INFLUENCE OF CATHODIC PROTECTION ON CRACKING AND EXPANSION OF THE BEAMS DUE TO ALKALI-SILICA REACTION

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ABSTRACT

Reinforced concrete beams with different alkali contents and water : cement ratios, 0.2 m by 0.3 m by 2 m, were made from the non-reactive river sand and the reactive andesitic coarse aggregate. After the curing of 28 days, reinforced concrete beams were exposed outdoors and the cathodic protection current of 50 mA/m^2 was applied to the steel reinforcement in concrete beams. The expansion and cracking in concrete beams were monitored for about 2 years in order to investigate whether the cathodic protection may promote the alkali-silica reaction of concrete beam. Practical implications with regard to the preventive measures of ASR in RC and PC bridges were discussed.
Keywords: Cathodic protection, Outdoor exposure test, ASR, Cracking, Expansion

INTRODUCTION

In Japan, the cathodic protection has increasingly been used as one of the effective rehabilitation methods for RC and PC structures damaged by the chloride induced corrosion of steel reinforcement, although its application to highway bridges and other sorts of concrete structures is not so much as in USA and Canada (1). Electrochemical methods such as realkalinisaction of carbonated concrete and chloride extraction of chloride contaminated concrete under a relatively high current density have also recently been investigated. It has been pointed out by the researchers that the potentially detrimental side effects may exist in cathodic protection method, which includes the hydrogen embrittlement of steel reinforcement, the decrease in bond strength and the increase in expansive alkali-silica reaction etc. (2). Page et al. (3) and Kuroda et al. (4) revealed that cathodic polarization of steel in concrete caused expansion and extensive cracking due to ASR in the specimens containing the alkali-reactive aggregate. The acceleration of ASR in the cathodic protection may be due to the electro-migration of Na^+ and K^+ ions from the surrounding matrix towards the steel reinforcement, but its mechanism is not fully understood. Furthermore, the expansion and cracking of concrete due to ASR may vary depending not only on the size and refinement of concrete structures but on environmental conditions around concrete structures, but there has been no reports which confirmed this detrimental effect of the cathodic protection in RC and PC bridges in service.

This study aims at investigating the influence of cathodic protection on expansion and cracking of reinforced concrete beams containing the reactive andesitic coarse aggregate subjected to cathodic protection. Reinforced concrete beams were exposed outdoors and subjected to the current density at 50 mA/m^2 in cathodic protection for about 2 years. The influence of the water : cement Ratio and the alkali content in concrete on the cracking and expansion behavior of reinforced concrete beams in the cathodic protection was assessed.

EXPERIMENTAL

Materials and Mix Proportions

The alkali contents of cements used are presented in Table 1. The cements used were ordinary Portland cement with the equivalent Na_2O of 0.75 % and high early-strength Portland cement with the equivalent Na_2O of 0.58 %. An andesitic crushed stone from the Noto peninsula in Ishikawa Prefecture was used as a reactive coarse aggregate ; the sand and the gravel from the Hayatsuki river as a non-reactive fine and coarse aggregate. The evaluation of alkali reactivity of the andesitic coarse aggregate according to JIS A 5308 was not innocuous ; soluble silica (Sc) and reduction in alkalinity (Rc) at the chemical method : 228 mmol/l and 131 mmol/l, respectively, expansion ratio at 6 months at the mortar bar test : 0.11 %. The main reactive component identified in the texture of the andesitic crushed stone was a volcanic glass. The two types of mix proportions, which are normally used for reinforced concrete girder (RC) and prestressed concrete girder (PC) in Japan, were selected ; their water : cement ratios were 0.53 and 0.35 for RC and PC mixtures, respectively. Mix proportions of RC and PC mixtures are shown in Table 2. As shown in Table 2, the alkali content originally supplied from the ordinary Portland cement and the high early strength Portland cement alone was 2.3 kg/m^3 and 2.6 kg/m^3 for RC and PC mixtures. RC and PC mixtures with an increased alkali content were also prepared by adding the NaOH solution, whose equivalent Na_2O content is 2.4 kg/m^3, in the mixing water, their total alkali contents being 4.7 kg/m^3 and 5.0 kg/m^3 for RC and PC mixtures.

