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DECK RIPPLING ON VARIOUS MICHIGAN BRIDGES
Third Progress Report

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ABSTRACT: Rippling of varying severity is described on bridge decks constructed or widened at various times, with different finishing methods. The general pattern is raised areas between bars and depressions over bars. Several deck failures are described with reference to age at time of repair and effect of bar splices on surface spalling. Comments are given concerning depth of concrete cover, shrinkage, cracking, and vibration of the bridge structure during concrete placement. Study of the rippling phenomenon will continue.

KEY WORDS: bridge decks, finishing, construction equipment, construction operations, concrete bridge decks, concrete finishing, concrete placing, spalling, cracking, vibrations.

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For information of W. W. McLaughlin, and in reply to points raised by N. E. McDougall in his letter to H. E. Hill dated August 3, 1966, the following report has been prepared. Mr. McDougall, in part, was concerned with information in the first correspondence on this research project, a memorandum from the author to E. A. Finney dated July 18, 1966, concerning rippling of the concrete deck on the Rouge River bridge. A second progress report on this subject has been prepared by L. T. Oehler and G. R. Cudney and published as Research Report No. R-607.

It is regretted that the last sentence of the first paragraph of the July 18 memorandum contained an error concerning dimensions--the Rouge bridge plan requires 2 in. from the concrete surface to the center of the top rebars, not 1-1/2 in. as erroneously stated. Section 5.06.03-c of the Standard Specifications for Road and Bridge Construction states, in part, "...the clear distance from the surface of the concrete to the reinforcement shall not vary from the distance shown on the plans by more than 1/4 of the plan dimension." Since the plan calls for 2 in. to the center of the bar, the clear distance above a 3/4-in. bar would be 1-5/8 in. The tolerance would then be $\pm$ 13/32 in. or roughly $\pm$ 3/8 in., making the allowable range for clear distance or "cover" about 1-1/4 to 2 in. E. L. Marvin of the Research Laboratory's Structures Unit has checked nearly 100 locations on 30 different spans of the Rouge River structure with the pachometer, and found no case in which the cover was less than the minimum specified. Troughs of the ripples coincide closely with the location of the top transverse bars in all cases checked.

Mr. Marvin also checked records of slump tests, as requested by the Bureau, and could find no correlation between slump and severe rippling. D. J. Hines, Resident Engineer, stated that some concrete with less slump had been tried, without evident reduction in the amount of rippling.

The maximum ripple depth observed was 7/32 in., on the southbound girder span, over the river, which is evidently the worst to date. Ripples slightly in excess of 1/8 in. deep were located on various spans of this structure, but the area covered by such ripples is very small.

There seems to be no correlation whatever between the use of the longitudinal finisher and the occurrence of ripples. Two local structures (the Bogue St. Bridge at MSU and the Oakland St. Bridge here in Lansing) were finished longitudinally and show no rippling. Several other structures on I 96 and I 496 in the Lansing area show rippling to varying degrees, although finished with a transverse machine. Figure 1 shows ripples nearly 1/8 in. deep that occurred in widening of a structure on I 94 near Benton Harbor that was hand finished with transverse strike-off. Note the similarity of the wave form to that found on the Rouge Deck. The I 94 bridges were widened under traffic, and therefore received severe vibration during cure.

During the widening of 19 structures on I 94 last fall, placement of deck concrete was observed on about 100 spans. Depressions over the bars in freshly finished concrete, similar to those shown on the Rouge Bridge deck in Figure 4 of Research Report No. R-607, were noted in many cases. Once the concrete had set, however, these depressions were very hard to find if no further rippling had occurred. Rippling of areas between bars took place over a period after the deck finishing was complete, as Mr. Hines has indicated to be the case on the Rouge deck. The final pattern was a combination of depressions over bars with raised areas between bars. It was noted that depressions over bars seemed more visible when the top deck steel was closer to the surface. Hand finishing a deck with a "bull-float" propagates a fluid-like wave preceeding and following the float, with some vertical displacement of the concrete. The bars prevent vertical motion of the concrete at those particular locations, which seems to be the cause of the small depressions over the bars when hand finishing is used. Any downward pressure on fluid concrete causes a local depression, with consequent elevation of nearby areas. It may be that the longitudinal finisher forms a slight "wave" before and behind itself, similar to the bull-float, resulting in discontinuities near bars with accompanying depressions. Since many of the bridges have surface cracks in the area directly over the bars, one might wonder if some changes in aggregate content and water-cement ratio do occur in the depressions over the bars.

