EXPANSION AND CRACKING DUE TO ALKALI-SILICA REACTION IN CONCRETES UNDER THE TWO DIFFERENT ENVIRONMENTS

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The degree of damage of concrete structures due to the alkali-silica reaction varies widely depending on environments. The influence of sea water on the deterioration of concrete due to the alkali-silica reaction was investigated by measuring the expansion and monitoring cracking patterns in relatively massive cubic specimens exposed to the two different environments with and without the supply of seawater for about 3 years. In concretes containing the reactive aggregate exposed to natural environments, fine cracks occurred without overall expansion of specimens, and the first cracking in concrete specimens was followed by the rapid progress of expansion and extension of cracks. However, the first cracks on concrete specimens stored in a fog environment at 38 °C were found when their expansions had reached about 0.04 %.

INTRODUCTION

It has been pointed out that environmental conditions around concrete structures greatly influence the occurrence of damage due to the alkali-silica reaction (1). In concrete structures in service, the moisture and temperature conditions are considered to be the most important factor affecting the damage of concrete due to the alkali-silica reaction. The effect of the size and shape of concrete structures on the changes in both moisture content and temperature in concrete them is also important. However, there are a relatively few studies concerning comparison in the deterioration due to the alkali--silica reaction between the same concrete exposed to different environments. Based on the results obtained by laboratory experiments, one of the authors has indicated that NaCl supplied from the surroundings significantly affected the expansion and cracks in concretes due to the alkali-silica reaction (2).

This study aims at revealing the expansion and cracks caused by the alkali-silica reaction in concrete under a marine environment. The influence of sea water on the deterioration of concrete due to the alkali-silica reaction was investigated by measuring the expansion and monitoring cracking patterns in relatively massive cubic specimens exposed to the two different environments with and without the supply of seawater for a long time. Furthermore, the significance of expansion tests in laboratory was assessed by comparing the differences in expansion and cracking patterns between concrete specimens stored in a fog environment at 38 °C and outdoors.

EXPERIMENTAL

Materials and Mix Proportions

The cement used was ordinary Portland cement with the equivalent Na_2O of 0.97 %. Its chemical compositions are given in Table 1. An andesitic crushed stone from Noto in Ishikawa

TABLE 1- Chemical compositions of ordinary Portland cement used (%)

ig. loss	insol.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	MnO
0.50	0.10	21.20	5.00	3.10	64.90	1.50	1.90	0.51	0.70	0.30	0.09	0.06

TABLE 2 - Alkali reactivity of andesitic aggregate evaluated according to ASTM C-289

Soluble silica (mmol/l)	Reduction in alkalinity (mmol/l)
609	223

TABLE 3 - Chemical compositions of andesitic aggregate (%)

ig. loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Cl
1.70	60.30	17.30	5.60	6.40	4.30	3.82	0.89	0.00

TABLE 4 - Mix proportions of concrete

Type of concrete	W/C (%)	s/a (%)	Water (kg/m^3)	Cement (kg/m^3)	River sand (kg/m^3)	Reactive coarse aggregate (kg/m^3)	Non-reactive coarse aggregate (kg/m^3)
C300	50	40	150	300	778	601	601
C400	50	40	200	400	693	535	535
C500	50	40	250	500	607	469	469
C600	50	40	300	600	522	404	404
C700	50	40	350	700	437	338	338

Prefecture was used as a reactive coarse aggregate ; the sand from the Hayatsuki river in Toyama Prefecture as a non-reactive fine aggregate. The alkali reactivity of the andesitic aggregate evaluated according to ASTM C-289 and its chemical compositions are presented in Table 2 and 3, respectively. The main reactive component found in the texture of the andesitic crushed stone was a volcanic glass. Mix proportions of concrete are shown in Table 4. As shown in Table 4, the concretes with the alkali content ranging from 2.91 kg/m^3 to 6.79 kg/m^3 were produced by changing the unit cement content in concrete from 300 kg/m^3 to 700 kg/m^3. The ratio of the reactive aggregate to the non-reactive aggregate by weight is 1.0.

