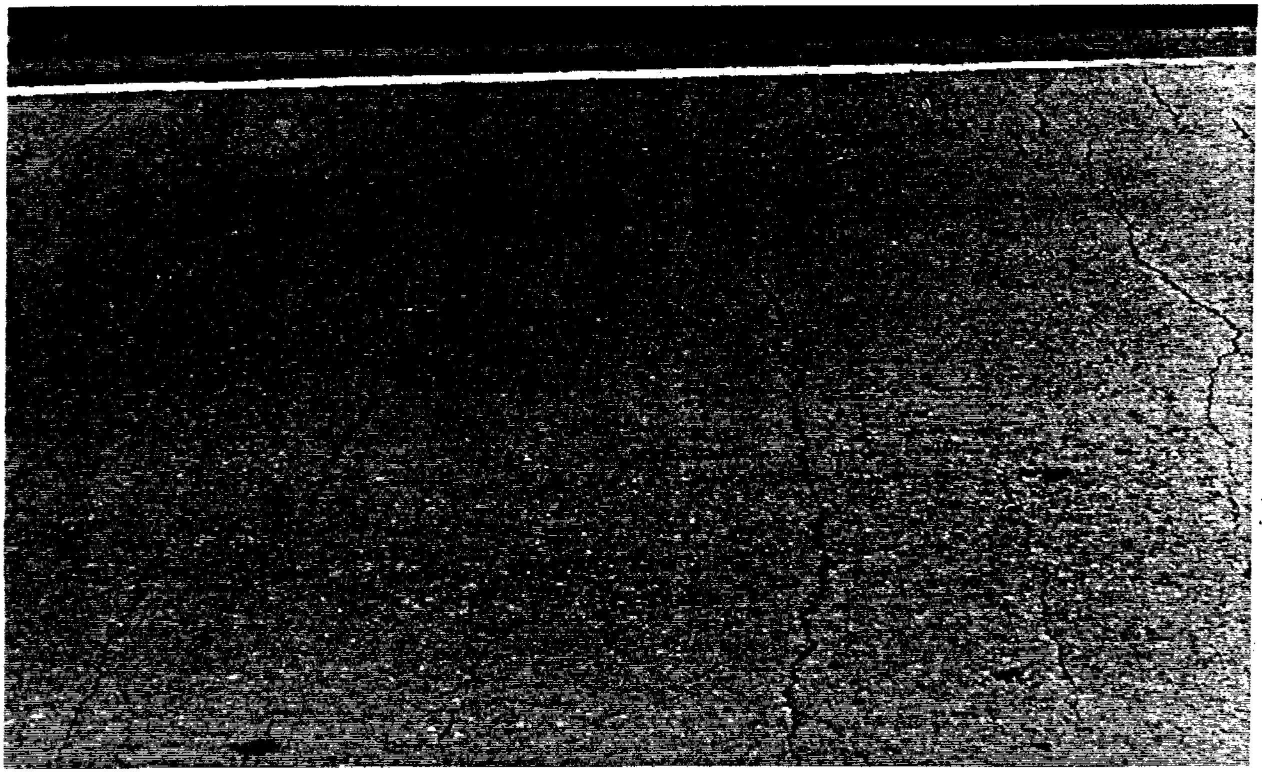

Figure 4. Closely spaced transverse crack.

