STUDY OF ALKALI–AGGREGATE REACTIONS IN ELECTRICAL FIELDS

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ABSTRACT

The damage caused by Alkali Silica Reactions (ASR) in structures with cathodic protection systems, such as reinforced and prestressed concrete bridges and substructures exposed to the marine environment, has raised the issue of possible effects of electrical fields on ASR.

If ASR can be influenced by currents when the cathodic protection system is applied to reinforced and prestressed concrete structures, ASR could be initiated and accelerated.

This experimental program includes concrete specimen expansion tests with and without the application of an electric current, measurements of alkali content, and measurements of the diffusion of sodium and potassium ions through concrete under the influence of a current.

Keywords: ASR, blast furnace slag, current density, expansion, fly ash

INTRODUCTION

Reinforced and prestressed concrete structures, such as coastal structures and roads covered with antifreezing materials in cold districts, are damaged due to the permeation of salt into concrete and subsequent corrosion of the reinforcing steel. This phenomenon is called salt attack, and is a serious problem for reinforced and prestressed concrete.

Recently, researchers in this field have come to believe that the cathodic protection system is the most effective method to prevent the corrosion of steel. Reinforced concrete structures are connected to a direct current source so that the reinforcing steel is negatively charged. Desalination causes the chloride ions to migrate from around the steel to the concrete surface due to the difference in current density.

There is a drawback to this protection method. Researchers have found that when the steel is negatively charged, it attracts alkali ions, and the resulting increase in their concentration may cause the concrete to expand due to ASR.

This paper reports on the expansion characteristics of concrete due to ASR when the concrete is subjected to a direct current. Parameters studied were the type of alkali, total alkali content, current density, and the presence or absence of admix materials.

OUTLINE OF THE EXPERIMENT

Materials

The materials used in this experiment were as follows. Cement: a low-alkali portland cement (0.46% Na_2O equivalent). Aggregates: sand, judged nonreactive by the chemical method, as the fine aggregate; reactive gravel (andesite coarse aggregate) with a maximum diameter of 20 mm as the coarse aggregate – the same reactive gravel used in concrete structures which later suffered damage. This coarse aggregate was judged to be reactive by both the chemical method and mortar bar method. Some properties of the aggregates are given in Table 1. Admix materials: blast furnace slag and fly ash were used as admix materials. Their chemical compositions are given in Table 2. Alkalis: NaOH and NaCl were added as alkali.

Table 1 Some properties of aggregate

Type	Specific gravity	Absorption (%)	Finess modulus	Potential alkali reactivity test		
				Rc(m mol/l)	Sc(m mol/l)	Sc/Rc
Reactive coarse aggregate	2.64	1.48	6.53	67.5	301	4.4
Non reactive fine aggregate	2.67	1.40	2.79	—	—	—

Table 2 Chemical compositions of blast furnace slag and fly ash

Type	Specific gravity	Chemical compositions (%)						
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Blast furnace Slag	2.90	31.9	13.4	0.2	42.1	6.1	0.27	0.28
Fly ash	2.18	54.5	25.2	5.7	5.8	1.3	2.5	1.4

Method

Three types of binding materials were used: ordinary portland cement; a mixture of 50% blast furnace slag and 50% ordinary portland cement; and a mixture of 20% fly ash and 80% ordinary portland cement.

The mix proportions are shown in Table 3. When ordinary portland cement was used alone, the total alkali content of the concrete was adjusted using two methods. NaOH was used to adjust the alkali content of the concrete to a 1.5% Na_2O equivalent. NaCl was used to adjust the alkali content of the concrete to 0.5%, 1.0%, 1.5%, 2.0%, 2.5% Na_2O equivalent. When blast furnace slag was used, the total alkali content was adjusted to 1.0%, 1.5%, 2.0%, and 2.5% Na_2O equivalent by the addition of NaOH. For concrete containing fly ash, the total alkali content was adjusted to 0.5%, 1.5% and 2.5% Na_2O equivalent by the addition of NaOH.

