Mechanisms of ASR surface cracking
in a massive concrete cylinder

Hiroyuki Kagimoto[*1], Yukihiro Yasuda[2a] and Mitsunori Kawamura[3b]

[1]*Wakamatsu Operations & General Management Office, Electric Power Development Co., Ltd., 1,Yanagasaki, Wakamatsu-ku, Kitakyushu, Japan*
[2]*JPower design Co.,Ltd, Chigasaki, Kanagawa, Japan*
[3]*Kanazawa University, Kakuma, Kanazawa, Ishikawa, Japan*

Abstract. Relative humidity and strains within a massive concrete cylinder (φ450 mm $\times$ 900 mm) in the drying and the re-saturating process were measured for elucidating the process of ASR surface cracking in concrete. The expansion behavior of mortars in dry atmospheres with various R.H. values and the re-saturating process was revealed. Non- or less-expansive layers were formed in near-surface regions in the concrete cylinder in the drying process, but ASR expansions actively progressed in inner portions. After re-saturating, R.H. values of near-surface regions rapidly increased with time, but expansions in the regions were found to be very small. However, in the middle portions, of which R.H. values were kept 80% ~ 90% R.H. in the drying process, expansion actively progressed, resulting in further development of surface cracks in the re-saturating process.

Keywords: alkali-aggregate reaction; massive concrete; humidity; expansion; cracks detection

1. Introduction

Recently, important researches have been conducted for better understanding of the nature of alkali-silica gels and microscopic damages caused by expansion of the gels (Dunant and Scrivener 2010, Leeman *et al*. 2011, Dunant and Scrivener 2012, Pignatelli *et al*. 2013, Moon *et al*. 2013). However, from a viewpoint of the maintenance and the repair of ASR-damaged concrete structures, it is also necessary to elucidate the process of development of macro-sized cracks found on the concrete structures.

It is an important subject for controlling the progress of cracks and damages in ASR-affected concrete structures to understand the mechanisms of surface and internal cracking in the concretes. ASR macro-cracks are caused by differences in expansions between different portions within ASR-affected concretes (Stark 1991, Hagelia 2004, Kagimoto *et al*. 2011). Thus, it is necessary to know well how environmental humidity affects ASR expansion in ASR-affected concretes for

∗Corresponding author, Doctor of engineering, E-mail: hiroyuki_kagimoto@jpower.co.jp
[a]Bachelor of engineering, E-mail: yasuda@jpde.co.jp
[b]Professor emeritus, E-mail: m.n.kawamura@aurora.ocn.ne.jp

better understanding of the process of the production of surface cracks and their development.

On the basis of the results of investigations of moisture conditions within field ASR-affected concrete structures, it was presumed that stresses induced by differences in volume changes between near-surface and deep regions were responsible for surface cracking in the concrete structures (Stark 1991).

Furthermore, in concrete structures under natural environments for long periods, alkali leaching from surfaces reduces expansion in near-surface regions (Kagimoto *et al*. 2011).

However, detailed processes from the initiation of ASR expansion to the first surface cracking and the subsequent extension of the cracks in ASR-affected concretes subjected to wetting drying repetitions in natural environments are not clear.

Some workers (Idorn 1967, Idorn *et al*. 1992, Wang *et al*. 1996) have reported surface cracks patterns on ASR-affected concrete structures and relatively small sized laboratory concrete specimens, but there are few reports on detailed observations of surface cracks, internal humidity and strains within large concrete bodies under given temperature and humidity which had been precisely controlled.

In the study of Kagimoto *et al*. 2011, we experimentally proved the validity of a notion that surface cracking in ASR-affected concretes was attributable to the formation of non- or less expansive near-surface regions using a relatively large concrete cylinder. In Kagimoto *et al*. 2011, in order to elucidate relationships between the progress rate of the front of non- or -less expansive layer toward inner portions and the formation of the first cracks, we measured relative humidity (R.H.) values and circumferential strains at various depths from surfaces in a relatively massive concrete cylinder (φ450 mm $\times$ 900 mm) in a dry environment (the drying process).

After a steady state in strain vs. time relation within the cylinder had been attained in the drying process, the environmental humidity was raised to > 95% R.H. (the re-saturating process) to simulate drying-wetting repetitions. In the study of Kagimoto *et al*. 2011, a noteworthy result that further surface cracks actively extended even in the re-saturating process, was obtained.

It was found from the study of Kagimoto *et al*. 2011 that variations in internal humidity at various depths from surfaces at given environmental humidity were decisive for the generation of internal stresses. Thus, it is significant to precisely understand expansion behavior of concretes with reactive aggregate in atmospheres with various R.H. values. Furthermore, surface cracking in many field ASR-affected concrete structures is due to tensile stresses induced in near-surface regions formed in the process of drying-wetting repetitions, although caused by differences in ASR expansion between near-surface regions and inner portions in dry atmospheres, e.g. the columns inside houses and the walls of internal galleries in large dams. Therefore, the past record of environmental humidity and temperature the concretes underwent is considered to intimately relate to the generation and extension of surface cracks.

It has been confirmed that relative humidity (R.H.) of ambient atmosphere greatly influenced expansion in mortar bar tests (Lenzner and Ludwig 1978, Olafsson 1986). Stark (1991) reported that expansion did not occur below 80% R.H.. However, in another study (Olafsson 1986), mortar bars started expanding about 12 months after they had been exposed to an atmosphere with a R.H. value of 73%. At present, it is ambiguous how environmental humidity influences expansion of mortars with reactive aggregate. Especially, expansion behavior of mortars bars which have been placed in dry environments for long times, in re-saturating process are little understood.

ASR expansion is caused by absorption of water by ASR gels. Water in concrete is strongly held by the cement paste phase. Hence, expansion does not always occur even if much ASR gel has been produced. Evaporable water content within mortar specimens in a dry atmosphere

gradually changes from central portions towards surfaces until an equilibrium state between internal and external humidity will be attained. As a result, ASR expansion depends on the size and shape of specimens. Hence, it is impossible to know a universal relationship between humidity and ASR expansion for a reactive aggregate-containing mortar and concrete. Furthermore, alkali leaches from mortar bars submitted to high moisture environments (Lindgard *et al*. 2012). Therefore, expansion does not necessarily increase with increasing R.H. value in a given shape and size of specimen especially in the range of high R.H. values.

