Durability of Concrete Bridge Decks—A Review of Cooperative Studies

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The paper summarizes the results of concrete bridge deck durability studies made by the Portland Cement Association in cooperation with the U. S. Bureau of Public Roads and 10 state highway departments. Condition surveys were made of over 1,000 randomly selected decks in California, Illinois, Michigan, Minnesota, New Jersey, Ohio, Texas, and Virginia to assess the extent of deterioration. Detailed field and laboratory investigations were made on 68 decks in Kansas, Michigan, California, and Missouri to determine the causes of deterioration. Attention is given to scaling, cracking, and spalling. Scaling is not a particularly serious problem and has been kept under control—although not eliminated—with use of air-entrained concrete. The observed scaling is usually associated with deficiencies in the entrained air void systems and with inadequate deck drainage. Many forms of cracking are of secondary importance because they do not lead to more serious forms of deck distress. Longitudinal cracking is sometimes found on the thicker slab-type bridges and apparently results from subsidence of high slump concrete around the reinforcing bars. Transverse cracking is the form most often encountered. Shrinkage and thermal volume changes in the concrete apparently are the primary factors producing these cracks. Surface spalling, a major problem in some states, is the result of internal expansive forces in the concrete generated by the corrosion of top reinforcing bars. Cracks over bars, shallow concrete cover over bars, and permeable concrete allow the de-icing chemical solutions to reach the bars and cause the corrosion. Recommendations for improved durability involve the use of higher quality concretes, improved construction practices, and attention to design details that have an influence on durability. Attention is also invited to 2-course bonded construction (such as is used for industrial floor construction) as an alternative to single course bridge deck construction.

•THIS PAPER is based on studies of concrete bridge deck durability begun in 1961 by the Portland Cement Association in cooperation with the U. S. Bureau of Public Roads and 10 state highway departments. The scope of the study program was described in an earlier paper (1). The initial objectives were to (a) assess the extent of bridge deck durability problems in various parts of the country, (b) determine the causes of the deterioration, (c) develop recommendations for obtaining improved durability of new bridge deck construction, and (d) develop methods for retarding any deterioration on existing bridges. It is believed that considerable progress has been made toward achievement of the first 3 objectives. However, the study has not developed sufficient data in regard to the fourth objective.

The source data for the studies were obtained from in-service bridge decks by means of 2 types of field investigations. Detailed investigations were made of a limited number

Paper sponsored by Committee on Effect of Ice Control and presented at the 49th Annual Meeting.

of decks in 4 states for the purpose of determining causes of deterioration. The second type of field inspection was made on a statistically representative sampling of bridge decks in 8 states, including 2 states in which detailed investigations were made. The purpose of this portion of the study was to estimate the extent of deterioration, but other related information was also gathered. In both types of studies, the bridges were selected from those built on the federal-aid highway system from 1940 to 1962.

For purposes of the study, the types of deterioration were defined as scaling, cracking, and spalling. Figure 1 shows some typical forms of deterioration. Scaling was described as light, medium, heavy, or severe scaling according to the depth of concrete that was affected. Six classifications of cracking were defined primarily on the basis of directional trend: transverse, longitudinal, diagonal, pattern or map, D, and random. Surface spalls were defined originally as small and large, but there is no real distinction between the two other than size. Joint spalls and popouts were also included in the studies, but there were usually minor problems, and they will not be discussed in the present paper.

