Investigative Techniques Used or Contemplated

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Concrete deterioration in the decks of Missouri bridges, which has rapidly developed to a degree demanding a program of extensive maintenance and reconstruction, impelled an investigation aimed at solving the problem. During this investigation, considerable information has been gathered and various techniques devised and executed or contemplated. These are presented for the benefit of others concerned with the problem.

Investigation of the system or systems of factors producing extensive deterioration of bridge deck concrete requires (a) terminology to insure accurate identification of the different types of deterioration in various stages of development; (b) methods and procedures for making exploratory, reconnaissance, or semi-detailed surveys of many decks that will represent the entire population, and detailed observations and surveys on a limited number of decks selected for special studies; (c) the selection, procurement, examination, and testing of concrete samples from decks; and (d) the formulation and verification of hypotheses suggested by the observations and data. Experiences while fulfilling these requirements are described and discussed. However, the scope of the paper and the present state of progress of the investigation do not permit the presentation and discussion of available data.

• THE INVESTIGATION in Missouri is concerned with all types of deterioration encountered in bridge deck concrete, regardless of known or postulated causes. The detrimental effect of defects varies with types, as well as the degree of development. Some of the defects are known to be destructive. Others that are generally not detrimental may indicate future development of more serious defects or their presence may typify concrete of certain characteristics. The major defects that make the problem critical in Missouri are believed to be (a) fracture plane, (b) potholes, and (c) surface mortar deterioration.

Although the effects of de-icing agents may be considered an important contributory cause, this investigation has not been primarily directed toward the effects of de-icers. The fact that the major defects were apparently rare before the extensive use of de-icing agents clearly indicates the existence of relationships between the use of de-icing agents and the development of destructive concrete deterioration. However, because it is conceivable that changes in, or reduced control of, other factors may have occurred simultaneously with the development of de-icing practices, other possible primary or contributory causes are also suspected.

In view of prospects for even more intensive use of de-icing agents in the future, the role of these agents in the production of bridge deck deterioration becomes increasingly important. It appears imperative to determine promptly whether the application of de-icing salts merely accelerates the development of defects in poor concrete or concrete that other factors have made susceptible to deterioration, or whether their use is the primary cause for the deterioration of decks built with good concrete. This paper describes certain investigative techniques that have been used or are contemplated in Missouri toward determing this.

DETERIORATION

The first step in investigating deterioration in concrete is to describe and define any defects that may be anticipated so that they may be readily and unmistakenly identified. It is desirable to use uniform, objective terminology, avoid descriptions based upon causative reference, and if possible, provide photographs to illustrate each defect. (Definitions in HRB Special Report 30, "Pavement Condition Surveys," were used as a guide.) The following defects have been encountered in Missouri:

1. Cracking. — A crack is a fissure or cleavage visible in the surface. The depth of a crack may vary, but it generally extends into the concrete in a direction approximately perpendicular to the surface.

   a. Transverse Cracks. — Cracks that follow a course approximately at right angles to the centerline of the roadway.
   b. Longitudinal Cracks. — Cracks that follow a course approximately parallel to the centerline of the roadway.
   c. Diagonal Cracks. — Cracks that follow a course approximately diagonal to the centerline of the roadway.
   d. Crazing. — Pattern cracking apparently extending through only the surface layer. These shallow cracks tend to intersect at an angle of approximately 120°.
   e. Checking. — Discontinuous cracking consisting of relatively fine, shallow, and short cracks that may have no regular directional tendency, or may develop in an orderly manner in the surface layer.
   f. Pattern. — Interconnected cracks forming networks similar to those seen on dried mud flats. They may vary in development from very fine, indistinct, and relatively shallow to well-defined, open, and deep cracks.
   g. Hair Checking. — Relatively short cracks that often (but not always) tend to develop roughly parallel to one another but do not form a closed pattern. These cracks are often relatively wide (as much as 1/8 in.) at the surface along much of their length, tapering to very fine, barely perceptible cracks toward the ends. They may extend to an appreciable depth but not through the deck.