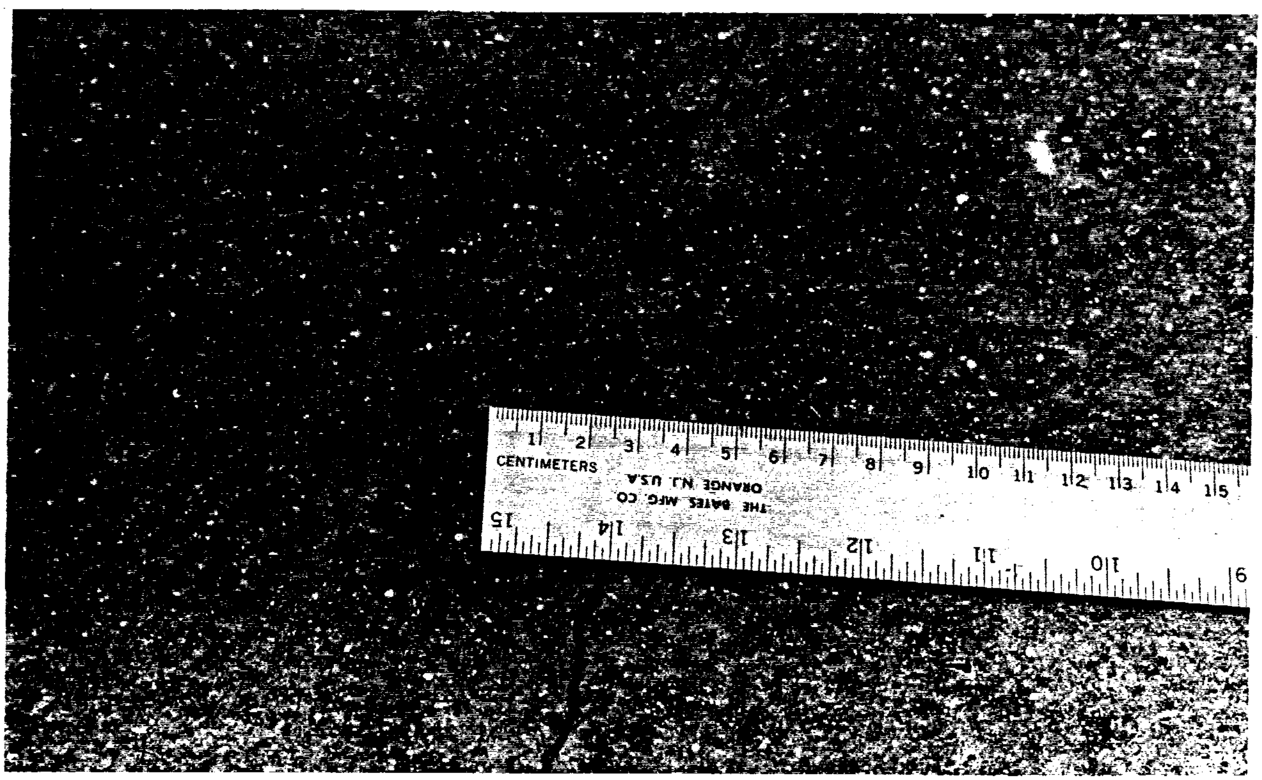

Figure 5. Transverse crack widened at top.

Figure 6. Core through transverse crack. Path of crack in depth of concrete has been marked.

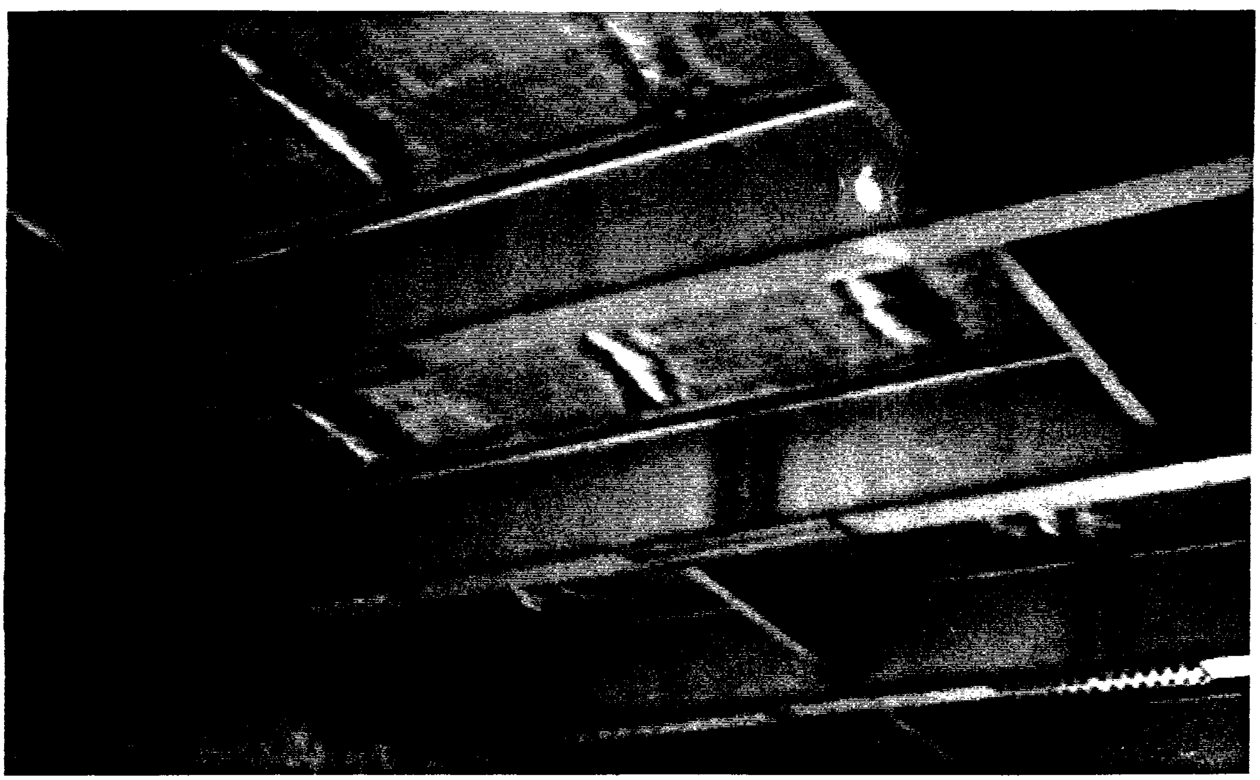

Figure 7. Underside of bridge deck slab with efflorescence marking crack locations.