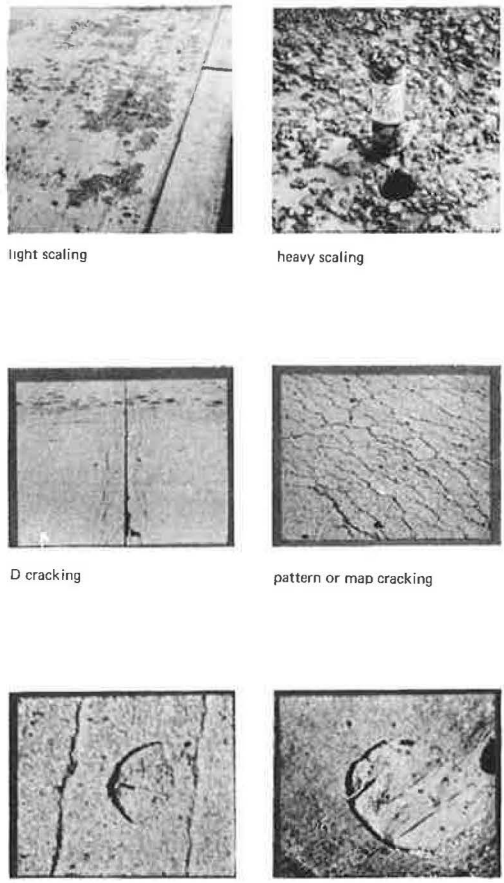

Figure 1. Examples of deterioration.

EXTENT AND SEVERITY OF BRIDGE DECK PROBLEMS

The random surveys were made to obtain quantitative information about the kinds of durability problems that occur on concrete bridge decks, and about the extent and the severity of the distress. The data also permitted some evaluation of the influence that factors such as deck age, bridge type, and use of air-entrained concrete have on the occurrence of the various types of defects.

Survey Method

The states included in the random surveys are given in Table 1 along with the number of bridges and spans studied in each state. In order to obtain a high level of uniformity of reporting, a special seminar was held for the participants in the survey. Data for

TABLE 1

RANDOM SURVEY STATES

State	Bridges	Spans	State	Bridges	Spans
Michigan	140	432	Illinois	158	516
Minnesota	110	353	Virginia	140	452
Ohio	146	442	Texas	132	803
New Jersey	123	321	Total	1,097	3,955
California	148	636			

each bridge were recorded on standard data sheets. Scaling was recorded as an estimated percentage of the affected span's deck area for the average severity condition ranging from light scale to severe scale. Occurrences of any of the 6 classifications of cracking were reported as being light, medium, or heavy. The numbers of large and small surface spalls were recorded for each span. Information was also gathered concerning the occurrence of joint spalls, popouts, and rusting of reinforcement.

The survey information on the data sheets was transferred to standard punched cards for processing by machine compilers. These compilations provided the source data that are presented and analyzed in an earlier report (6). In the comments that follow, only the major findings from this portion of the study are summarized.

Scaling

Scaling was found in all 8 states, but the incidence varied considerably from state to state. Virginia and Texas had the highest percentages of scaling, approximately 40 percent of the spans. In Illinois, Michigan, New Jersey, and Ohio from 20 percent to 30 percent of the spans had scaling. Decks in Minnesota had relatively little scaling; approximately 13 percent showed scaling. The insignificant amount of scaling in California occurred in an area where exposure is severe and where de-icing chemicals are used.

Although these percentages appear high, the scaling encountered in the 8 states was not too severe. Light scale, the least severe condition, accounted for 90 percent of the scaled spans. Furthermore, the scaling that occurred on about half of the scaled spans affected less than 8 percent of the deck area. Older decks usually had a higher incidence of scaling than newer decks. There was no marked trend toward greater incidence of scaling on the decks that carried the larger volumes of traffic.

The random survey data clearly illustrate the improved scale resistance of air-entrained over non-air-entrained concrete. Figure 2 shows that, compared with the air-entrained decks, the non-air-entrained decks had a higher incidence of scaling more extensive scaling on an area-affected basis, and more of the severe forms of scaling by a ratio of about 2½ to 1. Furthermore, the most extensive scaling was found in the 2 states that either did not use air-entrained concrete or began to use it at a relatively late date.

Cracking

Some form of cracking occurred on about two-thirds of the spans; the remainder may be regarded as having no readily visible cracking. Of the 6 classifications of cracking mentioned previously, D-cracking was virtually nonexistent; longitudinal cracking, diagonal cracking, and pattern or map cracking were not encountered with great frequency.

Transverse cracking was the form most frequently observed in each of the 8 states. About one-half of the spans had transverse cracking, with the large majority of these being described as having light transverse cracking. The incidence of transverse cracks appeared to increase with increasing age of deck and also with increasing span length. The superstructure type appeared to exercise some control over the occurrence of these cracks. Incidence of transverse cracks was greater on continuous spans than on simple spans, and was somewhat greater on structural steel spans than on reinforced concrete spans. Prestressed concrete spans and reinforced concrete simple spans generally had the lowest incidences of transverse cracking.