2. Fracture Plane. — This identifies a defect prevalent in many bridge decks. It has been found the predecessor of a splitting off or shelling out of the surface layer of the deck resulting in the formation of first, "potholes," and ultimately, the break-up and removal of the surface over large areas of the deck. The plane roughly parallels the surface of the deck and undulates from a maximum depth of about 2 in. to a minimum of ¼ in. or less below the top surface of the deck. The maximum depth is commonly found near the upper reinforcing bars and the minimum between consecutive parallel bars. In general, the concrete above the fracture plane has the appearance of being sound and of good quality. Sometimes it can be readily removed as unbroken slabs up to several square feet in area.

3. Potholes. — The depressions left in the surface of the deck when the concrete above the fracture plane has been removed. Their size, depth, and appearance depends on the amount of concrete removed.

   a. Incipient. — In the incipient stage, this defect may appear to be a small, irregularly-shaped area of scale. As development progresses halfmoon-shaped areas are common. The area produced by the breaking up of the surface above the fracture plane may assume meandering outlines but the depression characteristically is much deeper along one edge and feathers off along the opposite edge. The defect in its early stages often resembles a partially developed popout.
   b. Advanced. — In the advanced stages, the potholes enlarge and merge into one another resulting in large areas wherein, through traffic action, the surface layer of the deck is completely broken off and removed above the fracture plane. After this has occurred, the undulating characteristics of the fracture plane are evident; the exposed surface appears as a series of ridges and valleys paralleling the upper reinforcing bars which are exposed in the valleys, while the ridges can be seen, located in general midway between consecutive upper reinforcing bars.

4. Surface Mortar Deterioration. — Similar to what has often been called "progressive scale" by some observers or "salt scale" by others, it is a progressive eroding away of the surface due to deterioration of paste. The mortar in affected areas is not sound and is generally weak and friable.

a. Stage 1. — Areas where surface mortar has disappeared from spots, ranging in size from that of a nickel to a silver dollar, interspersed with larger areas where surface mortar is still intact. Depth of spots lacking mortar is only 1/8 to 1/4 in.; coarse aggregate is not protruding.
b. Stage 2. — Surface mortar disappearance is no longer spotty, but fairly well covers an entire area and has progressed in depth so that coarse aggregate is definitely protruding 1/8 to 1/2 in. above surface of remaining mortar.
c. Stage 3. — There has been sufficient progression in depth from Stage 2 that the topmost layer of coarse aggregate has shelled out and the underlying mortar is deteriorating.

5. Pitting. — The presence of pits or holes in the surface of the concrete due to disintegration of shale, lignite, mud balls, or other undurable particles. They may vary in size from that of fine aggregate particles to that of coarse aggregate particles.

6. Popouts. — The splitting out of an individual piece of concrete leaving depressions roughly the shape of an inverted cone.

7. Scaling. — Peeling away of the surface layer of mortar or paste. This layer may be paper thin with little strength or substance, or it may have sufficient thickness and strength to split off in small scales or plates, exposing sound concrete.

8. Spalling. — The breaking or chipping of the slab, at joints or cracks, usually resulting in removal of fragments of sound concrete, irregular in shape and thickness, feathering out along one or more margins to a thin edge.

9. Raveling. — The progressive disintegration from edges inward by the dislodgment of aggregate or concrete particles ("edges" may relate to cracks, joints).

RECONNAISSANCE FIELD SURVEYS

To determine the severity and distribution of the deterioration and to investigate the general relationships between the various defects previously identified and numerous specific causative factors, a reconnaissance field survey of a sample representing the entire population of bridge decks within the state is necessary.