The objective of this study is to reveal the mechanisms of surface cracking in a relatively large concrete cylinder exposed to a drying and re-saturating process taking into consideration the characteristics of expansion vs. humidity relations in mortars in the drying and the re-saturating process. Internal cracks in the concrete cylinder were also observed in detail by means of the impregnation of a fluorescent dye-bearing epoxy resin with a low viscosity into the concretes.

Firstly, the outline of the study of Kagimoto *et al*. 2011 is presented for better understanding of the plot of this paper.

2. Outline of an experimental study on the internal humidity and strain in a relatively large concrete cylinder (from Kagimoto *et al*. 2011)

As described previously, measurements of humidity and circumferential strains were made for revealing the process of formation of surface cracks in relatively large concrete cylinders (φ450 mm × 900 mm) with and without reactive aggregate. Reactive silica in the reactive aggregates was included as opal, glass, cristobalite and tridymite (Hirono and Torii 2012). Electrical strain gauges for measuring circumferential strains were embedded at depths of 10, 20, 30, 40, 50, 100 and 200 mm from surfaces in the cylinders (Fig. 1). Sensors for measuring relative humidity were also situated at these depths.

The temperature and R.H. in the storage room of concrete cylinders, which were maintained at 35°C and 60% R.H. at early stage, were raised to 40°C and 70% R.H. (the drying process). The environmental humidity has been raised to > 95% R.H. at 291 days for simulating wetting-drying repetitions that field ASR-affected concrete structures undergo.
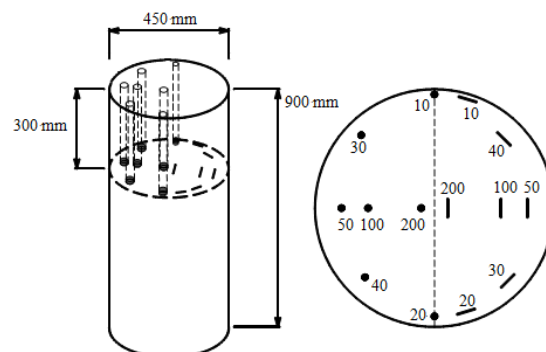

Fig. 1 Positions of sensor assemblies and strain gauges in a concrete cylinder (reprint from Kagimoto *et al*. 2011)

Changes in R.H. value with time at various depths in the concrete cylinder with reactive aggregate throughout the drying and the re-saturating process are provided in Fig. 2(a). Relations between R.H. values and time only in the drying process are provided in Fig. 2(b) to see details of variations of humidity at each depth. As shown in Fig. 2(b), at 110 days, R.H. value of the depth of 20 mm reached a critical R.H. value of 80% below which no ASR expansion is considered to occur (Stark 1991). Thereafter, the front of non- or less expansive layer gradually progressed inward, and R.H. values at depths smaller than 40 mm became below 80% about 150 days.

Strains measured at each depth within the reactive concrete cylinder in both the processes and only the re-saturating process are plotted against time, respectively, as shown Figs. 3 (a) and (b). It is found from Fig. 3(b) that, at all the depths except the depths of 10 and 20 mm, compressive strains increased with time up to about 40 days. Thereafter, compressive strains gradually turned over to tensile strains. These changes in strains reflected ASR expansion characteristics of the concrete.
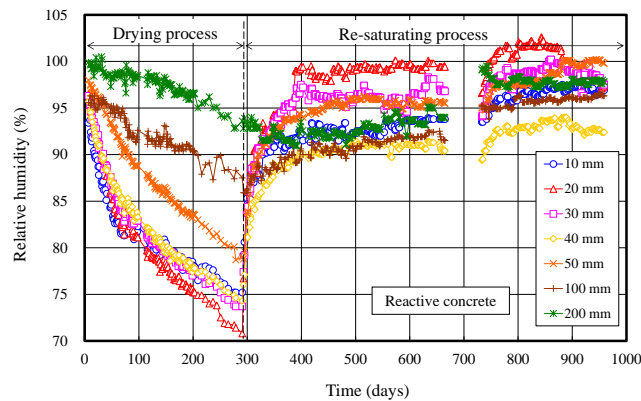

Fig. 2(a) R.H. value vs. time curves at various depths in a reactive concrete cylinder, Drying and re-saturating process (reprint from Kagimoto *et al*. 2011)
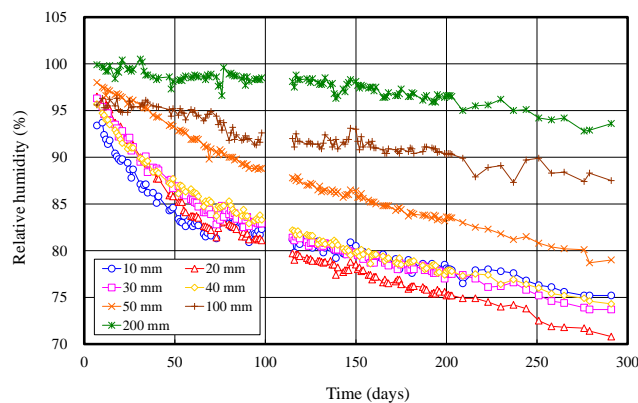

Fig. 2(b) R.H. value vs. time curves at various depths in a reactive concrete cylinder, Enlargement of drying process (reprint from Kagimoto *et al*. 2011)
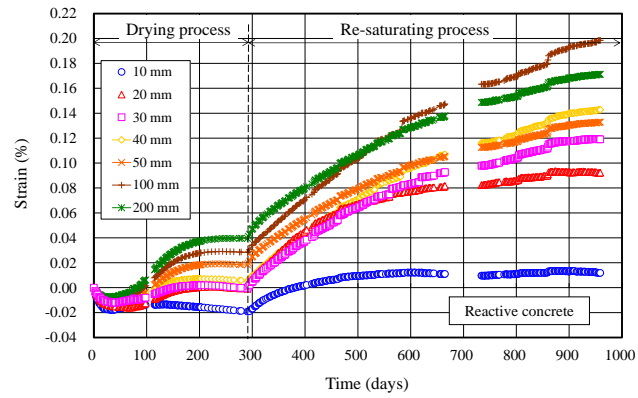
Fig. 3(a) Strain vs. time curves at various depths in a reactive concrete cylinder, drying and re-saturating process (reprint from Kagimoto *et al*. 2011)
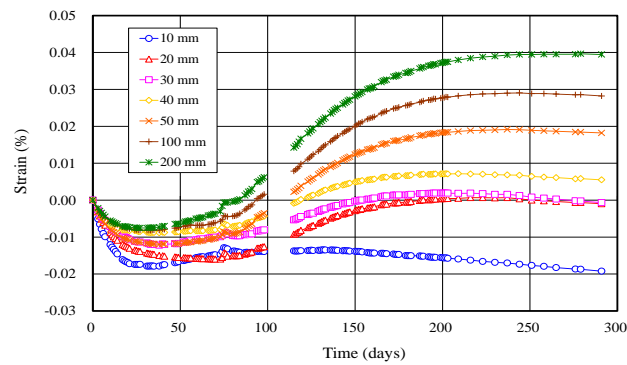

