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Measurements of strain and humidity within massive concrete cylinders related to the formation of ASR surface cracks

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ABSTRACT

This study aims at proving the validity of a notion that the formation of non-expansive near-surface layer is responsible for surface cracking in ASR-affected concretes by a laboratory experiment. Relationship between the progress rate of the front of non-expansive layer toward inner portions and the formation of the first surface cracks was scrutinized by measuring relative humidity (R.H.) values and strains within a massive concrete cylinder (ϕ450 mm × 900 mm) with reactive aggregates under a dry environment. It was presumed from the measurements that a non-expansive layer of about 40 mm had been formed at the first cracking. Thereafter, the environmental humidity was raised to >95% R.H. Pursuit of the growth of surface cracks and subsequent measurements of strains and R.H. values within the concrete cylinder under the moist environment suggested that the re-saturation continuously gave rise to the generation of tensile stresses in near-surface regions leading to active extension of surface cracks.

1. Introduction

Stark [1] revealed that ASR expansion did not occur below the 80% R.H. He also investigated moisture conditions within ASR-affected field concrete structures. On the basis of these results, Stark [1] insisted that stresses induced by differential volume changes confined to near-surface regions were responsible for surface cracking in ASR-affected concrete structures.

Idorn et al. [2] proposed a similar concept for ASR surface cracking on a concrete member exposed to natural environments. Recently, Hagelia [3] suggested that surface stresses caused by differences in expansion between internal and near-surface regions lead to surface cracking. However, detailed processes from the initiation of ASR expansion to the first surface cracking and subsequent extension of the cracks in ASR-affected concretes subjected to wetting–drying repetitions in natural environments are not clear. Thus, the validity of a notion that the formation of non-expansive layer is responsible for surface cracking in ASR-affected concretes has not been proven by laboratory experiments.

The main objective of this study is to prove the validity of the notion by an experiment. Relationship between the progress rate of the front of non-expansive layer toward inner portions and the formation of the first surface cracks was scrutinized by measuring relative humidity (R.H.) values and circumferential strains at various depths from surfaces in a relatively massive concrete cylinder made with reactive aggregate in a dry environment (the drying process). Heavily cracked surfaces found in field ASR-affected concrete structures are supposed to be brought about by wetting–drying repetitions. Then, 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. to simulate wetting–drying repetitions (the re-saturating process). Further extension of surface cracks in the re-saturating process was pursued measuring R.H. values and strains within the concrete cylinder.

Taking into consideration the fact that a strain measured at a given portion within concrete cylinders was not ASR expansion itself, we carefully discussed relations between time-dependent changes in strain and relative humidity value, and surface cracking. A reasonable interpretation for the suppression of ASR deterioration in field concrete structures by drying can be expected from the results obtained.

We also tried to calculate a critical ASR expansion at the first surface cracking using a thickness of non-expansive layer obtained in this experiment by a simple calculation method proposed by the second author [4].

Alkali leaching contributes to reduce expansion in the near-surface regions in concrete submitted to high moisture environment. However, effects of alkali leaching on the formation of non- or less expansive regions in concrete cylinders were not taken into consideration in this study.

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Table 1
Properties of aggregate.

Physical properties	
Reactive aggregate	Non-reactive aggregate
Coarse aggregate[a] Density: 2.64 g/cm^3 Absorption: 1.66% Fine aggregate[c] Density: 2.61 g/cm^3 Absorption: 1.94%	Coarse aggregate[b] Density: 2.71 g/cm^3 Absorption: 1.44% Fine aggregate[d] Density: 2.62 g/cm^3 Absorption: 1.42%
Alkali reactivity of reactive aggregate	
Coarse aggregate[a] Reduction in alkalinity: 91 mmol/l Dissolved silica: 253 mmol/l JIS mortar bar test: 0.34%/6 months	Fine aggregate[c] Reduction in alkalinity: 61 mmol/l Dissolved silica: 190 mmol/l JIS mortar bar test 0.38%/6 months

[a] Jogannji river gravel.
[b] Oume crushed stone.
[c] Joganji river sand.
[d] Oigawa river sand.