Experimental Procedures

Outdoor Exposure Test Massive concrete specimens, 22 cm cubes, were used in the outdoor exposure tests. As shown in Fig. 1, in a series of specimens all faces except the one were coated with a highly elastic acrylic rubber type material with the overall thickness of about 1 mm after the initial curing in the moist fog room at 20 °C for 28 days. The other series of concrete specimens with all surfaces coated were also prepared. In order to investigate the influence of sea water on the deterioration of concrete due to the alkali-silica reaction, these two series of concrete specimens were placed in two different locations ; the one series of specimens on the seashore facing the Sea of Japan near Kanazawa city and the other ones on a building in Kanazawa University campus which is far from the sea. Length changes of the upper faces of concrete specimens were measured approximately every 4 months by using the contact-type strain gauge. The expansion of the concrete specimens has been monitored for about 3 years. The degree of damage of concrete due to the alkali-silica reaction was quantitatively evaluated by measuring the number, total length and width of cracks on the exposed face of concrete cubes by means of the computer image analysis.

Expansion Test in Laboratory Uncoated prismatic concrete specimens, 10 cm by 10 cm by 40 cm, were used in the expansion test in laboratory. Concrete specimens were stored in the fog box at 38 °C immediately after the demoulding. Length changes were measured monthly for about 1 year.

RESULTS AND DISCUSSION

Expansive Behavior of Concrete Specimens Exposed to the Natural Environments

Expansion curves for concrete specimens with an uncoated face placed on the roof of the building are shown in Fig. 2. Concrete specimens with the unit cement content of 600 and 700 kg/m^3 started to expand around 240 days after the initiation of exposure and their expansion proceeded rapidly in summer and slowly in winter. Concrete specimens with the unit cement content of 400 and 500 kg/m3 started to expand around 400 days after the initiation of exposure and continued to expand slowly .

Expansion curves for concrete specimens with an uncoated face placed on the seashore are shown in Fig. 3. The expansive behavior of concrete specimens on the seashore is considerably different from that of concrete specimens on the roof of the building. Concrete specimens with the unit cement of 700 kg/m^3 started to expand around 300 days after the initiation of exposure. The relatively rapid progress of expansion occurred in the first and second summer. The commencement of the expansion of concrete specimens with the unit cement content of 600 and 500 kg/m^3 was delayed by 60 and 350 days, respectively, compared with those with the unit cement content of 700 kg/m^3. Expansion curves for the concrete specimens placed on the seashore are very similar to those for the concrete specimens on the roof of the building.

Expansion curves for concrete specimens coated on their all faces placed on the roof of the building and the seashore are shown in Fig. 4 and Fig. 5, respectively. As shown in Fig. 4, the concrete specimens without an exposed face having the unit cement content of 700 and 600 kg/m^3 started to expand around 350 and 570 days after the initiation of exposure when placed on the roof of the building, and relatively large and rapid expansions occurred during the second summer. On the other hand, as shown in Fig. 5, the expansion of concrete specimens without an exposed face placed on the seashore was considerably smaller than on the roof of the building, although the specimens placed under both environments started to expand around the same time. Furthermore, under both environments, the concrete specimens with unit cement content of 500 and 400 kg/m^3 did not expand at all during at least 3 years. This indicates that the damage of concrete due to the alkali-silica reaction can be reduced by the application of an appropriate surface coating.

It should be noticed that, in concrete specimens exposed to the natural environments, fine cracks occurred without overall expansion, and that the first cracking in concrete specimens was followed by the rapid progress of expansion and extension of cracks. Namely, in concrete specimens with an exposed face having the unit cement content of 500 kg/m^3 the first visible cracks were found in the first summer after the initiation of exposure, but the active expansion did not occur until the second summer, as shown in Fig. 3. Based on the observation of cracks of concrete specimens, it is confirmed that, in concrete specimens exposed to the natural environments, the first cracks must be caused by the complex stresses induced by the alkali-silica expansion, the repetitions of wetting and drying, and the changes in temperature, and that the intrusion of rain water and/or sea water through these cracks promoted the expansion due to the alkali-silica reaction. As mentioned above, all concrete specimens placed under the natural conditions showed characteristic expansion curves which reflected the changes in humidity and temperature during the seasons. These tendencies are in good agreement with the results obtained by Davies et al. (3).