Table 3 Mix proportion

Type of binder	Maximum size (mm)	Slump (cm)	Air (%)	W/C	s/a (%)	Unit weight (kg/m³)					
						W	C	Slag	Fly ash	S	G
OPC	20	Free	2	0.45	50	203	450	—	—	846	837
OPC+BS	20	Free	2	0.45	50	203	225	225	—	838	829
OPC+FA	20	Free	2	0.45	50	203	360	—	90	830	821

OPC : Ordinary portland cement, BS : Blast furnace slag, FA : Fly ash

The specimens used in this experiment were concrete rectangular prisms with dimensions of 10 x 10 x 40 cm, as shown in Fig.1. A titanium wire plated with platinum was embedded in the center of the upper surface of the specimen and was containing a conductive anodic material. The reinforced bar (13 mm in diameter) was located in the center of the cross section of the specimen. A direct current was applied to the reinforcing steel from a power source at the age of 5 days.

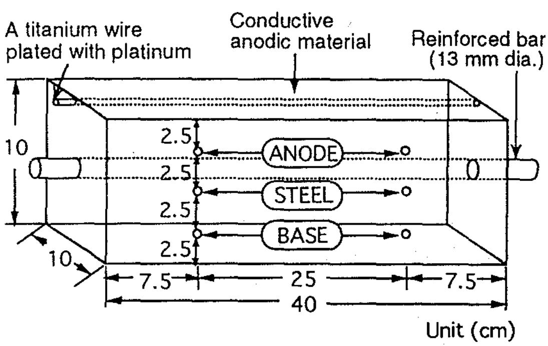

Fig.1 Outline of specimen

Current densities of 0, 25, 50, 100 and 200 mA/m² were applied on the 10 cm x 40 cm surface of the specimen using only portland cement. Specimens containing admix materials were subjected to current densities of 0, 50, and 100 mA/m². The specimens were stored at 40 ℃ at a relative humidity (R.H.) of 100%. The change in length of the specimens were measured at three points: between the anode and the steel (ANODE), along the steel (STEEL) and between the steel and the base (BASE), as shown in Fig.1. After the specimens were removed from storage (40 ℃, R.H. 100%), they were put in a constant temperature room (20 ℃) for 24 hours. Their length was measured after their temperature had stabilized at 20 ℃.

TEST RESULTS AND CONSIDERATION

Effects of current on ASR in concrete containing NaOH

Figs. 2 and 3 show the relationship between expansion and measurement points over time in specimens with a total alkali content adjusted to 1.5%. One group of specimens received no current; the other group were subjected to a current density of 50 mA/m².

The expansion due to AAR in concrete exposed to current flow was larger than the control group. That is to say, the expansion due to ASR in concrete was accelerated by the current.

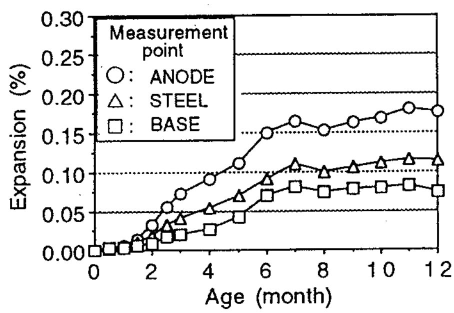

Fig.2 Expansion at measurement point over time (No current) (Alkali content : 1.5% (NaOH))

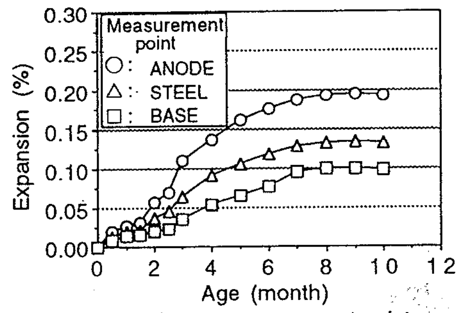

Fig.3 Expansion at measurement point over time (Current density : 50mA/m ²) (Alkali content : 1.5% (NaOH))

When the reinforced concrete is exposed to a direct current and the steel is negatively charged, the alkali ions are attracted towards the steel and their concentration rapidly increase in the vicinity of the steel. In addition, OH^- is produced around the steel due to a cathodic reaction. As a result, the concentration of alkali ions and OH^- increases and expansion due to ASR in concrete is accelerated.

