Effect of Water Infiltration of Penetrating Cracks on Deterioration of Bridge Deck Slabs

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ABSTRACT

The deterioration of bridge decks is a serious maintenance problem in Japan, but deterioration in Japan is different from that in the United States because all bridge decks in Japan are covered with an asphalt overlay about 7.5 cm thick. Deterioration to a depth of about 18 cm has been found in decks that were seldom treated with deicing salts. These decks exhibited partial depression and fall-off, not scaling or spalling. Fatigue tests of model slabs and field surveys of bridges were carried out to determine the mechanism of deterioration, investigate methods of repair, and evaluate existing bridge decks. A test specimen, faultily constructed and severely cracked in the laboratory, deteriorated rapidly due to water infiltration of cracks, leakage through cracks, and abrasive action caused by crack movement under repeated loading. The fatigue strength of this specimen was about one-third its static strength, which is remarkably low compared with the normal fatigue strength of reinforced concrete. The mechanism of deterioration of bridge decks is thought to be a combination of three conditions: break-out of penetrating cracks caused by faulty construction and drying shrinkage, infiltration and leakage of rainwater, and abrasion due to wheel loading. Experimental work on an actual bridge showed expansive concrete to be effective in preventing break-out of shrinkage cracks.

Nihon Doro Kodan (Japan Highway Public Corporation), which oversees all express highways in Japan, presently maintains 3200 km of expressway including 3,500 bridges. The deterioration of bridge deck slabs is a serious problem in Japan, but the deterioration is different from that in the United States because all bridge decks are covered with an asphalt overlay about 7.5 cm thick. Deteriorated bridge decks are often found where deicing chemicals are seldom used. These decks exhibit partial depression and fall-off, not scaling nor spalling. Because air-entrained concrete is used for all bridge deck slabs in Japan, deterioration due to freezing and thawing is seldom seen.

Bridge decks designed before 1970 exhibit a great deal of deterioration and damage. The span between main girders of these bridges is about 4 meters, and the depth of the slab is 16 to 18 cm. Concrete cover over both top and bottom reinforcement is 3 cm. Most of these bridges have been repaired by partial reconstruction of the bridge deck, reinforcement with additional stringers between girders, or steel-plate bonding.

The 1973 "Specification for Highway Bridges" (published by Japan Road Association) has been revised to require that the span between main girders be about 3.2 meters and slab depth 22 to 23 cm. The specification of a concrete cover over top reinforcement did not change. To study the cause of deterioration, investigate methods of repair and reinforcement, and establish a method of evaluating bridge decks, many fatigue tests of bridge deck slabs have been carried out in the laboratory of Nihon Doro Kodan since 1976.

The following results have been obtained from full-size model tests.

1. A full-size model bridge deck (18 cm in depth) designed according to the older standards had a static strength of about 490 kN and a fatigue strength of about 250 kN under midspan point loading (loading plate size is 20 x 50 cm) (1).
2. A model bridge deck (22 cm in depth) designed according to the newer standards had a static strength of about 930 kN and a fatigue strength of about 440 kN under the same loading (2).

The ratio of fatigue strength to static strength in the bridge deck (about 0.5) is consistent with the results of other tests that used small-size slab specimens (3). It can thus be confirmed that bridge decks ordinarily show the same fatigue conduct as do general reinforced concrete (RC) members. Maximum wheel loads measured on expressways in Japan are around 100 kN if tandem axle loads are converted to equivalent single axle loads for reinforcement design.

Judging from the results of the fatigue tests mentioned previously, fatigue strength of deck slabs far exceeds the actual wheel load level, so it is not expected that fatigue damage will occur even in thin slabs designed according to the old standard.

Observation of deteriorated bridge decks indicated that (4)

- Deterioration is found only in limited parts of bridges.
- Deterioration of one-lane roadways is heavier than that of two-lane roadways.
- Most deteriorated parts exhibit a gridlike pattern of cracks that progress because of water infiltration and leakage. Free lime, concrete powder, and rusty liquid from reinforcements are found on the bottom surface of bridge decks.

On the basis of these observations it was hypothesized that water leakage through cracks that run the entire depth of the deck (hereinafter called penetrating cracks) was one of the most important factors in deck deterioration. To test this hypothesis a model bridge deck that exhibited the characteristics that had been observed in the field was reconstructed in the laboratory. Model slabs with severe, artificially induced penetrating cracks were constructed and repeated loading tests were carried out in the presence of water leakage. The results were a great quantity of abraded concrete powder and many broken pieces that flowed out with water leakage. Progressive deterioration was clearly shown and as a result fatigue strength dropped considerably. In this paper the deterioration mechanism of bridge deck slabs, evidenced by these test results and field surveys, is considered and countermeasures to deterioration are described.