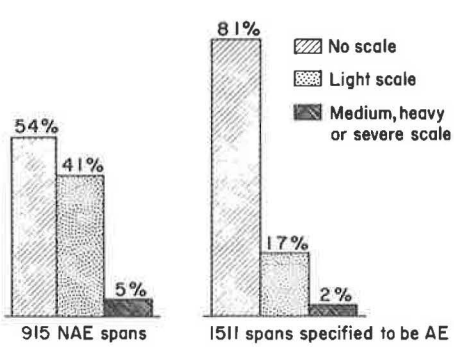

Figure 2. Influence of air entrainment on occurrence of scaling.

Surface Spalling

A significant amount of spalling was found in 4 of the 8 states. In Illinois about 25 per

of the spans showed surface spalling. In Ohio, Michigan, and Texas approximately 10 percent of the spans showed spalling. A negligible amount was observed in California, Minnesota, New Jersey, and Virginia.

Spalled bridges on the average contained about 10 surface spalls, while spalled spans on the average contained about 5 spalls. Older decks generally had a higher incidence of spalls than newer decks. Decks carrying higher volumes of traffic and those on a higher class of highway had a slightly higher incidence of surface spalls than less traveled decks on lower class highways. Span length, span continuity, bridge material, and superstructure type appeared to have little influence on the incidence of surface spalling. The indications are that decks in urban areas had a higher incidence than decks in rural areas.

Without doubt, surface spalling is the most serious and troublesome form of bridge deck defect. The deck is weakened locally, reinforcement is usually exposed, and riding qualities are impaired. Repair work is difficult and expensive, and there is no assurance that a repaired deck may not spall again.

Decks that scaled did not necessarily spall. The state that had the highest incidence of surface spalling had one of the lower incidences of scaling, and the states that had the highest incidences of scaling had little surface spalling.

Factors that contribute to surface spalling and the means for preventing this form of deck distress will be described later. At this point it might be noted that no one factor amenable to study by the procedures of this random survey could be singled out as a principal contributor to the surface spalling problem.

THE CAUSES OF BRIDGE DECK DISTRESS

Detailed investigations were made in Kansas, Michigan, California, and Missouri for the purpose of determining causes of deterioration. Decks were chosen that would illustrate a variety of types and degrees of deterioration, bridge age, location, and superstructure type. The selected decks were not necessarily typical of conditions in e state.

Investigation Procedure

The field inspections were made by a team representing the state highway department, the U. S. Bureau of Public Roads, and the Portland Cement Association. Table 2 gives the number of cores taken from the decks. Measurements were made of concrete cover over reinforcing steel. The cores were examined by various techniques in the laboratory. Air void characteristics were measured by the linear transverse method (PCA cores) and by the high-pressure method (BPR cores). Concrete quality was studied microscopically and was checked by pulse velocity measurements. The petrographers gave special attention to cracks in the cores to ascertain time of formation and possible causes. Concentration of chlorides as a function of depth was determined. Plans, specifications, and construction records were studied for possible correlation with the deterioration observed in the field.

The data and findings of the detailed investigations were presented in earlier reports (2, 3, 4, 5).

TABLE 2

DETAILED INVESTIGATION STATES

State	Bridges	Cores		
		PCA	BPR	Total
Kansas	18	128	122	250
Michigan	13	42	21	63
California	20	170	54	224
Missouri	17	143	44	187
Total	68	483	241	724

Scaling

Scaling to varying degrees of severity was observed on both non-air-entrained and air-entrained decks. When cores from these decks were studied in the laboratory, the scaling was almost invariably associated with either a total lack of entrained air, or with deficiencies in the air void systems of the intentionally air-entrained concretes.