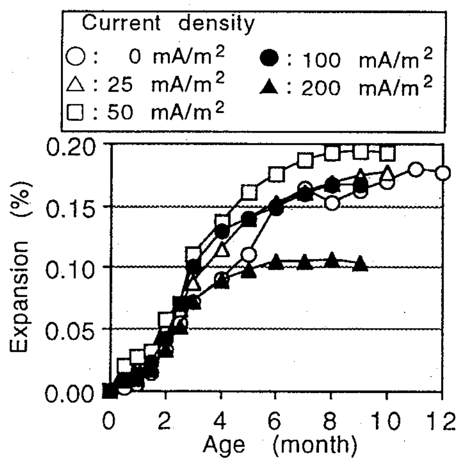

Fig.4 Expansion at ANODE over time (Alkali content : 1.5% (NaOH))

The maximum effect of current on expansion due to ASR in concrete is thought to occur in the ANODE position. (In the following results, a measurement at the ANODE position is shown.) Fig. 4 shows the relationship between expansion and current density over time in concrete containing a 1.5% alkali content for the respective current densities from 0 to 200 mA/m ². Fig. 4 shows that expansion does not always increase as current density increases.

The expansion in concrete exposed to a current density of 50 mA/m ² was the greatest, but expansion in concrete exposed to a current density of 200 mA/m ² was less than the expansion in concrete not exposed to current.

Effect of current flow on ASR in concrete containing NaCl

Fig. 5 shows the relationship between expansion and current density over time in concrete with a 1.5% alkali content and containing NaCl instead of NaOH.

This figure shows that expansion in concrete exposed to current starts at an earlier age than concrete not exposed to current, and the expansion in exposed concrete is greater. Therefore, expansion due to ASR is accelerated by current flow. In the authors view the ASR is accelerated by the production of OH^- around the steel due to the cathodic reaction.

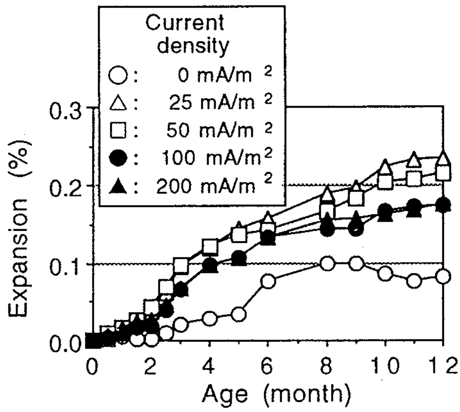

Fig.5 Expansion at ANODE over time (Alkali content : 1.5% (NaCl))

The relationship between expansion and current density

The relationship between expansion in concrete containing NaOH or NaCl at the age of 9 months and the current density is shown in Fig. 6. This figure shows that the expansion in concrete containing NaOH increases as the current density increases to 50 mA/m^2. When the current density exceeds 50 mA/m^2, the expansion decreases as the current density increases. For concrete containing NaCl, the expansion increases as current density increases up to 25 mA/m^2, but then decreases as the current density increases beyond 25 mA/m^2. Therefore, it is considered that this value is the pessimum value for the current density in concrete containing both kinds alkali. It is considered that the following reasons account for the existence of a pessimum value in current density.

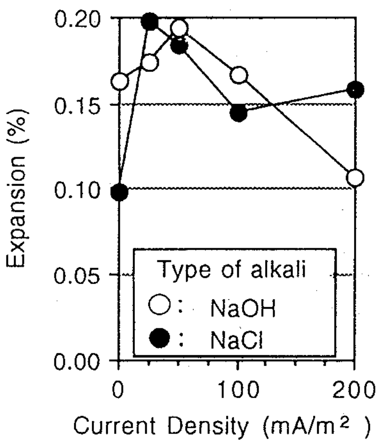

Fig.6 Relationship between expansion and current density (Alkali content : 1.5% (NaOH and NaCl)) (9 months)

When reinforced concrete is subjected to current, the positively charged alkali ions (Na^+, K^+) in the concrete are attracted towards the steel. Therefore, the concrete expansion due to ASR is accelerated because the concentration of alkali ions increases near the steel.

