DETERIORATION OF REINFORCED CONCRETE SLABS WITH ALKALI AGGREGATE REACTION

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ABSTRACT

This paper deals with inspection results of cracks due to Alkali Aggregate Reaction (AAR) in reinforced concrete (RC) slabs of highway bridges. The field records over the decade and the test result of load-carrying capacity performed on test specimens using reactive aggregate are presented. The assessment of AAR damage and maintenance methods are proposed based on these studies.

Cracks were initially found by periodical inspection. The pattern of cracks differed from the ordinary case of cracking in two perpendicular directions caused by live loads; they were at 120° angle and cracks seemed to be occurring in the same construction division. According to field inspections, the behavior of crack density and extension, the ratio of crack density in the longitudinal direction to that in the transverse direction indicated unique characteristics. The results of static load test on actual bridges showed no decrease of stiffness with crack extension, which is consistent with the test result on test specimens.

As a result of the above studies, in order to maintain the load-carrying capacity of slabs and avoid the progress of Alkali Aggregate Reaction, the installation of a water-proof layer on the slab and epoxy bonded steel plates with grout filling of the cracks beneath the slab are recommended from the viewpoint of durability.

Keywords: Alkali Aggregate Reaction, accelerated expansion test, Reinforced Concrete, Cracking, Epoxy bonded steel plate

INTRODUCTION

The problem of cracking deterioration in road structures due to Alkali Aggregate Reaction (AAR) has been known since over two decades ago. It is reported mainly on the relatively massive members, such as bridge piers, retaining walls, main girders, and so on; but very few on Reinforced Concrete (RC) slabs or concrete railing which are relatively thin. For RC slabs on Hanshin Expressway, inspections are conducted once in every two or three years. Different case of cracking from the ordinary case of perpendicular cracking had been observed in the periodical inspection of 1983. Cracks were found several years later after construction, and most of them crossed with the angle of 120 °. The reason was considered not as live loads or drying shrinkage, but possibly as AAR. The width of cracks, however, was smaller than that of cracks that occurred in bridge piers, and AAR could not be clearly recognized although accelerated expansion test and chemical test were carried out on core samples. In order to find out the reason for the different crack pattern and growth from those of bridge piers affected by AAR, the field investigation was performed.

INVESTIGATION RESULTS

Outline of investigation

The investigation was carried out on six slab-panels, including three panels in one span on Kobe Route and one panel in each of three spans on Matsubara Route. They were selected from the result of periodical inspections in 1987 and 1983, in which severe cracking damage, especially tilting cracks growing from transverse direction to bridge axis, remarkable cracks in longitudinal direction to bridge axis, as well as honeycomb cracks were observed. The field investigation was performed on the configuration, density, width and depth of cracks; measurement of deflection of RC slab by static load test; compressive strength and chemical analysis of concrete of core samples from the past four samplings as well as AAR experiments, such as core expansion test and chemical method.

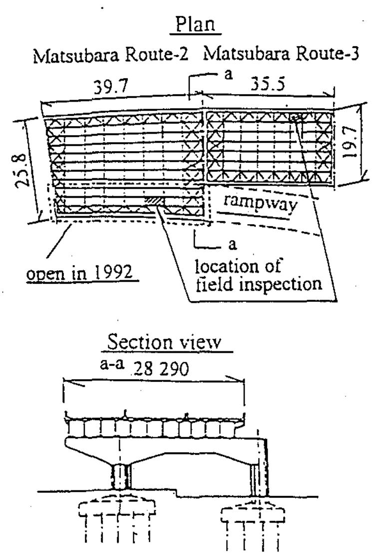

Fig.1 General view of structure (Matsubara Route-2, -3)

The general view of structures in Matsubara Route-2, -3 are demonstrated in *Fig.1*. Both spans are composed of steel simply-supported I-shape composite girders, which are the most popular in Hanshin Expressway and designed by Specifications for Highway Bridges (1983 Version). In this design specification, the slab thickness was increased as a result of the studies of fatigue damage due to live loads. The bridge has been in service since 1980-1981 and the rampway of Matsubara Route-2 was opened in 1992.