FATIGUE TESTS OF ARTIFICIALLY CRACKED MODEL SLABS

Fabrication of Specimens

To artificially produce penetrating cracks in a slab, the slab can be turned upside down and loaded so that cracks are initiated on the top surface. But this method is not very effective because, when the slab is righted, cracks on the top surface close due to the self-weight of the slab. At the beginning of loading little water infiltration was observed. Soon thereafter slight water leakage was noted, but it soon stopped. The progress of deterioration could no longer be followed.

At this point another method was tried to artificially produce cracks. A model bridge deck slab was fabricated on model steel girders under unfavorable construction conditions. The properties of the cement of this slab were

- Compressive strength--21.9 Mpa,
- Water-to-cement ratio--0.70,
- Slump--21.3 cm,
- Entrained air--3.6 percent, and
- Temperature--30°C.

Weather conditions were

- Skies--cloudy,
- Temperature--30°C (86°F), and
- Relative humidity--70 percent.

The slab was dried by the artificial wind (velocity 2 to 8 meters per second) of an electric fan. There was no moisture curing.

Details of this specimen are shown in Figure 1. The result was that many cracks, mainly above the positions of reinforcements, were generated in about 30 minutes after the concrete was cast. By the beginning of the fatigue test, about 3 months after construction, these cracks had grown wider because of shrinkage of the concrete and restriction of the steel girders as shown in Figure 2(a). Some of the transverse cracks are more than 1 to 2 mm in width. Figure 2(b) shows that wider transverse cracks reached the bottom surface of the slab, and during rainfall some free lime with water leakage could be observed.

Loading Method and Repetition Patterns

Figure 1 shows the loading apparatus, the positions of the moving load, and the water that was ponded on top of the slab during fatigue loading of the top surface of the slab. As a preliminary loading, approximately 2,000 78.4-kN repeated loadings were applied to points 1 to 23 to produce a gridlike pattern of cracks over the entire bottom surface. Consequently, cracks occurred and finally crack density reached 10 m/m² (total crack length per unit area) as shown in Figure 2(c).

The fatigue loading patterns were as follows. The loading point was changed to the next point after every cycle (0.3 million repetitions).

Case 1. Fatigue load level was 78.4 to 24.5 kN; one cycle on points 3, 5, 13, 19, and 21, respectively; three cycles on points 4, 11, 12, and 20, respectively; 5.1 million repetitions total.

Case 2. Fatigue load level was 103 to 24.5 kN; one cycle on points 11, 12, 20, 101, and 102, respectively; 1.5 million repetitions total.

Case 3. The upper load level was decreased to 88.3 kN; three rounds of one-cycle loadings on the same points as in case 2; 4.5 million repetitions total.

Case 4. The loading point was moved to point 103, which was between points 101 and 102 where serious damage had been observed. Fatigue load level was 88.3 to 24.5 kN; and after 0.65 million repetitions at this point fatigue failure occurred.

Various kinds of measurement were carried out by the static loading of points 9 through 15 after one-cycle loadings had been applied to all points. Water that leaked was collected in a container under

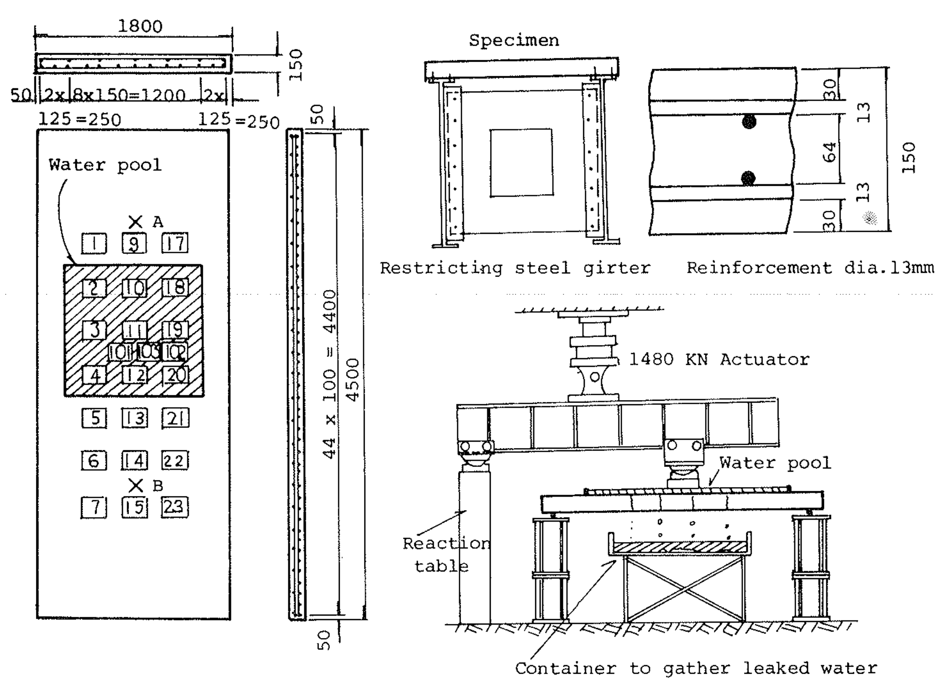

FIGURE 1 Shape of specimen, loading points, and loading apparatus.

