SURVEYS AND REPAIRS OF AAR-DAMAGED CONCRETE STRUCTURES (BRIDGE SUBSTRUCTURE AND WATER TANK)

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ABSTRACT

Reaction rims were observed on the fine aggregate in concrete core samples taken from a bridge substructure in the Kyushu Region of Japan, and were identified from the amount of concrete expansion and cracking patterns on the concrete surface as resulting from alkali-aggregate reaction (AAR). A detailed survey revealed that the bridge substructure had undergone significant cracking within a period of three years and that the progress of AAR damage was being accelerated by extraneous elements (sulphur and carbon) that had entered through the cracks.

A large number of cracks exhibiting abnormal development patterns were observed on an industrial water tank (ϕ 10 m, H = 10 m) in the same region. Tests conducted on the internal and external faces of the tank revealed that the damage here too was attributable to AAR. Repair work was implemented both on the inside and outside of the tank. The repair work on the inside involved emptying the tank for 50 hours and coating the internal faces with ultra-rapid-hardening elastic epoxy paint.

In this paper, reports are made on the results of the surveys (expansion, crack development, EPMA, SEM) and countermeasures conducted on the bridge substructure, and on the results of the surveys and repair work implemented on the industrial water tank.

Keywords: AAR, repair, ultra-rapid-hardening elastic epoxy paint, water tank

INTRODUCTION

Countless cracks unique to AAR were discovered on the concrete surface of a bridge substructure located in the Kyushu region, Japan, and studies have determined the cause to be AAR. An industrial water tank in the same region, found to have identical damage, was also surveyed and repaired.

The report on the detailed study on the bridge substructure is given under Part 2, and a report on the survey, repair design and repair work is given under Part 3.

SECULAR CHANGE OF AN AAR-DAMAGED CONCRETE BRIDGE SUBSTRUCTURE

Outline

The concrete substructure of the roadway bridge in question was built in 1972 and is located at the bay of a coastal industrial park. Experts agreed that countless cracks unique to AAR had materialized since 1983. The authors learned of the matter in 1985, and conducted the first survey in 1988, as well as later surveys to study the secular change. The gist of the studies is given in this paper.

Survey particulars

The survey of the concrete structure were divided into three occasions, as given in Table 1.

Survey results and evaluation

Synopsis of laboratory tests up to February 1989

1) The sample test cores were allowed to sit in the laboratory for more than a month, after which moisture due to seepage could still be confirmed around the fine aggregate on the external surface of the core. Large amounts of water-soluble alkalis (sodium and potassium) were detected.
2) Mixed materials consisting mainly of limestone, such as andesite and sandstone, were used as coarse aggregate. White discoloration of approximately 1 mm was observed on the surface of a considerable amount of limestone coarse aggregate, but no cracks or instances of deficient adhesion with the mortar could be confirmed.
3) The fine aggregate was judged to be marine sand stemming from parent rock such as sandstone and andesite. Black reactive rims could be confirmed on a portion of the andesite fine aggregate.
4) According to a JCI (Japan Concrete Institute) accelerated expansion test of the sample cores, the starting expansion strain was 140×10^{-6}, and the permanent expansion strain 450×10^{-6} (Fig. 1).

From these results, and from the characteristics of the cracks, the cause of the damage to the bridge substructure was determined to be AAR of the fine aggregate.

Table 1 Particulars of concrete bridge substructure survey

Survey Date	Survey Purpose; Survey Particulars
April 1988	Deduction of cause Lab tests on sample core (measuring expansion, microscopic observation, etc.)
February 1989	Quantitative survey; clarification of cause; repair design External survey of entire substructure; survey of crack distribution Lab tests (appearance, microscopic observation, x-ray diffraction analysis, etc.)
March 1993	Survey of crack distribution Lab tests on sample core (measuring expansion, EPMA, SEM observations, etc.)

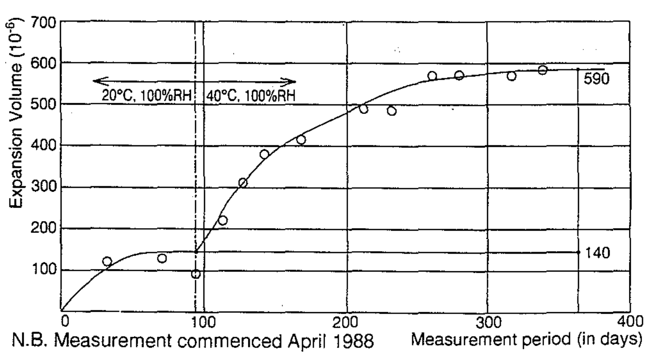

Fig. 1 Measurement results of expansion caused by AAR

Crack distribution pattern

The condition of the cracks in the substructure in February 1989 and March 1993 is given in Fig. 2. The results of a survey of crack density and crack width within 3 m-long horizontal and vertical courses of traverse is given in Table 2. During a period of three years, the amount of cracks increased from 11.1 m/m^2 to 15.0 m/m^2, and crack density and width increased as well.