Field surveys in Missouri were designed to acquire not only the exploratory and reconnaissance data but, simultaneously, voluminous quantitative data with the objective of determining (a) the distribution of bridges in various stages of deterioration with respect to age, location within the state, materials used, traffic volume, loading intensity, and design type; and (b) the distribution of defects and their progression with respect to position within spans, location and depth of reinforcing bars, length of span, quality of concrete, and variations in construction and maintenance procedures.

Attainment of these objectives requires, in addition to the field work involved in surveying a large number of bridge decks, the collection of a vast amount of data from plans, construction records, traffic studies, and other sources. To finish the work with a minimum of time and expense, procedures were established and detailed instructions prepared to permit the survey to be made by several two-man teams working simultaneously in the ten districts of the State. This tended to insure a steady influx of reports to the central office; each of which provided a commensurable record, complete for each bridge, and contained the desired data in usable, numerical form that could be readily assembled by office personnel to expedite analyses.

Figure 1 shows a prototype copy of the field report form, filled in for a hypothetical deck according to the following survey instructions:

1. Before beginning the actual survey, record on the reverse side of one sheet (Fig. 2), preferably the last for each bridge selected for study, the bridge data from office records. Any bridge longer than 100 ft and/or wider than two traffic lanes requires two or more sheets.

2. In surveying a deck, first measure off and mark the longitudinal limits of the subsections and locate the position of bents, expansion and construction joints, and lane widths on the roadway diagram on the data sheet.

A subsection (Column 1, Figure 1) is an area 10 ft long by one traffic lane wide. A traffic lane is the width reserved, or generally considered necessary, for a single lane

SHEET 1 OF 2

INV. 59-2 , BRIDGE DECK CONDITION SURVEY - TYPE C - RECONNAISSANCE

DATE 2-15-60 OBS. G. P. Powers BRIDGE NO. L-915

DETERIORATION

10' SUB-SECT. NO.	EXTENT OF DETERI-ORATION	CRACK-ING		HAIR CHECK-ING		FRAC-TURE PLANE		POT HOLES		SURFACE MORTAR DETER.		PITTING OR POPOUTS		OTHERS		ROADWAY 14'x14' LT. CURB C/L RT. CURB
		LT.	RT.	LT.	RT.	LT.	RT.	LT.	RT.	LT.	RT.	LT.	RT.	LT.	RT.	
10	NONE						1		0							
	SLIGHT	1	0	✓		2		1				✓	✓			Bent
	MODERATE	0	0		✓		1			2						
	SEVERE										1					
9	NONE					2	2	0	0							
	SLIGHT	0	0									✓	✓			
	MODERATE	0	0		✓											
	SEVERE			✓						1	1					
8	NONE			✓	✓											
	SLIGHT	2	3			4						✓	✓			
	MODERATE	0	0				2	2						①		C. J
	SEVERE						1		1	1	1					
7	NONE			✓	✓	2	2	0	0							
	SLIGHT	0	0				1					✓	✓			
	MODERATE	0	0													
	SEVERE									2	2					
6	NONE			✓				0	0							
	SLIGHT	0	0			2	5					✓	✓			
	MODERATE	2	2		✓						3					
	SEVERE					1				2						
5	NONE			✓	✓	2	2	0	0							
	SLIGHT	0	0							2	2					
	MODERATE	0	0									✓	✓			Bent
	SEVERE															
4	NONE			✓	✓	3	2			0						
	SLIGHT	2	0					3			1		✓			
	MODERATE	0	1						3			✓				
	SEVERE															
3	NONE			✓	✓	2	2	0	0	0	0		✓			
	SLIGHT	0	0									✓				
	MODERATE	0	0													C. J.
	SEVERE													②		
2	NONE			✓	✓	3	3			0	0	✓	✓			
	SLIGHT	2	0					1								
	MODERATE	0	1						1							
	SEVERE															
1	NONE			✓	✓	4	2	0	0	0	0	✓	✓			
	SLIGHT	1	1													
	MODERATE	3	0													
	SEVERE															Exp. Jt.