Result of periodical inspection

Fig.2 shows the results of the past three periodical inspections of slabs on Kobe Route. Inspection result is ranked as A, B, C in a decreasing order of damage. For instance, Rank A states that biaxial cracks are over 0.1mm wide and below 40cm spacing, slab corner spalls, and so on. *Fig.2* shows that damage of slabs is progressing with a rather high speed.

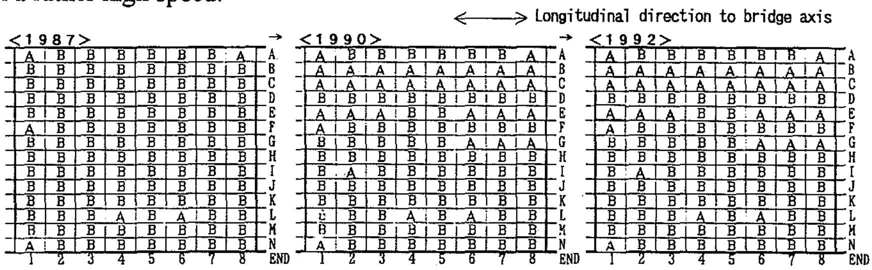

Fig.2 Change of periodical inspection result (Kobe Route-1)

Moreover, *Table 1* shows the number of panels in various damage ranks resulting from the latest periodical inspection for each neighbor construction division that was constructed in the same period as Kobe Route-1. It is understood that C Division, which includes the investigated slabs, is much more damaged than other construction divisions.

Table 1 Summary of results of periodical inspections

Construction division	Number of Spans	Number of Panels	Judgement Rank				Occurrence Rate of Damage A+B
			general part				
	total	total	A	B	C	OK	total panels
A	13	546	3	7	69	467	1.83%
B	5	548	4	4	34	506	1.46%
C	6	672	91	395	185	1	72.32%
D	7	460		2	22	436	0.43%
E	9	378		1	6	371	0.26%
F	9	378			37	341	0.00%
G	15	745	1	5	154	585	0.81%
H	3	126		15	61	50	11.90%
I	3	168	1	13	40	114	8.33%

※ Kobe Route-1 is included in C division

Crack inspection results

(1) Configuration of cracks

An example of crack configuration change is demonstrated in *Fig.3.* In general, it is difficult to clarify the cracks in longitudinal direction and transversal direction to bridge axis because tilting crack growth was remarkable. The particular cracking configuration of AAR that cracks cross in the angle of about 120° was well observed. It is worth mentioning that in the

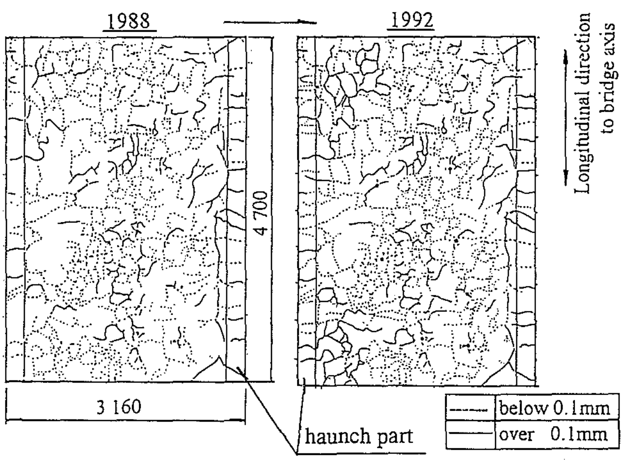

Fig.3 Change of cracking configuration (Kobe Route, Panel L-4)

haunch part cracks only occurred in the direction of the adjacent section. Change of crack configuration shown here is what happened during four years. New cracks are continuously occurring and growing in the whole slab.

Width of cracks is just less than 0.2mm with the maximum value of 0.3mm. Most of the cracks on Matsubara Route are fine cracks of less than 0.1mm width. Therefore, the cracks observed on the surface are different from those that occurred on bridge piers. Out-plane surface gaps, usually seen on the surface of AAR-damaged bridge piers, have been observed.

