Random Cracking of Bridge Decks Caused by Plastic Shrinkage

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•IN THIS STUDY the problem was to determine the causes of severe random cracking that had affected two of four reinforced concrete spans on an Interstate System bridge. This cracking, shown in Figure 1, was severe enough to allow water and de-icing salts to pass through the slab and attack the stringers as shown in Figure 2. The cracking covered 100 percent of the surface of span 1 and approximately 25 percent of the surface of span 4. The remaining two slabs were unaffected. The reasons for determining the causes of the cracking were to provide bases (a) for preventing recurrence on subsequent projects and (b) for recommending repair procedures.

INVESTIGATION OF THE PROBLEM

The overall characteristics of the cracking based on visual survey were similar to those attributed by Lerch (3) to "plastic shrinkage" and suggested that the cracking had occurred early in the life of the deck. Because the cracking had not been noticed until after two winters of traffic, the first step was to establish the nature of the cracking in terms of time of occurrence.

To accomplish this, two 4-in. diameter cores were removed from the cracked area for petrographic examination. Examination of these cores indicated that the cracks traveled around rather than through aggregate particles. Considering this finding and the fact that the strength of the concrete was high based on information from construction records and the petrographic examination, it was possible to conclude that the cracking occurred when the concrete was relatively green and perhaps fresh. This conclusion was supported by an earlier investigation (4) of a similar though less severe occurrence in which it was shown, from a petrographic examination of cores, that the curing compound actually penetrated into the crack as shown in Figure 3, thus proving that formation of the crack preceded or very closely followed the application of curing compound. Results from an earlier, unpublished laboratory study of similar quality concrete suggested that the absence of broken aggregate associated with the crack indicates that the crack occurred during the initial 24 hours.

Figure 1. Random cracking in span 4 (surface damp).

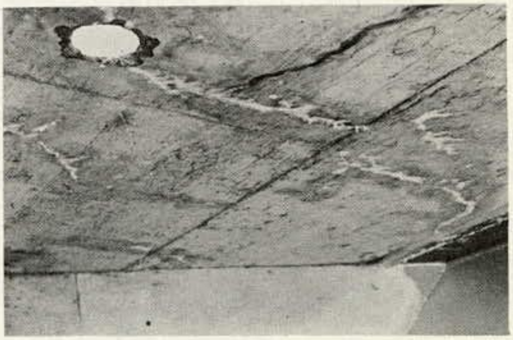

Figure 2. Underside of span 4 showing leaching through cracks and corrosion of longitudinal stringer. Core was removed from hole at upper left.

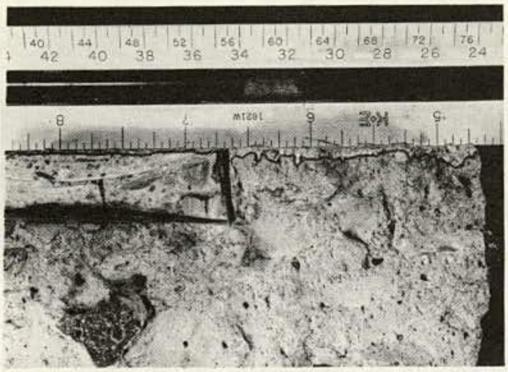

Figure 3. Top of core removed from a bridge showing random cracking. The right side shows penetration of curing compound into crack to a depth indicated by the dark line. The normal depth of curing compound is indicated on the sawed left section of core.

The petrographic examination of the cores revealed no characteristics indicative of any adverse reactions that would suggest delayed or continuing formation of cracks.

Although the cracking was mostly random, in certain areas it appeared to be influenced by the top reinforcing steel. This may be seen in Figure 1. This is also consistent with the view of plastic shrinkage expressed by Blakey (1) that, as evaporation takes place and the surface drys, the resistance to sedimentation is greater over the reinforcement, which then controls the location of the crack that would otherwise form randomly.

After it was established beyond reasonable doubt that the problem was early and probably plastic cracking, the next step was to determine the factors that influenced the crack formation. Operating on the assumption that the cracking was caused primarily by plastic shrinkage, data concerning the mixtures and weather conditions were accumulated for study. Lerch (3) has identified the following factors as important contributors to the development of excessive plastic shrinkage: (a) high concrete temperatures (more precisely, large differential temperature between concrete and surrounding air); (b) low relative humidity; and (c) high wind velocity.