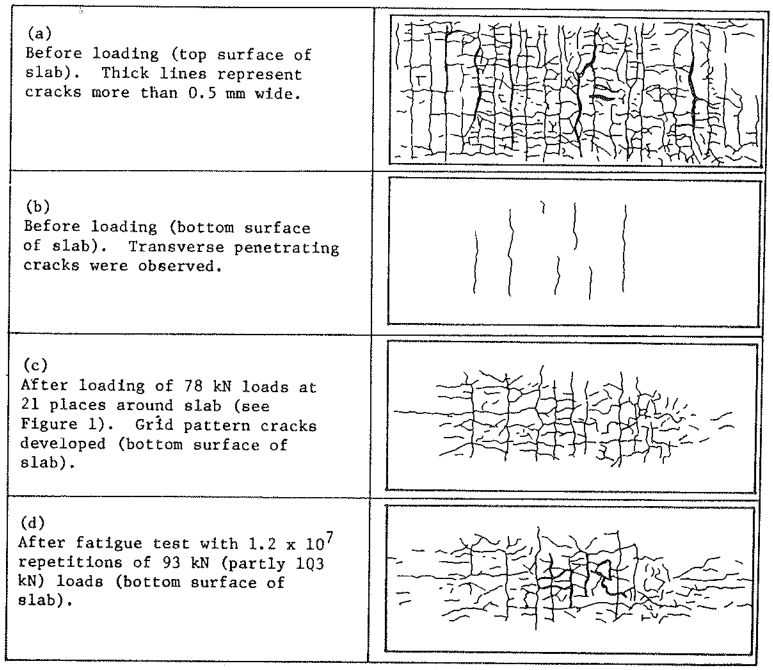

FIGURE 2 Change in cracks of slab specimen.

the specimen slab at every cycle on each point and its volume was measured. The water was then allowed to evaporate and any remains were measured as abrasion weight.

Fatigue Test Results

Progress of Deterioration

Figure 3 shows how the deterioration of the specimen progressed under repeated loading from case 1 through case 4. Figure 3(a) shows the loading process (one unit of the abscissa indicates one cycle or 0.3 million repetitions of load). In case 1 tensile strain of the bottom reinforcement was 400 ∿ 500 x 10^{-6} and the change in crack width was about 0.1 mm. Water leakage volume was slight and little deterioration occurred except for the flowage of some white, soft, free lime. In case 2 the upper limit of tensile strain of the reinforcements was arranged to be about 900 x 10^{-6} so that fatigue failure of the reinforcements would not occur, and the upper load level was increased to 103 kN. The result was that the volume of water leakage from cracks suddenly increased to 1000 to 2000 cm^3 per hour and abrasion weight during one cycle of loading reached 5 to 10 gm. The change of crack width due to loading was more than twice as large; clearly, deterioration was remarkably rapid [see Figure 3(b), (c), and (d)].

Because the tensile strain on the bottom reinforcement increased as deterioration progressed, the upper load was decreased to 88.3 kN and repeated loading was continued. As shown in Figure 3, deterioration progressed even as the load level was dropped to 88.3 kN.

Figure 4 shows that abrasion volume increased in proportion to the increase in total leakage volume. Apparently water infiltration of cracks and abrading action occurred. Figure 5 shows this abrading action. Figure 5(d) represents relative movement parallel to the crack direction near point 12 on the bottom surface. The sliding direction of a crack reverses when the loading point is moved from point

