Relationships between humidity and ASR expansion in mortar bars exposed to dry atmospheres and re-saturating process

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ABSTRACT

The major objective of this study is to reveal the expansion behavior of mortars in dry atmospheres with various R.H. values and the re-saturating process. Mortar specimens made with two types of reactive aggregates were exposed to dry atmospheres with 70.0, 74.7, 79.9, 82.3, 89.0 and >95% R.H. at 40°C. Mortars which have been stored at 82.3% R.H. started rapidly expanding immediately after the beginning of re-saturating process. Once mortars had been dried in atmospheres with less than about 80% R.H., expansive ability of the mortars were lost even when re-saturated by exposing them to moist atmospheres with >95% R.H.. Expansions in near-surface regions in a massive concrete body were smaller than in the internal regions throughout the drying and re-saturating process, bringing about continuous surface cracking.

1. Introduction

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 were 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 with various R.H. values for long times, in re-saturating process are little understood.

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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 between internal moisture states and external humidity will be attained. As a result, ASR expansion depends on the size of specimens. Furthermore, alkali leaches from mortar bars submitted to high moisture environments. Therefore, expansion does not necessarily increase with increasing R.H. value for a given shape and size of specimen.

Tensile stresses induced in non- or less-expansive layers in near-surface regions formed in the process of drying-wetting repetitions in natural environments are responsible for surface cracking in ASR-affected concrete structures. Hence, the past record of environmental humidity and temperature the concretes underwent is considered to intimately relate to surface cracks.

The major objective of this study is to reveal the expansion behavior of mortars in dry atmospheres with various R.H. values and in the re-saturating process.

In another study (Kagimoto and Kawamura 2011), we have conducted an experimental work in which humidity and strains within in a relatively large concrete cylinder were measured for proving the validity of a notion that the formation of non- or less-expansive surface layer was responsible for surface cracking in a massive concrete body. In this paper, the mechanisms of surface cracking in a relatively large concrete cylinder exposed to a drying and re-saturating process were discussed taking into the consideration the characteristics of expansion vs. humidity relations in mortars exposed to the drying and re-saturating process.

2. Outline of experiments

2.1 Materials and mix proportions

Two types of reactive aggregate used were a calcined flint (C.F.) produced by Lafage Cement Ltd. (Lumley 1989) and sand (J.S.) from the Joganjigawa river in Toyama Prefecture in Japan. The Japanese standard sand was used as non-reactive aggregate. The dissolved silica (Sc) and the reduction in alkalinity (Rc) of the reactive aggregates (J.S. and C.F.) are provided in Table 1.

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 per 1 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.

<table>
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<tr>
<th>Table 1 Alkali reactivity of J.S. and C.F</th>
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<td>J.S.</td>
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<td>Reduction in alkalinity</td>
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2.2 Method of 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 beginning of re-saturating process in a moist atmosphere of >95% R.H.. As a result, lengths of the mortars bars exceeded the limit of measurable range of the comparator, and then we used the slide calipers for measuring lengths of the mortar bars. The dots for values obtained by the use of the slide calipers were marked in Figs. 2, 3, 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 mortar expansion tests.

2.3 Measurements of expansion of mortar bars in ambient atmospheres with various R.H. values

Mortar bars were initially stored over water in sealed containers at 40°C until their expansions reached approximately 0.10%. 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, (NH₄)₂SO₄, KCl, KNO₃ and pure water corresponding to relative humidity of 74.7, 79.9, 82.3, 89.0 and >95% R.H. at 40°C, respectively (Fig. 1). 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 moisture states within specimens and humidity of ambient atmospheres had been nearly attained.

Fig.1 Mortar bars cured at various humidity conditions.
3. Results and discussion

3.1 Expansions of mortars in the drying process.
Figs. 2 and 3 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 re-saturating process are presented in Fig. 4. Expansions measured in C.F. and J.S. mortar specimens (Figs. 2 and 3) contain both of ASR expansion and drying shrinkage. Hence, net ASR expansions (Figs. 5 and 6) are given as differences between length changes measured in mortar specimens with and without reactive aggregate.
As described above, when expansions of mortar bars exceeded 0.1%, they were transferred to the plastic containers in which atmospheres with various R.H. values were invariably maintained. Hence, at the beginning of ASR expansion in the drying process in various atmospheres, ASR chemical reactions must have already terminated. However, moisture within specimens placed in all the atmospheres except >95% gradually went out into atmosphere. 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. Therefore, specimens expanded corresponding to high internal R.H. values as a whole.

Plotting ultimate expansions against R.H. values in the drying process gives Fig. 7.
As seen in this Figure, C.F. and J.S. mortars showed the greatest expansion at 82.3% and 89.0%, respectively.

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 expansion of 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.

