BRIDGE DECK PERFORMANCE IN VIRGINIA

Howard H. Newlon, Jr., James Davis, and Michael North,
Virginia Highway Research Council

•ONE OF THE MOST comprehensive programs for evaluation and definition of the problem of premature deterioration of bridge decks was that undertaken cooperatively by the Portland Cement Association, the Bureau of Public Roads, and eight state highway departments. Detailed studies of a few bridges were made in four states and these have been reported (1, 3, 5, 6). As a part of this program, surveys were made on 100 to 150 bridges in each of eight states including Virginia. These bridges were randomly selected to represent all bridges within a state. The results of these random surveys have been reported (13), and the entire project has been summarized (14). The data from this research are voluminous but some important results are given in Table 1.

Compared with those in the other states, the bridges in Virginia showed substantially less cracking and spalling and significantly more scaling. The lower incidence of cracking was attributed to a greater proportion of simple spans in the Virginia sample. It was also concluded that the higher frequency of scaling was due to the comparatively late adoption of air entrainment in the state. It is interesting to note that the other southern state, Texas, which did not use air-entrained concrete, also showed a high incidence of scaling, whereas Minnesota, with a much more severe climate but also a longer utilization of air entrainment, showed the lowest incidence of scaling of any of the states (excluding California).

Although spalling was the least common of the three major defects, it was, in the words of the final report (14), "without doubt—the most serious and troublesome kind of bridge deck distress." No reasons for the very low incidence of spalling in the Virginia decks were offered. In the 10 years since the field surveys were conducted, concern has been expressed nationally that spalling is becoming more prevalent, and several significant cases in Virginia have required major repairs. Unpublished reports from California indicate that spalling, which was not a significant problem in 1961, now is one.

To determine the change in performance characteristics of the Virginia bridge decks, during the summer of 1970 we resurveyed the structures included in the PCA-BPR survey, last inspected in 1961. This was apparently the first such resurvey conducted in the eight states included in the random survey.

The purpose of the resurvey was to establish the change in condition of the decks, particularly with regard to the further development of surface spalling. Some insights concerning the reproducibility of the survey techniques were also anticipated.

PROCEDURE

Each state cooperating in the PCA-BPR survey used a standard investigation procedure. A copy of the survey form and definitions used are available in the previously referenced report and are listed in the Appendix.

The PCA-BPR method of inspection was meticulously utilized throughout the resurvey. Data were collected in a manner that permitted evaluation of the deterioration on each span of each bridge as well as on the bridge deck as a whole. In this procedure, scaling, spalling, cracking, rusting, and popouts are the types of deterioration emphasized.

Sponsored by Committee on Performance of Concrete—Physical Aspects

Scaling is reported as a percentage of the span's deck area for the average scaled condition, and simultaneously the most severe scaling condition on each span is noted. Surface abrasion is included in scaling where a mixture of the two occurs. Scaling is defined as light, medium, heavy, or severe. Surface spalling is recorded as the number of large or small spalls on the span. Generally, any spall smaller than a foot in length or diameter is considered small.

Cracking is recorded by type and severity. A few cracks per span is classified as light. A large amount of cracking is considered heavy, and an intermediate condition is defined as medium cracking. The types of cracking are transverse, longitudinal, diagonal, pattern or map, random, and "D" cracking. When the bridge span inspected has a skew, cracking parallel to the direction of the skew is classified as transverse.

Joint spalls were recorded by their position on the bridge deck and their size or length along the joint. Rusting was noted as the number of rust spots, and popouts were listed as few or many in accordance with the inspector's opinion of how numerous they appeared on the bridge span deck.

Before the bridges were inspected for signs of deterioration, several engineers, laboratory technicians, and the authors performed preliminary practice inspections on local bridge decks. The object of this was to try to achieve the most uniform and accurate rating of the deterioration by each person individually analyzing the bridge deck and then to compare respective estimates of the amounts and types of deterioration. Differences in interpretation were reconciled and observation techniques refined. In this way, a consistent definition of the several types of deterioration could be obtained.

Following these preliminary practice inspections, the junior authors performed all of the field inspections of these bridge decks. On the first inspection trip, an experienced concrete technician accompanied them to aid in the initial inspections and to refine the observation techniques.

In the 1961 PCA-BPR survey in Virginia, 140 bridges comprising 452 spans were randomly chosen. Of these, 84 bridges had 262 uncovered spans, which were inspected. In 1970, 66 bridges comprising 206 uncovered spans were available for the resurvey. The important characteristics of these bridges are given in Table 2.

After all the data had been collected, they were analyzed by a computer. Prior to analyzing the resurvey data, the computer program was applied to those data obtained for the 1961 survey and published in the PCA-BPR random survey report (13). The original field data sheets were available so that reproduction of the published results was used as a check on both the computer program and the data analysis. After this check was obtained, the new data from the resurvey were inserted into the program, and new results were obtained by the same procedure utilized in 1961.

RESULTS

The results are given in Table 3. The format is the same as that used in Table 2B of the PCA-BPR report (13) so that comparisons can easily be made. In Table 4, the same data are given, but spans with defects classified in the least severe category have been combined with those showing no defects. It is believed that this grouping permits a more realistic comparison between the results of the two surveys and minimizes the differences attributable to judgment of the individuals conducting the surveys. For example, the classifications light scaling and light pattern cracking depend strongly on the point of view of the inspector. It is reasoned that a defect of sufficient magnitude to be classified above the minimum level would have been recorded by both groups of inspectors and that valid comparisons could thus be made.

As would be expected, the observed deterioration increased in frequency and severity on all of the bridges. As reflected in Tables 3 and 4, by far the most prevalent defects were scaling and cracking. The relative order of the three most prevalent defects, i.e., scaling, cracking, and popouts, remained the same between 1961 and 1970. In 1970 surface spalling was the fourth most prevalent, whereas in 1961 it was of the same order as rusting and joint spalling. In 1970, only 5 percent of the decks were free of scaling and only 25 percent were free of cracking in some form. It should be noted, however, that much of this distress would be classified as light. Eighty-seven percent

Table 1. Percentage of three most common defects observed in PCA-BPR study and in Virginia study.