Figure 8. Surface of Colonial Parkway bridge (Figure 7). Exposed aggregate finish is used on parkway pavements.

The contributions of vibration and other dynamic loading effects to the propagation of transverse cracking were indicated often by comparisons of bridges on the same limited access highway but exposed to different traffic conditions. Although the bridges were of essentially the same age, overpasses carrying fewer trucks and at lower speeds exhibited less cracking than bridges on the main highway. Despite the apparent correlation between the severity of cracking and the traffic volume, transverse cracking was noted to some extent on structures with very low traffic volumes. Figure 9 shows a transverse crack in the positive moment area of the single-lane service road bridge shown in Figure 10 that serves a single residence and small orchard.

As might be expected, there was a correlation between traffic speed and the extent and severity of cracking. Bridges located on downgrades on divided highways were seen to have more and wider cracks than their twin structures in the opposite, rising lane. More severe cracking was also noted on decks that showed evidence of excessive water or other problems. Obviously, concrete quality is especially important in continuous span bridge decks. On the other hand, the placement sequences, either placing concrete in the positive moment areas before the negative moment areas or from one end of the continuous span section to the other, had no discernable effect on cracking. Similarly, the framing plan, either beam and slab, girder and floor beam, or suspended span on cantilevered sections, had no noticeable effect.

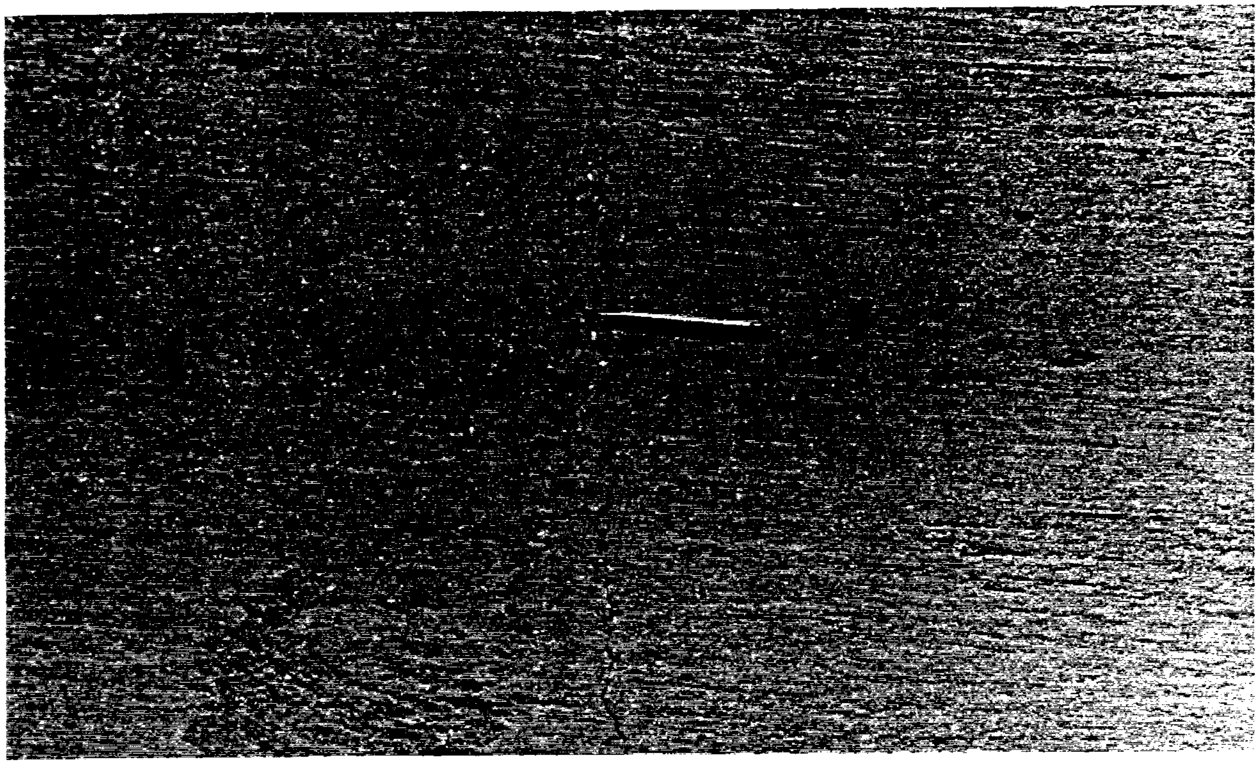

Figure 9. Crack in positive moment area of single-lane service road bridge (Figure 10).