3.2 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 smaller than 79.9% R.H., finally reached about 0.4% and 0.3%, respectively. It is also seen in these figures that expansions of the mortars at R.H. values less than 79.9% were very small after they had been 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 the expansion of the mortars was the greatest at about 1 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% and 89.0% R.H. in the drying process had already completed at the beginning of re-saturating process. Hence, these mortars little expanded in the re-saturating process.

4. Measurements of strain and humidity within a relatively large concrete cylinder

We have measured strains and humidity within a massive concrete cylinder (φ450 mm x 900 mm) made with J.S. aggregate for revealing the process of surface cracking in an ASR-affected concrete cylinder in the process of drying for about 300 days, followed by the re-saturating process for about 971 days (Kagimoto and Kawamura 2011). We carefully observed surfaces of the concrete cylinder. Longitudinal cracks were found in four different parts on the surfaces at 150 days for the first time. Development of surface cracks with time is shown in Fig. 8.

Surface cracks formed during the drying process continued to actively develop in the re-saturating process, finally resulting in the tortoise shell-like surface cracks patterns. ASR expansion strain vs. time curves at various depths from surfaces in the reactive concrete cylinder (Fig. 9) is reprinted from Ref. (Kagimoto and Kawamura 2011). As seen in this figure, the rates of increase in strain with time at the depth of 100 mm were higher than those at a depth of 200 mm from the beginning of the re-
Fig. 8 Sketches of surface cracks on a reactive concrete cylinder in the drying and re-saturating process (Kagimoto and Kawamura 2011).

Fig. 9 Compensated strain vs. time curves at various depths in a reactive concrete cylinder (Kagimoto and Kawamura 2011).
saturating process, and then the former exceeded the latter about 75 days after the beginning of re-saturating process.

Fig. 10 reprinted R.H. value vs. time curves at various depths in the reactive concrete cylinder given in Ref. (Kagimoto and Kawamura 2011). The R.H. value at the depth of 100 mm was about 86% R.H. at the beginning of re-saturating process, and reached about 93% R.H. after about 2 months.

5. Expansions within a concrete cylinder estimated from the characteristics of expansion of mortar bars in atmospheres with various R.H. values

5.1 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%. In order to specify the depth at which a critical R.H. had been attained at 90 days (the beginning of expansion), 150 days, and 291 days (the beginning of re-saturating process), R.H. values measured in the study of Ref. (Kagimoto and Kawamura 2011) were plotted against depth from surfaces, 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 of 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 were small compared with those in portions deeper than that.

Fig.10 R.H. value vs. time curves at various depths in a reactive concrete cylinder. (Kagimoto and Kawamura 2011).
5.2 Re-saturating process

As seen in Fig.10, 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. 6, 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. This result suggests that ASR expansions 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.12 reprinted from Ref. (Kagimoto and Kawamura 2011)), immediately after a concrete cylinder (φ450 mm × 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, being the greatest about 200 days. R.H. values in the portions changed from about 86% to 93% in the re-saturating process up to about 200 days (Fig. 10). Hence, active progress of expansion around 100 mm depths can be understood by the fact that R.H. values around the portions were within the range of 82.3% to 89.9% R.H. in the drying process in which mortars actively expanded in the re-saturating process (Fig. 6).

ASR expansion in the portions up to about 50 mm depths in the concrete cylinder must have been small throughout the drying and re-saturating process. R.H. values greater than 92% were maintained in central portions about 200 mm depths even for long periods of drying. In other words, ASR expansion in the central portions has already come to an end at the beginning of re-saturating process. However, strains at depths of 100 mm to 200 mm have rapidly increased, being the greatest about 200 days.
6. Effects of the characteristics of ASR expansion of concretes subjected to drying-wetting repetitions on surface cracking

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

It has been proven that surface cracks originated from differences in expansion between near-surface and internal regions (Kagimoto and Kawamura 2011). Therefore, in field ASR-affected concrete structures, a relatively small increase in R.H. value in internal portions of ASR-affected concretes of which R.H. values have been maintained
above about 80%, e.g. supply of water by rainfall, can drastically accelerates surface cracking.

7. Conclusions

The 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.
(2) It may be due to the combination of various factors, e.g. alkali and calcium content of ASR gels, micro-cracks and pore sizes filled with water that ultimate expansions did not necessarily increase with increasing R.H. value.
(3) The relative humidity below which mortars showed expansions smaller than 0.1% was about 70% in both the C.F. and the J.S. mortars in the drying process.
(4) Expansions of most mortars after they were transferred to a moist environment of >95% R.H. were very small. But, mortars which have been stored in an atmosphere with 82.3% R.H. started rapidly expanding immediately after the beginning of re-saturating process, and finally the expansion of the mortars was the greatest at about 1 month.
(5) Once mortars with reactive aggregate had been exposed to dry atmospheres with R.H. values smaller 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..
(6) A relatively small increase in R.H. value in internal portions of field ASR-affected concrete structures of which the R.H. value have been greater than about 80%, e.g. supply of water by rainfall, can drastically accelerate surface cracking.

REFERENCES