Linear traverse measurements of cores from non-air-entrained decks

TABLE 3

COMPARISON OF AIR VOID PARAMETERS OF AIR-ENTRAINED CONCRETES HAVING UNIFORM AND NONUNIFORM AIR VOID DISTRIBUTIONS

State	Air Void Distribution	Percent Air	Voids per Linear In.	Specific Surface (in.^{2}/in.^{3})	Void Spacing Factor (in.)[a]
Michigan	Uniform	2.2-8.0	4.1-18.0	485-1,145	0.004-0.010
	Nonuniform	3.5-5.2	7.0-9.2	645-870	0.006
California	Uniform	2.2-8.6	4.1-22.8	690-1,180	0.003-0.009
	Nonuniform	1.8-6.8	3.3-15.7	735-1,450	0.004-0.010
Missouri	Uniform	2.7-6.6	4.6-15.8	475-1,100	0.004-0.009
	Nonuniform	2.9-10.1	5.0-18.6	490-1,150	0.003-0.010

[a]Based on assumed paste content of 25 percent.

resulted in calculated void spacing factors, $\overline{L}$, greater than 0.019 in., i.e., well in excess of the 0.008 to 0.010 in. limit that is generally considered necessary to protect cement paste during freezing in the presence of de-icer solutions. However, there were large areas of many non-air-entrained decks that had been subjected to de-icing chemicals and that had not scaled. It is believed that effective drainage of these areas eliminated one of the conditions that is necessary before scaling can occur. This point will be mentioned again later.

Deficiencies in the air void systems of intentionally air-entrained concretes were manifested in 3 ways: (a) differences in air content from one portion of a deck to another, (b) a lack of air in thin irregular zones at the wearing surface of the concrete, and (c) nonuniform distribution of air voids throughout the depth of the concrete.

Large differences of air contents measured in cores from a single deck are indicative of batch-to-batch variations. However, this condition was detected on only a few of the bridges; there was generally good control of air contents in most of the decks in each state.

Nearly all of the observed scaling or incipient scaling in air-entrained concretes was attributed to nonuniform air void distribution, particularly when this occurred in thin irregular zones at the wearing surface. In cores displaying this condition, the horizontal microcracks, which are indicative of incipient scale, would typically be found in the air-deficient zones. Detection of this condition could be made only by microscopic examination. Furthermore, the results of linear traverse measurements (ASTM C 457) of the full length vertical sections of the whole cores failed to disclose the the existence of these zones. Similar air void parameters were measured by this averaging technique for cores having both uniform and nonuniform air void distribution (Table 3).

Several cores in the investigation contained uniform air void distribution and satisfactory void spacing factors, but displayed light surface scaling. It is likely that the aforementioned air-deficient zones were once present at the wearing surfaces of these concretes, but they have since scaled to the level where an adequate protective air void system was encountered.

The observed nonuniformities in air contents and air void distribution appear to be the result of a number of factors. Batch-to-batch variations in air content may result from inadequate control of concrete batching and mixing operations. Thin, irregular zones deficient in air may result from improper placing and finishing procedures.

It was reasoned that cores from scaled areas might contain, on the average, an amount of chlorides different from that contained by companion cores from non-scaled areas. Quantitative analyses were made to learn if this was the case; however, the results indicated no substantial or significant differences for cores in the 2 groups.

In addition to these concrete properties, deck drainage has an important influence on the occurrence of scaling. Scaling was confined to the gutter areas of 32 of the 38 scaled decks (both air-entrained and non-air-entrained) and extended beyond the gutters on 4 other decks. The more extensive scaling in the gutter areas is undoubtedly brought about by the tendency for water and de-icer solution to pond in these areas.