E. L. Marvin has extracted information from Pickett's hypothesis concerning shrinkage (published in the ACI Journal, Vol. 27, pp. 581-90). Pickett worked with shrinkage of concrete as a function of aggregate content and water-cement ratio. Using Pickett's equations and the design mix for the Rouge deck, Mr. Marvin calculated that shrinkage of a paste could vary from the shrinkage of the parent concrete by factors of 5 to more than 10 to 1, depending on the extent to which aggregate is displaced and water cement ratios are increased. Since cracking over the bars leads to large-scale spalling of the deck, it seems to be more important to prevent cracking than mere rippling, although the ripples may aggravate the cracked deck by concentrating salt in the cracked areas.

If the cause of cracking over bars is as predicated here, there is a new development that might be helpful in preventing formation of such depressions. Some finishing machine manufacturers are now making finishers with screeds that vibrate rather than oscillate. If such a finisher could be used without subsequent floating, it might produce a more durable deck. Also, since concrete flows more easily under local vibration, the tendency of the screed to ride up on the concrete might be decreased, resulting in a smoother deck. On the negative side, such a machine could possibly cause undesirable flow on decks with considerable grade or superelevation, depending upon the depth to which the screed affects the concrete. It would be interesting to see one of these new machines in service.

Many instances have been noted where salt has caused disintegration of concrete, in bridge decks and pavement joints, even when no cracks are present. It would therefore seem reasonable to keep the top rebars as far below the surface as possible to prevent corrosion due to salt penetration. Any expansive action at the bar level would tend to initiate the fracture-plane type of deck failure discussed by G. R. Cudney in Research Report No. R-584. Once this type of fracture is initiated, it can expand to cover large portions of a deck.

The Missouri State Highway Department requires a minimum 2 in. of concrete cover over the bars, limits concrete slump to 4 in., and emphasizes certain curing and finishing operations in an attempt to improve performance of bridge decks. Although no research is known to have indicated a given depth beyond which no further problems will occur, decks with steel cover in the range of about 1 in. have been observed to tend to spall off quite quickly, and cover in the 2-in. range seems to last appreciably longer. Some interesting data along this line should result from Research Project 65 F-84, concerning the performance of the widened decks on I 94 in the St. Joseph Area.

Michigan's present specifications do not allow more than 2 in. of cover, but do permit cover as low as 1-1/4 in., which would not seem to be sufficient for long-time performance of a deck. It would seem reasonable, then, to attempt to set the steel toward the lower limit of Michigan's specification wherever possible, especially where bar splices are concerned. Also, since spalling is more probable over bar splices, it might be wise to emphasize deeper setting of bars in splice areas. It is recognized that there is a decrease in the theoretical slab action by setting steel deeper; however, any theoretical gain due to setting steel high is extremely short-lived when the high steel causes surface spalling. Once the concrete has spalled away from a bar splice, the splice no longer functions and one has essentially the equivalent of a broken bar as far as tensile or compressive forces in the steel are concerned.

The effect of bar splices on surface distress is shown very well in Figure 2, taken by M. G. Brown on X01 of 38101, on I 94 north of Jackson where repairs are currently underway. All loose concrete has been removed from the area, and it is being made ready for patching. The structure was built in 1949 and reportedly has 1-1/4 to 2 in. of cover.

Another structure currently under repair is S05 of 38111, on US 127 over I 94 northeast of Jackson. This structure was built in 1958, and has extensively cracked and spalled areas on the deck as shown in Figure 3, also obtained from M. G. Brown. Note that slight deck rippling is apparent in these photos, especially in the foreground of Figure 3b. The pothole in the left of Figure 3c is probably the result of the fracture-plane cracking previously mentioned. Concrete cover on this bridge is reportedly 1-1/4 in. or slightly less.