Figure 10. Low-volume service road bridge provides access to residence and orchard.

The effect of span length was difficult to discern, probably because the effects of truck volumes and speeds on dynamic responses and resultant cracking masked the effect of the flexibility of the span. Intuitively, it would seem that span flexibility was important. One relatively rigid bridge, a 3-span continuous structure with cantilevered end spans and no abutments, displayed no cracking. Sustained vibrations were noted on several bridges with severe cracking.

Incidence of Deck Distress

During the general survey any visible evidence of deck distress, including patches, was noted. Fourteen of the bridges, or 10% of those surveyed, showed indications of corrosion-oriented distress. The ages of the affected bridges ranged upward from 5 years. Four of the structures were less than 10 years old. In only 3 cases could the distress be linked directly to cracking, as when the spalls or patches were located over transverse cracks. In other instances the relationship between cracking and delamination was less clear; occasionally, the distress seemed to be due, at least in large part, to insufficient concrete cover over the reinforcing steel.

Admittedly, the incidence of distress was probably greater than that disclosed by the general survey. Decks with asphalt overlays were eliminated from the study, and 2 of the older bridges in the survey had been redecked. It is likely that deck distress was a causative factor in these maintenance operations, but the role of cracking could not be determined.

It is known that transverse cracks that follow the line of a reinforcing bar are serious because of the potentially long corroded length, equal to the length of the crack, and because the crack weakens the resistance of the concrete to spalling.(4) The detailed deck evaluations, discussed in the next section, indicated that the chloride content in cracks can be higher than in adjacent sound concrete. However, possibly because the transverse cracks were generally fine through the deck thickness and most of the population of surveyed bridges were relatively new, deck distress did not emerge from this study as a widespread problem.

Detailed Deck Evaluations

Rte. I-81 (NBL) over Buffalo Creek, Rockbridge County

The Buffalo Creek bridge, built in 1966, contains 3 continuous spans with lengths of 105, 135, and 105 ft. Two simply supported spans are at the ends of the bridge. The bridge, which is located at the low point of a sag-vertical curve, is subjected to high-speed traffic approaching on a downgrade.

The bridge was evaluated with the cooperation of district bridge personnel who were assessing the need for placing an overlay on the deck. Half-cell potentials and pachometer readings were taken at points on a 5 ft by 5 ft grid. Samples for chloride content determinations were taken at 15 randomly selected locations.

Transverse cracking was noted throughout the bridge, in both the simply supported and continuous spans. Spacing of the cracks on the continuous spans was often as little as 1 to 2 ft, and the cracks extended across the full roadway width. All were located over reinforcing bars. Attempts had been made to seal the cracks, but cracking has continued.

Many delaminated areas were noted on the bridge. Most extended as elongated rectangles centered on reinforcing bars from points on or near the face of the curb. Sounding with chain drags disclosed delaminated areas totalling 502 ft^2, or 3.1% of the deck area of the entire bridge, including the simple spans. On the continuous span section the delaminations totalled 297 ft^2, or 2.9% of the continuous deck surface. There was evidence of shallow cover in the delaminated areas. Specifications at the time of bridge construction called for 2 in of cover to the center of the bar, or 1 11/16 in clear cover over a 5/8 in bar. Pachometer readings at 344 points on the continuous spans disclosed cover depths ranging from 3/4 in to 2 1/2 in, with an average value of 1.5 in and a standard deviation of 0.289 in. It is likely that this relatively shallow cover contributed significantly to both the formation of the cracks and the ensuing delaminations.

Potentials measured at the delaminated areas were in the range of -.35 to -.45 V CSE, which indicated active corrosion. Readings taken over undelaminated cracks ranged from -.20 to -.30 V CSE, in the indefinite range. Overall, the cracking had little effect on the potential readings at the 5 ft by 5 ft grid points. The final summation showed only 100 ft^2, or 0.6% of the deck area, having potential readings greater than -.35 V CSE. Only one grid point on the continuous span section had a reading indicating active corrosion. However, as mentioned previously, high readings were measured at the delaminations.

The chloride contents determined from the 15 randomly located samples were low. They ranged from 0.08 to 1.19 lb/yd^3 with only the single value being above 1 lb/yd^3. Chloride contaminated concrete is removed when the chloride content exceeds 2 lb/yd^3.

Because of the small delaminated area, and the generally low half-cell potential and chloride content values, major deck rehabilitation was deferred. Thus, the extensive cracking had little effect on the deck evaluation. Other detailed surveys conducted as part of the subject study concentrated on closely defining the influence of the transverse cracking on durability.