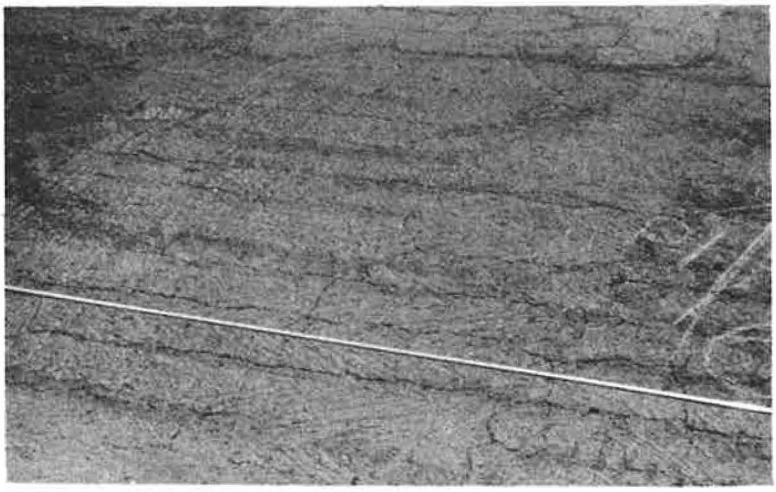

Figure 3. Heavy longitudinal cracking.

Cracking

Figure 3 shows heavy longitudinal cracking on a solid slab bridge. The cracks are relatively wide, are readily visible, and occur over each line of top longitudinal reinforcement. The cracks are not in the direction that would be expected of cracks due to dead loads or live loads, and their width and location indicate that these are not structural cracks. An apparent factor in the cracking found on the thicker concrete slab bridges is restraint to subsidence of the concrete (settlement during bleeding) imposed by the fixed reinforcement, or by void tubes in hollow slab bridges. Resistance to subsidence tends to result in cracking over and parallel to the top reinforcement, horizontal cracking at the sides of the bar, and a void beneath the bar—a situation that is aggravated as concrete slump increases.

Transverse cracking was the predominant form of cracking encountered in decks supported by longitudinal steel or concrete girders. The cracks usually developed in patterns characteristic of the superstructure type. Decks on steel girders tended to have rather uniformly spaced transverse cracking over the entire length of the deck. Decks supported by concrete girders, on the other hand, tended to have closely spaced tight transverse cracking in the negative moment areas over the supports and relatively little transverse cracking in the positive moment areas of the span. The significant longitudinal dead-load stresses that are developed in the decks of the concrete bridges apparently influence the transverse crack pattern, as compared to the uniformly spaced transverse crack pattern on the steel bridges that have only small dead-load stresses in the deck.

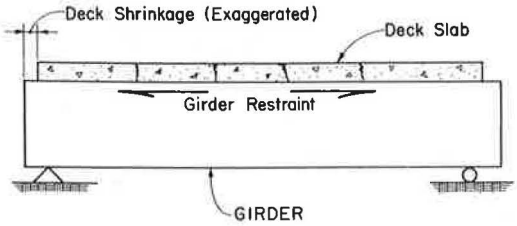

Figure 4. Girder restraint to longitudinal volume change.

The detailed investigations indicate that shrinkage and thermal volume changes of the concrete are particularly significant factors in the formation of transverse cracks. Figure 4 shows one aspect of the volume change effect in which the longitudinal steel girders restrain the shrinkage of the deck slab. The effect is less in decks supported by concrete girders because the difference in shrinkage between slab and girder is less. Restraint to overall shrinkage is also provided by the reinforcement in the deck slab.

Another aspect of shrinkage is the stresses induced by the differential drying rate through the thickness of the slab, as shown in Figure 5 for a slab drying from 2 faces. These stresses are in addition to the stresses induced by the overall shortening of the deck shown in Figure 4.

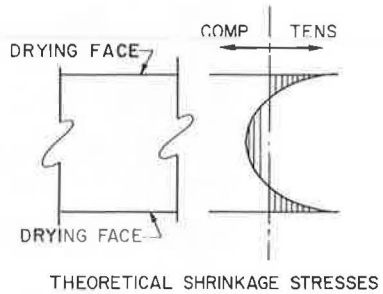

Figure 5. Distribution of shrinkage stresses through thickness of slab.

The pattern of transverse cracks shown in Figure 6 occurred on a deck with "trussed" or bent bars as part of the transverse reinforcement. The cracks developed only where the bent bars were near the top of the slab. It is believed that the reinforcement causes this type of cracking partially by the restraint to subsidence effect mentioned previously and, also, because the bar subsequently restrains the shrinkage of the top surface of the slab. The great majority of transverse cracks on decks supported by longitudinal girders were observed to occur directly over top reinforcing bars. In addition to providing restraint to shrinkage, these cracks are believed to form over bars because the bars act as stress risers in the concrete section under tension.