Table 1 Alkali content of Portland cements used

Type of Concrete	Type of Cement Used	Na_2O (%)	K_2O (%)	Equivalent Na_2O (%)
RC Mix.	Ordinary Portland Cement	0.41	0.51	0.75
PC Mix.	High Early Strength Portland Cement	0.34	0.37	0.58

Table 2 Mix proportions of RC and PC mixtures

Type of Concrete	Slump (mm)	Air (%)	W/C (%)	s/a (%)	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Crushed Stone (kg/m^3)	Gravel (kg/m^3)
RC Mix.	80 ± 15	2 ± 1	53	42	308	164	784	563	563
PC Mix.	80 ± 15	2 ± 1	35	37	440	155	650	587	587

Preparation of RC Beams and Exposure Condition

Fig.1 shows dimensions of RC beams used. As shown in Fig.1, all model beams had a cross-section of 0.2 m × 0.3 m and a length of 2 m, where D13 longitudinal steel reinforcements and D6 stirrups were provided. As shown in Fig.2, a titanium wire galvanized with platinum was fixed on the top surface of concrete beam as a anode system, which was coated with the conductive paint overlay. An anode to steel resistance and potentials of steel reinforcement were monitored using the embedded lead (Pb) reference cells in concrete beams. The current density of 50 mA/m^2 at the highest value in the application to real concrete structures was achieved and the measurements of instant cut-off potentials and E vs Log I curves were run at the intervals of 3 months. The total

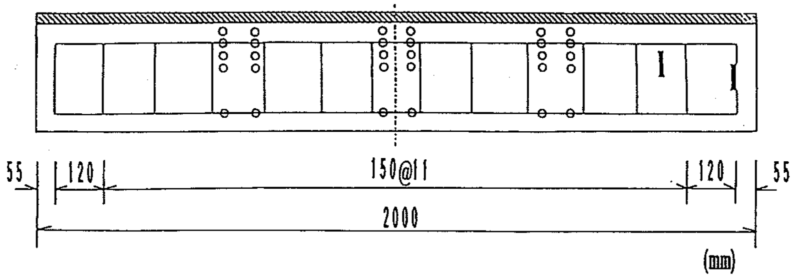

Fig. 1 Dimensions of the reinforced concrete beam used.

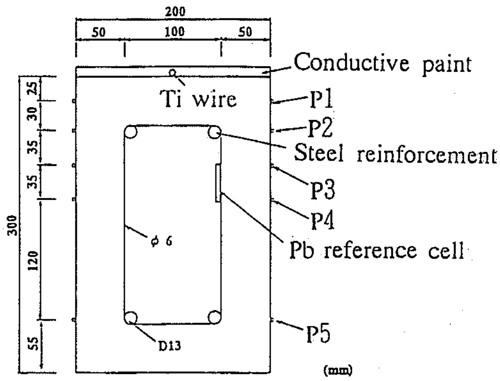

Fig. 2 Cross-section of the reinforced concrete beam used.

Fig. 3 External appearance of the exposure site on the roof of building in Kanazawa University campus.

nine model concrete beams including one RC mixture beam with all surfaces coated were made in the concrete factory near Nanao city in September 1993, and after the curing of 28 days a direct current was applied to the half of them. In June 1994, all concrete beams were moved to the exposure site located on the roof of a building in Kanazawa University campus, where they were placed on the wooden support bars, as shown in Fig.3. The variations of expansion at the distance from the anode side were measured every a couple of months by means of a contact gauge over 100 mm, and the development of cracking of concrete was traced on the transparent plastic sheets. Concrete cylinders, 100 mm in diameter and 200 mm high, were also prepared and exposed near concrete beams in order to examine the changes in mechanical properties of concrete such as compressive strength and splitting tensile strength with the exposure time.

RESULTS AND DISCUSSION

Compressive Strength and Splitting Tensile Strength of the Cylinders

Compressive strength and splitting tensile strength of the cylinders with and without additional alkali are presented in Table 2. For RC mixture, no visible cracks were found on the surface of cylinders independently of alkali content. On the other hand, for PC mixture with the additional alkali, the first cracks with the width of 0.05 mm to 0.1 mm occurred during the summer in 1994, and developed to the pattern-cracking, while for PC mixtures without the additional alkali the first fine cracks were found in December 1994. Compressive strengths of RC and PC mixtures at 1 year were increased compared to those at 28 days, although visible cracks were observed for PC mixtures with the additional alkali. However, splitting tensile strengths of RC and PC mixtures at 1 year were almost the same as or lower than those at 28 days. It appears that especially at early stages of deterioration due tp ASR, the cracks influenced more seriously the splitting tensile strength than the compressive strength. Furthermore, it is very interesting that the deterioration due to ASR has really occurred even for PC mixtures with the alkali content of only 2.3 kg/m^3 under natural environments, because the Japanese Industrial Standard of Ready-mixed Concrete, JIS A 5308, has recommended since 1989 to keep the total alkali content of concrete at the level of less than 3.0 kg/m^3 as one of the main protective measures against ASR. From the point of view of deterioration of concrete due to ASR, the exposure test condition under natural environments appears to be severer than the accelerated test condition in a moist environment at 38 °C described in JCI AAR-3.