Rte. 100 (WBL) over Big Walker Creek, Giles County

The Big Walker Creek bridge contains a 2-span continuous segment (80-ft spans) with 43 ft simple spans at the ends. The general survey disclosed transverse cracking throughout the continuous spans. Some cracks in the positive moment areas had top widths approaching 1 mm. The detailed evaluation concentrated on evaluating the effect of these wide cracks on deck durability. Only the traffic lane and shoulder area of the continuous spans were tested.

The specified depth of cover at the time of the construction of the Big Walker Creek bridge, 1977, was 2 in clear cover, to the top of the bar. Pachometer readings at 51 randomly selected points yielded an average depth of cover of 2.32 in, and a standard deviation of 0.49 in. The pachometer was calibrated continuously during testing and its accuracy verified by drilling to a reinforcing bar at one point on the deck. The data are in line with those of an earlier study of the depths of cover of 129 bridges constructed after 1966.(5) That study found the average cover for all measurements to be 2.40 in and the standard deviation to be 0.49 in. Thus, the Big Walker Creek bridge can be considered representative of structures in its age group.

Potential readings were taken on a 5 ft by 5 ft grid covering the traffic lane and shoulder area, and additional readings were obtained at random locations over the transverse, longitudinal, and pattern cracks. Most of the grid-point readings (approximately 80%) ranged from -.20 to -.30 V CSE. Only one area of active corrosion, about 2 ft square and surrounded by readings in the -.20 to -.30 V CSE range, was defined. No difference was found in the readings over the cracks, which ranged from -0.18 to -0.16 V CSE.

The chloride content determinations were designed to define the role of the relatively wide cracks in allowing the entry of chlorides into the deck. Concrete samples were taken at 3 locations on cracks and at 3 nearby locations on the uncracked deck. Each sample was divided into 3 parts: part A was composed of pulverized concrete from depths of 1/2 in to 1 in, part B from 1 in to 1 1/2 in, and part C from 1 1/2 in to 2 in. The top 1/2 in at the deck surface was discarded. The chloride content data are presented in Table 2.

Table 2 indicates that chlorides were present in the crack at a level sufficient to support corrosion. The chloride content at a depth of 2 in, approximately 1/4 in above the top of the bar, was over the 2 lb/yd^3 threshold beyond which concrete removal is required at each of the cracked locations. In comparison, the chloride content at the uncracked locations was consistently less than half the value at the cracked locations. Potential readings around the chloride sample locations were all in the indefinite range.

No delaminated areas were disclosed by soundings that covered the complete traffic lane and shoulder area and any suspect areas in the passing lane.

TABLE 2

Chloride Contents - Big Walker Creek Bridge

Sample No.	Location on Deck	Sample Depth in Deck, in	Chloride Content, lb/yd³
1A	On wide crack	1/2 - 1	5.17
1B	in positive	1 - 1 1/2	4.84
1C	moment area	1 1/2 - 1	3.66
2A	Uncracked concrete	1/2 - 1	2.52
2B	near site 1	1 - 1 1/2	1.57
2C		1 1/2 - 2	1.16
3A	On crack near	1/2 - 1	3.86
3B	negative moment	1 - 1 1/2	3.39
3C	area	1 1/2 - 2	2.58
4A	Uncracked concrete,	1/2 - 1	3.16
4B	5 in from	1 - 1 1/2	1.91
4C	site 3	1 1/2 - 2	1.12
5A	On crack in	1/2 - 1	4.37
5B	positive moment	1 - 1 1/2	3.26
5C	area	1 1/2 - 2	2.55
6A	Uncracked concrete	1/2 - 1	2.59
6B	near site 5	1 - 1 1/2	1.55
6C		1 1/2 - 1	1.13

While there were no signs of deck distress in the deck of the Big Walker Creek bridge, a significant amount of chlorides had entered the cracks within approximately 5 years of service. The remaining detailed evaluations sought to explore the effectiveness of protective systems, crack sealing, and epoxy coating reinforcing steel.

Rte. 29 Bypass (SBL) over Staunton River and Norfolk and Western Railway, Pittsylvania County

The Staunton River bridge, built in 1973, is composed of 4 continuous spans with lengths of 125, 148, 148, and 125 ft. The general survey noted the presence of fine transverse cracks at close spacings as little as 15-18 in throughout the length of the structure. Some of the older cracks had been routed and filled, Figure 11; however, cracking had continued after the sealing operation. Typically, the cracks are routed to a minimum depth of 1/4 in using sandblasting equipment with a fine nozzle and filled with a low viscosity, low modulus epoxy adhesive as shown in Figure 12, where a chloride sample was taken over a crack.