The expansion of concrete specimens placed on the roof of the building up to at least about 3 years of exposure was much larger than that of the corresponding concrete specimens exposed on the seashore. Especially, the differences in expansion between both environments were more marked in the concrete specimens coated on their all surfaces than in the concrete specimens with an exposed face. Furthermore, it should be noted that, in concrete specimens with an exposed face having the unit cement content of 450 and 500 kg/m^3, expansion started to actively proceed around 2 years after the initiation of exposure on the seashore. Judging from these results, it is likely that the expansion of concrete specimens due to the alkali-silica reaction may be accelerated by the intrusion of sea water into the specimens. However, the difference in humidity and temperature between both environments seems to influence more significantly the expansive behavior of concrete specimens up to at least about 3 years of exposure.

Cracking Pattern of Concrete Specimens Exposed to the Natural Environments

The number, total length and width of cracks appearing on the exposed face of concrete specimens placed under the two different natural environments at 370 days, 760 days and 1120 days after the initiation of exposure are presented in Table 5. It is found from Table 5 that the number and total length of cracks in concrete specimens exposed to the natural environments gradually increased with the exposure time in accordance with the progression of expansion. However, at 1120 days, the number and total length of cracks in the specimens exposed on the roof of the building were greater than in the specimens placed on the seashore. Taking into consideration that the average value of crack width decreased with the time between 370 days and 760 days, finer cracks were newly developed during the period in the concrete cubes exposed to the natural environments.

TABLE 5 - Number, total length and width of cracks on the exposed face of concrete specimens placed under two different natural environments

Unit cement content (kg/m^3)	Total number of cracks			Total length of cracks (mm)			Average width of cracks (mm)		
	370 days	760 days	1120 days	370 days	760 days	1120 days	370 days	760 days	1120 days
Concrete specimens placed on roof of building									
C400	5	13	19	31	199	594	0.28	0.24	0.24
C500	40	50	56	456	1081	1225	0.28	0.23	0.22
C600	159	196	201	2473	2861	2922	0.30	0.25	0.23
C700	173	197	238	2875	3269	3564	0.30	0.27	0.23
Concrete specimens placed on seashore									
C400	0	0	0	0	0	0	0	0	0
C500	3	34	36	46	531	667	0.28	0.21	0.24
C600	64	70	73	739	1106	1187	0.28	0.22	0.24
C700	128	185	257	1885	2705	2932	0.28	0.22	0.23

* The area measured by computer image analysis ; 220 mm by 220 mm

Expansive Behavior and Cracking Pattern of Concrete Prisms Stored in the Fog Box at 38 °C

Expansion curves for concrete specimens stored in the fog box at 38 °C are shown in Fig. 6. The concrete specimens with the unit cement content of 700 and 600 kg/m^3 started to expand without an induction period, while those with the unit cement content of 500 kg/m^3 started to expand around 110 days. The first cracks on concrete specimens stored in the fog box at 38 °C were found when the expansion reached 0.030 % to 0.045 %. It was found from this result that the critical expansion of 0.04 % above which cracks occur in mortar bars is also applicable in prismatic concrete specimens (4). The number, total length and width of cracks in concrete specimens stored in the fog box at 38 °C during the period of 200 days are presented in Table 6. The expansion of concrete specimens with the unit cement content of 700, 600 and 500 kg/m3 increased with increasing number of cracks.