LENGTH OF SPAN: 54½' ; 44'

BEGINNING OF DECK (LOW STA. N. END)

NOTES: * Surface mortar deterioration generally confined to outside ¼ to ⅓ of lanes, next to curb

① 3 small asphalt patches totalling 5 □'
probably filling pot holes.

② Margins of construction joints badly ravelled.

Figure 1.

BRIDGE DATA

COUNTY Cook BRIDGE NO. L-915 PROJ. NO. F-41(10) DATE LET 10-5-52

RT. 37 S. BOUND traffic only.

LOCATION 7.3 miles south of Crow Co. OVER Skunk River

TYPE OF SUPERSTRUCTURE 3 span(44'-54½'-45½') continuous I-Beam.

LENGTH 144' ROADWAY 28 FT. 2 LANES of 2

NOTES:

Figure 2.

of traffic. Any bridge 18 to 28 ft wide is considered to have two traffic lanes, regardless of whether the flow of traffic is in the same or opposite directions. Wider decks should be considered to have three or more traffic lanes unless specifically marked for only two lanes.

3. The procedures for estimating and recording the intensity and extent of the different defects in each subsection are explained in the following:

a. Cracking. — Opposite "slight," record number of cracks less than one-half traffic lane long. Opposite "moderate," record number of cracks greater than one-half traffic lane long. (Most of the bridges surveyed had transverse stress bars as top reinforcing; hence, the column under "cracking" was used mostly for transverse cracks. If other types of cracking were encountered, an explanation was given under "notes." It would be preferable to differentiate in the survey notes between longitudinal, transverse, and diagonal cracking.)

b. Hair Checking. — Place a check mark opposite:

None, if none is present;
Slight, if under 5 percent subsection area is affected;
Moderate, if 5 to 15 percent of subsection area is affected; or
Severe, if over 15 percent of subsection area is affected.

c. Fracture Plane. — For each subsection of bridge, test areas as follows:

(1). When no cracks or potholes are present, sound for hollowness, using a steel rod or hammer, at least one area 2 ft in diameter in each wheel track;
(2). When no cracks and/or potholes are present, sound at least two 2-ft diameter equivalent areas, either along a crack and/or around a pothole.

Record opposite:

None, number of "tested areas" revealing no hollowness;
Slight, number of "tested areas" revealing hollowness over area under 2 sq ft;
Moderate, number of "tested areas" revealing hollowness over area 2 to 6 sq ft;
Severe, number of "tested areas" revealing hollowness over area over 6 sq ft.

d. Potholes. — Three stages of potholing are defined as follows:

Stage 1. — Incipient, as described under previous definition of potholes,
Stage 2. — An incipient pothole in which the spalled area has increased in depth to ½ in. or more, but has not extended laterally sufficiently to expose a reinforcing bar;
Stage 3. — A pothole in which the spalled area is ½ in or more deep, and which has extended laterally to or over a reinforcing bar.

For each subsection of the bridge, record the stage number that designates the most advanced stage opposite:

Slight, if affected area is under 2 sq ft;
Moderate, if affected area is 2 to 6 sq ft;
Severe, if affected area is over 6 sq ft.

e. Surface Mortar Deterioration.— Three stages of surface mortar deterioration have been described. Show the stage number, designating the most advanced stage present, opposite:

Slight, if affected area is under 2 sq ft;
Moderate, if affected area is 2 to 6 sq ft;
Severe, if affected area is over 6 sq ft.

f. Pitting, Popouts. — Place a check mark after:

None, if none is present;
Slight, if general average is 1 or less per sq ft;
Moderate, if general average is 1 to 3 per sq ft;
Severe, if general average is over 3 per sq ft.

g. Others. — Record other pertinent defects and explain under notes at bottom of page, using legend if necessary.

The data collected in these surveys are to be sorted, tabulated, and subjected to statistical analyses.