However, when the current density becomes very large, the gel becomes a high-alkali type due to ASR because the concentration of alkali ions rapidly increases. Under these conditions, expansion is small because the viscosity of high-alkali type gel is low and the expansive pressure of the gel in concrete decreases (K. Kishitani, 1986). It is thought that this creates a pessimum value for current density.

Comparing concrete containing NaCl with concrete containing NaOH, when the samples are not exposed to current, the expansion in concrete containing NaCl is smaller. However, in the case of concrete exposed to current, the expansion in concrete containing NaCl approaches that of concrete containing additional NaOH. Thus, the increase in expansion due to current flow in concrete containing NaCl is larger than that in concrete containing NaOH. The effect of current flow on the concrete containing NaCl is greater than that on the concrete containing NaOH. The reason for this ASR–induced expansion in concrete with NaCl is as follows:

Cl^- easily replaces the fixed OH^-. The Cl^- becomes fixed on the hydrate, and the concentration of free OH^- increases (T. Yonezawa, 1988). Since the concentration of OH^- inside the concrete pores increases, ASR occurs. The ASR in concrete containing NaCl, but not exposed to current progresses more slowly than in concrete containing NaOH because the Cl^- effect indirectly influences the ASR. In concrete containing NaCl, the increase in rate of expansion in concrete exposed to current is higher than concrete not exposed to current because the current causes the concentration of alkali ions to increase in the vicinity of the steel, and the OH^- concentration increases due to a cathodic reaction. We hypothesize that the replacement of OH^- by Cl^- is activated by the current, and the concentration of OH^- in the concrete pore solution.

Effect of total alkali content on ASR in concrete subjected to current flow

The relationships between expansion and current density over time are illustrated in Figs. 7 and 8. Total alkali content in the concrete samples were 0.5%, 1.0%, 1.5%, 2.0% and 2.5%.

Fig.7 shows that in samples not subjected to current flow, the specimens containing 0.5% and 1.0% alkali content hardly expanded at all by the age of 9 months. The specimens containing alkali content of 1.5% or greater, exhibited greater expansion at an earlier age, and the extent of expansion increased as total alkali content increased.

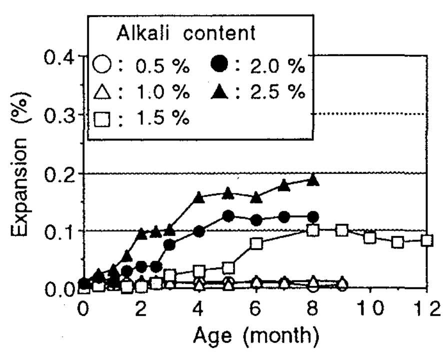

Fig.7 Expansion at ANODE over time (No Current)

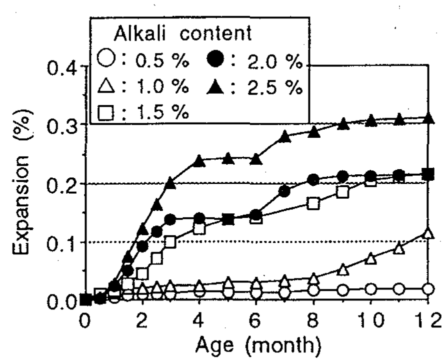

Fig.8 Expansion at ANODE over time (Current density : 50 mA/m²)

Among samples exposed to current, as the total alkali content increased, expansion occurred at an earlier age and the rate of expansion increased. Specimens with a 1.0% alkali content expanded rapidly on and after the age of 8 months. Comparing specimens exposed to current with ones not exposed reveals that if concrete has an alkali content of 1.5% or greater, the expansion in an exposed specimen increases more rapidly because the expansion due to ASR is accelerated by the current.

In environments where NaCl permeates concrete, there is a possibility that ASR is accelerated by current flow and reinforced concrete structures are damaged at an early stage.