Photo 1 shows the inspected slab. *Photo 2* shows an example of slab crack damage (Rank A) due to live load. It is understood from *Photo 2* that cracks in transversal direction to bridge axis are more obvious and its density is much smaller than those of inspected slabs.

Photo 1 Cracking configuration (Density: 21.3m/m^2)

Photo 2 Example of cracking damage due to live load

(2) Density of cracks

Besides the six panels of slabs in the present inspection, field inspection is also performed on slabs with ordinary deterioration. *Fig.4* shows that the density of crack over 0.05mm width in those slabs varies with the years passed.

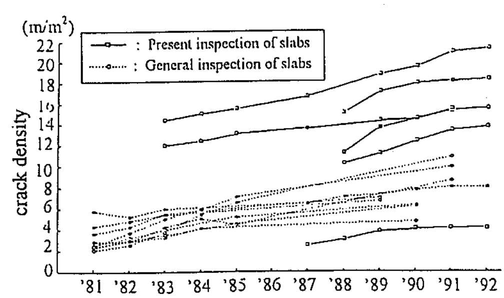

Fig.4 Growth with the years passed of crack density

Generally, the maximum density of slab crack is about 11m/m^2 . The present inspection of panels shows that it is almost over 12m/m^2 and the maximum is even up to 21m/m^2. The crack densities observed on the surface of the slabs are increasing almost at the same rate. It seems that the crack densities will grow constantly in the future. The initial value of crack density of the inspected slabs are over 10m/m^2. It can be inferred that a lot of cracks on Matsubara Route have occurred in the early days after the construction, i.e. after the opening to traffic in 1980, especially after 1983 when inspection of Matsubara Route started.

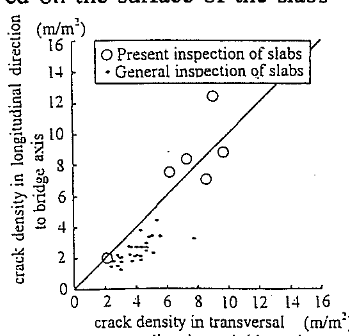

Fig.5 Comparison of crack density

Fig.5 gives the ratio of density of over 0.05mm wide cracks in longitudinal direction to that in transversal direction to bridge axis. For slabs, especially designed by the design code of 1964 version, cracks first occurred in transverse direction to bridge axis due to insufficient reinforcements. After slab slit caused by transverse cracks was formed, cracks finally appeared in longitudinal direction related to the main reinforcements. Therefore, cracks in transversal direction to bridge axis are more prominant as shown in *Fig.5* by black circles. However, the present inspection of slabs may not show this tendency.

In case of cracks over 0.1mm wide, the same phenomenon was observed. For cracks due to AAR, generally not all the cracks grew in the same direction if the restraint, i.e. prestress does not exist.

(3) Width of cracks

At the beginning of inspection, crack width was measured for cracks over 0.1mm wide. *Fig.6* shows the variation of crack width with the years passed in three panels on Kobe Route. Although the temperature effect on crack width is considered, the change is not so much. Therefore, the cracks over 0.10mm wide have not grown so much. The reason is thought to be the growth of neighbor small cracks or the occurrence of new cracks.

(4) Depth of cracks

At the beginning of inspection, crack depth was measured for cracks over 0.2mm wide by ultrasonic detector. *Fig.7* shows the variation of crack depth with the years passed in three panels on Matsubara Route. Crack depth was over 5cm at the beginning of inspection that propagated from the cover layer 3cm apart from the existing steel bar, and then did not increase so much. It is necessary to beware of corrosion of steel bar.