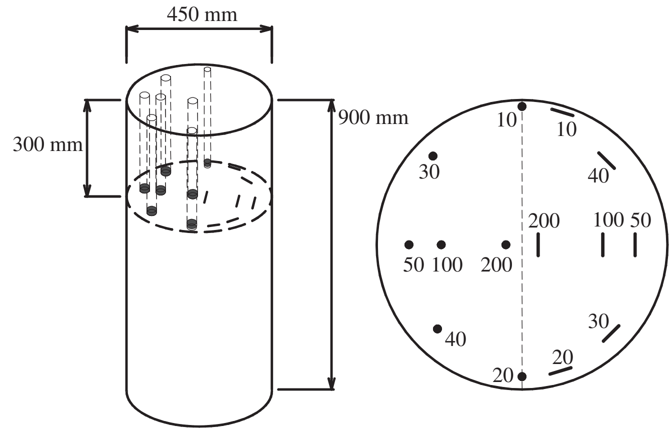

Fig. 2. Positions of sensor assemblies and strain gauges in a concrete cylinder.

Table 2
Mix proportions of concrete.

Maximum aggregate size (mm)	Water: cement ratio	Sand ratio	Unit content (kg/m^3)			
			Water	Cement	Sand	Gravel
20	0.55	0.45	175	318	833	1030

2. Experimental procedures

2.1. Materials, mix proportions of concrete and measurements of free expansion

The coarse and fine reactive aggregates used were gravel and sand from the Joganjigawa river in Toyama Prefecture in Japan; non-reactive aggregates were a crushed rock produced in Oume and sand from the Oigawa river in Japan. Table 1 provides the dissolved silica (S_c) and the reduction in alkalinity (R_c) obtained in the application of the standard chemical method for seeing potential reactivity of aggregate (JIS A 1145). A low alkali cement with an equivalent percentage of Na_2O_{eq} of 0.53% was used.

The mix proportions of concrete are provided in Table 2. 5.21 kg NaOH per 1 m^3 concrete was added at a dosage level of alkalis equivalent to 1.8% Na_2O_{eq} in cement to promote expansion of the concrete with reactive aggregate.

In order to see expansion characteristics of the reactive aggregate-containing concrete, especially during the period up to the beginning of rapid ASR expansion (latent period), free expansions were measured using concrete prisms (100 mm × 100 mm × 400 mm). They were stored in three different environmental conditions of a moist environment of >95% R.H. at 35 °C and 40 °C, and the same environmental condition of changing 60% R.H. at 35 °C to 70% R.H. at 40 °C at 73 days as the massive concrete cylinders were stored.

2.2. Setup of arrangements for measuring R.H. values and strains within concrete cylinders

As shown in Fig. 1 and Fig. 2, electrical strain gauges were embedded in concrete in the circumferential direction at the positions corresponding to depths of 10, 20, 30, 40, 50, 100 and 200 mm from surfaces in the two concrete cylinders with and without reactive aggregate (ϕ450 mm × 900 mm).

At the placement of concrete into the form, acrylic rods of 30 mm in diameter by 400 mm long, which have a cylindrical protrusion (ϕ10 mm × 10 mm) on the end, were embedded vertically so as to make rooms for accommodating sensor assemblies to measure humidity. About 24 hours after the placement of concrete, all of the acrylic rods were extracted leaving ϕ30 mm × 300 mm cylindrical holes attached with ϕ10 mm × 10 mm cylindrical spaces on the end behind (Fig. 1).

Sensors for measuring relative humidity were fixed into the holes drilled in the central portions of the other series of acrylic cylinders (ϕ30 mm × 40 mm) prepared in advance (Fig. 1). After these sensor assemblies were embedded into the end of ϕ30 mm × 300 mm cylindrical holes, mortars were poured into remaining upper portions in the holes. Thus, we measured R.H. values in atmospheres in small rooms (ϕ10 mm × 10 mm) in concrete that were in equilibrium with moisture states in the surrounding concretes.

Measurements of strains and R.H. values within concrete cylinders and observations of cracking on their surfaces were initiated

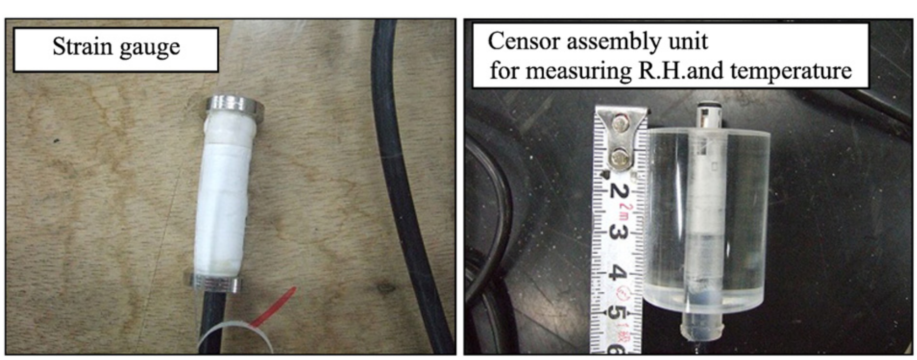

Fig. 1. Electrical strain gauge and sensor assembly unit embedded in a concrete cylinder.