Fig. 3(b) Strain vs. time curves at various depths in a reactive concrete cylinder, enlargement of the drying process (reprint from Kagimoto *et al*. 2011).
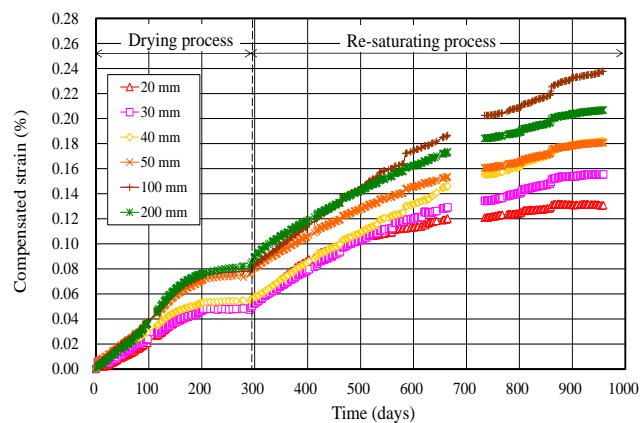

Fig. 4 Compensated strain vs. time curves at various depths in a reactive concrete cylinder (reprint from Kagimoto *et al*. 2011).

Strains measured within the reactive concrete cylinder include ASR expansions, shrinkage strains and strains due to internal stresses including creep. Therefore, strains caused by only ASR are obtained by compensating strains in the reactive concrete cylinder for those in the reactive aggregate-free one. Fig. 4 shows the compensated strain vs. time curves at all the depths except 10 mm.

As seen in Fig. 2(a), R.H. values at different depths increased with time at different rates after re-saturating. R.H. values at depths of 10, 20, 30, 40 and 50 mm rapidly rose to levels higher than 80% by about 10 days.

Strains measured within the reactive aggregate concrete include ASR expansions, shrinkage strains, and strains due to internal stresses including creep. Strains caused by only ASR in Fig. 4 were obtained by compensating strains in the concrete cylinder with reactive aggregate for those in the non-reactive aggregate concrete one (Kagimoto and Kawamura 2011).

In Fig. 4, it is seen that after a rise of the environmental humidity to > 95% R.H., strains at depths greater than 20 mm in the reactive concrete rapidly increased. Especially, it should be noted that the rates of increase in strain at a depth of 100 mm were higher than those at a depth of 200 mm from the beginning of the re-saturating process, and then the former exceeded the latter about 75 days.

This result indicates that cylindrical zones showing strains greater than those in the surrounding concretes were produced in the middle areas between the center and surfaces in the concrete cylinder presently after the beginning of the re-saturating process. Such peculiar behavior of strains at a depth of 100 mm appears to result from characteristics in expansion vs. R.H. value relation in the zones before and after re-saturating. These results suggest that internal stresses newly induced after re-saturating grew surface cracks. Thus, R.H. values in the near-surface regions have been reduced to 70-75% in the drying process. However, it was not clearly whether ASR expansion was generated in the near-surface regions in the re-saturating process in the study of Kagimoto *et al.* 2011. Then, in this study, mortar bar tests were carried out to elucidate the characteristics of expansion vs. humidity relations both in the drying and the re-saturating process.

3. Mortar bar expansion tests under atmospheres with various R.H. values

3.1 Materials and mix proportions

One of the two types of reactive aggregate (J.S.) was a fine reactive aggregate used in the concrete cylinder (Kagimoto and Kawamura *et al.* 2011). The other reactive aggregate of a calcined flint (C.F.) (Lumley 1989) was used as a reference. The Japanese standard sand was used as non-reactive aggregate. The dissolved silica (Sc) and the reduction in alkalinity (Rc) of the reactive aggregates are provided in Table 1.

Table 1 Alkali reactivity of J.S. and C.F

	J.S.	C.F.
Reduction in alkalinity	61 mmol/l	70 mmol/l
Dissolved silica	190 mmol/l	1,063 mmol/l
JIS mortar bar test	0.38%/6 months	—

Mortars were produced with a water/cement ratio of 0.5 and a cement/aggregate ratio of 0.5 according to JIS A 1146. 9.97 kg NaOH / m^3 was added at a dosage level of alkalis equivalent to 1.8% in cement. Mortar bars (25.4 mm × 25.4 mm × 285 mm) for measuring expansion were made by the use of the molds fabricated according to ASTM C 227. The production procedure of mortar specimens followed JIS A 1146.

3.2 Measurements of length changes in mortar bar tests

Length changes of mortar bars were measured by the comparator with a dial gauge according to ASTM C 490-74. However, expansions of some mortar bars discontinuously increased immediately after the change of dry atmospheres to an environment with > 95% R.H.. As a result, lengths of the mortars exceeded the limit of measurable range of the comparator, and then we used the slide calipers for measuring lengths of the mortar bars. Dots for values obtained by the use of the slide calipers were marked in Figs. 5 and 6. The accuracy of lengths of measured by the comparator is higher than the accuracy of those done by the slide calipers. But, since the values obtained by the side calipers are correct to two places of decimals, they are reliable enough to be used as data in this study.