The construction, materials, and testing records indicated no differences among the concretes in the four spans that would be expected to result in high shrinkage. The information of primary interest in these records was the time during which concreting took place. Routine construction records did not contain sufficient weather data to

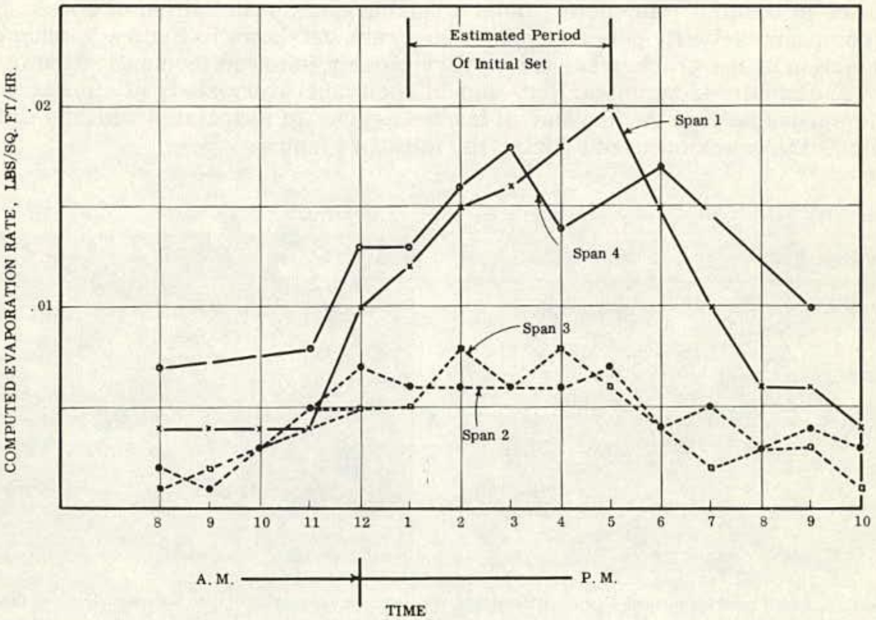

Figure 4. Variation with time of computed evaporation rates for spans 1 and 4 (cracked) and 2 and 3 (uncracked).

TABLE 1

IMPORTANT ATMOSPHERIC CONDITIONS FOR SPANS 4 (CRACKED) AND 2 (UNCRACKED)

Hour	Air Temperature (deg F)		Wind Velocity (mph)		Relative Humidity (percent)	
	Span 4	Span 2	Span 4	Span 2	Span 4	Span 2
8 a.m.	37	32	16	0	57	88
9 a.m.	—	37	—	2	—	82
10 a.m.	—	42	—	3	—	76
11 a.m.	44	49	16	4	43	45
12 noon	48	52	14	3	43	41
1 p.m.	49	53	13	3	38	28
2 p.m.	50	57	17	4	36	27
3 p.m.	53	59	18	3	33	30
4 p.m.	54	59	15	4	32	43
5 p.m.	55	57	16	4	30	47
6 p.m.	—	52	—	2	—	50
7 p.m.	—	49	—	6	—	60
8 p.m.	49	47	22	2	50	65

indicate conditions at critical times. Fortunately, however, the project was within 10 miles of an airport at which the Federal Aviation Agency hourly monitors important weather conditions. From this station, hourly measurements of air temperature, wind velocity, and relative humidity were obtained for use in estimating the rate of evaporation as recommended by the Portland Cement Association based on the work of Lerch (5). Unfortunately, concrete temperatures were not available so evaporation rates were computed based on the assumption that the concrete temperature was 10 F higher than that of the air.