The 'apparent expansion strain,' obtained by dividing the increase in crack width by the 3 m course of traverse, was similar in the horizontal and vertical directions, coming to 563×10^{-6} and 573×10^{-6} respectively. This apparent expansion strain is larger than the 450×10^{-6} permanent strain. Moreover, exfoliation of the concrete and brittle fracture of the steel reinforcements, which were not observed in 1989, were confirmed in the upper portions of the bridge structure in 1993 (Fig. 3). Such phenomena exceed the damage predicted by the measurement of expansion shown in Fig. 1.

Test core analysis results

The EPMA elementary analyses of the surface of the test cores revealed that extraneous elements had entered the concrete. The penetration depth was 30 mm in the case of chlorine (high concentration up to 9 mm), 5 mm in the case of sodium, 25 mm in the case of sulfur (high concentration up to 5 mm), and 16 mm in the case of carbon. The depth of neutralization determined by the phenolphthalein method was 15 mm. Owing to the substructure's proximity to the sea and an industrial park, these

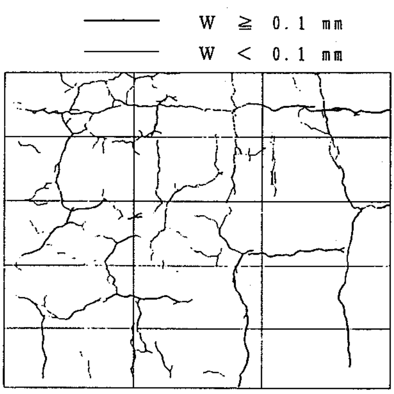

Fig. 2a Crack distribution pattern (February 1989)

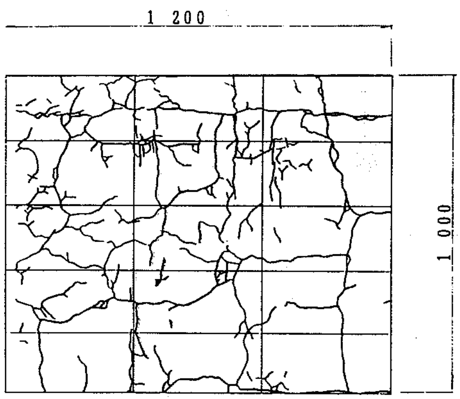

Fig. 2b Crack distribution pattern (March 1993)

Table 2 Crack distribution survey results

Survey Date		February 1989	March 1993
Crack Quantity (m/m^2)		11.1	15.0
(cracks thereof exceeding 0.1 mm)		6.4	6.6
Horizontal Course of Traverse	Crack Density (lines/meter)	5.7	7.7
	Totalled Crack width (mm)	2.41	4.10
	Increase in Crack Width (mm)	1.69	
	Strain Increase	563×10^{-6}	
Vertical Course of Traverse	Crack Density (lines/meter)	6.0	3.0
	Totalled Crack Width (mm)	3.37	5.45
	Increase in Crack Width (mm)	1.72	
	Strain Increase	573×10^{-6}	

penetrative elements are thought to have been provided by airborne salt and factory flue gas, in addition to carbon dioxide.

According to observations by scanning electron microscope (SEM), hairline cracks had arisen in the interior of the core at a depth of approximately 40 mm, and a large number of needle crystals were observed in their vicinity (Fig. 4). Powder x-ray diffraction showed these needle crystals to be $C_3A{\cdot}3CaSO_4{\cdot}32H_2O$ (Ettringite) and $C_3A{\cdot}CaCO_3{\cdot}12H_2O$ (para-alumohydrocalcite), as shown in Fig. 5.