Defect	Seven States	Virginia
Cracking (all types)	69.7	33.2
Scaling	22.9	43.1
Spalling	8.1	0.4

Table 2. Comparison of Virginia bridge characteristics in PCA-BPR study and in Virginia study.

Bridge Characteristics	1961	1970
Number		
Covered	56	14
Uncovered	84	66
Total	140	80[a]
No. of spans		
Covered	190	42
Uncovered	262	206
Total	452	248[a]
Year built[a]		
1940 to 1947	8	7
1948 to 1955	112	87
1956 to 1961	142	112
Traffic volume[b], ADT		
1 to 750	115	113
751 to 7,500	114	66
>7,500	33	27
Span length[b], ft		
<45	139	111
45 to 90	118	90
>90	5	5
Air entrainment[b]		
Specified	134	96
Not specified	126	108
Unknown	2	2

[a]Four bridges comprising 14 spans were relocated or replaced between the two surveys.
[b]Uncovered spans only.

Table 3. Distribution of span defects.

	1961 Condition		1961 Condition of Covered Spans		1961 Condition of Uncovered Spans		1970 Condition	
Span Defects	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
No scaling	149	57	19	45	125	61	11	5
Scaling	113	43	23	55	81	39	195	95
No cracking	175	67	23	55	143	70	51	25
Cracking	87	33	19	45	63	30	155	75
Transverse	66	25	15	36	47	23	121	59
Longitudinal	12	5	4	10	7	3	30	15
Diagonal	7	3	2	5	4	2	9	4
Pattern	19	7	5	12	12	6	47	23
"D"	0		0		0	0	0	0
Random	13	5	4	10	9	4	105	51
No rusting	261	>99	41	98	206	100	206	100
Rusting	1	<1	1	2	0	0	0	0
No surface spalling	260	99	41	98	205	>99	186	90
Surface spalling	2[a]	1	1	2	1	<1	20	10
No joint spalling	260	99	40	95	206	100	200	97
Joint spalling	2	1	2	5	0	0	6	3
No popouts	233	89	35	83	184	89	169	82
Popouts	29	11	7	17	22	11	37	18

[a]Data published by PCA-BPR (13) erroneously listed 1 rather than 2 spalled spans.

Table 4. Distribution of more severe span defects.

	1961 Condition		1961 Condition of Covered Spans		1961 Condition of Uncovered Spans		1970 Condition	
Span Defects	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
No or light scaling	215	82	35	83	183	87	143	69
Medium, heavy, and severe scaling	47	18	7	17	23	13	63	31
No or light cracking	252	96	39	93	199	97	180	87
Medium or heavy cracking	10	4	3	7	7	3	26	13
Transverse	6	2	2	5	4	2	13	6
Longitudinal	0	0	0	0	0	0	1	<1
Diagonal	2	<1	0	0	2	1	1	<1
Pattern	0	0	0	0	0	0	4	2
"D"	0	0	0	0	0	0	0	0
Random	2	<1	1	2	1	<1	7	3
No rusting	261	>99	41	98	206	100	206	100
Rusting	1	<1	1	2	0	0	0	0
No or small surface spalls	261	>99	42	100	205	>99	193	94
Large surface spalls	1	<1	0	0	1	<1	13	6
No joint spalls	262	100	42	100	206	100	200	97
Joint spalls	0	0	0	0	0	0	6	3
No or few popouts	262	100	42	100	206	100	199	97
Many popouts	0	0	0	0	0	0	7	3

of the spans were free of medium or heavy cracking, while about two-thirds of the spans were free of the more serious forms of scaling.

Surface spalling has progressed to the point where 10 percent of the spans are affected, 6 percent in the more severe classification. Although this increase is substantial, it is interesting to note that the current frequency of spalling on the Virginia sample is equal to or less than that reported from three of the seven other states in 1961.

No rusting was observed in 1970. Apparently rusting or the conditions leading to rusting were the basis for resurfacing of the one span observed in 1961.

In general, the performance of these bridge decks is not alarming and would be considered adequate or above average when compared with other published information on performance of decks in other areas of the country.

In the analysis of the data from the 1970 survey, a primary concern was to determine and report the increase of concrete deterioration on the bridge decks during the interval between surveys. It must not be overlooked that decks on 14 of the 80 bridges that were inspected had been resurfaced with a bituminous surface. Thus, 42 spans were covered. Inasmuch as concrete deterioration often necessitates deck resurfacing, the inspectors tried to discover whether this was the reason for the placement of bituminous concrete on the bridges. The district bridge engineers were requested to convey any information pertaining to the conditions of these deck slabs prior to the placement of the overlays.

From the replies, it would seem that for the most part these resurfacings were for reasons other than concrete distress. This is consistent with the data given in Table 4, which show that the condition of spans in 1961 was close to the average for the entire sample.

As judged by the data given in Table 4, it appears that the performance of the decks has been adequate with the possible exception of the resistance to surface scaling. The increase in spalling, though limited to a few spans, should be viewed with concern because of the difficulty associated with its correction.

SPECIFIC DEFECTS

The classes of defects will now be discussed individually in more detail, using comparisons shown in Figures 1 to 9. The data designated as "1961—all uncovered spans" are the same as those in the PCA-BPR report (13).

Scaling

The distribution of the maximum and average scaling conditions is shown in Figures 1 and 2. The progression of scaling increases with both age and traffic volume. The progression with traffic volume is shown in Figure 3. The degree of progression with age was very similar to that with traffic volume. [In the full report (14) from which this paper was taken, a more extensive discussion of the specific factors is given.] It is likely that these increases represent the combined effects of several factors including (a) more applications of de-icing chemicals on roads with high traffic volumes, (b) greater numbers of freezing and thawing cycles with age, and (c) difficulties of separating abrasion from light scaling. In any event, the differences due to age and traffic are not particularly significant.