Table 3 Compressive and splitting tensile strengths of RC and PC mixtures

Type of	Compressive Strength (MPa)		Splitting Tensile Strength (MPa)	
Concrete	28 Days	1 Year	28 Days	1 Year
RC Mix.	26.5	31.1	2.7	2.7
RC Mix. *	20.9	30.0	2.1	2.1
PC Mix.	56.4	62.5	3.7	4.5
PC Mix. *	49.0	63.5	3.6	3.2

* The NaOH solution with the equivalent Na_2O of 2.4 kg/m^3 was added into the mixture.

Cracking Patterns of the RC Beams in Cathodic Protection

Cracking patterns of concrete beams in the cathodic protection are illustrated in Fig.4, 5, 6 and 7. In case of RC mixture without the additional alkali (Fig.4), some fine cracks with the width of smaller than 0.05 mm occurred in the upper and center portion of the beam when the direct current of 50 mA was applied for about 1 year, although no significant cracks were observed in the control beam in the absence of the cathodic protection. When the alkali of 2.4 kg/m^3 was added to RC mixtures, the extensive cracks occurred in the center and upper portion during the first summer in 1994, and followed by the development of a severe pattern cracking. Also, in these RC mixture beams, the widespread cracks developed at regular intervals of 50 to 100 mm from the bottom of the beam were observed (Fig.5). It is apparent in the comparison between RC mixture beams with and without the cathodic protection that the application of cathodic protection significantly increases the cracking of RC mixtures with the additional alkali, especially in the upper portion around the steel cathode. On the other hand, there were little cracks both in PC mixtures without the additional alkali whether or not the cathodic protection had been applied (Fig.6). However, in the case of PC mixtures with the additional alkali (Fig.7), the cathodic protection increased the cracking in the center and upper portion of the beam, but cracking patterns of PC mixture beams with the additional alkali were different from those of RC mixture beams with the additional alkali ; that is, the cracks were relatively finer and discontinuous, and there were little cracks developed from the bottom of the beam.

Expansion Behaviors of the RC Beams in Cathodic Protection

Expansion behaviors of concrete beams at the distance from the anode with and without the cathodic protection are shown in Fig.8, 9, 10 and 11. It has been pointed out by the researchers that expansion behaviors of concrete in service due to ASR may vary widely depending on the "micro-climate" condition around concrete structures i.e. temperature, humidity and shining time etc.(5, 6). Under the outdoor exposure condition, the RC and PC mixture beams without the additional alkali did not show a significant expansion during about 2 years, their expansion ranging within ± 0.03 %. When the alkali of 2.4 kg/m^3 was added, RC and PC mixture beams expanded around June 1994 just after they had been exposed on the roof of a building in Kanazawa University campus, and the relatively large and rapid expansion occurred during the first summer in 1994, their expansion ranging from 0.05 % to 0.15 %. The results suggest that the expansion of concrete due to ASR proceeds rapidly in summer and slowly in winter as pointed out by the authors (5). Also, the expansion of all the concrete beams proceeded more rapidly and extensively at the west side than at the east side because the temperature of concrete became higher at the west side during the summer. The seasonal expansion behaviors are insistent with the results of visual observations of cracking. With regard to the difference in expansion behaviors of concrete beams at the distance from the anode, it was found that when the cathodic protection was applied to the RC and PC mixture beams with the additional alkali, the expansion at P 1 and P 2 around the steel cathode was larger than that at P 5 near the bottom. It appears that the alkali-silica reaction may be accelerated especially around the steel cathode due to the electro-migration of Na^+ and K^+ ions from the surroundings towards the steel cathode and the subsequent formation of OH^- ions. However, taking into considerations the fact that PC mixture beams showed a smaller expansion than RC mixture beams independently of the total alkali content, the influence of cathodic protection on the expansion of concrete due to ASR can be reduced when the water : cement ratio of concrete is low. This may be related primarily to the decrease in the mobility of both the alkali ions and the water in concrete with a low : water cement concrete due to the formation of dense microstructure. Furthermore, as shown in comparison between Fig.9 and 10, expansion behaviors were almost similar for RC mixture beams with and without the epoxy resin-type coating Assuming that a