Figure 4 was also obtained by M. G. Brown, and shows a portion of deck deterioration on X01 of 38131, on US 127 over NYCRR north of Jackson, before and after the removal of loose concrete. This structure was built in 1957. Here again some of the first areas to spall away were over bar splices. Similar failures occurred on S02 of 38131, on M 50 over US 127.

These specific cases and many other observations, coupled with the combination of circumstances on the Rouge deck (i.e., depressions over bars with anticipated cracking in those areas, ripples between bars which will concentrate salt solutions over them, and a bar splice in the gutter area) were the basis for the conclusions stated in the author's July 18 memorandum to E. A. Finney.

Concrete for repairs costs somewhere between $200 to $400 per cu yd depending upon traffic conditions and amount of formwork required. Concrete patching under traffic has not been entirely satisfactory. Several areas are being patched with higher priced but more flexible and durable materials, especially in urban areas where traffic cannot be removed from structures during repair. With costs increasing sharply for repair work in high traffic density areas, it would seem reasonable to apply preventive maintenance to structures wherever possible prior to opening to traffic. This means far less cost to the Department in the long run, and eliminates the traffic tie-ups and disruptions that inevitably result from maintenance under traffic.

The real solution to bridge deck performance probably lies in the use of some type of flexible sealant to keep water out of cracks that form, combined perhaps with whatever measures can be reasonably instituted to keep cracking to a minimum. It may be that a reasonable system of sealant plus a flexible wearing course can be developed, similar to that suggested by Orrin Riley in "The Development of a Bridge Protective System," for HRB Committee M-10, Maintenance of Structures.

To summarize briefly, ripples are fairly common on Michigan bridges. Those on the Rouge bridge are of greater magnitude than normally encountered. Rebars are located at troughs of the ripples in all cases checked, both on the Rouge and elsewhere. Ripples of small magnitude are not necessarily detrimental in themselves, but may aggravate other undesirable tendencies.

The Rouge deck seems to differ from most other decks in five ways--the use of slag aggregate, the volume involved, the length of the girder spans, the amount of retarder used, and the amount of grade and superelevation. Since acceleration or vibration on the structure have not been measured, no positive statements can be made in that regard. However, it seems to be agreed that the major rippling occurs over a period soon after finishing is completed. No forces are known to be acting upon the concrete then other than gravity and inertial forces due to vibration of the structure.

Concrete cover of at least 2 in. is believed necessary for longer bridge deck life, but even that amount will not necessarily suffice, especially over bar splices. The new design requirement of 2-1/2 in. to center of bar should be a step in the right direction. However, that requirement will apply only to structures let after June 2, 1966, and so probably no decks will be built to these specifications until the summer of 1967. In the meantime, it might be well to emphasize that bars, especially in splice areas, should be set near the lower limit of the present specifications wherever possible.

The general cause of rippling has not yet been determined. Further studies are planned that will attempt to duplicate the problem in the laboratory, and expand the field observations to structures of various types. This work will take considerable time, and therefore will not aid the immediate problem in the Rouge project. It is understood that some changes have been made on specifications for slump and curing of deck concrete.

Observations on the Rouge bridge and other structures suggest that vibration of the structure may be the final ingredient in the process of deck rippling. Efforts directed toward minimizing excitation of the structure during placement and curing of deck concrete might be useful.

Figure 1. General view and closeup of deck rippling on S16 of 11015, an I94 structure near Benton Harbor, where widening was hand finished with transverse strike-off. Heavy traffic continued to use the structure during construction and curing.