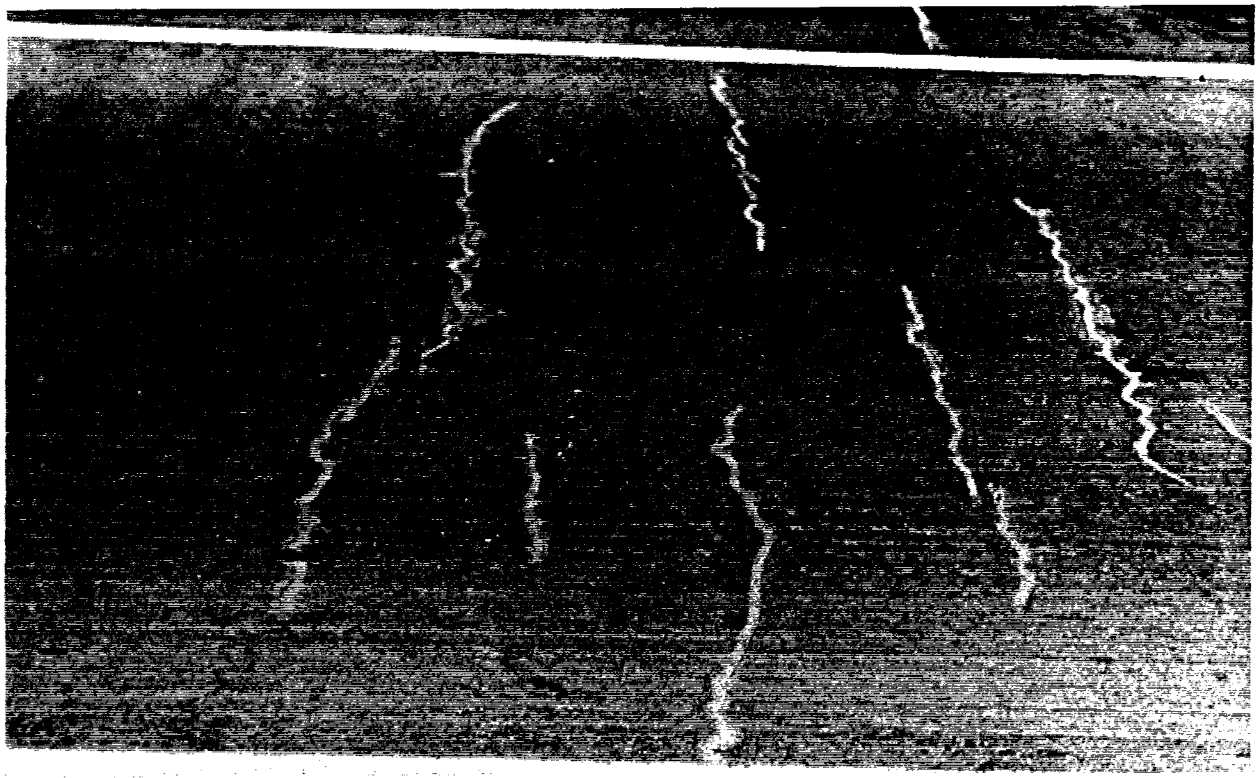

Figure 11. Sealed transverse cracks on Staunton River bridge.

Figure 12. Cracks routed to a depth of 1/2 in and sealed.

Some separation at the edges of the sealing compound was noted, as was the formation of short cracks adjacent to the sealed cracks. It appeared that the deck offered an opportunity to evaluate the effectiveness of the sealing operation. Accordingly, the traffic lane, where the oldest and most extensive cracking had occurred, was tested.

Close inspection disclosed that while cracks had continued to form after the sealing operation, the deck was in good condition. The sealing compound had hardened somewhat with age, but was generally effective. Crossing trucks were found to cause noticeable vibrations that remained apparent for several seconds after the vehicle crossed, perhaps accounting for the formation of the large number of closely spaced transverse cracks.

Pachometer readings at 94 randomly selected locations in the traffic lane had an average value of 2.11 in, with a standard deviation of 0.37 in. This is approximately 1/16 in less than the specified value of 2 1/2 in to the center of the bar or 2 3/16 in clear cover on a 5/8-in bar. The pachometer also indicated that reinforcing steel was located under the cracks.

Potential readings were taken at points on a 5 ft by 5 ft grid system over the length of the traffic lane, and supplemental values were obtained from points over both sealed and unsealed cracks. Of the 540 readings, all but 2% were less than -.10 V CSE, which indicated no active corrosion, and the remainder were below -.35 V CSE. The supplemental readings also indicated that no active corrosion was occurring.

The absence of active corrosion was generally borne out by the limited number of chloride content determinations presented in Table 3. Only one of the samples, 1C, had a chloride content above the corrosion threshold, approximately 1 to 1.3 lb/yd^3, at the level of the reinforcing steel. More importantly, the Table 3 data indicated the effectiveness of sealing the cracks. The chloride contents were significantly lower in the sealed portion of the crack, sample 2.