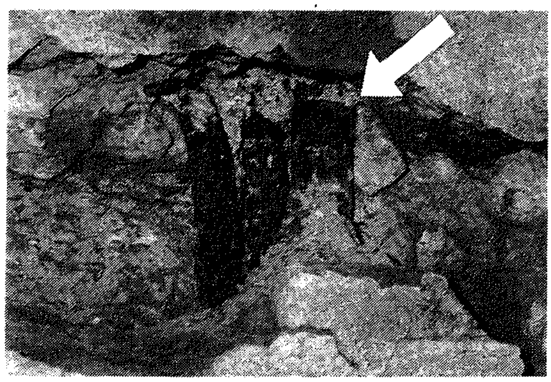

Fig. 3 Fracture of steel reinforcements

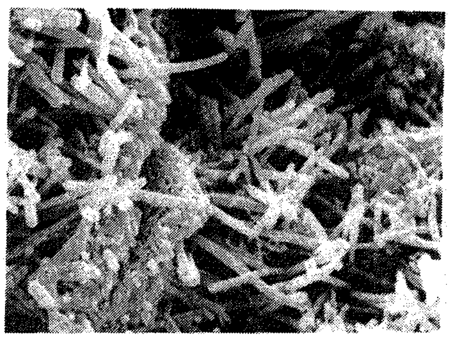

Fig. 4 SEM observation

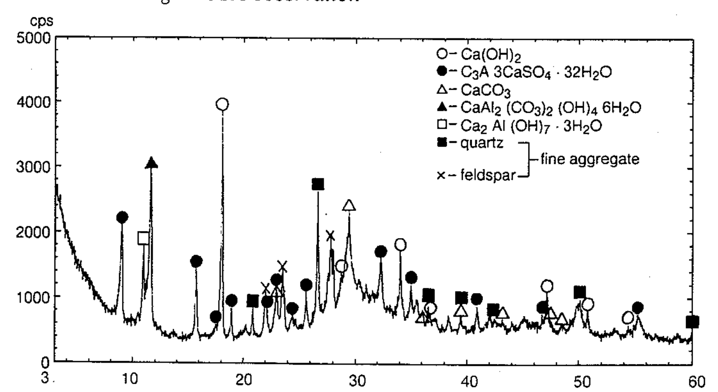

Fig. 5 Results of powder X-ray diffraction analysis (CuK_α)

From such results, it can be deduced that cracks occurring in the structure as a result of AAR were aided in their growth by needle crystals which formed as a result of extraneous sulfur and carbon.

In summary, the damage to the structure studied increased significantly in the space of three years. It is thought that the development of cracks occasioned by AAR was fostered by the penetration of extraneous elements originating in the surrounding environment. In other words, it is foreseeable that in structures located in coastal or industrial areas, the progress of damage caused by AAR is more rapid than average.

Further issues for study are whether or not the use of limestone aggregate affects the formation of para-alumohydrocalcite.

SURVEY, REPAIR DESIGN AND REPAIR WORK OF AN AAR-DAMAGED WATER TANK

Outline

A 700 ton water tank in the same area as the bridge substructure reported on under Part 2 is a ferroconcrete structure that was built more than 19 years ago. In recent years, marked damage was observed in this surge tank, such as cracks forming on the exterior and the deposition of free limestone.

The cracks formed in an alligator pattern, and as the tank was constantly holding water for industrial supply, the suspicion was strong that the damage had been caused by AAR.

This part of this paper reports on the study on the causes of the damage, on the repair design, and on the repair work, which had to be completed within a limited period of time.

Survey

The water stored by the surge tank is taken from rivers, and is constantly supplied to businesses. For this reason, the survey of the inside of the water tank had to be carried out when the tank could be emptied, during the short period (6 hours) following an increase in the water supply occurring after a rise in fluvial water levels. Water levels allowing the tank to be emptied were only likely during the rainy season or a typhoon, and the survey was carried out approximately one year after preparations were completed.

The water tank is depicted in Fig. 6, and the survey results of the exterior and

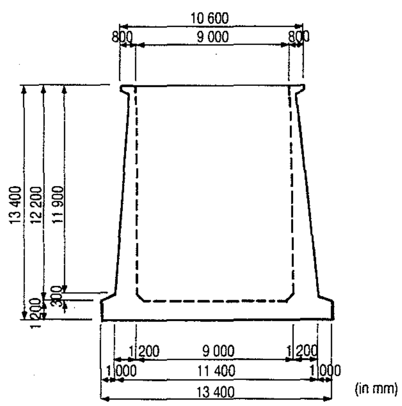

Fig. 6 Water tank cross section

interior of the tank are given in Table 3.

The results show that the damage to the water tank is due to AAR. As given in Table 3, the crack density on the exterior is 1.6 times as much as on the interior. The crack density and crack width were most advanced on the exterior of the northern side. It is believed that insolation, which affects the contrast between moistness and dryness on the concrete surface, affects the degree of damage caused by AAR.