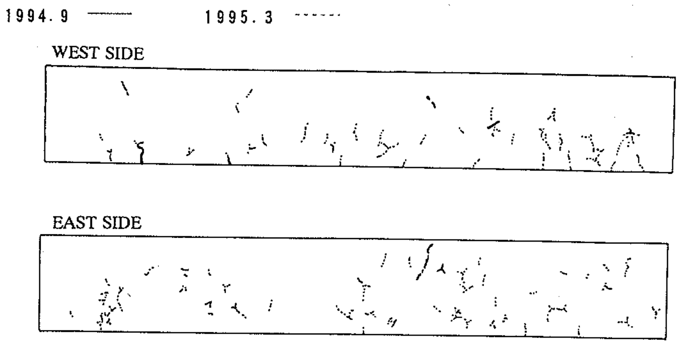

Fig. 4 Cracking patterns of RC mixture without the additional alkali (2.3 $kg/m^3 Na_2O$ eq., 50 mA/m^2).

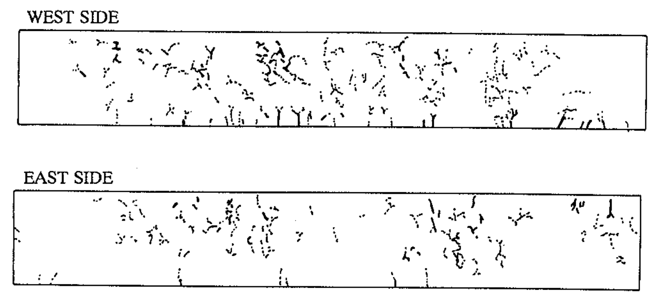

Fig. 5 Cracking patterns of RC mixture with the additional alkali (4.7 kg/m^3 Na_2O eq., 50 mA/m^2).

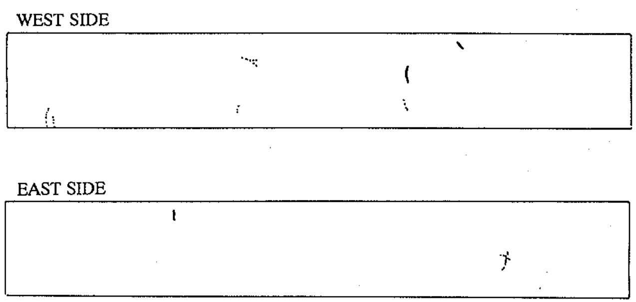

Fig. 6 Cracking patterns of PC mixture without the additional alkali (2.6 kg/m^3 Na_2O eq., 50 mA/m^2).

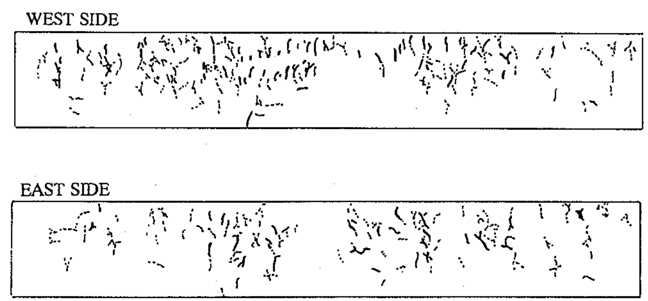

Fig. 7 Cracking patterns of PC mixture with the additional alkali (5.0 kg/m^3 Na_2O eq., 50 mA/m^2).

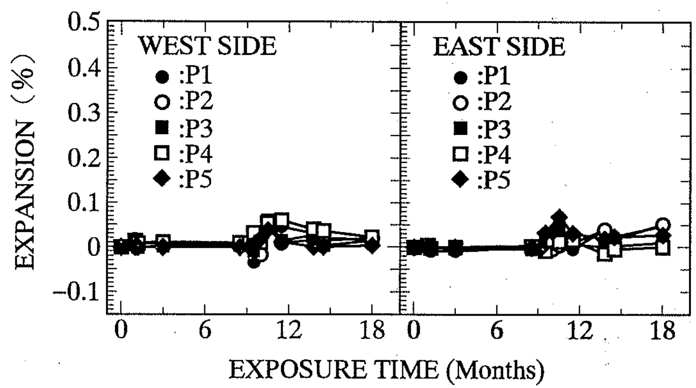

Fig. 8 Expansive behaviors of RC mixture without the additional alkali (2.3 kg/m^3 Na_2O eq., 50 mA/m^2).