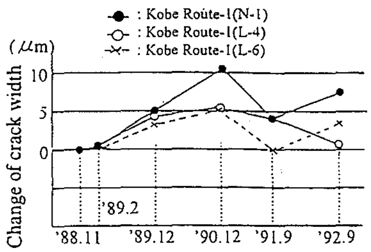

Fig.6 Measurement result of crack width

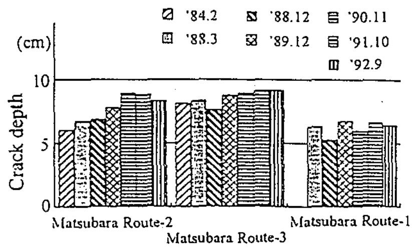

Fig.7 Measurement result of crack depth

Testing of core samples

The concrete properties, ultrasonic wave propagation velocity and static elastic modules, measured from samples from slabs indicated no problem. But the core samples from bridge piers damaged due to AAR have compressive strength of about 15MPa, ultrasonic wave propagation velocity of about 1,500 m/sec and static elastic modules of about 0.18×10^4MPa. This may be because of the fine cracks existing in concrete that cause its strength drop. This phenomenon is much different from slabs.

It is verified from the chemical test that if the equivalent amount of Alkali in concrete exceeds 0.25%, a remarkable expansion will occur. No such high value has been detected in the test so far.

The type of rock was judged as rhyolitic welded tuff which has been identified as a reactive aggregate. No cristobalite, a reactive mineral, was detected by X -ray test.

Table 2 Summary of core sampling test results

Year of core sampling		1984	1988	1993
Location of core sampling		Matsubara-2	Kobe-1	Kobe-1
physical properties	Compressive strength	—	(mean value of 3 samples) 39.0MPa	(mean value of 3 samples) 39.6MPa
	Ultrasonic wave propagation velocity	—	(mean value of 3 samples) 4310m/s	(mean value of 3 samples) 4490m/s
	Elastic modulus	—	(mean value of 3 samples) 2.67×10^4 MPa	(mean value of 3 samples) 2.53×10^4 MPa
Core expansion (see Fig.8)		163(releasing)+225(remaining) $=388\times10^{-6}$ (mean value of 3 samples)	68(releasing)+137 (remaining) $=205\times10^{-6}$ (mean value of 2 samples)	103(releasing)+267 (remaining) $=370\times10^{-6}$ (mean value of 3 samples)
X-ray diffraction		—	Harmful crystal composite is not found,such as cristobalite. But the amount of mica is rather much.	—
Chemical method	Sc	—	224 m mol/l (mean value of 3 samples)	—
	Rc	—	68 m mol/l (mean value of 3 samples)	—
	Sc/Rc	—	3.29 m mol/l (mean value of 3 samples)	—
Equivalent amount of Alkali		0.173%<0.25%	0.15%<0.25%	—
Judgement of rock type		—	rhyolitic welded tuff	welded tuff
Accelerated curing test		—	—	Gel is found on the tenth day

There has been the case judged by JIS chemical method at the construction stage that the aggregate used in slabs on Kobe Route was contaminated. The same result was obtained in the present study.

Fig.8 shows the measurement result of core expansion during accelerated curing. Hanshin Expressway Public Corporation prescribes that the overall expansion is the sum of releasing expansion up to the fifth week and the remaining expansion from the fifth to the tenth week. Accordingly, for the thin members outside the above regulation, such as slabs and railing, the standard value of overall expansion for AAR judgement is taken as $1,000\mu\varepsilon$.

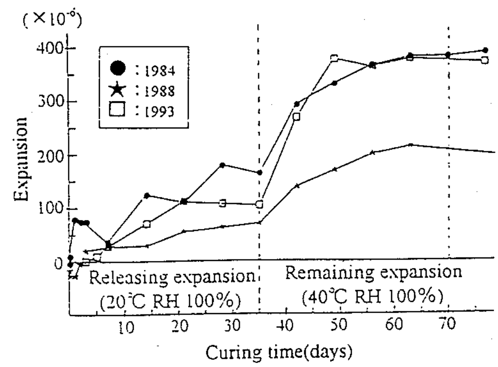

Fig.8 Measurement result of core expansion

Expansion in present test was measured after 60 days of sampling for all samples and the overall expansion was about $150\text{-}400\mu\varepsilon$ which is much smaller than that of bridge piers. In the tests of 1984 and 1988, gel was not found. It was the same at the beginning of 1993, but reaction ring was found in the section of core sample slice.