COMPREHENSIVE FIELD SURVEYS AND STUDIES

In making the reconnaissance surveys it became apparent that the available data in construction records were inadequate to determine the relationship of the defects to variations in (a) quality of the concrete, and (b) concrete placement, finishing and curing procedures. This is due to construction records not being sufficiently detailed to permit location of such variations.

Therefore, an extensive study of construction details and comprehensive sampling and testing of the concrete was made during construction of several deck pours. These observations and tests provide information regarding the following variables and the location of the concrete in the deck affected by them:

1. Air and concrete temperatures;
2. The slump or consistency of the concrete;
3. Air content of the concrete;
4. Elapsed time between start of mixing and placement of concrete on deck;
5. Elapsed time between start of mixing and the various finishing operations, including start of wet curing;
6. Elapsed time between placement of contiguous portions of concrete;
7. Elapsed time between placement of portions of concrete in any transverse section;
8. Positioning and tying of reinforcing steel;
9. Amount and difficulty of finishing the concrete;
10. Time and rate of bleeding; and
11. Unusual construction practices or procedures that might affect the serviceability of the concrete.

During these observations the occurrence and location of cracks were noted, although most of them were obliterated by the final finishing and brooming operations.

A detailed survey of the decks was made within a few weeks after completion, and defects in the surface were located on a strip map. Additional detailed surveys of the decks will be made periodically to determine the time of occurrence and rate or progression of defects.

The data obtained from these observations and surveys should permit an evaluation of the relationship of defects to some variations in construction practices and properties of the concrete.

Periodic detailed surveys of other selected decks are being made to obtain additional information on the time of occurrence and the progression of defects. Some difficulty has been encountered in continuing surveys because of preventive treatments that were deemed necessary for bridge maintenance.

Although the previously described surveys of defects in the top surface of decks are being made, it may be both expedient and profitable to survey the bottom surface of a deck. For example, it became necessary to determine the extent of deterioration of the concrete in a deck that was covered by approximately 4 in. of bituminous mixture. In accomplishing this, a detailed survey of the apparent deterioration on the bottom surface of the deck from the ground, some 20 to 30 ft below, was most valuable.

In addition to these surveys, measurements of the depth of the concrete over the top reinforcing bars have been made on several bridges. These measurements were made with a covermeter having a maximum range of 2 in. It is hoped that within a short time a covermeter can be obtained that will have a greater range. In checking the depth of cover, a minimum of three readings were obtained along every tenth transverse bar in each traffic lane of the deck. Due to the amount of time involved in making these measurements, a check of the depth of cover will be made only on selected areas or bridges. These measurements are to be used to determine the relationship between defects, particularly fracture plane, potholes, and depth of cover over the top reinforcing bars.

An exploratory study, made in conjunction with personnel of the Portland Cement Association, had as its principal objective determination of the feasibility of soniscope tests in detecting the presence of any fracture plane in deck slabs. Two conclusions (1) were reached:

1. The soniscope appears to be a suitable piece of testing apparatus for investigating the condition of concrete in a bridge deck slab.
2. "Sonic" tests, as they were tried, are too slow and costly to be useful.

PROCUREMENT, EXAMINATION, AND TESTING OF CONCRETE SAMPLES

The information obtained from field surveys and observations must often be supplemented and verified by examination and testing of numerous concrete samples taken from bridge decks. Following is a brief discussion of procedures used in procuring, examining, and testing such samples.

Procurement of Samples

In general the samples of concrete are 4-in. diameter cores drilled with a diamond bit. The use of the diamond bit permits sampling of deteriorated as well as undamaged concrete. The cores are exceptionally smooth, and it is believed that the properties of the concrete in the specimens are not seriously affected by the drilling operations.

The location, number, and length of cores to be taken from each deck depends on the objectives and the destructiveness of tests. It may be as simple as taking a short core from a specific location to determine the depth or degree of rusting of the top reinforcing steel, or the depth of a crack. Also, it may be as intricate as obtaining sufficient cores (full depth of deck) to determine the extent of deterioration in a deck, or the variations in the properties of concrete in deteriorated and undamaged areas. To accomplish these varied objectives, it may or may not be necessary to use a system of random sampling.