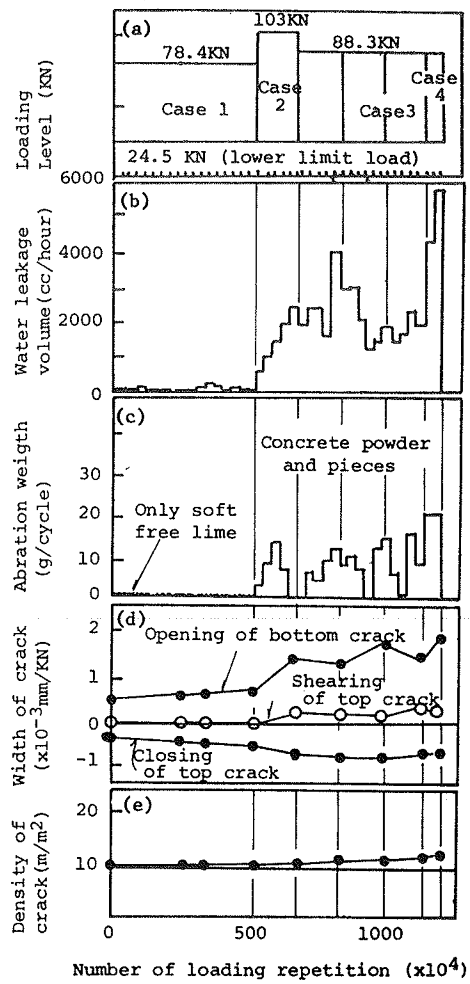

FIGURE 3 Progress of deterioration caused by loading repetition.

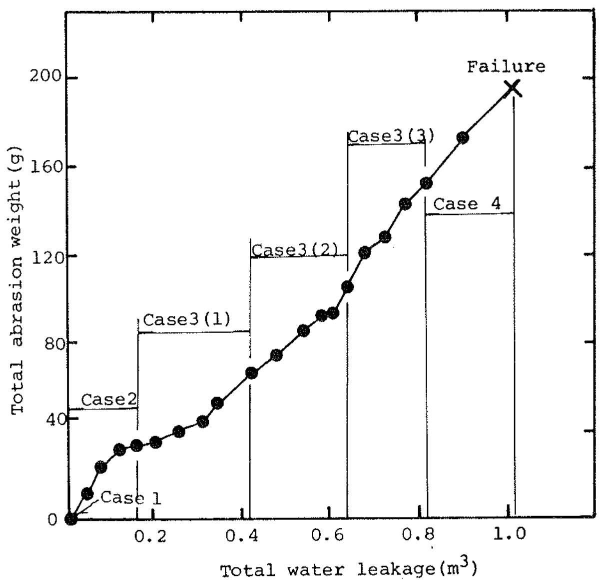

FIGURE 4 Relationship between total water leakage and total abrasion weight.

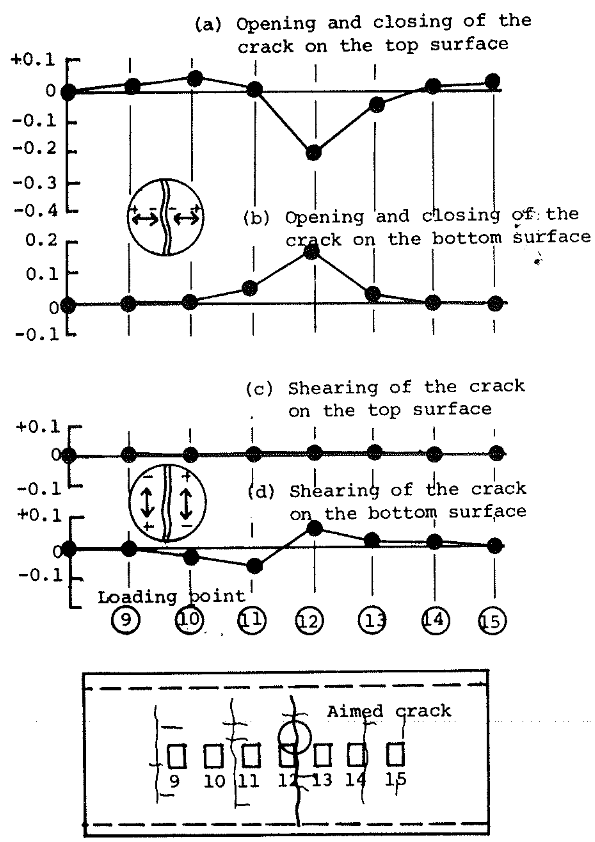

FIGURE 5 Change of representative crack caused by moving load.

11 to 12, abrading action occurs, and crack width is about 0.15 mm. After loading in case 3, the loading point was moved to point 103 in case 4. When point 103 was loaded, water leakage volume increased considerably to 4000 to 5000 cm^3 per hour, and at 0.65 million repetitions of load it suddenly increased significantly.

Therefore the loading machine was stopped and the specimen was observed in detail. On the top surface of the slab punching-shear cracks had occurred around point 103, and on the bottom surface shear cracks, which are different from bending cracks, had penetrated from the top surface. The vertical opening of a shear crack close to point 103 (measured with a dial gauge) was about 0.3 mm at a loading level of 0 to 88.3 kN. It was judged that punching-shear failure had occurred and the fatigue testing of this specimen ended.