The combined influence of air entrainment and age is shown in Figure 4. This influence was less obvious in 1970 than it was in 1961. The reason is at least twofold. One is the difficulty in distinguishing between light scaling and abrasion. Whereas reduction of scaling is attributed to entrained air, at the same time slight reductions in strength accompanying its use might be associated with increased abrasion. It is much more likely that the lack of significant reduction in scaling from air entrainment reflects the fact that the amount of air specified was not sufficient to provide resistance to scaling. The specifications in force at the time of construction required 3 to 6 percent air. Based on the observations from the Virginia Highway Research Council's (VHRC) special study of deck construction, there was a strong tendency to work to the lower limit rather than to the center of the range. It is thus probable that the majority of the spans do not contain what is currently deemed as adequate air entrainment. The Virginia specifications were revised in 1965 to require an air content of $6\frac{1}{2} \pm 1\frac{1}{2}$ percent.

Figure 1. Distribution of maximum scaling condition.

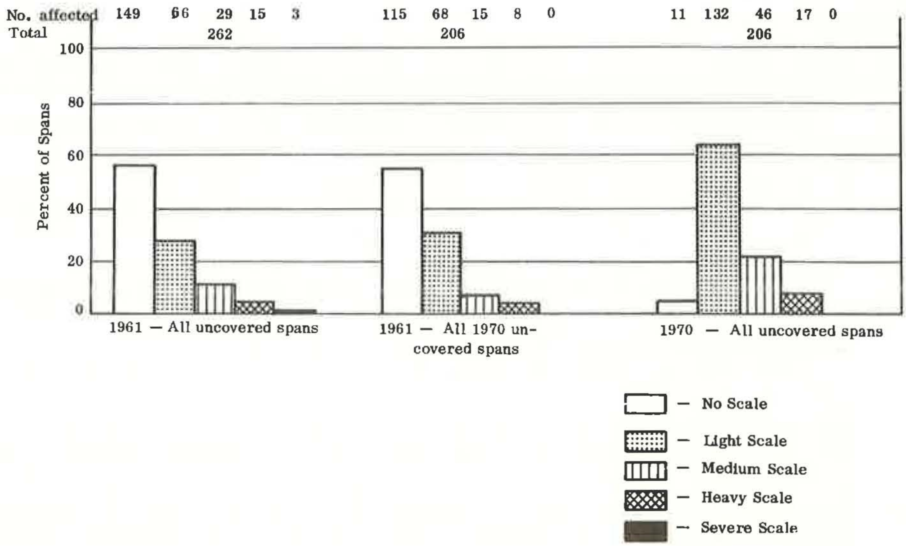


Figure 2. Distribution of average scaling condition.

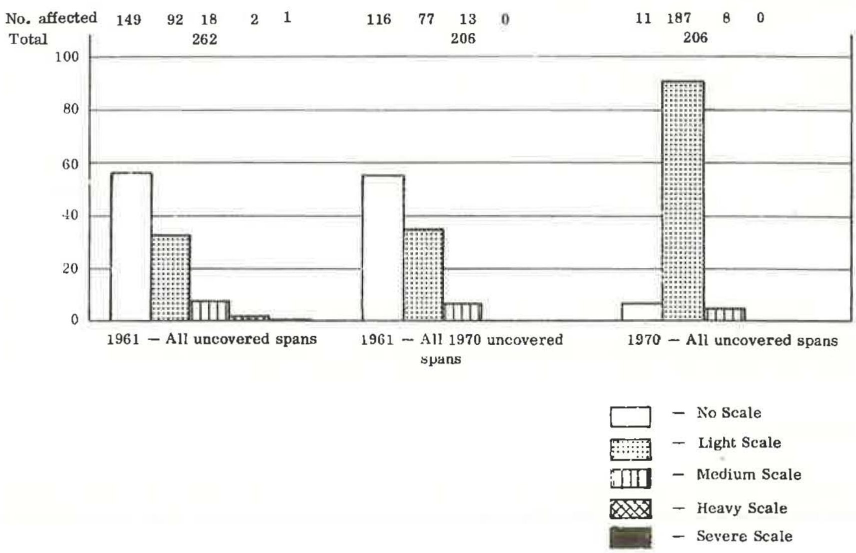
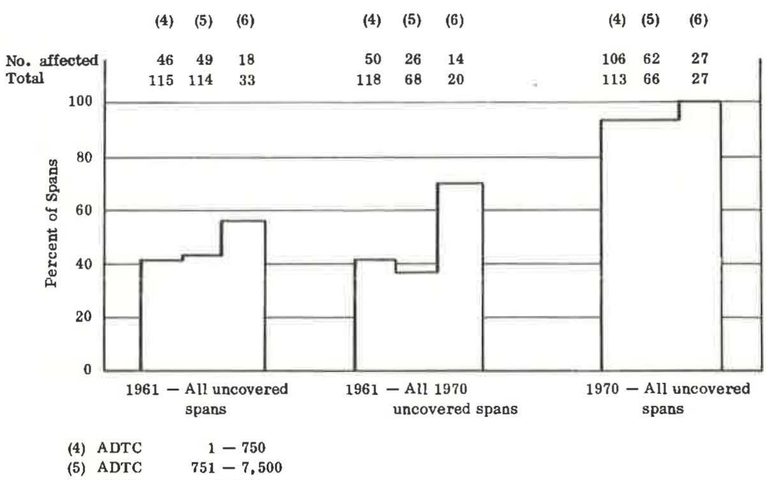


Figure 3. Influence of traffic volume on occurrence of scaling.



(4) ADTC 1 — 750
(5) ADTC 751 — 7,500
(6) ADTC > 7,500

It is significant to note that the 11 spans that were free from scaling were all air-entrained. At the same time, the average daily traffic counts of all of these unscaled spans is less than 7,500, and more than half have an average daily traffic count less than 750. Spans on low-volume roads would be expected to have received few if any applications of de-icing chemicals.

Cracking

Cracking was the second most prevalent defect in both 1961 and 1970. Most of the cracking is light and of little comparison (Table 4). The largest increase, tenfold, was in the category of random cracking. Most of this was light and is believed to reflect differences between the ratings of the inspection teams rather than in actual performance. This probability is discussed later.

The most prevalent type of cracking was transverse, and its occurrence is shown in Figure 5. In 13 spans (6 percent) the severity is classified as medium or heavy. Approximately three times as many spans showed this level of cracking in 1970 as did in 1961.