As would be expected from the previous results, sounding of the deck surface disclosed no delaminations in the traffic lane.

TABLE 3

Chloride Contents - Staunton River Bridge

Sample No.	Location on Deck	Sample Depth in Deck, in	Chloride Content, lb/yd^3
1A	Unsealed crack in	1/2 - 1	2.43
1B	positive moment area	1 - 1 1/2	1.79
1C		1 1/2 - 2	1.57
2A	Sealed crack in	1/2 - 1	0.58
2B	negative moment area	1 - 1 1/2*	0.15
3A	Unsealed section on	1/2 - 1	1.42
3B	same crack as site 2	1 - 1 1/2*	1.07

* Steel depth at sites 2 & 3 was only 1 1/2 in.

While there were a large number of closely spaced cracks on the Staunton River bridge they had had no adverse effect on the deck durability. It is difficult to say with any certainty why the longer spans of this bridge were in better condition than those of the newer Big Walker Creek structure. One possible explanation is that the cracks were finer on the Staunton River deck. There are indications that fine cracks have little effect on durability.

Rte. I-77 (NBL & SBL) over Rte. 620, Carroll County

Each of the Route 77 bridges is composed of 3 continuous spans with lengths of 52, 73.5, and 52 ft. These bridges, the first in Virginia on which epoxy coated reinforcing steel was used, have been monitored at intervals since their construction in 1977, as part of a study of coated reinforcement. The field evaluations have included visual inspections and sounding of the full decks of both bridges, but potential measurements have been limited to 10 bars in each structure. Lead wires had been attached to these bars, which are electrically insulated, to allow the readings.

An inspection in 1979, after the bridges had seen 2 years of service, disclosed pattern cracking and fine transverse cracks over the bars in both positive and negative moment areas on the two decks. Since 1979 an increase in the number of transverse cracks has been noted. All of the cracks are narrower than 0.01 in (0.25 mm), but the worst are approaching that width. In 1984 the inspection disclosed that 2 transverse cracks in an end span (positive moment area) had propagated through the depth of the slab, as evidenced by efflorescence on the bottom surface.

Potential measurements taken at 5-ft intervals along the 10 instrumented bars on each bridge have shown no evidence of active corrosion during 7 years of service. Some values in the indefinite range have been recorded during every evaluation since 1978, but the majority of the values remain below -0.20 VCSE. Unfortunately, only one crack has formed over a bar with lead wires which allow potentials to be measured. There is no evidence of active corrosion at that location.

Three samples of concrete were obtained from random locations on each deck during each periodic evaluation. While the chloride contents of these samples exhibited considerable variability, the values were between 0 and 0.58 lb/yd^3, which indicates that the corrosion threshold level has not been reached at the depth of the steel.

There has been one exception to these low chloride contents. During the 1984 evaluation, 4 samples were taken in areas of pattern cracking and at a transverse crack that had propagated through the deck. The results are shown in Table 4.

TABLE 4

Chloride Contents - I-77 (NB) Bridge over Rte. 620

Sample No.	Location	Sample Depth in Deck, in	Chloride Content, lb/yd^3
1	Pattern cracking in positive moment area	1 3/4 - 2 1/4	0.23
2	Pattern cracking over south pier	1 3/4 - 2 1/4	0.92
3	Pattern cracking over north pier	1 3/4 - 2 1/4	0.16
4A	On transverse crack in positive moment area	1 1/4 - 1 3/4	2.53
4B		1 3/4 - 2 1/4	2.72

As indicated by the data in Table 4, the chloride content at a mean depth of 2 in for sample 2, taken in an area of pattern cracking, was considerably higher than was found in the random samples discussed earlier. However, at 0.92 lb/yd^3, the level is below the corrosion threshold. The values for samples 4A and 4B taken over the transverse crack are above the level at which concrete is removed during deck repair. It is evident that chloride ions are entering the crack in sufficient quantities to support corrosion of the reinforcing steel. Half-cell potential measurements could not be taken at the crack location.

Soundings have not disclosed any delaminations at the crack locations or elsewhere on the decks.

The data on the effectiveness of these earliest Virginia installations of epoxy coated reinforcing steel remain inconclusive, as the chloride contents have not reached the corrosion threshold over most of the decks. However, research by the Federal Highway Administration indicates that the system is effective even if the coating does not meet current specifications.(6) Based on a life of 1 year for bare steel the relative effectiveness of the coated steel is 12 years if only the steel in the salt contaminated top portion of the concrete is coated and 46 years if all the steel is coated.