Deflection of slabs

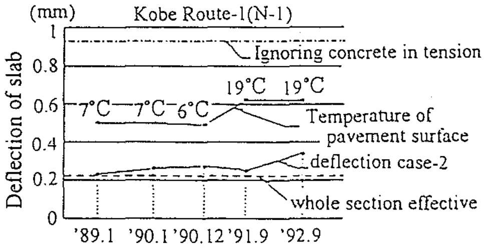

Fig.9 Measurement result of slab deflection

Fig.9 shows the measurement result of slab deflection under the load of a truck with gross weight of 20tf. The computed values, based on the assumptions that the whole section is effective in isotropic plate and that concrete in tension is neglected, and the temperature of pavement surface are also considered. The measured deflection is close to the computed value. Moreover, although variation in pavement stiffness due to temperature difference was taken into account, the change of deflection with years passed is very small and there is no problem in load-carrying capacity and stiffness.

Assessment

Reasons of Damage

A field inspection has been conducted for ten years. However, those cracks had not been recognized due to AAR because the field records observed on these slabs were different from those observed on the bridge piers damaged by AAR in some respect. Considering that maintenance is necessary from the viewpoint of durability diagnosis of AAR is the most proper judgement in the present stage. AAR is regarded as the cause of these cracks in slabs due to the following reasons.

1) Reaction ring showing gel exudation has been found in accelerated curing test of core samples in 1993.

2) There is a trend that damage of slabs is concentrated just in one construction division among all of construction divisions.

3) Particular configuration of cracks due to AAR has been observed, but water leakage, separating lime and rust were not found.

4) Although ten years have passed since construction, new cracks are continuously found.

5) For Matsubara Route 2, although slabs were not opened to traffic damage occurred and progressed.

6) Crack density is high and may not be very obvious in transversal direction to bridge axis.

7) Aggregate samples taken from Kobe Route are judged to be harmful by chemical method.

8) It is thought that quality and strength of concrete is good; design of mixture and construction are no problem.

According to the above, movements due to drying shrinkage, temperature, load action, construction defects and corrosion of steel bars, as well as all of material faults (except reactive aggregate) are excluded from the reasons of crackings.

Although AAR is taken as a cause, it is still remaining problematic to apply the existing standard on crack width and core expansion for judgement of AAR. The reasons are presumed as follows.

1) Because the maximum aggregate size of 25mm in slabs is smaller than that of 40mm in bridge piers, expansion is dispersed.
2) Because thickness of members, diameter of reinforcement bars is smaller and the covering layer of 3cm is smaller than that of 10cm in bridge piers, crackings are dispersed due to less constraint.
3) The behavior is not so much as that of AAR.

Assessment of AAR damaged slab

Damage is considered for durability and load-carrying capacity, respectively. The corresponding results of investigation are shown as follows.
1) Cracks are very dense and remaining expansion is small. There is a tendency that damage will continue in the future.
2) Crack width is almost less than 0.2mm. The maximum is only 0.3mm. This value suggests that repair is necessary in non-corrosion environment based on concrete design code.
3) Water leakage, separating lime and rust are not observed. Crack depth is more than covering layer of concrete.
4) Compressive strength of concrete is over design value. It can be said from load experiment that stiffness of slabs has not decreased.

According to above description, load-carrying capacity has no problem so far. However, there is possibility of more dense cracking and concrete spalling if corrosion of reinforcements starts. Eventually, some countermeasures are necessary for durability.

Conclusion

From the results of this investigation, it is observed that deterioration of RC slabs due to AAR is rather different from that of bridge piers because the situation of reinforcements and constraint conditions are different, while load-carrying capacity is not much affected. In order to protect from decreased durability in future due to increase of cracking density and corrosion of reinforcements, a maintenance action was carried out. Generally, the AAR products possess hygroscopic property and expansion occurs after water is absorbed. Therefore the present maintenance against AAR was focused on the water-proofing measures. Aimed at stopping the damage due to AAR and protect reinforcements from rust, the water-proofing layer was installed on slabs and the epoxy bonded steel plates are attached on the back side of slabs. Moreover, because further progress of damage as well as decrease in load-carrying capacity and durability are known, it is necessary to continue the periodical field inspection and to observe the damage progress of RC slabs due to AAR in the future.

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