The influence of span length on cracking is shown in Figure 6. The effect of traffic volumes on the occurrence of transverse cracking is shown in Figure 7. Both figures reflect the expected trends, namely, an increase with span length and traffic volume. In 1961 these trends were not evident because the longer spans and heaviest traveled bridges were also the youngest. In 1970 there was little difference between the two highest classifications of either volumes or span lengths, but spans shorter than 45 ft and carrying fewer than 750 vpd showed significantly less transverse cracking than did the other two classes. Transverse cracking can result from either loads or long-time volume changes, both of which are time-dependent. The effect of age on the occurrence of transverse cracking was also as expected although there is little difference in the occurrence on the spans in the two youngest categories. Because cracking and surface spalling are often related phenomena, the relationship between these two defects was evaluated and is discussed later.

In addition to transverse cracking, only random cracking showed a substantial change (Fig. 8). In all cases the severity was not alarming. No "D" cracking was observed in either survey. "D" cracking is a serious problem in pavements placed in some areas of the country, but the conditions necessary for its occurrence are not operative except in slabs-on-grade.

In general, cracking is not a serious problem and is believed to be within expected limits.

Spalling

Because of the recent nationwide concern over the development of surface spalling, particular attention was given to this defect. Its occurrence is shown in Figure 9. As noted earlier, spalling was more prevalent in 1970 than in 1961 and has shown proportionally a greater increase than other defects. The number of spans with spalling increased from one to 20. At the same time spalling is still much less of a problem on the bridges in the Virginia sample than on those in many of the other states included in the random survey. On 13 spans (6 percent), spalling was recorded as large. One bridge contained 33 spalls, another had 24, one had 17, and the remainder had less than 10. Thus, only three bridges were significantly affected.

The magnitude of the problem did not warrant and the scope of this project did not permit an extensive evaluation for incipient spalls or "hollow areas," but the comparative absence of spalls suggests that a further, more intensive study might shed some light on why some decks spall and others do not.

The data were studied for relationships between the simultaneous presence of spalling and transverse cracking. The formative mechanism of spalls is such that transverse cracking could be expected to precede the appearance of spalls. As noted earlier, 121 of the 206 spans (59 percent) contained transverse cracks. Of these 121 spans, 107 (89 percent) had no spalling, whereas 14 (11 percent) did. Spalls were found in 20 spans, and, of the 20, six had no transverse cracking while 14 had both. From a study of these

Figure 4. Influence of air entrainment and age on occurrence of scaling.

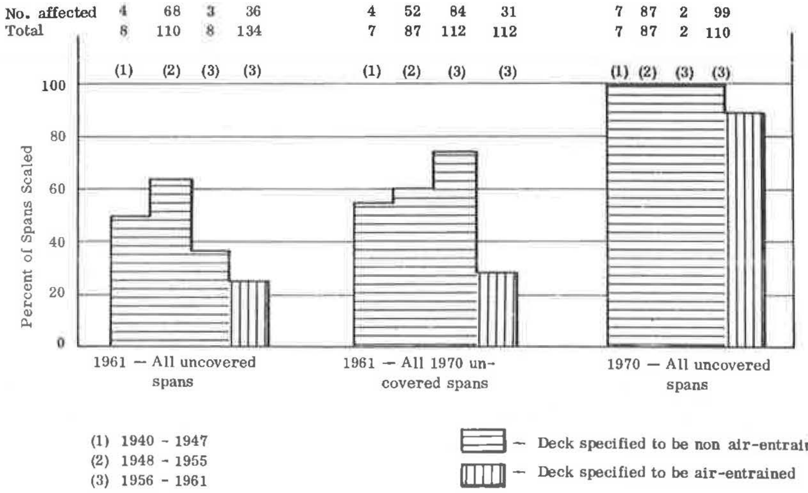


Figure 5. Distribution of transverse cracking.

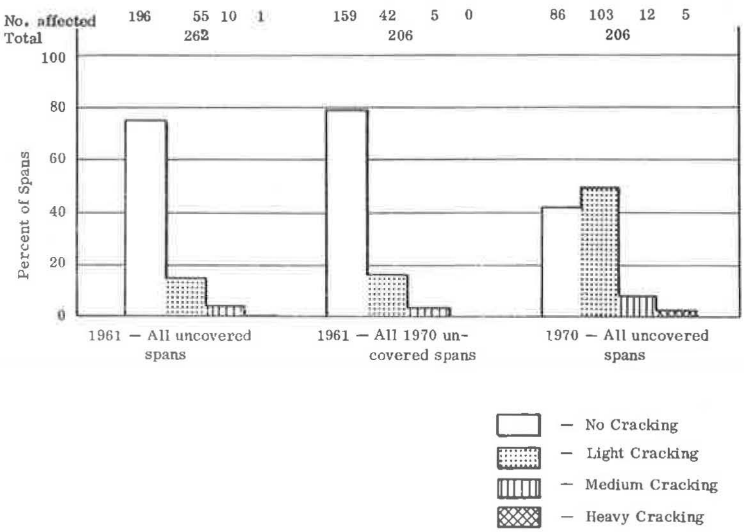
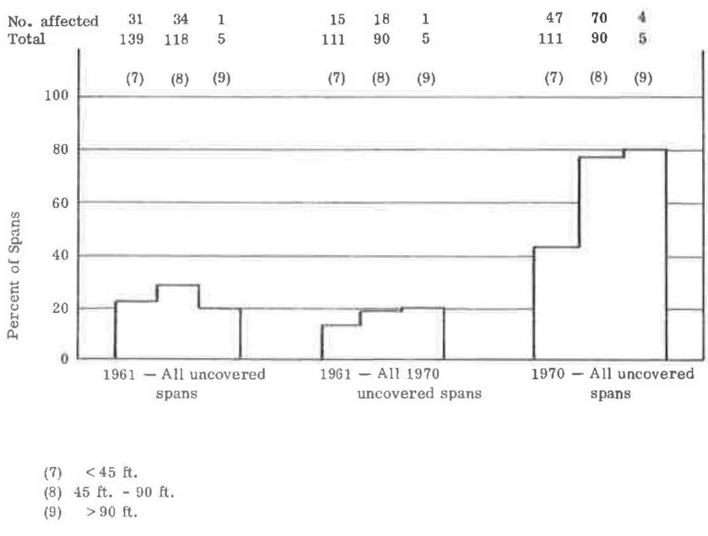
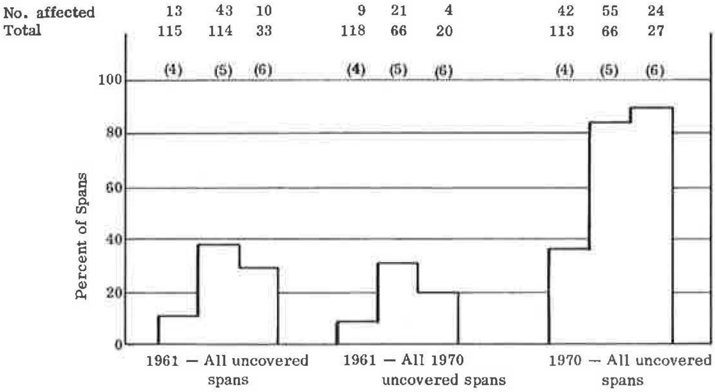