FURTHER RESEARCH

The results of the survey indicate that extraordinary measures to prevent cracking over the supports of continuous span bridges are not warranted. However, mitigation of the widespread cracking found throughtout the lengths of the spans is a worthwhile objective for future research. Continued research might also concentrate on the effect of cracking on deck durability. The results of this study, though useful and interesting, are based on limited data.

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CONCLUSIONS

The findings from this study are based on field surveys of 137 steel beam continuous span bridges representing 26% of those included in Virginia's structure inventory at the beginning of the project. While the location of the bridges was not found to have an effect on deck performance, all of the state's 9 construction districts were represented in the survey to some extent. Ages of the structures ranged from 2 to over 50 years, with the preponderance of them having seen 10 years' or less service. While the bridges were essentially selected at random from the inventory listing, efforts were made to include old structures. The general survey was supplemented by detailed evaluations designed to provide specific items of needed information. It is believed that the survey population is sufficiently large and varied to support the conclusions that follow.

1. Transverse, longitudinal, and diagonal cracks were found on the surveyed decks. Cracking was widespread; only 12 of 137 bridges exhibited no signs of cracking.

2. Transverse cracks present the most serious problem on continuous span bridges, as both the severity and extent of the cracking increase under service. Transverse cracks over and parallel to reinforcing bars, as in the survey decks, are also the most likely to cause spalling.

3. Transverse cracking occurred often with equal severity in the negative moment areas over interior supports and in the positive moment central regions of the spans.

4. The transverse cracks propagate from short pattern cracks resulting from differential subsidence of the plastic concrete over the reinforcing steel and plastic shrinkage of the concrete mass. The cracks are usually located over reinforcing bars and they extend to the depth of the steel.

5. Vibration of the spans under dynamic loading causes the formation and propagation of transverse cracks throughout the deck. The cracks often propagate across the width of the bridge roadway. Formation of transverse cracks has been documented as early as 2 years in the life of a bridge.

6. The cracks widen at their tops under continued vibration and may propagate through the depth of the slab. The width of the crack generally remains fine within the deck.

7. Factors found in this study to affect the incidence of cracking included the apparent quality of the deck concrete and the volume and speeds of crossing traffic. The sequence in which the deck was placed, the nature of the framing plan, and other design details had no discernable effect. The effect of span length was masked by other factors.

8. Chloride content determinations indicated that chlorides are present in transverse cracks to a significantly greater degree than in adjacent uncracked concrete. Sealing the cracks with a low viscosity, low modulus epoxy adhesive compound (VDHT type EP-5, LV) appeared to be effective in limiting the entry of the chlorides.

9. In spite of the extensive cracking noted in the study and the indications that chlorides enter the cracks, corrosion-induced deck distress was not found to be a widespread problem on continuous span bridges. It should be noted, however, that approximately 68% of the surveyed bridges were less than 10 years old and 82% were under 15 years of age.

RECOMMENDATIONS

1. The widespread incidence of transverse cracking throughout continuous spans, propagated by vibrations of the spans, indicates that the employment of extraordinary measures to pre-load those portions of the spans over the supports is not warranted.

2. The development of methods to reduce vibrations in continuous spans was beyond the scope of this study. However, certain actions can be taken to reduce the harmful effects of vibrations.

   a) Good quality concrete, properly placed, consolidated, finished, and cured is essential to the durability of any bridge deck. Proper procedures can both reduce the formation of cracks and enhance the resistance of the concrete to spalling.

   b) Construction personnel should be alert to the presence of cracks in plastic concrete during finishing. Reworking the surface before initial set, preferably by use of a vibrating screed but also by re-trowelling, is effective in eliminating cracks in plastic concrete.

   c) The routing and sealing of cracks when the tops have widened is effective in slowing the entry of chlorides and should be continued. Since the cracks move during deck vibrations, a flexible sealing compound such as type EP-5, LV, should be used instead of a more rigid adhesive.

   d) The current policy of specifying epoxy coated reinforcing steel in bridge decks is the most promising approach to eliminating distress due to cracking of the deck. Since the cracks can propagate through the deck thickness, consideration should be given to coating both the top and bottom steel.

3. The findings that corrosion-induced distress was not widespread and that distress was also noted in simple spans indicate that the elimination of the use of continuous span bridges is not justified. Continuous spans offer advantages, notably in the elimination of deck joints, that outweigh their disadvantages. Additional study to improve the resistance of these structures to the formation of cracks would be beneficial.

ACKNOWLEDGEMENTS

The subject research originated from concerns expressed to the Council's Bridge Research Advisory Committee by W. L. Sellars, district bridge engineer, and L. G. Daniel, highway engineer of the Lynchburg District. The field work was coordinated and conducted by James W. French, and the laboratory analyses were performed by Bobby F. Marshall, both materials technician supervisors at the Research Council.

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