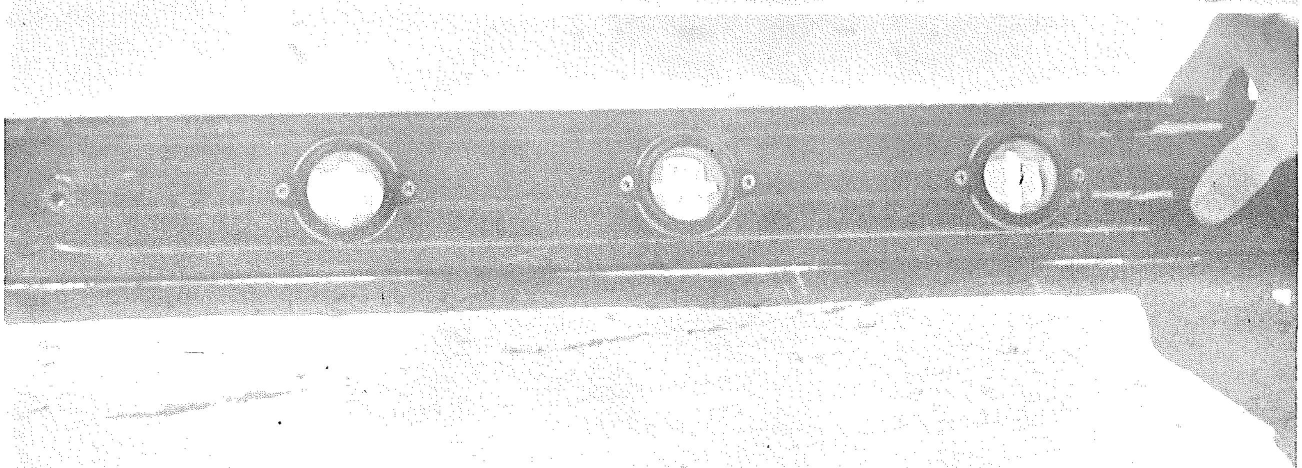
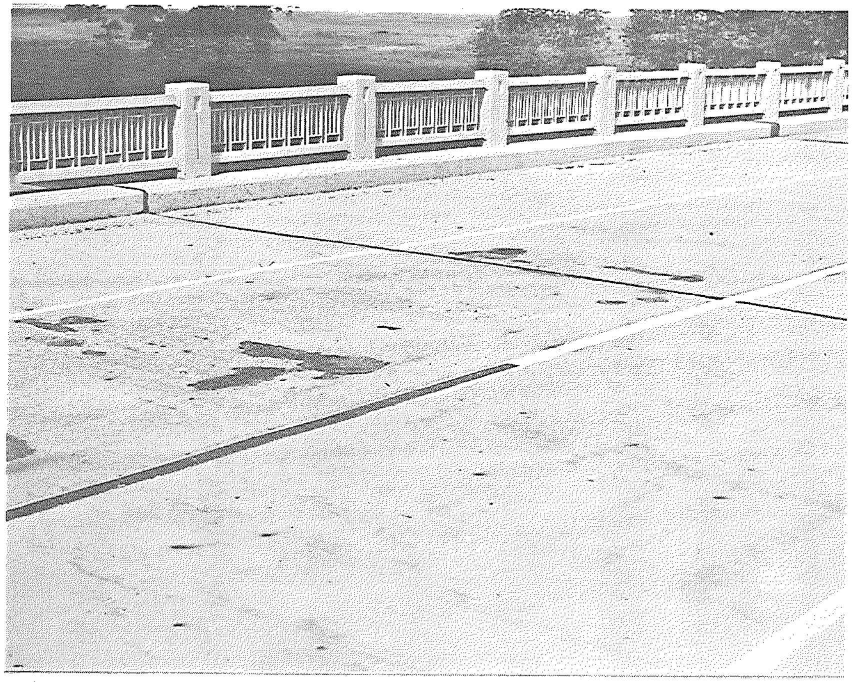
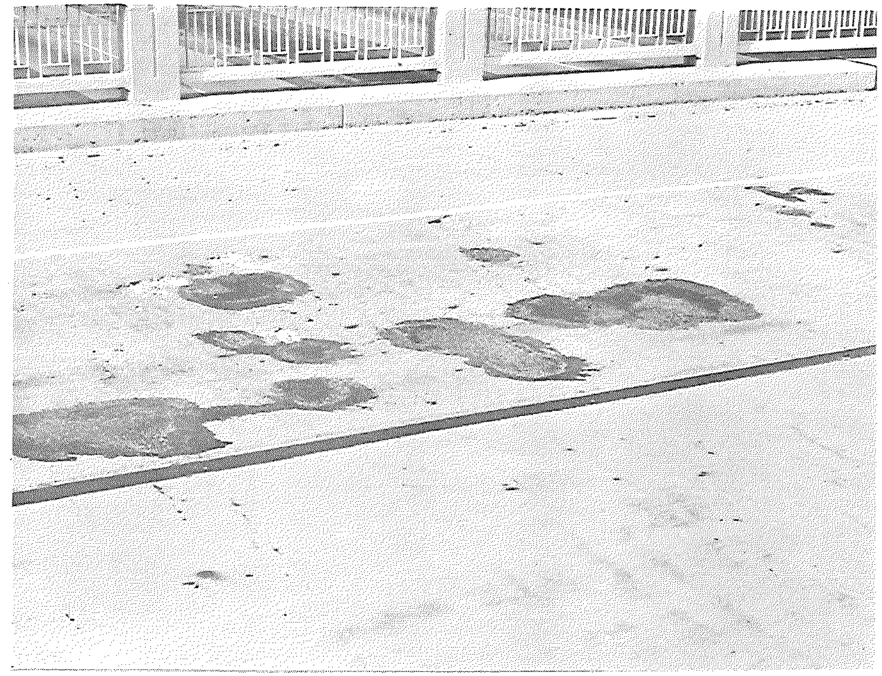