It was assumed, on the basis of data from a previous study (2), that the time between placement and setting, during which plastic cracking could occur, was 5 hours. Computed evaporation rates, based on a differential temperature between concrete and air of +10 F, are plotted in Figure 4. The evaporation rates for placement days on which slabs cracked are similar and significantly higher than those for the days on which unaffected slabs resulted. The computed values are above 0.10 lb/sq ft/hr and approach 0.20 lb/sq ft/hr. Guides furnished by the PCA (5) state that there is no way to predict with certainty when plastic shrinkage cracking will occur. When the rate of evaporation is as high as 0.2 to 0.3 lb/sq ft/hr, precautionary measures are almost mandatory. However, if the rate of evaporation exceeds 0.1 lb/sq ft/hr, cracking may occur.

Although plastic shrinkage cracking is normally associated with hot weather concreting, experience in Virginia has shown that spring and fall are more critical times because of the occurrence of higher winds and lower humidities than are common in summer. For comparative purposes, the important atmospheric data for span 4 (cracked) and span 2 (uncracked) are given in Table 1. In these cases the controlling factor was the wind velocity. In other cases where the wind has been moderate and the temperature higher, the relative humidity has been the controlling factor.

Because the purpose of this paper is to indicate very briefly the approach used to document the cause of the observed distress, an extended discussion of plastic cracking is not warranted. This may be found in the references cited. Many factors exert an influence to reduce the severity of the cracking and some of these may not yet be recognized. The results of the investigation outlined in this case study have, however, been substantiated in other cases studied by the author as well as in an extensive case study in progress.

The results obtained in this and other case studies indicate that when early random cracking occurs, the severe drying conditions as reflected in the computed evaporation rate exist. The existence of the severe conditions does not always result in this early cracking. This would suggest that the cracking can be prevented, or at least can be reduced in severity, by construction factors that modify the influence of the four major variables of air temperature, concrete temperature, wind velocity, and relative humidity. This suggestion confirms the views expressed in the references cited earlier, as well as the study reported by Shalon and Ravina (6), that there is still need for study of the phenomenon of early cracking.

ACKNOWLEDGMENTS

Appreciation is expressed to the Field Forces of the Virginia Department of Highways who assisted in the accumulation of the data used in this report. The late Tilton E. Shelburne, State Highway Research Engineer, who guided a continuing program of highway research, was a great help in this study. The work was financed from Highway Planning and Research funds administered by the U.S. Bureau of Public Roads.

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Discussion

BRYANT MATHER and H. G. GEYMAYER, U.S. Army Engineer Waterways Experiment Station—The author has presented in a most interesting and instructive way a case history of plastic shrinkage cracking. This condition has been considered to be a reaction of unset concrete to the consequences of certain combinations of ambient conditions that result in an excessive rate of evaporation of moisture from the concrete surface. Little or no attention appears to have been given to other factors that may influence the degree to which a given concrete surface develops cracks in this period.

At the instant the consolidation of the concrete has been accomplished, it might be assumed that the surface of that concrete could be considered to have no tensile stresses. If, over a period of time, such stresses develop so that at some later moment the stresses have a magnitude in excess of the tensile strength that develops concurrently in the surface, cracking will occur. However, the magnitude of the stresses is not predictable entirely from the evaporation rate nor is the development of tensile strength a constant for all concretes.

In his last paragraph, the author suggests that the existence of severe evaporation conditions does not always produce cracking. We believe it might also be suggested that, when cracking does occur, the stresses that cause cracking are not always caused solely by the consequences of the evaporation induced by the severe ambient drying conditions. Some of the tensile stress that can, and certainly must in some cases, contribute to early cracking must be produced by autogenous volume changes in the concrete itself as hydration of the cement proceeds. Similarly, the failure of cracking to develop under severe ambient conditions must, in some cases, be due to the prolonged retention of plasticity, the accelerated development of tensile strength, or the possession by the concrete of a pore structure that causes the drying influence to act with reduced efficiency in extracting moisture from the mass. These appear to be some of the factors that merit further study.

HOWARD H. NEWLON, JR., Closure—The author agrees that the factors outlined by Mather and Geymayer can be influential in the occurrence of cracking or lack thereof. It did not seem necessary to consider them in the specific case described, which is most typical of those brought to the author's attention. Such factors are always considered when studying cases of cracking where records show that severe environmental factors did not exist. In the vast majority of cases of slabs exhibiting the type of cracking described in the paper, detailed study has shown that high wind and low humidity did exist. Seldom, if ever, have we studied cracking of this type where the severe environment was absent.