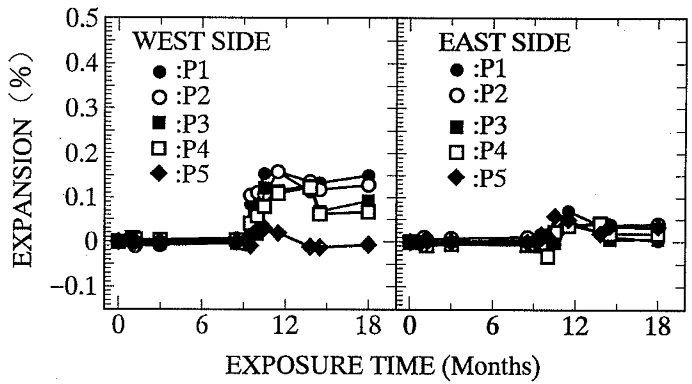

Fig. 9 Expansive behaviors of RC mixture with the additional alkali (4.7 kg/m^3 Na_2O eq., 50 mA/m^2).

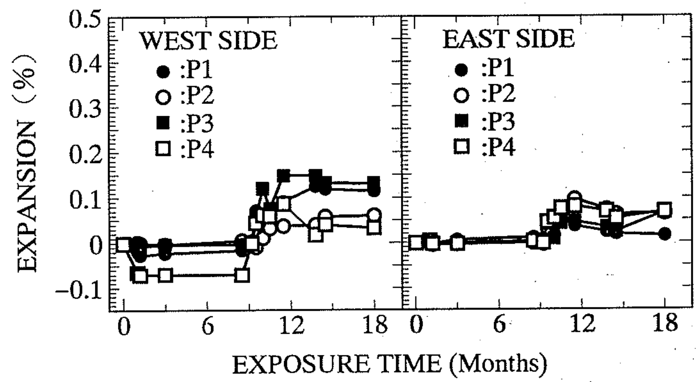

Fig. 10 Expansive behaviors of epoxy-resin coated RC mixture with the additional alkali (4.7 kg/m^3 Na_2O eq., 50 mA/m^2).

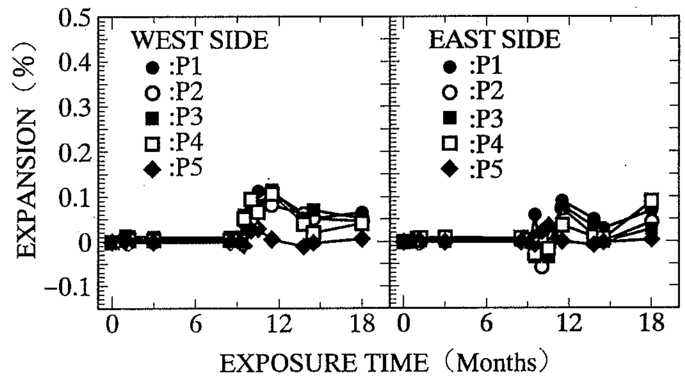

Fig. 11 Expansive behaviors of PC mixture with the additional alkali (5.0 kg/m^3 Na_2O eq., 50 mA/m^2) .

critical humidity to inhibit the progression of ASR in concrete structures is as high as 80 % (7), it is considered that the effect of surface treatments to prevent an overall expansion of concrete is not so significant as expected in the laboratory study, especially for the relatively large-sized concrete beams exposed outdoors.

CONCLUSIONS

From the experimental results, it was found that the application of cathodic protection in reinforced concrete beams increased significantly a risk of damaging expansion and cracking in concrete containing potentially alkali-reactive aggregates. This also indicates the importance of the examination in advance concerning both the alkali-reactivity of the aggregates used and the mix proportions of concrete before the cathodic protection or the electro-chemical chloride removal method is applied to the old RC and PC bridges.

The measurements of expansion behaviors in the reinforced concrete beams are still ongoing. We have a plan at 3 years of exposure time to carry out the structural loading test for all the concrete beams and the chemical analysis and petrographic examination of concrete cores taken from the concrete beams.

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