State of Cracks

Later, fatigue test specimens were subdivided with a concrete cutter into small pieces and their cross sections were observed. Figure 6 shows a cross section connecting loading points 19 and 20. Fatigue punching-shear cracks, including vertical bending cracks generated at the position of reinforcement, were observed. Figure 7 shows cracks near point 20 magnified. Because of water infiltration and abrasion caused by loading, the inside width of the crack expanded to about 0.5 mm and its edge was round. The condition of the top surface of the slab is shown in Figure 8. A similar pattern of deterioration can often be seen on deteriorated in-service slabs after removal of the asphalt overlay.

Comparison with Static Strength

After fatigue tests were completed, static loading tests were carried out on points A and B shown in Figure 1. Static strength was 282 kN at point A and 273 kN at point B. If the average of these values is taken as the static strength of this slab, the ratio of fatigue upper loads of 88.3 kN and 103 kN

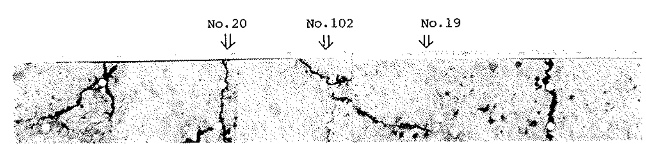

FIGURE 6 Cross section where punching-shear failure took place (seen from transverse direction).

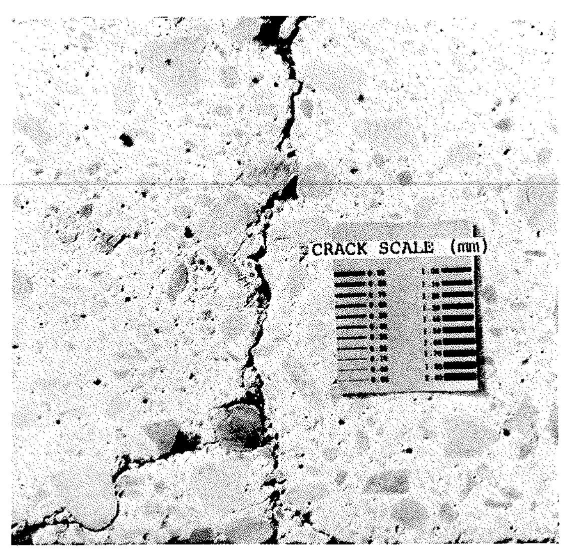

FIGURE 7 Magnified cross section under point 20 (width of crack expanded because of abrading action).

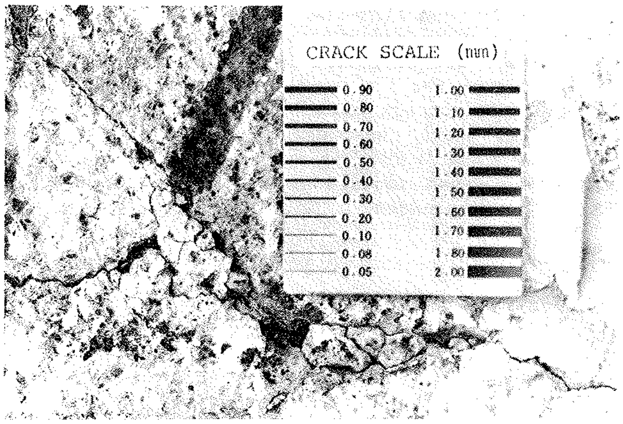

FIGURE 8 Deterioration of top surface of specimen.

to static strength is 0.32 and 0.37, respectively. These values are remarkably low compared with the value usually obtained without water infiltration. This is an example of a case in which the punching-shear strength of the concrete is less than the fatigue strength of the reinforcement.

DETERIORATION MECHANISM OF BRIDGE DECKS

It is assumed that the fatigue strength of the specimen with water leakage mentioned previously is about 88 kN. Because specimen depth was 15 cm and the steel ratio was different from that used in actual bridges, Kakuta's proposed formula (5), which gives a favorable calculation value of strength for this type of test specimen, was used. Conversion of these calculated values to the old standard (slab depth = 18 cm) gave about 120 kN. This is close to the maximum converted wheel load of 100 kN. To confirm this finding, full-size model tests need to be carried out. Investigation of this subject is now under way.

On the basis of the findings discussed previously, it may be concluded that the deterioration mechanism of bridge decks is a combination of three conditions:

1. Break-out of penetrating cracks that were caused by drying shrinkage and faulty construction,
2. Infiltration of cracks by rainwater and leakage of rainwater from cracks, and
3. Wheel loads great enough to cause abrasion.

It is widely known that bridge decks are thin compared with other concrete structures and that the influence on durability of slight construction errors and imperfections is serious. Furthermore bridge decks are loaded directly by traffic and subjected to severe curing conditions.