Figure 6. Influence of span length on occurrence of transverse cracking.





(4) ADTC — 1 - 750
(5) ADTC — 750 - 7500
(6) ADTC — >7500

Figure 7. Influence of traffic volume on occurrence of transverse cracking.

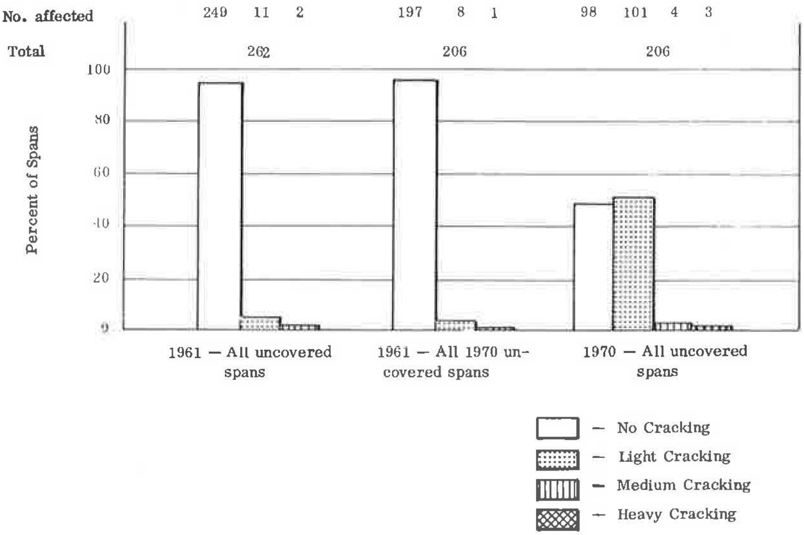


Figure 8. Distribution of random cracking.

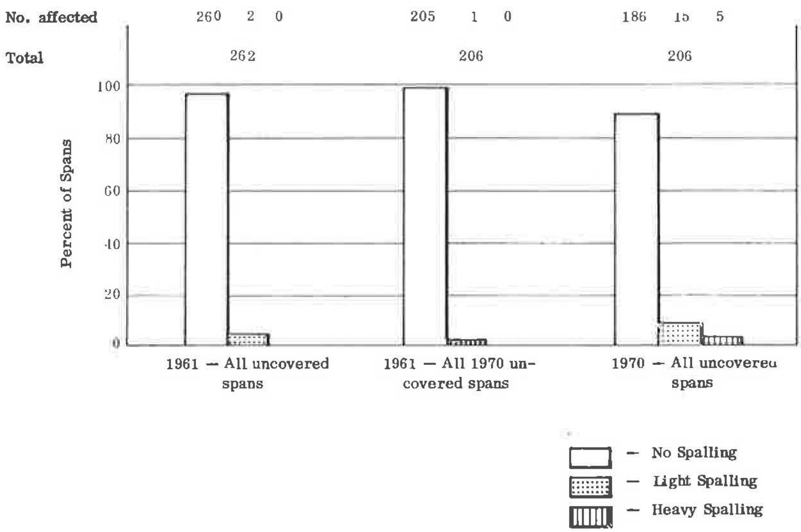


Figure 9. Distribution of spalling.

data, there seems to be no particularly consistent relationship between spalling and transverse cracking, although the two defects often occur simultaneously.

Popouts

The number of spans containing popouts did not increase substantially. It was observed, however, that the occurrence of popouts was largely confined to the Northern Virginia area. This is explained by the occurrence of lightweight chert in the locally available coarse aggregate.

PCA-BPR SAMPLE VERSUS VHRC STUDY

In 1963, a special study was made of 17 randomly selected bridges then under construction to study the influences of finishing and other construction procedures on the properties of the freshly mixed and hardened concrete and those on the performance of the decks. On each of these 17 structures, one span was studied in detail during construction. The 17 bridges contained 78 spans. Two of the structures were much larger than the others, containing eight and 13 spans respectively. The remaining 15 bridges, containing 60 spans, were more representative of the typical bridge constructed in Virginia. The detailed evaluation of these decks has been discussed in a VHRC report. Here a comparison will be made of the changes in condition of the two samples during the period since the initial surveys (Table 5).

The agreement is unusually good. Several of the categories (popouts, surface spalling, and rusting) are in exact agreement. Joint spalling shows the largest disparity, and scaling and cracking show slight differences. In both samples the relative order of severity for the six different types of cracking is the same, and the individual values are in good agreement.

Factors Influencing Performance

The variety of conditions and the long time periods for construction and performance of the structures making up the Virginia sample do not lend themselves to a detailed cause-effect analysis. Several factors known to affect deck performance are worthy of mention as a general backdrop against which to view the results. The following four will be discussed: (a) specification requirements for concrete used in decks, (b) required cover over upper reinforcing steel, (c) policy on de-icing, and (d) climatological characteristics.

The degree to which compliance with the requirements for the first two factors was obtained is obviously an important but nondocumentable factor. Many problems can be traced to failure to fulfill completely the requirements specified for concrete quality and cover. Assuming a relatively constant degree of quality control, the requirements specified furnish a basis for comparison, particularly with performance in the other states included in the nationwide survey.