Effect of current flow on expansion due to ASR in concrete containing mineral admix materials

Fig.9 illustrates the relationship between expansion and current density over time. In this figure, concrete is used in which 50% of the ordinary portland cement has been replaced by blast furnace slag and the total alkali content is 2.5%. Fig.9 shows that for concrete containing blast furnace slag, the expansion due to ASR in concrete exposed to current is smaller than concrete not exposed. As the current density becomes higher, this tendency is more remarkable, and is different from that of concrete using ordinary portland cement alone.

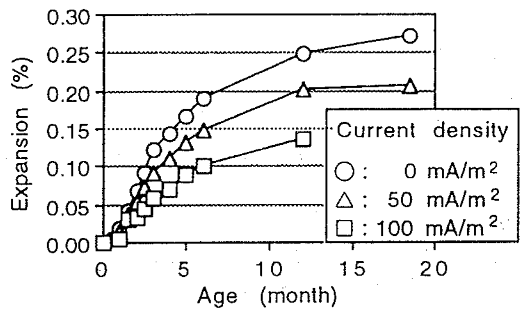

Fig.9 Expansion over time in concrete containing blast furnace slag (50%) (Alkali content : 2.5% (NaOH))

Fig.10 illustrates the relationship between expansion and total alkali content at 12 months and current density. In the case of a total alkali content of 1.5% or less, the degree of expansion in concrete is almost the same regardless of current density. In concrete with a 2.0% alkali content, the degree of expansion is somewhat smaller as current density increases. In concrete with a 2.5% alkali

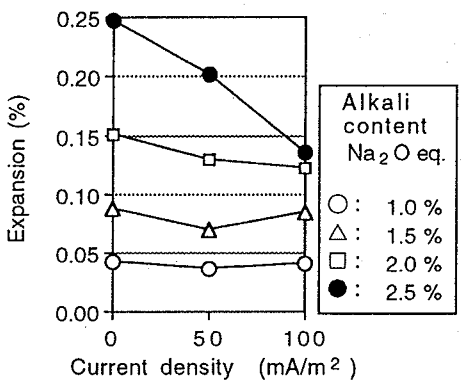

Fig.10 Relationship between expansion and current density in concrete containing blast furnace slag (50%) (12 months)

content, this tendency is remarkable and the degree of expansion becomes rather small as current density increases.

Fig.11 illustrates the relationship between expansion, current density and total alkali content at 9 months for concretes containing fly ash. No expansion was observed in the concrete with a 0.5% alkali content. In concrete with a 1.5% alkali content the degree of expansion in concrete exposed to current was slightly smaller than that in concrete which was not exposed. In concrete with a 2.5% alkali content, the expansion in concrete exposed to current densities of 50 and 100 mA/m ^{2} was much smaller than that of concrete which was not exposed.

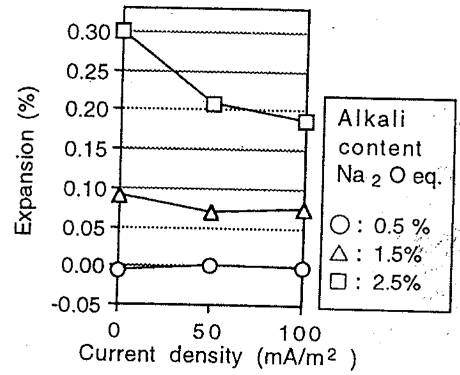

Fig.11 Relationship between expansion and current density in concrete containing fly ash (20%) (9 months)

Considering the circumstances mentioned above, expansion in concrete containing blast furnace slag or fly ash is not accelerated by current flow. Concrete containing a high alkali content shows a smaller expansion when subjected to current flow than concrete containing a high alkali content which is not exposed.

CONCLUSIONS

1) In the case of concrete containing ordinary portland cement alone, the direct current accelerates expansion, due to ASR, because the positively charged alkali ions are attracted to the negatively charged steel and the concentration of alkali ions increases near the steel. But a pessimum value for the current density exists, and when the current density exceeds this value, the expansive decreases as current density increases.

2) In the case of concrete containing blast furnace slag or fly ash, the expansion is scarcely accelerated at all by exposure to current. Expansion due to ASR in concrete containing a high alkali content which is exposed to current flow is smaller than when there is no current.

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