Mortar bars were initially stored over water in sealed containers at 40℃ until their expansions reached approximately 0.10%. Since ASR chemical reaction has almost completed at an expansion of 0.1% (Diamond *et al*. 1981), effects of alkali leaching on expansion have not to be taken into consideration in this expansion test. About 0.10% expansions were attained in C.F. and J.S. mortar bars at 7 and 28 days, respectively. 0.1% expansion was attained in C.F. mortars at 7 days in a preliminary test, but generation of expansion was somewhat delayed in actual tests. Nevertheless, at 7 and 28 days, four series of mortar specimens were exposed to dry atmospheres over saturated salt solutions of NaCl, $(NH_4)_2SO_4$, KCl, KNO_3 and pure water corresponding to relative humidity of 74.7, 79.9, 82.3, 89.0 and > 95% at 40℃, respectively. Expansion tests for one set of mortar bars were also conducted at 70% R.H. which was mechanically controlled. Mortar bars were placed for a long period of 560 days in dry atmospheres so that an equilibrium between the state of moisture within specimens and humidity of ambient atmospheres had been attained.

3.3 Results and discussion

3.3.1 Expansions of mortars in the drying atmospheres

Figs. 5 and 6 show apparent expansion curves for C.F. and J.S. mortars in dry atmospheres with various R.H. values for 560 days and in the re-saturating process under > 95% R.H. for 320 days, respectively. Length changes with time in the Japanese standard sand mortar bars without reactive aggregate in the drying and the re-saturating process are presented in Fig. 7. Expansions measured in C.F. and J.S. mortar specimens (Figs. 5 and 6) contain both of ASR expansion and drying shrinkage. Hence, net ASR expansions (Figs. 8 and 9) are given as differences between length changes measured in mortar specimens with and without reactive aggregate.

As described above, when expansions of mortar bars had exceeded 0.1%, they were transferred to the plastic containers in which atmospheres with various R.H. values were invariably maintained. Diamond *et al*. (1981) experimentally confirmed that the alkali-silica response can be separated into the chemical reaction in the early stage and the physicochemical processes in the

later stage. Therefore, ASR gels are considered to be produced during the early stage of the chemical reaction process. At the beginning of ASR expansion after the attainment of the expansion of 0.1% in the drying process in various atmospheres in this study, ASR chemical reactions must have already terminated. Hence, it is not necessary to take into consideration the influence of alkali leaching on ASR expansion in the following discussion in this study.

Moisture within specimens placed in all the environments except > 95% gradually went out into atmospheres. As a result, internal moisture content increased from surfaces toward central portions. In atmospheres of which R.H. values ranged from 70.0% to 79.9%, humidity in near-surface regions in specimens decreased to some extent in the initial stage. On the contrary, R.H. values in their central portions must have been still high in the early stages. Therefore, specimens expanded corresponding to internal high R.H. values as a whole.
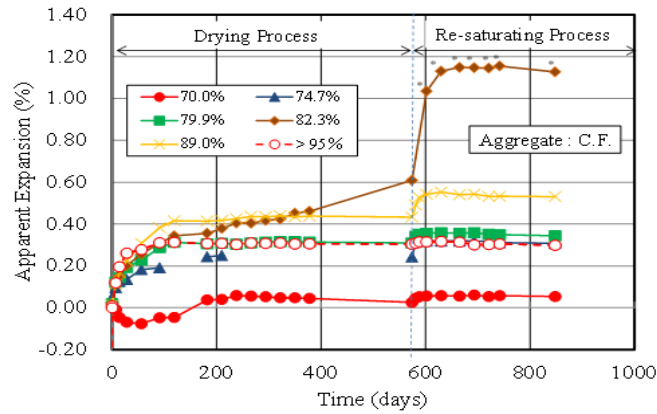

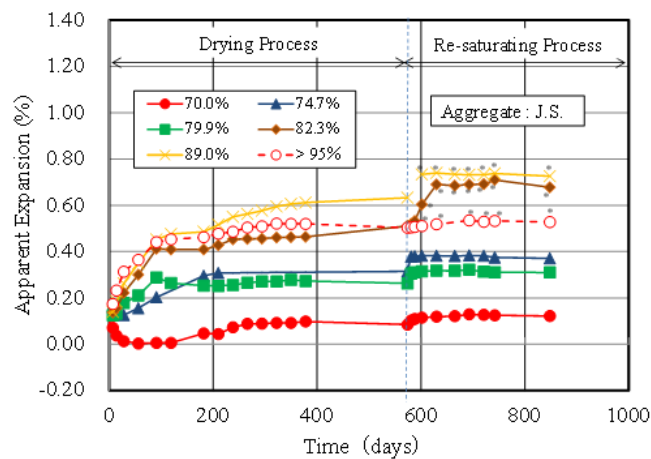Fig. 5 Expansion curves of C.F. mortars

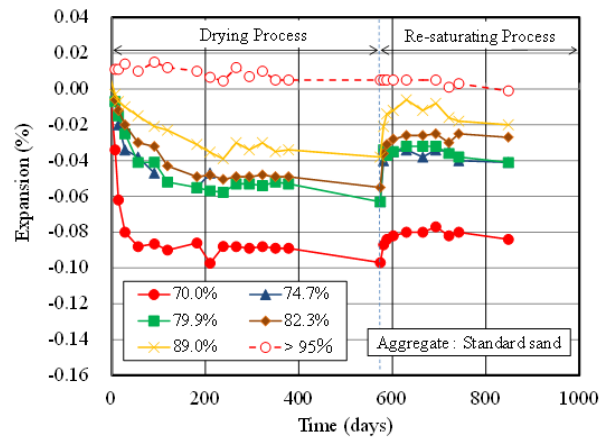Fig. 6 Expansion curves of J.S. mortars

Fig. 7 Length changes in standard sand mortars in the drying and the re-saturating process
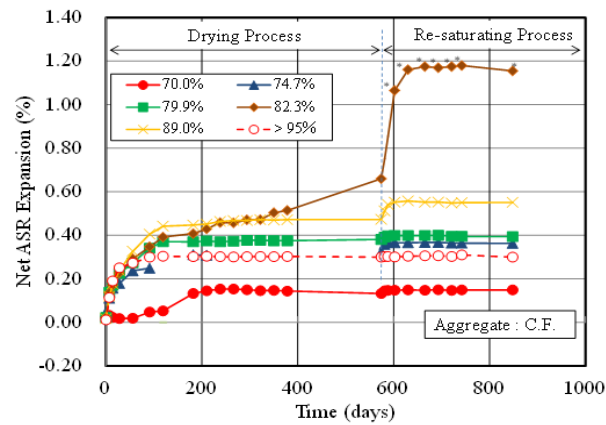