Concrete Quality—Significant specification requirements for concrete are given in Table 6. It can be seen that, during the time period of construction of the sample bridges (1940 to 1961), the requirements were essentially the same. The most significant change was the introduction of air entrainment in 1954. The oldest group of bridges (1940 to 1947) in the survey may have contained concrete of a slightly higher water-cement ratio than those covered by the later specifications. The number of bridges in the oldest class was small compared with the total. Significant upgrading of the requirements did not occur until 1966. Prior to that time the concrete specified would have had borderline resistance to weathering when judged in light of subsequently developed knowledge.

Cover—Insufficient cover of the upper reinforcing steel has been widely identified as a primary cause of surface spalling. Research in Kansas (2) showed a very high tendency for deterioration at covers of 1.5 in. or less and very little deterioration for covers of 2 in. or more. Spellman and Stratfull (12) have developed an empirical relationship to relate the variation of chloride content in concrete to the depth below the surface. A minimum of 2 in. of clear cover is widely recommended by various agencies prominent in concrete technology (8).

During the period of construction of the bridges included in the sample, the requirements for location of the uppermost steel was 2 in. to the center of the uppermost bar. This would be approximately $1^{11}/_{16}$ in. of clear cover. This cover requirement is adequate with respect to protection from spalling but is close to the breaking point of the data developed in Kansas (2). The requirement was increased in 1966 to provide $2^1/_4$ in. to the center of the uppermost bar, which is approximately $1^{15}/_{16}$ in. of clear cover. This is very close to the 2-in. value now judged to be necessary.

De-icing Policy—Prior to World War II there was little use of de-icing chemicals. Use was limited to very heavily traveled routes, with the remainder of the roads being cleared by plowing. The bare pavement policy developed in the mid-1940s, essentially after World War II, and resulted in the widespread use of chemicals for de-icing. For concrete pavement surfaces, calcium chloride, rather than sodium chloride, was required until about 1960. Since then, either sodium or calcium chloride has been used on concrete pavements. As in other areas, Virginia witnessed a fivefold increase in the use of chloride during the period 1953 to 1970.

Environmental—It is well recognized that the environment to which concrete is exposed greatly influences its performance. It is apparent that this performance is affected by temperature variations, particularly in the vicinity of the freezing point and simultaneously with the presence of moisture. The combination and quanitification of these two characteristics into a meaningful measure applicable for concrete are complex, and numerous techniques have been used. There is still much to be done as reflected by the fact that the area of assessing and quantifying the environmental characteristics to which concrete is exposed in practice was given highest priority in a recent summary of research needs (7).

There is a wide variation of effective freezing and thawing cycles across Virginia: as few as 23 in the southeast and as many as 91 in the northeast. With respect to freeze-thaw cycles, 65 to 70 are typical in the western areas of the state. These represent frequencies as high as are found in the United States with the exception of the Rocky Mountain areas (14).

Attempts to correlate performance characteristics with single calculated parameters such as freezing or weathering indexes were unsuccessful. Larson and Malloy (4) likewise found that a correlation of macroclimate with performance had not been successful and that an approach directed toward study of microclimate should be pursued.

RELIABILITY AND REPRODUCIBILITY OF THE SURVEYS

The many factors affecting deck performance and the variability, even within a given span, raise questions on the reliability and reproducibility of these and similar surveys. Although no direct proofs are possible, several indications from the experiences in Virginia lend support to the reliability.

It should be borne in mind that the random survey (13) did not include the same number of bridges from each geographic area.

The sample turns out to be a relatively good distribution, however, although there were relatively few in two areas that have comparatively mild exposures. The same is true, however, for one area that has a severe exposure. Thus the sample to some extent represents the median exposure.

The concept on which the PCA-BPR random survey was based was that the condition of the bridges within a given state would be estimated from surveys of a randomly selected source and that randomly drawn samples from the eight participating states would reflect the condition of bridges over the nation. The sample size was determined by statistical concepts with the intent that the limit of error would be ±8 percent, with a probability of not exceeding this limit fixed at two standard deviations; that is, 95 percent of the results would fall within the ±8 percent limit.

At approximately the same time that the random survey was conducted in Virginia, VHRC was conducting a less detailed survey of all of the decks in the four western districts. This survey, made in 1964, was a part of the study of potentially carbonate aggregates (11). Some results from a single district are of interest and are given in Table 7.

Table 5. Distribution of span defects in PCA-BPR study and in finishing study.

Defect	PCA-BPR Spans (percent)	Finishing Study Spans (percent)	Finishing Study Structures
Covered	17	23	2
Uncovered	83	77	15
No scaling	5	18	3
Scaling	95	82	12
No cracking	25	10	1
Cracking	75	90	14
Transverse	59	63	12
Longitudinal	15	30	7
Diagonal	4	8	3
Pattern	23	38	8
"D"	0	0	0
Random	51	55	13
No rusting	100	100	15
Rusting	0	0	0
No surface spalling	90	91	13
Surface spalling	10	9	2
No joint spalling	97	71	14
Joint spalling	3	29	1
No popouts	82	82	11
Popouts	18	18	4

Table 6. Concrete requirements, 1938 to 1970.

Year	Cement Content (sacks/ cu yd)	Water-Cement Ratio (gal/ sack)	Air Content (percent)	Slump (in.)	Maximum Agg. Size (in.)	28-Day Strength (psi)	Maximum Aggregate Loss: Los Angeles Abrasion of Coarse Agg. (percent) 100 Rev.	Los Angeles Abrasion of Coarse Agg. (percent) 100 Rev.	Sulfate Soundness Coarse Agg. Percent	Sulfate Soundness Coarse Agg. Cycles	Sulfate Soundness Fine Agg. Percent	Sulfate Soundness Fine Agg. Cycles	Freeze-Thaw Coarse Agg. Percent	Freeze-Thaw Coarse Agg. Cycles	Freeze-Thaw Fine Agg. Percent	Freeze-Thaw Fine Agg. Cycle
1938	$6\frac{1}{4}$	6	–	2 to 5	1	3,000	10	40					10	15		
1947	$6\frac{1}{4}$	6	–[a]	2 to 5	1	3,000	9	35	8	5	8	5	5	15	5	15
1954	$6\frac{1}{4}$	$5\frac{1}{2}$	3 to 6[a]	0 to 5	1	3,000	9	35	8	5	8	5	5	15	5	15
1958	$6\frac{1}{4}$	$5\frac{1}{2}$	3 to 6	0 to 5	1	3,000	9	35	8	5	8	5	5	15	8	15
1966	$6\frac{3}{4}$	$5\frac{1}{4}$	$6\frac{1}{2} \pm 1\frac{1}{2}$	2 to 4	1	4,000	9	40	12	5	12	5	5	20	5	20
1970	$7\frac{1}{4}$	$5\frac{1}{4}$	$6\frac{1}{2} \pm 1\frac{1}{2}$	2 to 4	1	4,000	9	40	12	5	18	5	5	20	8	20