TABLE 6 - Number, total length and width of cracks on the exposed face of concrete specimens stored in the fog box at 38 °C

Unit cement content (kg/m3)	Total number of cracks	Total length of cracks (mm)	Average width of cracks (mm)
	220 days	220 days	220 days
C400	0	0	0
C500	10	224	0.23
C600	30	685	0.27
C700	51	1153	0.26

* The area measured by computer image analysis ; 100 mm by 400 mm

Differences in Expansive Behavior and Cracking Pattern Between Concrete Specimens in the Outdoor Exposure and the Laboratory Test

In the outdoor exposure test, concrete specimens placed on the roof of the building and the seashore showed cracks above the unit cement content of 400 and 500 kg/m^3, respectively (Fig. 1). On the other hand, in the laboratory test in the fog box at 38 °C, concrete specimens with the unit cement content greater than 400 kg/m^3 expanded and showed cracks during the period of 300 days. Comparison in the extent of cracking in concrete specimens between both tests indicates that the environmental condition in the exposure test on the roof of the building is more severe than in the laboratory test in the fog box at 38 °C. Furthermore, the average length of cracks in concrete specimens in the laboratory test in the fog box was generally larger than in the outdoor test, while the total number of cracks in concrete specimens in the laboratory test was smaller than in the outdoor test. This result demonstrates that cracks in the specimens placed in the fog environment did not easily connect with one another. The difference in expansive behavior and cracking pattern between the outdoor exposure and the laboratory test is considered to be attributed to the difference in factors such as the cause of cracking, the process of extension of cracks and the shape of concrete specimen.

CONCLUSIONS

The major results obtained in this study are as follows ;

(1) The expansion of concrete placed outdoors proceeded more actively in summer than in winter. This shows the importance of changes in humidity and temperature during the seasons in the ASR expansion of concrete.

(2) The expansion of concrete specimens placed on the roof of a building was larger than on the seashore. During the exposure time up to at least 3 years, the influence of seawater on the deterioration of concrete due to the alkali-silica reaction was not definite.

(3) In the outdoor exposure test up to about 3 years, only concrete specimens with the unit cement content of beyond 400 kg/m3 i.e. beyond the alkali content of about 4 kg/m^3 expanded and cracked.

(4) The surface coating with a highly elastic acrylic rubber type material reduced the expansion and the extent of cracks of concrete specimens.

(5) In concretes placed outdoors, the first cracks appearing on the specimens without expansion may be caused by the stresses induced by both the alkali-silica reaction and other actions such as the repetitions of wetting and drying, and the changes in temperature. The occurrence of the first cracks brought about the rapid expansion. However, in concretes stored in the fog environment, the cracks occurred only when the expansion reached about 0.04 %.

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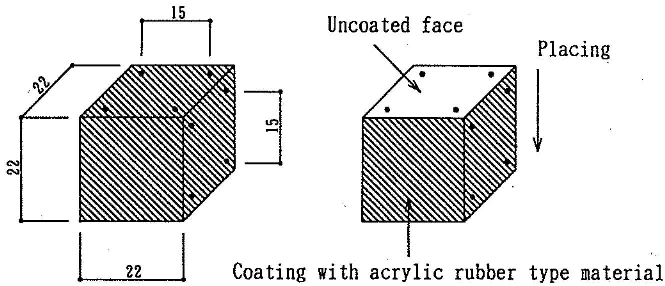

Figure 1 Schematic diagrams of concrete specimens exposed to natural environments

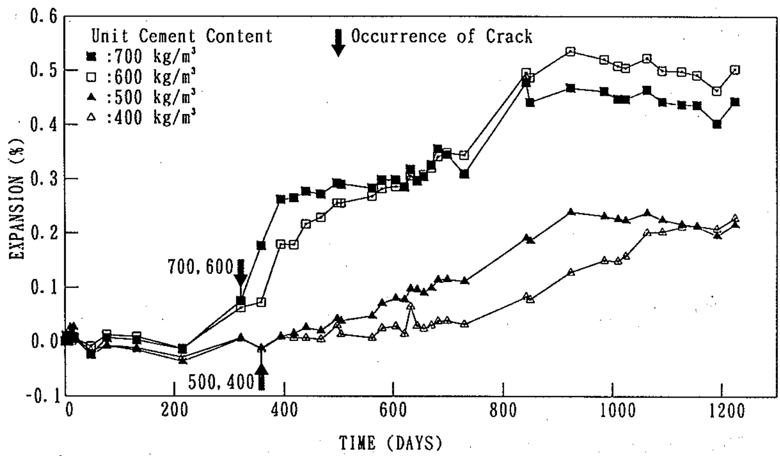

Figure 2 Expansion curves for concrete specimens with uncoated face placed on roof of building