To confirm these findings, in 1983 the condition of cracks on the top surface of 24 bridge decks on the Tomei Expressway was investigated. Asphalt overlay sections 1 m x 2 m were torn off and the relationship between water leakage and cracks on the top surface of bridge decks was studied. Cracks, serious or not, occurred in all parts of the top surface of decks. Figure 9 shows serious cracking. From this figure it can be seen that cracks on the top surface of a deck are similar to those on the bottom surface and that rainwater is infiltrating penetrating cracks. (Only cracks on the bottom surface from which free lime flowed were considered.) In most places concrete over top reinforcement did not deteriorate even if there were cracks in it, and

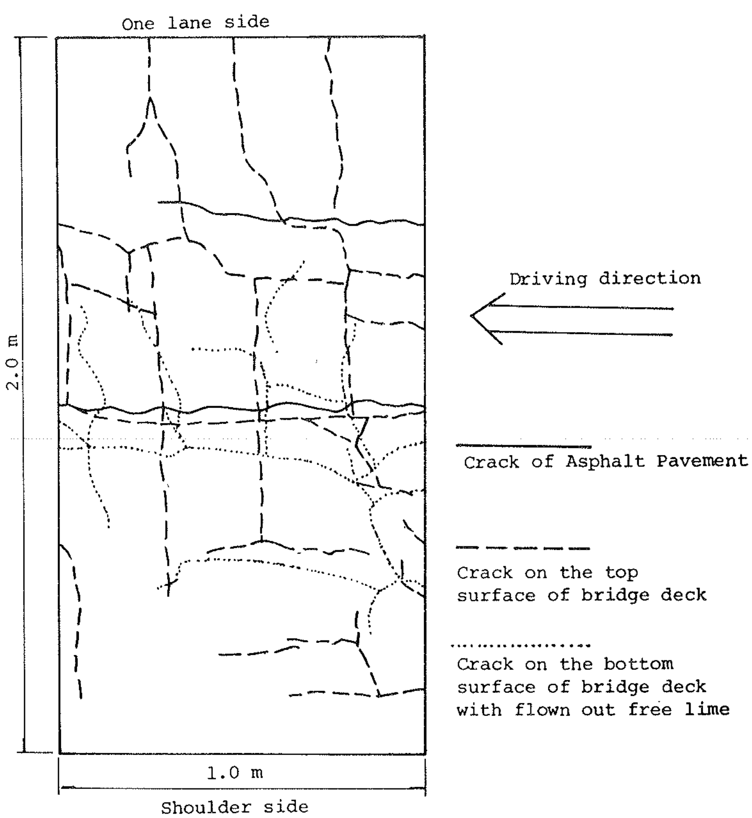

FIGURE 9 Typical crack pattern of deteriorated bridge deck in service.

minimal serious spalling of concrete and corrosion of reinforcement were found.

Table 1 shows the results of regression analysis of 24 investigated data. From the data in Table 1, it can be seen that in case 1 the correlation between asphalt overlay and bottom surface of the deck is not strong and that the correlation in cases 2 and 3 is fairly strong. In case 2, there is a difference between each coefficient of partial correlation. This difference shows that where there are cracks in the asphalt overlay there are always cracks in the top surface of the deck, but that there are not always cracks in the asphalt overlay where there are cracks in the top surface of deck.

In case 3 the difference between coefficients of partial correlation noted in case 2 obtains. The analysis of case 3 shows that where there are cracks in the bottom surface of a deck there are always cracks in the top surface of a deck, but that there are not always cracks in the bottom surface where there are cracks in the top surface.

From this analysis it is clear that rainwater infiltration of penetrating cracks results in damage to the bottom surface of a deck. Cracks in the top surface of a deck bring about reflection cracks in the asphalt overlay. In general, more deterioration was observed on one-lane than on two-lane bridges. This indicates that wheel load influences the rate of deterioration.

It is possible that the three previously mentioned conditions that contribute to deterioration occur at the same time. If this is the case, a method for maintaining deteriorated bridge decks can be devised based on the assignment of numerical values to the density of the gridlike pattern of cracks, from which free lime has flowed, on the bottom surface on bridge decks.

INFLUENCE OF DEICING CHEMICALS

Corrosion of reinforcement by deicing chemicals must also be considered. It is probable that such corrosion of reinforcement influences the progress of deterioration to some extent even if punching-shear failure due to wheel load does not occur. In the United States corrosion of reinforcement by deicing salts and spalling of covering concrete are known to be a problem (6). Even though asphalt overlays are less frequently used on bridge decks in the United States than in Japan, it is possible that the same type of deterioration occurs on the top surface of decks in both countries.