[a]Air entrainment was first used in pavements in 1948. It was used experimentally in several bridge decks prior to being incorporated into specifications.

Table 7. VHRC and random survey results on comparable spans.

Defect	Random Survey (1961)	VHRC Survey of One District (1964)
Deck resurfaced	40	38
Moderate or heavy scaling	18	22
Cracking	33	40
Spalling	0	0

The general agreement between surveys of three different groups of bridges given in Tables 5 and 7 and the concurrence reflected in the reasonable progression of defects recorded from two separate surveys of the same group suggest that the observational techniques and method of selecting the sample size used in the PCA-BPR survey do result in essential agreement and are reliable and reproducible.

DISCUSSION OF VIRGINIA'S DECK PERFORMANCE

When compared with the performance of decks in the other states included in the random survey and with published reports from other areas, the performance of the decks included in the Virginia sample is comparatively good. It is true that 51 percent of the spans have been resurfaced within 20 years of their original construction, but there are indications that many of these resurfacings had been placed more as a matter of convenience than for correction of below-par performance. Others were placed with the hope of delaying potential problems. The rate of resurfacing has been decreasing in recent years.

Although Virginia is located in a temperate climate, the weathering conditions are in some respects severe, particularly with respect to cycles of freezing and thawing. The late adoption of air entrainment is reflected in the high incidence of scaling. For those bridges constructed with air-entrained concrete, the concrete did not contain amounts consistent with the amounts subsequently shown to be required for durability of structural concrete.

The absence of widespread spalling and serious cracking is fortunate, and, although reasons cannot be definitely stated, the use of $1^{11}/_{16}$-in. clear cover and a high proportion of simply supported spans are likely major contributors. Seventy-five percent of the uncovered spans in the original sample were simply supported.

As given in Table 6, the specification requirements for deck concrete have been progressively upgraded since about 1965. This upgrading has been concomitant with upgrading of construction techniques including the requirement of machine screeding and a general emphasis on the demands for diligence in inspection and controls. Intensive training and certification programs for producer and department personnel involved in concrete construction have also provided benefits. Although no quantitative data are available for assessing the improvement in deck performance, it is generally conceded that, despite the increased demands being placed on concrete in decks and the increased use of de-icing chemicals, the performance has improved since the survey was made. The initial PCA-BPR survey and this updating provide a basis, along with the VHRC's special study, from which to assess quantitatively from future surveys the benefits of improvements in materials and construction procedures and increased attention to the details of good practices.

CONCLUSIONS

Based on the observations and data developed, the conclusions given below appear warranted. It should be emphasized that the behavior reflected by the results is that obtained under specifications and techniques used during the period of construction (1940 to 1961) rather than those currently in use.

1. Listed in order of decreasing frequency, the defects observed during the 1970 resurvey were scaling, cracking, popouts, spalling, and rusting. This is the same order as reported for the initial survey in 1961.
2. The percentage of spans affected by each of the defects increased between surveys. Considering all defects except those in the lowest severity category of each classification, scaling increased from 13 to 31 percent, cracking from 3 to 13 percent, and spalling from 0 to 6 percent. Changes in the other defects were insignificant. These changes are believed to be reasonable in view of the environmental factors and the specification requirements, subsequently upgraded, that existed at the time of construction.
3. The types of cracking observed in 1970 in decreasing order of frequency were transverse, random, pattern, longitudinal, and diagonal. No "D" cracking has been found in either of the Virginia surveys or in the nationwide survey.

4. The order of frequency of defects from the sample in the random survey as well as from the smaller sample included in the VHRC study of finishing methods on bridges exposed for about the same period as those in the random survey was approximately the same, and the percentages of spans affected by each type of defect agreed closely. The percentages of spans showing the various types of cracking also agreed closely.

5. Because details concerning the construction of decks included in the random survey are not available, correlations of the materials and construction characteristics with performance is not possible. The close agreement between the performance of the decks in the random survey and those in the VHRC finishing study, for which detailed observations were made during construction, indicates that causative relations developed from that study can be extrapolated to the performance of the larger sample.

6. Agreement among the results from surveys conducted at different times and on different samples validates the survey methodology and sampling plan developed for the original survey.

7. Action taken in 1966 to upgrade specifications for bridge deck concrete (Table 6) included upgraded requirements for entrained air content and water-cement ratio, both of which should greatly reduce the incidence of the most prevalent defect observed in the survey, namely, scaling.

8. Although not documentable, the comparatively low frequency of surface spalling when compared with performance in the other states included in the survey is probably related to the provision of $1^{11}/_{16}$-in. clear cover reinforcement. Adequate cover, per se, is not a complete solution to the problem of surface spalling inasmuch as the quality of concrete is also important, but there is no evidence to support the belief that the concrete quality was significantly better in Virginia than in other states.