Spalling

Transverse and longitudinal cracks over reinforcement are of concern primarily because they may be contributing factors in the development of surface spalls. Figure 7 shows a core taken from a deck with an incipient surface spall. The black spot near the top of the core is a section of the reinforcing bar. The photo shows the typical crack over the reinforcing bar and, also, the cracks radiating from the bar that form the spall surface. Figure 8 shows a closer view of the bar, and the cracking may be seen to be associated with the cap of corrosion products on the top of the bar. This phenomenon—in which the corrosion products simply break away or push off the concrete over the top of the bar—was observed on nearly every reinforcing bar in cores taken through surface spalls.

Surface spalls were found frequently over bars with inadequate cover. In the Missouri detailed investigation (5), 13 cores were taken through reinforcement from sound areas of bridge decks. The average cover on the bars in these cores was $1\frac{3}{4}$ in. In

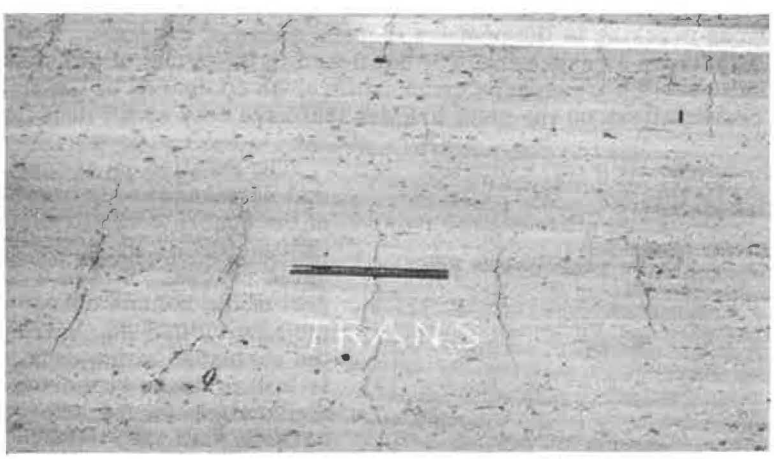

Figure 6. Transverse cracks over trussed reinforcing bars.

Figure 7. Core through incipient surface spall.

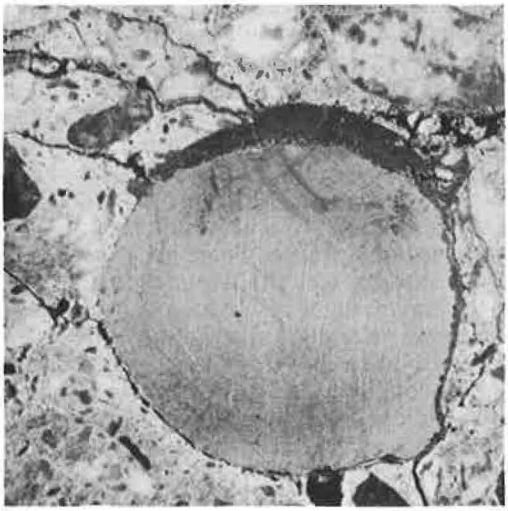

Figure 8. Corroded reinforcing bar (detailed view of core shown in Figure 7).

12 cores taken through spalled areas, the average cover was $1\frac{1}{4}$ in. However, there was not a consistent or direct relationship between depth of cover and the occurrence of surface spalls in the cores studied.

More than a thousand quantitative chemical analyses for chloride content as a function of depth were made on ground-up samples of the mortar in the cores. These analyses showed progressively higher chloride contents in (a) cores from sound decks, (b) sound cores from spalled decks, and (c) spalled cores from spalled decks (Fig. 9). This may reflect a higher permeability of spalled decks, or that more chlorides have been placed on the spalled decks. In either case, the higher chloride content at the level of the reinforcement has been shown to be related to the problem of corrosion and spalling.

It was mentioned previously that the random survey results indicated an apparent lack of influence on the part of factors such as superstructure type (steel versus concrete members), span length, or superstructure continuity (simple spans versus continuous spans) with the occurrence of surface spalling. All of these factors significantly influence the vibration characteristics of bridge superstructures. Although little data are available on the subject, it is reasoned by many that superstructure vibrations are a basic factor in bridge deck deterioration—primarily in transverse cracking and surface spalling.