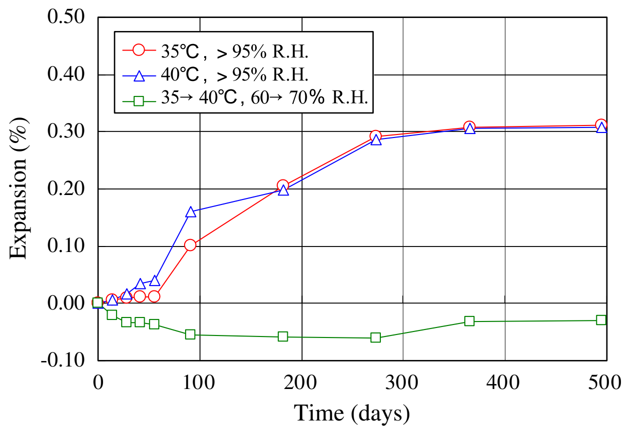

Fig. 3. Expansion curves in concrete prisms (100 × 100 × 400 mm) under the three different environmental conditions.

immediately after de-molding. The temperature and R.H. in the storage room, which were maintained at 35 °C and 60% R.H. at an early stage, were raised to 40 °C and 70% at 73 days (the drying process). In order to simulate wetting-drying repetitions that field ASR-affected concrete structures undergo, the environmental humidity under which the concrete cylinders with and without reactive aggregate were placed, has been raised to > 95% R.H. at 292 days and 643 days, respectively (the re-saturating process). Measurements of strains in the reactive aggregate-free concrete cylinder were concluded at 971 days.

2.3. Evaluation of the degree of cracking

We pursued time-dependent increases in width at the widest portions in the cracks firstly formed at 150 days in the four different parts on the side surfaces of the concrete cylinder with reactive aggregate. Widths of cracks were measured with a special measure with a unit of 0.05 mm. Lengths of growing cracks were also measured along curved surfaces on the concrete cylinder at intervals.

3. Results and discussion

3.1. Expansion in concrete prism tests

Changes in expansion with time in concrete prisms under the three different environmental conditions are presented in Fig. 3. As shown in this figure, concrete prisms under >95% R.H. at 35 °C and 40 °C started to rapidly expand at about 60 days. Namely, the latent period of ASR expansion was about 60 days. However, concrete prisms which were stored in an environmental condition of changing 60% R.H. at 35 °C to 70% R.H. at 40 °C at 73 days, continued to shrink.

3.2. Strains and R.H. values within the concrete cylinders in the drying process

It is generally accepted that, for most reactive aggregates, ASR expansion does not occur below the 80% R.H. [1,5]. The near-surface region in an ASR-affected concrete cylinder in which R.H. value is below the threshold 80%, is called the non-expansive layer in the following discussion.

Relations between R.H. value and time at various depths in the concrete cylinder with reactive aggregate are provided in Fig. 4. Deficits of dots and disorders in R.H. value vs. time curves at various depths during the period of 667 days to 734 days are due to difficulties in the temperature and humidity controller. In this figure, it is seen that R.H. values measured at a depth of 20 mm reached the threshold value of 80% about 115 days. Thereafter, the front of non-expansive layer gradually progressed inward, and R.H. values at depths smaller than 40 mm became below 80% about 147 days.

Strains measured at each depth within the reactive concrete cylinder are plotted against time, as shown in Fig. 5. At all the depths with exceptions at a depth of 20 mm, compressive strains are found to increase with time up to about 40 days. Thereafter, compressive strains gradually turned over to tensile strains. At a depth of 20 mm, compressive strains increased with time up to about 75 days, followed by gradual changes toward tensile strains. As previously described, rapid ASR expansion started after about 60 days in concrete prisms testing. Thus, changes in strains measured within the concrete cylinder reflect ASR expansion characteristics of the concrete indeed.

Compressive strains at a depth of 10 mm turned over toward tensile strains about 40 days. After that, tensile strains slightly increased with time for a while, and then gradually deceased. Thus, strains measured in the vicinity of surfaces showed peculiar behaviors.