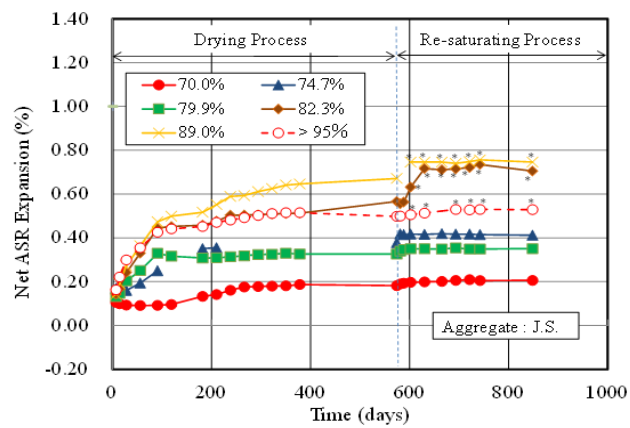Fig. 8 Net ASR expansion curves of C.F. mortars

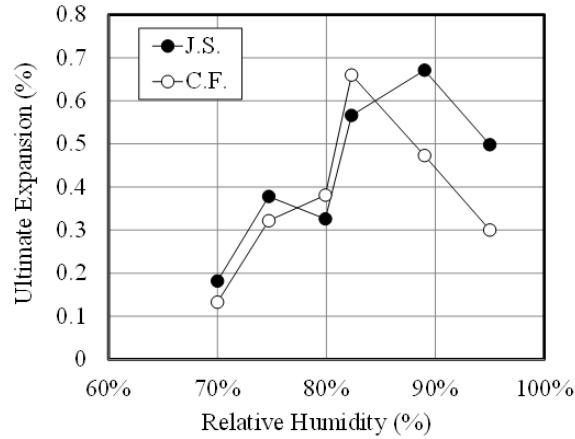Fig. 9 Net ASR expansion curves of J.S. mortars

Fig. 10 Relationships between ultimate expansion and relative humidity in C.F. and J.S. mortars
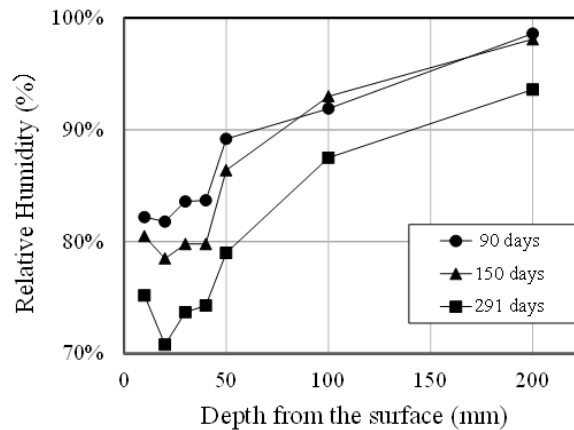

Fig. 11 Values of relative humidity at various depths at 90 days (the beginning of expansion), 150 days (the first cracking) and 291 days (the beginning of re-saturating process)

Plotting ultimate expansions against R.H. values in the drying process gives Fig. 10. As seen in this Figure, C.F. and J.S. mortars showed the greatest expansion at 82.3% and 89.0%, respectively. Thus, the pessimum humidity existed both in the C.F. and J.S. mortar, even when effects of alkali leaching on expansion in high moisture environments were not taken into consideration in this study, as described above introducing Diamond *et al.* (1981)' finding (Fig. 10).

Generally speaking, the amount of pore solutions which ASR gels can absorb from the surrounding cement paste matrix, depend on characteristics of ASR gels, e.g. alkali and calcium content, and pore sizes filled with pore solutions in the cement paste phase, micro-cracks caused by ASR gels. Pore sizes filled with water are considered to greatly influence expansion of ASR gel pockets. In this respect, we should pay an attention to the fact that sizes of pores in mortar filled with pore solutions depend on R.H. values in ambient atmospheres. Micro-cracks accelerate the movement of pore solutions to ASR gels. Thus, it may be due to the combination of these various factors that ultimate expansions did not necessarily increase with increasing R.H. value.

3.3.2 Expansions of mortars in the re-saturating process

As seen in Figs. 5 and 6, expansions of C.F. and J.S. mortars exposed to atmospheres with lower than 79.9% R.H., finally reached about 0.4% and 0.3%, respectively. It is also seen in these figures that expansions at R.H. values less than 79.9% were very small after they were transferred to a moist environment of > 95% R.H.. However, mortars which had been stored in an atmosphere with 82.3% R.H. started rapidly expanding immediately after the beginning of re-saturating process, and finally showed the greatest expansion about one month. As seen in Figs. 5 and 6, expansion curves of both mortars are found to be similar to each other. Smaller expansions in J.S. mortars than in C.F. mortars under the atmosphere of 82.3% R.H may be due to a difference in reactivity of aggregate. It is also found from Figs. 5 and 6 that expansion of mortars in the atmospheres with > 95% R.H. in the drying process had already completed at the beginning of re-saturating process. Hence, the mortars in atmospheres with > 95% R.H. only a little expanded in the re-saturating process.

4. Expansions within an ASR-affected concrete cylinder estimated from mortar testing

4.1 Drying process

It has been confirmed from Fig. 6 that a critical value of R.H. in the drying process below which little expansion occurred in the re-saturating process was about 80%. However, expansion in mortars in atmospheres > 95% R.H. has already terminated at the beginning of re-saturating process. In order to specify the depth at which a critical R.H. of 80% had been attained at 90 days (the beginning of expansion), 150 days (the formation of the first cracks), and 291 days (the beginning of re-saturating process), R.H. values measured in a relatively large concrete cylinder (Kagimoto *et al*. 2011) were plotted against depth from surfaces at these days, as shown in Fig. 11. It is found from this figure that R.H. values in portions up to a depth of 40 mm were smaller than about 80% R.H. at 150 days. As also seen in Fig. 11, a critical depth for 80% R.H. reached about 50 mm at 291 days (the beginning of re-saturating process). Taking into consideration the results of mortar expansion tests, it can be mentioned that expansions in portions up to about 50 mm in the concrete cylinder were considerably small compared with those in portions deeper than 50 mm in the drying process.