Figure 10 shows a concrete core taken from a severely deteriorated bridge deck where deicing chemicals were scattered. There are wide crack links between main reinforcing bars due to corrosion of the bars, and the covering concrete is spalling off. In this figure chlorine quantity inside the core far exceeds the specified value (in Japan NaCl weight in concrete must be less than 0.1 percent of sand weight).

Although deterioration due to deicing salts has not been observed frequently on bridge decks in Japan, it should be added to the three previously discussed conditions that accelerate deterioration.

COUNTERMEASURES TO DETERIORATION

The increase in the depth of bridge decks to 22 to 23 cm in the 1970 specification has been effective. Not only has shear strength increased, but adverse effects of construction errors and imperfections have decreased. In fact, if static strength were increased from 1.8 to 2.0, bridge decks would not fail because of wheel loads even if they were somewhat deteriorated.

The addition of stringers between main girders has been used for reinforcing bridge decks designed by the old standard. Because bending moment occasioned by wheel load is decreased by this rehabilitation method and crack movement due to wheel load becomes smaller, this method can be helpful. Al-

TABLE 1 Regression Analysis of Cracks in Asphalt Overlay: Top and Bottom of Slab

Case	Analysis	Coefficient of Multiple Correlation	Coefficient of Partial Correlation: Asphalt Overlay	Top of Slab	Bottom of Slab
1	Asphalt overlay versus bottom of slab	0.67	0.45	–	0.39
2	Asphalt overlay versus top of slab	0.77	0.77	0.27	–
3	Top of slab versus bottom of slab	0.84	–	0.55	0.83

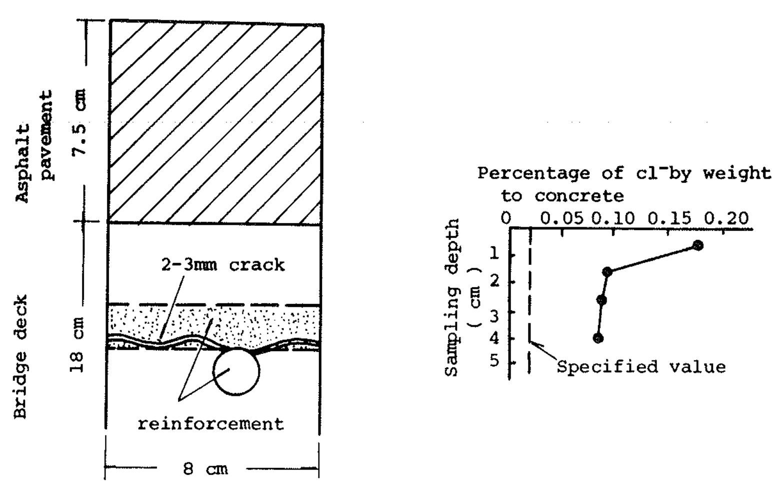

FIGURE 10 Cl⁻ content of concrete core of actual bridge deck and crack caused by corrosion of reinforcement.

though it slows the rate of deterioration, it is not a perfect method because a decrease of moment does not mean a decrease of shear force and an increase of shear strength of cross section.

Even with the new increased standard strength of bridge decks, the concrete cover top reinforcement remains 3 cm. Cracks caused by drying shrinkage and construction-induced cracks over reinforcements continue to occur. Therefore, reinforcements will continue to be corroded by infiltrating deicing chemicals, and covering concrete will eventually tear off.

There are two methods of preventing bridge-deck deterioration due to water infiltration of cracks. One method is to prevent the break-out of cracks due to factors such as drying shrinkage. Another method is to prevent water infiltration even if cracks occur. An example of the former will be given hereafter.

In 1980, for the first time in Japan, an expansive concrete bridge deck was constructed on a interchange ramp bridge (simple steel, composite plate girder) 41.5 m long and 8.5 m wide (7). The unit content of the expansive component is 35 kg/m^3 estimated as part of cement content. Test specimens made with this mix proportion expanded to about 300×10^{-6} in a standard confined expansion test after 7 days of 20° C water curing. These test specimens had a steel-to-concrete ratio of 0.01.

Figure 11 shows the change in length of an expansive concrete deck in actual service compared with a like-shaped normal concrete deck constructed at the same time. Expansion of the expansive concrete deck reached its maximum value at 5 days, and expansive strain was measured as 160×10^{-6} longitudinally and 220×10^{-6} transversely. After about 700 days this expansion became nearly zero because of drying shrinkage. From this time on, expansive concrete completely compensated for the drying shrinkage of concrete. The normal concrete deck shrank to about 200×10^{-6} due to drying and, as shown in Figure 12, many cracks developed after 30 days. Few cracks developed in the expansive concrete deck. Another experimental construction of an expansive concrete bridge deck was carried out in 1982 on an expressway plate girder bridge with a span of 36.0 m. The results of this experiment were similar to those of the first.