Figure 2 (left). Deck repair of spalls over bar splices, where cover was 1-1/2 to 2 in. (X01 of 38101).





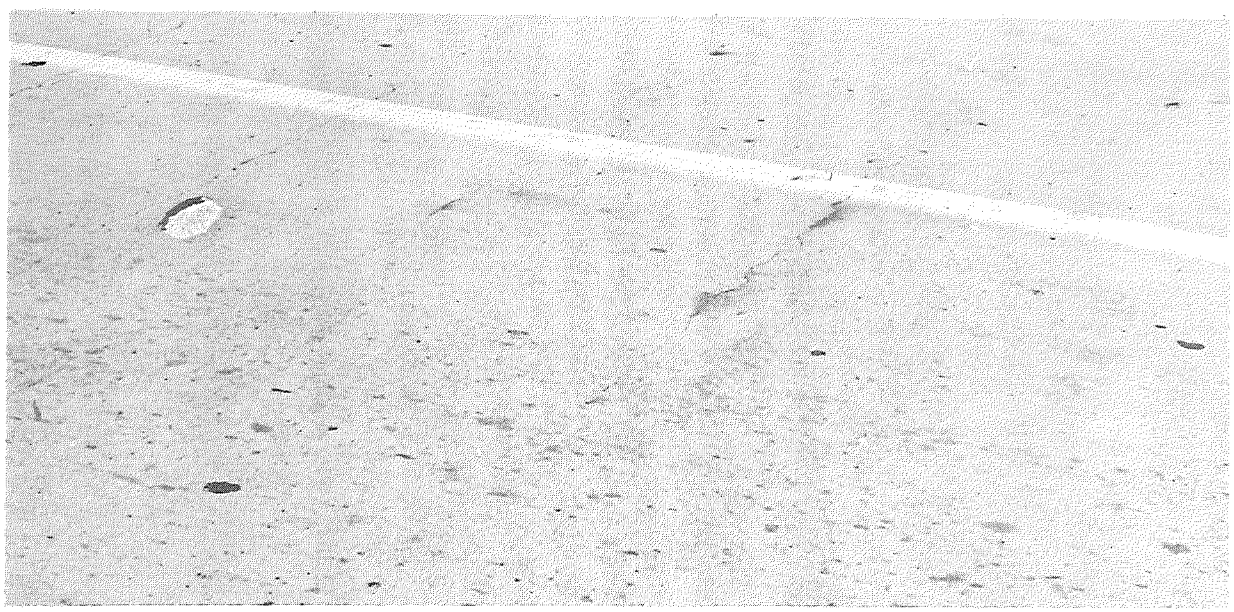


Figure 3. Three views of deck condition on S05 of 38111, showing ripples (foreground, right) with cracks in troughs, and cracking that appears to follow bars (lower left). Pothole at left may be evidence of fracture plane cracking.

Figure 4. Deck failure over bar splice, before and after removal of loose concrete for repair (X01 of 38131).