In order to develop some data, the theoretical natural frequencies of vibration were calculated for 46 of the superstructures from the 4 detailed investigations, and the results were compared to the conditions

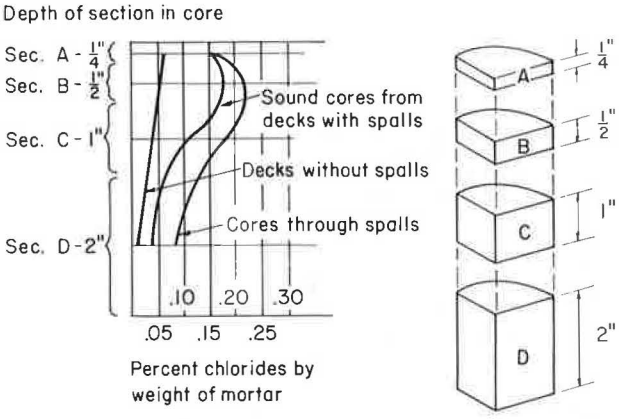

Figure 9. Average chloride distribution as a function of depth of concrete.

of the decks. The following types of superstructures were included: composite and noncomposite simple span steel bridges, simple span concrete bridges, noncomposite continuous span steel bridges, and continuous span concrete bridges. Calculations were made by considering both composite and noncomposite action for the steel spans, and gross section and transformed cracked section for the concrete spans. The calculations revealed no relationship between high or low frequency of vibration, or high or low dynamic impact values, and the condition of the bridge decks. It is emphasized, however, that this finding is only relevant to the levels of "flexibility" represented by the bridge designs studied, which reflect design practices used between 1940 and 1960. Many of these designs are very conservative compared to present practices.

To summarize, the basic cause of surface spalling is considered to be the corrosion of the top layer of reinforcement as a result of the use of de-icing chemicals. Cracks located over and parallel to the reinforcement, shallow cover, permeable concrete, and pressures developed by the freezing of water or de-icer solution in this weakened region contribute to the formation of spalls. Although the direct blows of vehicle tires undoubtedly contribute to the breaking up of the weakened concrete, the vibration characteristics of the bridges studied do not appear to be a primary factor in surface spalling.

SUGGESTIONS FOR IMPROVED DURABILITY

The massive use of de-icing chemicals on bridge decks, which has developed largely during the past 10 to 15 years, represents a significant increase in the severity of exposure conditions for reinforced concrete bridge decks. In order to provide durable decks in this type of environment, more attention must be given to design, construction, and quality of concrete for bridge decks.

Design recommendations for slab-on-beam bridges are shown in Figure 10. A minimum concrete cover of 2 in. is recommended over the top slab reinforcement. The 2-in. cover must be of dense, impermeable, low water-cement ratio concrete in order to provide an effective barrier against penetration of chlorides and corrosion of steel. The primary transverse top bars have been placed below the longitudinal "shrinkage and temperature" bars. This is a related measure for controlling the widths of shrinkage cracks that form over and parallel to the primary reinforcement.

Another design feature that has not received adequate attention in relation to bridge deck durability is drainage of the deck. The number, location, size, and details of the deck drains should be sufficient to drain the deck even in the event that some minor imperfection should develop during deck construction.

Consideration should also be given to the use of the 2-course bonded construction technique for initial construction of concrete bridge decks. The details of this type of

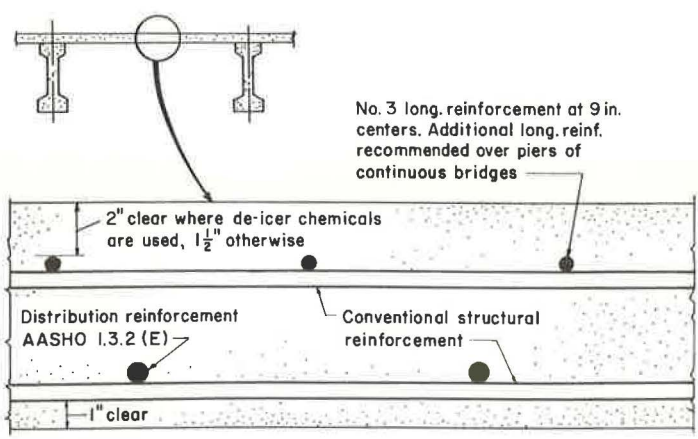

Figure 10. Design recommendations for slab-on-beam bridges.