4.2 Re-saturating process

As seen in Fig. 2, R.H. values at all the depths except 200 mm (central parts) rapidly rose with time immediately after the beginning of the re-saturating process. The R.H. value of about 86% at the beginning of re-saturating process at the depth of 100 mm is found to reach about 93% after about 2 months. On the other hand, as shown in Fig. 9, mortars specimens stored in an atmosphere of 82.3% and 89.9% R.H. began to rapidly expand immediately after the beginning of the re-saturating process. It is estimated from these results that ASR expansion actively progressed around the depth of 100 mm in the concrete cylinder in the re-saturating process.

As shown in net ASR expansion vs. time curves at various depths in the concrete cylinder (Fig. 4), immediately after a concrete cylinder (φ450 mm $\times$ 900 mm) which had been dried in an atmosphere of 70% R.H., was exposed to an atmosphere of > 95% R.H., especially expansions in

the portions around 100 mm depth rapidly increased with time, being the greatest about 200 days after re-saturating. R.H. values in the portions of about 100 mm deep changed from about 86% to 93% in the re-saturating process up to about 200 days (Fig. 2). Hence, active progress of expansion around the 100 mm depth can be understood by the correspondence of R.H. values in the areas in the cylinder with the results of mortar expansion tests. Namely, R.H. values around the portions of 100 mm depth in the cylinder were within the range of 82.3% to 89.9% R.H.. Mortars which had been placed in the range of R.H. values in the drying process, very actively expanded immediately after the beginning of the re-saturating process (Fig. 9). ASR expansion in the central portions has already come to an end at the beginning of re-saturating process. However, expansion of the central portions in which the highest R.H. value had been maintained, terminated to a modest extent. This result can be estimated from the existence of the pessimum humidity in expansion vs. humidity relations in Fig. 10.

5. Effects of drying-wetting repetitions on surface cracking in the concrete cylinder

In relation to changes in R.H. value at various depths from surfaces within a relatively large concrete cylinder with time (Kagimoto *et al*. 2011), a special attention should be paid to the result that mortars which had gradually expanded for long times under 82.3% R.H., started to rapidly expand in the re-saturating process (Figs. 5 and 6). It can be mentioned that mortars placed in dry atmospheres with lower than 79.9% R.H. for long times little expanded, but the ones exposed to atmospheres with above a critical R.H. value (about 80% R.H.) rapidly expanded when water is externally supplied in the re-saturating process.

It has been revealed that alkali hydroxide in pore solutions were substantially fixed when concrete was dried to modest R.H. values (Diamond 1996). The results obtained in this study demonstrate that once concretes had been exposed to dry atmospheres with R.H. values lower than 79.9%, expansive ability of ASR gels themselves in the concretes were lost even when exposed to moist atmospheres with > 95% R.H..

It has been proven that expansion of the areas with about 80% ~ 90% R.H. in the concrete cylinder was very sensitive to externally supplied water. In field ASR-affected concrete structures, a relatively small increase in R.H. value of internal portions in ASR-affected concretes of which R.H. values have been maintained about 80% ~ 90% for long times, e.g. supply of water by rainfall, can drastically accelerate surface cracking.

6. Observations of surface cracks on the concrete cylinder (from Kagimoto *et al.*2011)

Surfaces of the concrete cylinder (φ450 mm×900 mm) were observed at regular intervals. Longitudinal cracks were found in four different parts on the surfaces at 150 days in the drying process. Sketches of cracks at 164 days, 179 days and 213 days in the drying process, and 516 days and 953 days in the re-saturating process are provided in Fig. 12. Widths of visible cracks sketched in Fig. 12 were greater than 0.05 mm. It is found from this figure that cracks extended and branched off with time throughout both the drying and the re-saturating process. This figure clearly shows that cracks separately formed in Part 2 coalesced to form tortoise shell-like patterns occasionally found in field ASR-affected concrete structures.

7. Mechanisms of surface cracking in ASR-affected concretes under the drying and the re-saturating process

It was confirmed that longitudinal cracks were produced in four different parts at 150 days in the drying process (Fig. 12). As also seen in Fig. 11, a critical depth for 80% R.H. reached about 50 mm at 291 days (the end of drying process). From the results of mortar expansion tests (Figs. 8 and 9), it is found that expansions in portions up to about 50 mm were considerably small compared with those in portions deeper than that in the drying process, resulting in the formation of cracks.