Strain vs. time curves at various depths in the non-reactive concrete cylinder are given in Fig. 6. Disorders seen in the curves several times during the drying process are due to difficulties generated in the temperature and humidity controller for relatively short periods. Compressive strains (shrinkage) measured at each depth increased with time. Strains were the greatest and the smallest at the depth of 50 and 200 mm, respectively. Small differences were

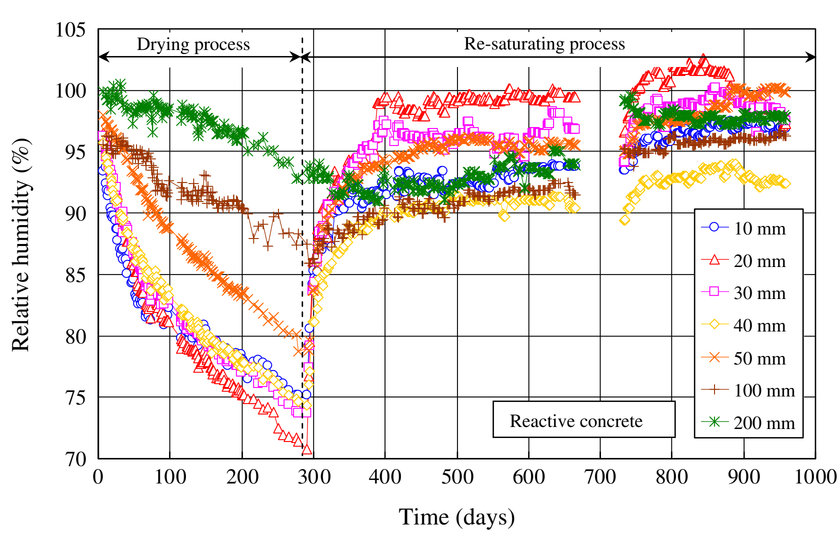

Fig. 4. R.H. value vs. time curves at various depths in a reactive concrete cylinder.

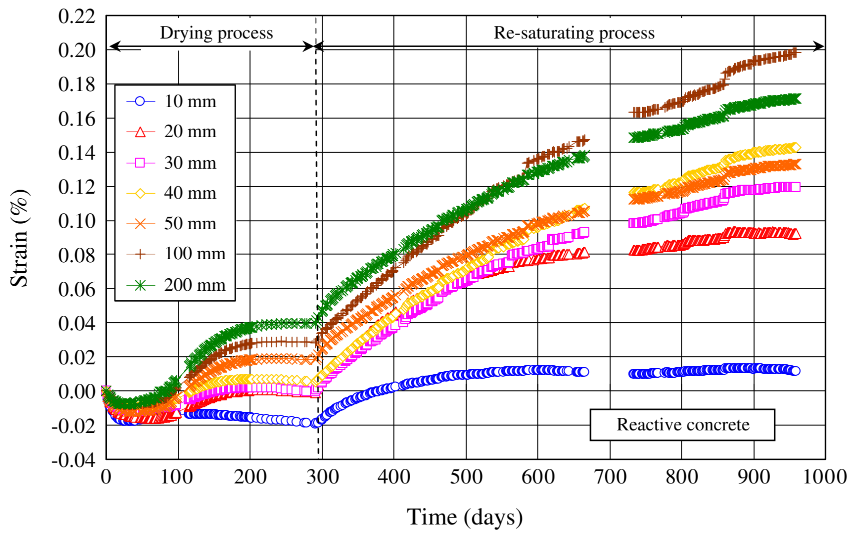

Fig. 5. Strain vs. time curves at various depths in a reactive concrete cylinder.

found between strains measured at the other depths. It is not clear whether relatively great compressive strains measured at a depth of 50 mm were ascribed to the occurrence of some problems in the measurement system of strains.

Strains measured within the reactive concrete cylinder include ASR expansions, shrinkage strains and strains due to internal stresses including creep after the initiation of ASR expansion (60 days). Therefore, strains caused by only ASR were obtained by compensating strains in the concrete cylinder with reactive aggregate for those in the reactive aggregate-free one. However, it should be noted that the compensated strains include strains due to internal stresses induced by differences in ASR expansion between different depths. Fig. 7 shows the compensated strain vs. time curves at depths of 20, 30, 40, 50, 100 and 200 mm.

As described previously, the environmental humidity has been raised to >95% R.H. at the different dates of 292 days and 643 days in the concrete cylinders with and without reactive aggregate, respectively. The compensated strains in the re-saturating process were obtained assuming that the difference of age in such old concretes slightly affects the primary swelling of concrete cylinders in the re-saturating process.