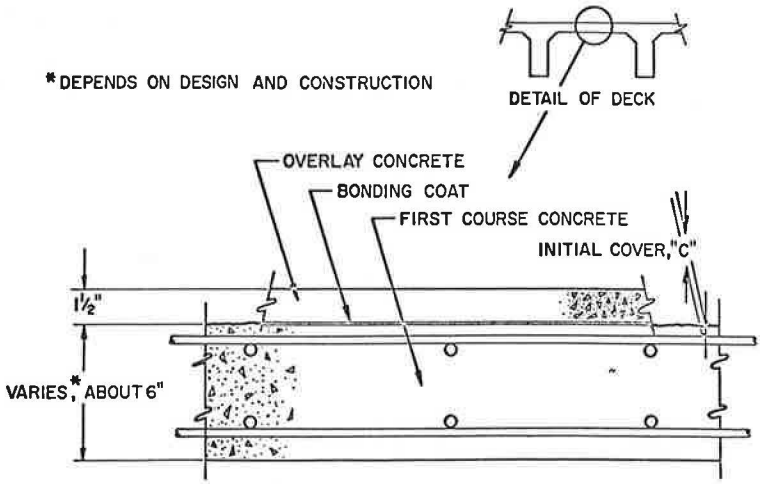

Figure 11. Two-course bonded construction.

construction (which is widely used for industrial floors) are shown in Figure 11. The surface course would be of very high-quality, low-slump, air-entrained concrete bonded to the first course with a portland cement, or an epoxy, bonding coat. The use of high-quality aggregates might be justified for the surface course, and precautions would be taken to obtain low shrinkage characteristics for the surface course. The technique tends to minimize the effect of restraint to subsidence by the reinforcement, and ensures that a specified amount of cover is obtained over the top reinforcement with placement of the overlay.

In regard to concrete quality, it is recommended that concrete used for bridge decks should conform to the specifications given in Table 4. The 4,500 and 4,000 psi compressive strengths are recommended on the basis of durability considerations, regardless of the values assumed for the purpose of structural design of the deck slab.

It is apparent from these cooperative studies, and from bridge deck studies made by many others, that inadequate construction practice has played a major role in the development of many present durability problems. Examples of shallow cover, ponding of water in gutters, high water-cement ratio pastes at the wearing surface, excessive

TABLE 4

SUGGESTIONS FOR QUALITY OF BRIDGE DECK CONCRETE

Maximum Size of Concrete Aggregate (in.)	Maximum Water-Cement (gal/bag)	Minimum Cement Content (bag/cu yd)	Air Content (±1 percent)	Slump (±½ in.)	Minimum 28-Day Compressive Strength[a] (psi)
		Freeze-Thaw Areas			
½	5	7.6	8	2½	4,500
¾	5	7.0	7	2½	4,500
1	5	6.6	6	2½	4,500
1½	5	6.2	5.5	2½	4,500
		Areas of No Freeze-Thaw			
½	5.5	7.0	5.5	2½	4,000
¾	5.5	6.4	5	2½	4,000
1	5.5	6.0	4.5	2½	4,000
1½	5.5	5.6	4	2½	4,000

[a]Not more than 20 percent of the strength tests should have values less than those indicated here.

variations in air content, improper finishing, inadequate curing, and other durability-reducing practices have all been observed, and are described in the volume of literature on this subject. Although the problems are generally recognized, much remains to be done to provide the adequate inspection and to obtain the improved practices that are required.

ACKNOWLEDGMENT

The views expressed in the paper are those of the authors and do not necessarily reflect the views of the U. S. Bureau of Public Roads or of the cooperating state highway departments.

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