Macroscopic and Microscopic Examination of Cores

Visual examination of the cores includes an inspection of the top reinforcing bars for depth of cover and degree of rusting, the concrete for evidence of poor quality and compaction, the aggregate for deleterious particles, and the core for type and depth of deterioration.

Microscopic examination of cores, in addition to that required in making linear traverse measurements, reveals more extensive cracking than macroscopic examination.

It is contemplated that the microscopic examination of the concrete will include a study of the concrete adjacent to cracks for evidence that the crack did or did not form while the concrete was plastic, and a determination of the air bubble size distribution.

Testing

Various tests have been made on whole cores and segments of cores.

The dynamic moduli have been determined for whole cores andfor disks sawedfrom the core at different depths. Appreciable variations in the dynamic moduli have been found, particularly for whole cores. In fact, the variations exceeded that anticipated from macroscopic examination. The probable reasons for the sensitivity of this test is that in the deterioration of bridge decks the planes of weakness tend to be parallel to the surface. Therefore, as these planes of weakness develop, the flexural resonance frequency of the core is greatly reduced.

The mix composition of the whole and various segments of some of the cores is being determined, using an unpublished testing procedure. (A paper describing this testing procedure is to be published in 1962.) This testing procedure requires the determination of the porosity and of the cement paste, air, and aggregate content of the hardened concrete. From these determinations the cement factor, water-cement ratio, and the cement to aggregate ratios are calculated. To date, the results of this test have been most encouraging, and valuable information is being obtained to substantiate or to disprove some hypotheses that have been advanced to explain the system of factors producing various types of deterioration.

A few cores from deteriorated and nondeteriorated areas have been tested in compression. As expected, the results again demonstrated that concrete may be rather severely deteriorated, yet show only minor loss in compressive strength.

Another contemplated phase of laboratory testing of the concrete in bridge decks is to determine the change in chloride concentration of the concrete before and after the season of salt applications. Samples of the concrete will be obtained from several locations on a bridge deck late in the fall and early in the spring. To determine the effect of depth, samples will be taken to represent the concrete in each $\frac{1}{2}$ in. of the top 2 in. of the deck, and the chloride content of each sample determined.

FORMULATION AND VERIFICATION OF HYPOTHESES

Numerous hypotheses have been formulated by observers to explain the systems of factors producing the various types of disintegration. To attempt to enumerate all of these hypotheses is not within the scope of this paper; however, it might be noted that such a list would undoubtedly include most factors dealing with design, material, construction, traffic and maintenance.

It is hoped that the investigative techniques described herein will provide a basis for greatly reducing this list of hypotheses. Even then, the task of verifying the remaining hypotheses by laboratory tests will undoubtedly be difficult in that new and untried testing techniques may be required. In fact, verification of some hypotheses (particularly those indicating a relationship between the defects and bridge type or design features) by laboratory tests would appear to be impossible for most, if not all, laboratories due to the necessity for large specimens and elaborate testing procedures.

To date the work on verification of hypotheses has been very limited and only partially successful. Primarily the laboratory work on this phase has been largely limited to trying to develop fracture planes in 8- by 18- by 8-in. reinforced concrete blocks. Although transverse settlement cracks over the top reinforcing bars (which is believed indicative of the formation of a plane or thin zone of weakness in the deck similar in location and shape to those of a fracture plane) have been produced, no fracture planes have been developed.

ACKNOWLEDGMENT

Most of the investigative techniques described herein were initiated under the supervision of T. F. Willis, former Chief of Research, who died on August 21, 1961.

REFERENCE

1. Oleson, C. C., "Soniscope Tests – Missouri River Bridge, Jefferson City, Missouri." Portland Cement Association Research and Development Laboratories, Skokie, Ill.