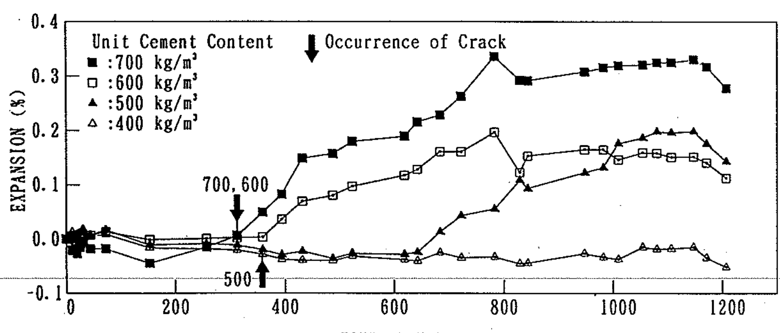

Figure 3 Expansion curves for concrete specimens with uncoated face placed on seashore

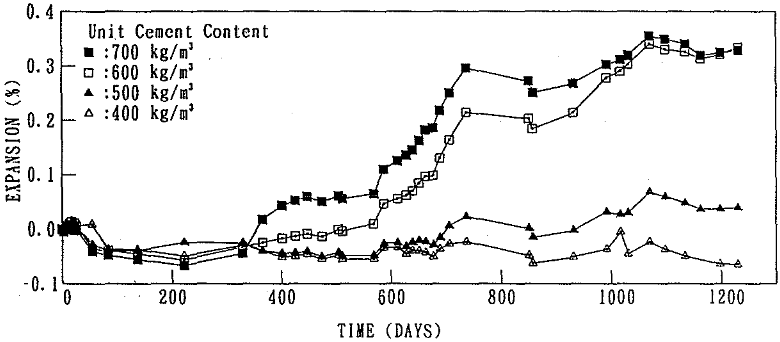

Figure 4 Expansion curves for concrete specimens coated on their all surfaces placed on roof of building

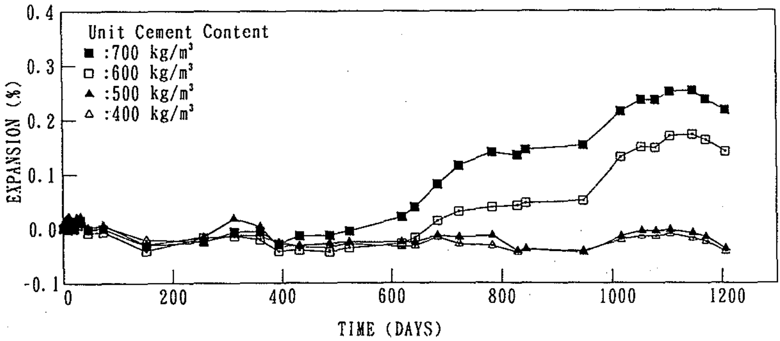

Figure 5 Expansion curves for concrete specimens coated on their all surfaces placed on seashore

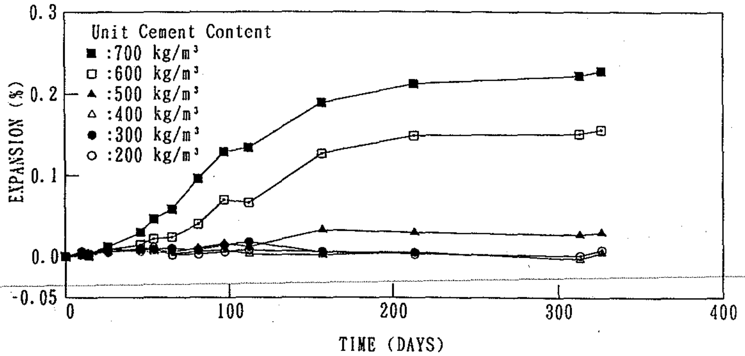

Figure 6 Expansion curves for concrete specimens stored in fog box at 38°C