REFERENCES

1. Durability of Concrete Bridge Decks, Report 3. Portland Cement Association, 1967.
2. Crumpton, C. F., Pattengill, M. G., and Badgley, W. A. Bridge Deck Deterioration Study—Part 8. Kansas State Highway Dept., 1969.
3. Durability of Concrete Bridge Decks, Report 1. Portland Cement Association, 1965.
4. Larson, T. D., and Malloy, J. J. Durability of Bridge Deck Concrete. Rept. 3, Vol. 1, Pennsylvania State Univ., 1966.
5. Durability of Concrete Bridge Decks, Report 2. Portland Cement Association, 1967.
6. Durability of Concrete Bridge Decks, Report 4. Portland Cement Association, 1968.
7. Walker, R. D., Larson, T. D., and Cady, P. D. Research Needs Relating to Performance of Aggregates in Highway Construction. NCHRP Rept. 100, 1970.
8. Concrete Bridge Deck Durability. NCHRP Synthesis of Highway Practice 4, 1970.
9. Newlon, H. H., Jr., Davis, J., and North, M. Bridge Deck Performance in Virginia. Virginia Highway Research Council, Charlottesville, Rept. VHRC 70-R39, May 1971.
10. Newlon, H. H., Jr. Comparison of Properties of Fresh and Hardened Concrete in Bridge Decks. Virginia Highway Research Council, Charlottesville, Rept. VHRC 70-R56, June 1971.
11. Sherwood, W. C., and Newlon, H. H., Jr. A Survey for Reactive Carbonate Aggregates in Virginia. Highway Research Record 45, 1964, pp. 222-233.
12. Spellman, D. L., and Stratfull, R. F. Chlorides and Bridge Deck Deterioration. Highway Research Record 328, 1970, pp. 38-49.
13. Durability of Concrete Bridge Decks, Report 5. Portland Cement Association, 1969.
14. Durability of Concrete Bridge Decks, Final Report. Portland Cement Association, 1970.

APPENDIX

DEFINITIONS OF DETERIORATION TYPES

The following definitions and the random survey data sheet (Fig. 10) are those used in the PCA-BPR studies (1, 3, 5, 6, 13, 14).

Scaling

Light—loss of surface mortar up to ¼ in. in depth and exposure of surface of coarse aggregate.

Medium—loss of surface mortar ¼ to ½ in. in depth with some loss of mortar between coarse aggregate.

Heavy—loss of surface mortar and mortar surrounding aggregate particles ½ to 1 in. in depth such that aggregate is clearly exposed and stands out from the concrete.

Severe—loss of coarse aggregate particles as well as surface mortar and mortar surrounding aggregate, greater than 1 in. in depth.

Cracking

Transverse—Reasonably straight cracks perpendicular to centerline of roadway; vary in width, length, and spacing; frequently occur over primary slab reinforcement; sometimes extend completely through slab; may be visible before bridge is open to traffic or at some later date. (On some skewed bridges, the transverse slab steel is placed at an angle other than 90 deg to the roadway centerline; cracks parallel to this steel are also defined as transverse cracks.)

Longitudinal—fairly straight cracks, roughly parallel to centerline of roadway; vary in width, length, and spacing; sometimes extend completely through slab; may be visible before bridge is open to traffic or at some later date.

Diagonal—roughly parallel cracks forming an angle other than 90 deg with the centerline of the roadway, except as noted under transverse; usually shallow in depth; vary in width, length, and spacing; may be found immediately after completion of construction or may not appear until after bridge is open to traffic.

Pattern or map—interconnected cracks forming networks of any size and usually similar geometrically to those seen on dried mud flats; may vary in width from fine and barely visible to well defined and open; may develop early in the life of the concrete or at some later date.

"D"—usually defined by dark-colored deposits and generally located near joints and edges.

Random—cracks meandering irregularly on surface of slab, having no particular form, and not fitting other classifications.

Surface Spalling

Small—roughly circular or oval depression generally not more than 1 in. deep or more than about 6 in. in any dimension; caused by separation and removal of a portion of the surface concrete, revealing a roughly horizontal or slightly inclined fracture; generally a portion of the rim is vertical.

Large—may be a roughly circular or oval depression generally 1 in. or more in depth and 6 in. or more in any dimension; caused by separation and removal of a portion of the surface concrete, revealing a roughly horizontal or inclined fracture; generally a portion of rim is vertical (in some cases the spall may be an elongated depression over a reinforcing bar).

Hollow area—an area of concrete that, when struck with a hammer or steel rod, gives off a hollow sound, indicating the existence of a nearly horizontal fracture below the surface.

Other Defects

Joint spall—elongated depression along expansion, contraction, or construction joint.

Figure 10. Sample random survey data sheet.

STATE ILLINOIS COUNTY COOK HIGHWAY NOS I 294 BRIDGE NO. 72

YEAR BUILT 1958 DECK: UNCOVERED ✓ COVERED ___ TYPE OF COVER ___

IS DETAILED CONSTRUCTION DATA AVAILABLE ? YES

WHAT TYPE OF DECK REPAIR OR RECONSTRUCTION HAS BEEN DONE ? NONE

SPAN NO I HAS BEEN SELECTED AS THE N (S) E W END OF BRIDGE

SPAN NO.		1	2	3	4	5	6	REMARKS
LENGTH, FT.		45	78	78	45			
SPAN TYPE		← SS-IB-CN →						
SCALING	1				3			
	2				X			
	3			15				
	4			X				
CRACKING	1	L	L	L	L			
	2		L					
	3							
	4			M	L			
	5							
	6			H				
RUSTING				R				
SURFACE SPALLS	1				2			
	2		1		3			
JOINT SPALLS	1		2					
	2			3				
	3							
POPOUTS		M	F	F	F			

COMMENTS: DECK SPECIFIED TO BE OF AIR-ENTRAINED CONCRETE

A.D.T.C. — 8600

DATE OF INSPECTION 4/23/62 INSPECTOR J. SMITH DISTRICT OFFICE ILLINOIS

Popouts—conical fragments that break out of the surface of concrete, leaving holes that may vary in size from that of a dime to as much as a foot in diameter (generally, a shattered aggregate particle will be found at the bottom of the hole, with part of the particle still adhering to the small end of the popout cone).

Pitting—loss of thin coats of surface mortar directly over coarse aggregate particles without apparent damage to the aggregate particles; pits usually not over $1/8$ in. in depth (this is in contrast to popouts).

Mudballs—small holes in the surface left by dissolution of clay balls or soft shale particles.

Other Definitions

Bleeding channels—essentially vertical, localized open channels caused by heavy bleeding.

Water-gain voids—voids formed during the bleeding period along the underside of aggregate particles or reinforcing steel; initially filled with bleeding water that subsequently evaporated or was absorbed.