Repair design; repair work

As the survey showed that no rust could be confirmed on the steel reinforcements and the fall in durability was less than expected, caulking with crack filler and a surface membrane was selected as the appropriate repair technique. From the results of the tests on the sample core, it was judged that AAR would progress slightly after repair, and an elastic material was selected as filler and membrane for both the interior and exterior surfaces.

Owing to the nature of the surge tank, assembling the scaffolding, the repair work, and dismantling the scaffolding had to be carried out within a time limit of only 50 hours. Hence, the main objective which featured in the selection of repair method and materials was the completion of the best possible work within the limited time permitted.

The considerations taken into account for the repair design and repair work are as follows:

1) In order to ensure the removal of moisture from the inside of the concrete, the exterior surface was cured with sheet polyethylene after the work on the interior was completed. Repair work on the exterior surface was conducted 3 months later.
2) 10 hot-air jet heaters were used to force-dry the interior after high-pressure cleanup (120 kgf/cm^2), but as the allowed drying time was insufficient, ultra-rapid-hardening elastic epoxy resinous paint, a covering for moist surfaces which displaces water well, was employed as putty for filling the cracks and as material for the membrane used to cover the exterior surface. The particulars for the coating on the interior surface are given in Table 4.
3) In order to shorten the work duration, the scaffolding used inside the tank was assembled outside, lowered into the tank using a 25 ton hydraulic crane, and lifted out again after the work was completed.
4) Thirty workmen participated in the repair of the interior, and as a variety of work had to be carried out within a short duration, the number of supervisors was eight.

Table 3 Survey results

Survey Subject	Exterior	Interior
Cracking	0.5 mm alligator cracks are most common 3.4 m/m^2 (5.3 m/m^2 on the northern side) Cracks extend up to steel reinforcements (92 mm from surface)	0.2 mm-0.5 mm alligator cracks are most common 2.1 m/m^2 Cracks do not reach steel reinforcements
Neutralization	Solution of 1% phenolphthalein Colorless area is 1mm-2mm	————
Steel Reinforcement Corrosion	None	None (other than superficial rust)
Test Core Observations	Reactive rims apparent	Reactive rims apparent
Compressive Strength Test of Sample Core	Dynamic modulus of elasticity: 1.92 x 10^5 kg/cm^2 Young's modulus: 1.17 x 10^5 kg/cm^2 Compressive strength: 124 kgf/cm^2 (measured after expansion volume test)	Compressive strength: 184 kgf/cm^2 (submersed section) 241 kgf/cm^2 (portion above water line)
Expansion Volume Test	(JIS A 1129) 0.10% in 6 months	
Chemical Method	(Aggregate: ASTM C 289) Rc=423 m mol/l (decrease in alkali concentration) SC=309 m mol/l (quantity of soluble silica) → deleterious limits	

Table 4 Internal coating particulars

Coat	Material	Design Thickness (μ)	Standard Application Quantity (kg/m^2)	Application Method	Application Interval (at 20°C)
Undercoat	Ultra-rapid-hardening elastic epoxy paint	400	0.30	Rollers	3 hours
Middle	ditto		ditto	ditto	ditto
Overcoat	ditto		ditto	ditto	ditto

Table 5 External coating particulars

Coat	Material	Design Thickness (μ)	Standard Application Quantity (kg/m^2)	Application Method	Application Interval (at 20°C)
Undercoat	Watertight penetrative silane × 2	1100	0.24	Brushes; rollers	8 hours
Middle	Flexible polymer cement compound × 3		2.10	ditto	1 hour
Overcoat	Acrylic-resinous emulsion compound × 2		0.20	ditto	1 hour

Thanks to such efforts, the work could be carried out with a 6 hour interval for drying the undercoat and for allowing each of the coats to set. The repair work on the interior surface could thus be concluded on time (within 50 hours).

5) As the cracks on the exterior were deep, an elastic epoxy resin of low viscosity was injected using the low pressure provided by rubber containers.

6) As the water tank had stored water continuously, its material held an excess amount of water. In order to remove this water, a water-repellent silane was used as undercoat for the surface membrane on the exterior, and to ensure deaeration, permeable substances were employed for the middle coat and overcoat. The particulars for the coating on the exterior surface are given in Table 5.

It is now three years since the repair work was carried out, but apart from some stains on a portion of the outer membrane, no abnormalities are observable.

As the progress of AAR after repair work is feared, at present a follow-up survey is being conducted (using a contact gauge to measure crack width).

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