It has been confirmed that expansive concrete is effective in preventing crack break-out. Therefore, Nihon Doro Kodan is now investigating the use of expansive concrete decks as a standard construction method.

To prevent water infiltration, waterproofing membranes were considered first, but, to date in Nihon Doro Kodan, membranes have been used only in limited projects, such as the reconstruction of a small area of deteriorated bridge deck. This is because

1. There were misgivings that asphalt overlays on the membranes would slide,
2. No reliable method of waterproofing had been established, and
3. Membranes are very expensive.

These problems will probably be solved in the future on the basis of recent technological developments. Large-scale experimental construction will determine

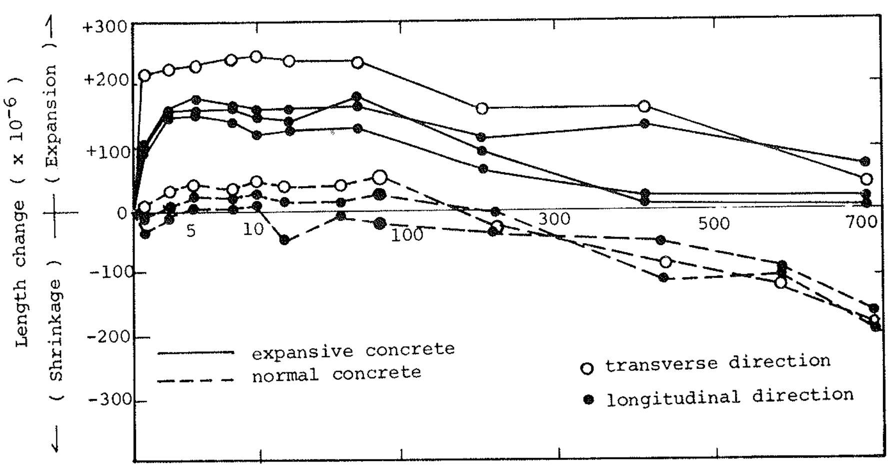

FIGURE 11 Change in length of normal and expansive concrete bridge deck.

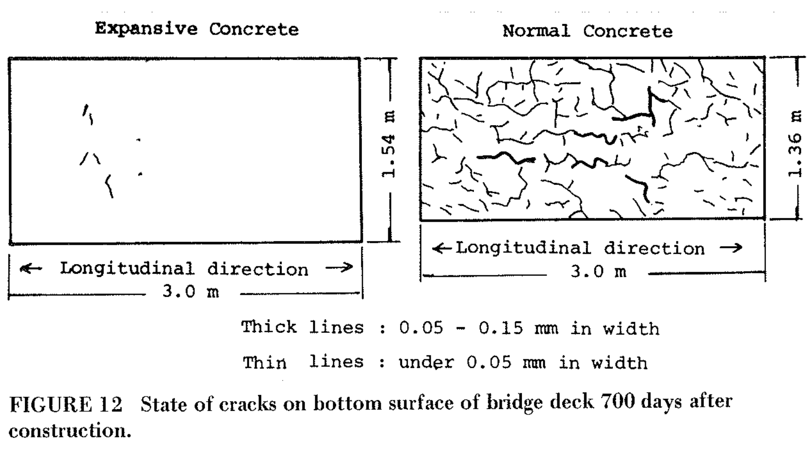

FIGURE 12 State of cracks on bottom surface of bridge deck 700 days after construction.

whether the practice of using waterproofing membranes will be adopted.

CONCLUSIONS

Mechanisms of bridge-deck deterioration, repair methods and methods of evaluating bridge-deck fatigue were investigated using tests of model slabs and field surveys of bridges in service.

The results may be summarized as follows:

Test specimens--constructed of low-quality concrete under adverse curing conditions and severely cracked by artificial means--deteriorated rapidly because of water infiltration of the cracks and abrasion caused by repeated loading.

Abrasive action was proved by the measurement of concrete powder and pieces that flowed out of penetrating cracks and by the measurement of abrading movement of cracks.

Fatigue failure, due to the punching shear of the slab, occurred. The fatigue strength of this specimen was about one-third its static strength, which was remarkably low compared with the usual fatigue strength of RC members.

From the test results and field surveys, the deterioration mechanism of bridge deck was estimated to be the combination of three conditions: breakout of penetrating cracks caused by drying shrinkage, infiltration and leakage of rainwater with and without dissolved deicing chemicals, and wheel loads that generate abrasive action.

Experimental constructions show that expansive concrete is extremely effective in preventing breakout of shrinkage cracks.

Some type of numerical characterization of the density of gridlike cracks from which free lime has flowed is needed to facilitate evaluation of existing bridge decks.

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