It is estimated from the results of mortar expansion tests (Fig. 9) that portions up to about 50 mm from surfaces in the concrete cylinder in which R.H. values had reduced up to about 80%, little expanded in the re-saturating process. On the contrary, humidity in the portion around a depth of 100 mm had been maintained at greater than 86% R.H. Therefore, the results of mortar expansion tests also presume that the middle areas (around 100 mm in deep) actively expanded in
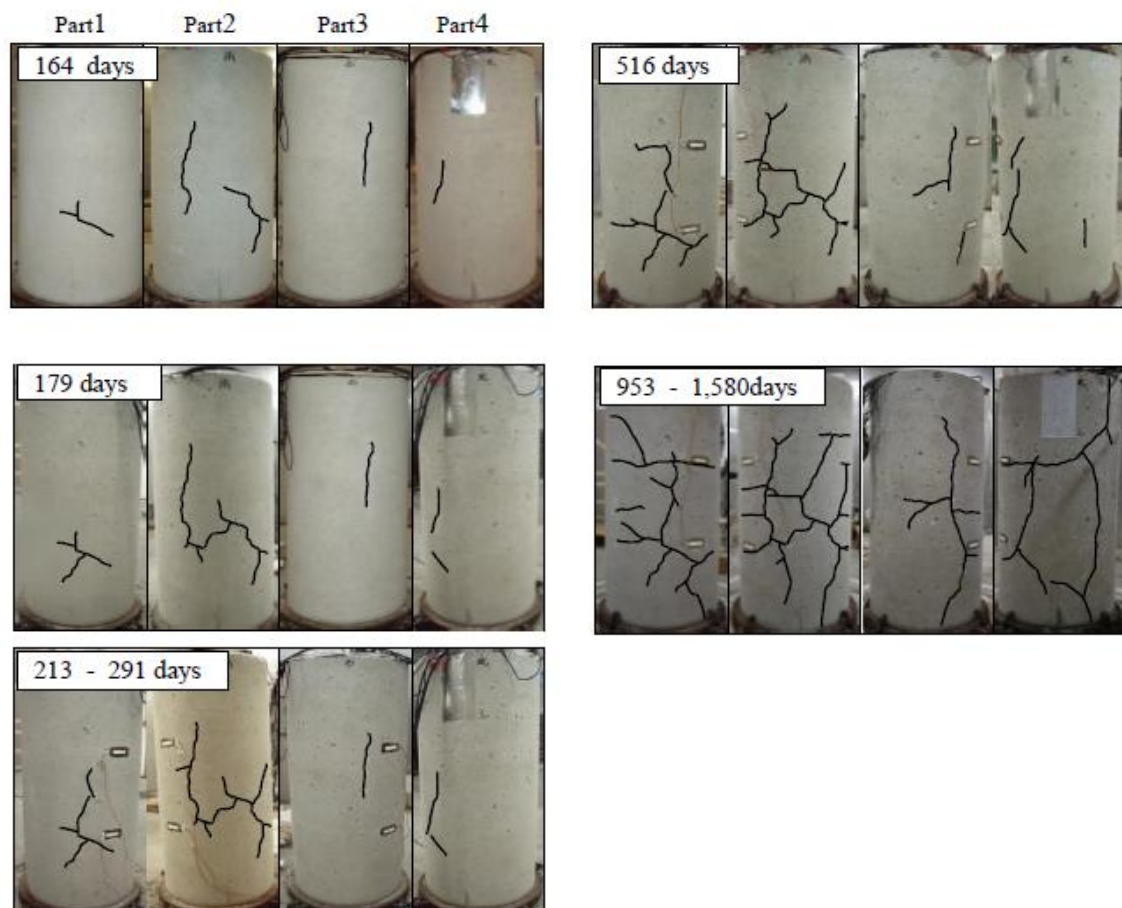

Fig. 12 Sketches of surface cracks on a reactive concrete cylinder in the drying and re-saturating process

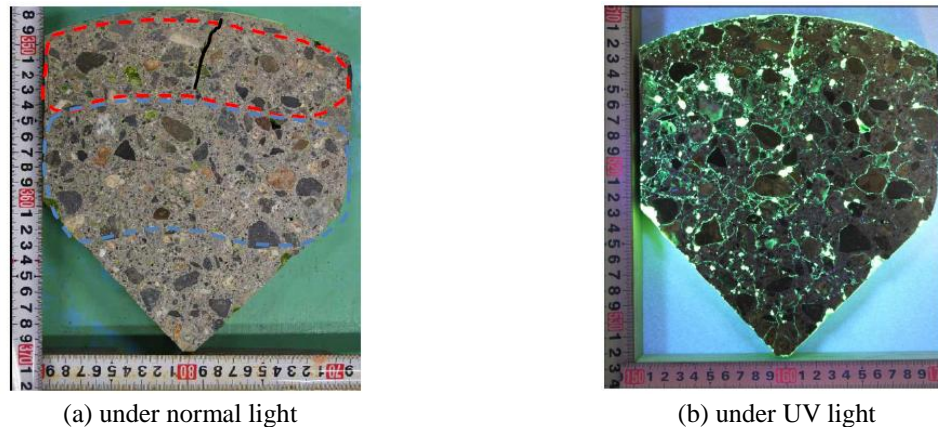(a) under normal light   (b) under UV light

Fig. 13 Photographs of a part of cut section of a reactive concrete cylinder in the transversal direction

the re-saturating process. Expansion in central portions around a depth of 200 mm almost terminated to the modest extent at the beginning of re-saturating process. In conclusion, continuous extension of surface cracks in the concrete cylinder was attributed to differences in expansion between near-surface and internal regions throughout both the drying and the re-saturating process.

8. Observations of internal cracks in the concrete cylinder

Concrete disc 50 mm thick were cut from the concrete cylinder (φ450 mm × 900 mm) using the saw. A concrete disc was divided into four equal fan-shaped parts. Then, they were gently dried in an atmosphere with 60% R.H. at 20℃ for about 24 hours, and then transferred to a vacuum desiccator. They were impregnated with an epoxy resin with a low viscosity containing a fluorescent dye. After the resin hardened at room temperature, cutting faces of specimens were polished with the SiC powder for observing polished surfaces under normal and UV light.

Figs. 13 (a) and (b) show photographs of a polished surface of a fan-like section taken under normal and UV light, respectively. The results obtained from careful observations of cracks patterns are as follows;

(1)   A thick crack about 50 mm in length and about 1 mm wide has developed from surfaces to inner portions. This crack is a part of surface cracks in the sectional direction (Fig. 12).

(2)   Only a few cracks were found in near-surface regions up to about 50 mm in depth.

(3)   Many peripheral cracks along the boundary between coarse aggregate particles and the mortar phase were conspicuously seen especially in the middle areas between center and surfaces. Strains in the zones were greater than those in surrounding portions.

(4)   Several fine cracks radiating from some fine aggregate particles were found.

(5)   Many cracks passed through the cement paste phase.

More careful treatments may be needed in the production of concrete samples, in which an epoxy resin containing a fluorescent dye was impregnated, for seeing thin cracks patterns.

The presence of surface cracks, radial cracks from fine aggregate particles and many cracks propagating through the cement paste phase in ASR-affected concretes have been reported by many workers (e.g. Idorn *et al*. 1992, Idorn 1967) However, few literatures have referred to

peripheral cracks around coarse aggregate particles. The formation of such peripheral cracks suggests that there were differences in expansion between coarse aggregate particles and the mortar phase. Both fine and coarse aggregates used in this study were reactive, but presumably, fine aggregate were more reactive than coarse aggregate. It is found from observations in this study that, in massive reactive concrete bodies, micro-cracks were produced around ASR gel pockets, but the formation of meso-scale cracks were related to the secondary stresses induced by differences in expansion between different regions and/or phases.

9. Conclusions

Taking into the consideration the expansion behavior of mortars in atmospheres with various R.H. values, near-surface regions in the concrete cylinder in the drying and the re-saturating process were estimated to less or little expand compared with internal portions. The results of mortar expansion tests also indicate that the middle areas of about 100 mm deep in the concrete cylinder greatly expanded in the re-saturating process. It is concluded that the active development of surface cracks in the concrete cylinder throughout the drying and the re-saturating process was attributed to differences in expansion between near-surface and internal portions throughout both the processes.

Other results obtained are summarized as follows;

(1)　C.F. and J.S. mortars showed the greatest expansion at the R.H. value of 82.3% and 89.0, respectively. The pessimum humidity existed both in the C.F. and J.S. mortar, even when effects of alkali leaching on expansion in high moisture environment had not to be taken into consideration.

(2)　The presence of the pessimum R.H. in expansion vs. R.H. relations may be due to the combination of various factors, e.g. possible factors of calcium content of reactive components, micro-cracks and pore sizes filled with water.

(3)　Mortars which have been stored in an atmosphere with 82.3% R.H. and 89.9% R.H. rapidly started expanding immediately after the beginning of re-saturating process. This result coincides with the production of the greater expansions in the middle areas in which 80%~90% R.H. had been maintained during the re-saturating process in the concrete cylinder.

(4)　Once mortars with reactive aggregate had been exposed to dry atmospheres with R.H. values lower than 79.9% for a long time, expansive ability of ASR gels in the mortars were lost even when re-saturated by exposing them to moist atmospheres with > 95% R.H..

(5)　A relatively small increase in R.H. value in internal portions of field ASR-affected concrete structures of which the R.H. value have ranged from about 80% to 90%, e.g. supply of water by rainfall, can drastically accelerate surface cracking.

(6)　In the middle areas showing great expansions in the concrete cylinder in the re-saturating process, numerous meso-scale cracks were found.

(7)　The meso-scale cracks may be formed not only by the development of micro-cracks around ASR gel pockets, but also by internal stresses induced by differences in expansion between various phases and/or regions.

References

Diamond, S., Barneyback, R.S. and Struble, L.J. (1981), "On the physics and chemistry of alkali-silica reaction", *Proceedings of the 5th International Conference on alkali-aggregate reaction in concrete*, Cape Town, South Africa, S/252/22.

Diamond, S. (1996), "Alkali silica reaction – some paradoxes", *Proceedings of the 10th International Conference on Alkali-Aggregate Reaction in Concrete,* Melbourne, Australia, pp. 3-14.

Dunant, C.F. and Scrivener, K.L. (2010), "Micro-mechanical modelling of alkali-silica-induced degradation using the AMIE framework", *J. Cement Concrete Res.*, **40**(4), 517-525.

Dunant, C.F. and Scrivener, K.L. (2012), "Effects of uniaxial stress on alkali-silica reaction induced expansion of concrete", *Cement Concrete Res.*, **42**(3), 567-576.

Hagelia, P. (2004), "Origin of map cracking in view of the distribution of air voids, strength and ASR-gel", in: M. Tang, M. Deng (Eds), *Proceedings of the 12th International Conference on Alkali Aggregate Reaction in Concrete*, Beijing, China, pp. 870-881.

Hirono, S. and Torii, K. (2012), The alkali-silica reactivity of representative andesite aggregates produced in Hokuriku district and its mitigation mechanisms by fly ashes, *J. Cement Concrete Res.*, **66**, 499-506.(in Japanese)

Idorn, G.M. (1967), "Durability of concrte structure in Denmark", Ph. D thesis, Technical University of Denmmark, 1967, p. 208.

Idorn, G.M., Johansen, V. and Thaulow, N. (1992), "Assesment of causes of cracking in concrete", in :J. Skaluny (Ed.), Materials Science of Concrete III, The American Ceramic Society, Westerville, OH, 1992, pp. 71-104

JIS A 1146(2007), Method of test for alkali-silica reactivity of aggregates by mortar-bar method, Japanese Industrial Standards, Japan

Kagimoto, H. and Kawamura, M. (2011), "Measurements of strain and humidity within massive concrete cylinders related to the formation of ASR surface cracks", *Cement Concrete Res.,* **41**(8) (2011) 808-816.

Leeman, A., Le Saout, G., Winnefeld, F., Rentsch, D. and Lothenbach, B. (2011), "Alkali-silica reaction: the influence of calcium on silica dissolution and the formation of reaction products", *J. Am. Ceram. Soc.,* **94**(4), 1243-1249.

Lenzner, D. and Ludwig, V. (1978), "The alkali aggregate reaction with opaline sand stone from Schleswig-Holstein", *Proceedings of the 4th International Conference on Effects of Alkalis in Cement and Concrete*, Purdue university, U.S.A., 11-34.

Lindgard, J., Andic-Cakir, O., Fernandes, I., Ronning, T.F. and Thomas, M.D.A. (2012), "Akali-silica reaction(ASR): Literature review on parameters influencing laboratory performance testing", *Cement Concrete Res.,* **42**(2) , 223-243.

Lumley, J.S. (1989), "Synthetic cristobalite as a reference reactive aggregate", *Proceedings of the 8th International Conference on Alkali-Aggregate Reaction in Concrete*, Kyoto, Japan, 561-566.

Moon, J., Speziale, S., Meral, C., Kalkan, B., Clark, S.M. and Monteiro, P.J.M. (2013), "Determination of the elastic properties of amorphous materials: Case study of alkali-silica reaction gel", *Cement Concrete Res.,* **54**, 55-60.

Olafsson, H. (1986), "The effect of relative humidity and temperature on alkali expansion of mortar bars", *Proceedings of the 7th International Conference on Concrete Alkali-Aggregate Reactions*, Ottawa, Canada, 461-466.

Pignatelli, R., Comi, C. and Monteiro, P.J.M. (2013), "A coupled mechanical and chemical damage model for concrete affected by alkali-silica reaction", *Cement Concrete Res.*, **53**, 196-210.

Stark, D. (1991), "The moisture condition of field concrete exhibiting alkalisilica reactivity", in: V.M. Malhotra (Ed.), *Proceedings of the 2nd International Conference on Durability of concrete*, ACI SP-126, Montreal, Canada, 973-987.

Wang, T., Nishibayashi, S. and Nakano, K. (1996), "Fractal analysis of cracked surface in AAR concrete", *Proceedings of the 10th International Conference on Alkali-Aggregate Reaction in Concrete,* Melbourne, Australia, 426-433.

CC