There were no data available in the non-reactive concrete cylinder after 643 days, and then compensated strain vs. time curves were extended using the data obtained for the concrete cylinder at 643 days.

Compensated strains are supposed to be strains caused by only ASR, but such latent periods as seen in expansion curves in the concrete prism tests (Fig. 3) were not found in compensated strain vs. time curves. As seen in Fig. 3, slight ASR expansions were generated in the concrete even in the latent period. Therefore, slight ASR expansions must have also occurred in the interior concretes under high relative humidity in the massive concrete cylinder even before the beginning of rapid ASR expansion, causing tensile strains in near-surface regions. The additional tensile strains increased the values of compensated strains during the latent period. Namely, differences in internal stresses during the latent period between the concrete cylinder with and without reactive aggregate are responsible for the absence of latent period in the compensated strain vs. time curves.

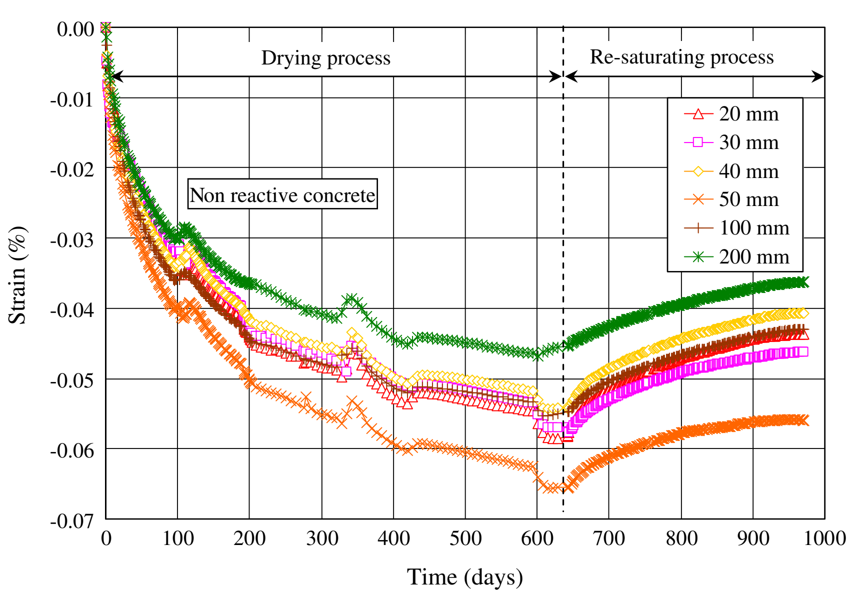

Fig. 6. Strain vs. time curves at various depths in a non-reactive concrete cylinder.

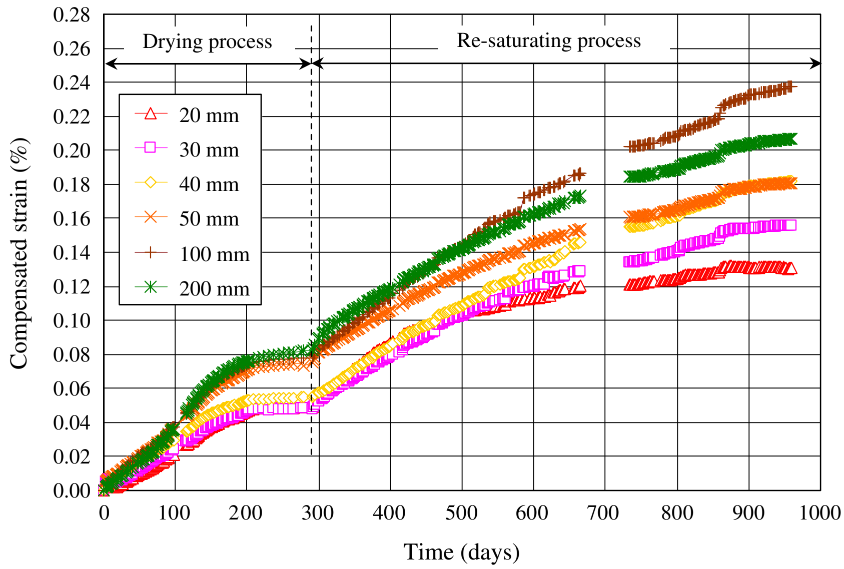

Fig. 7. Compensated strain vs. time curves at various depths in a reactive concrete cylinder.

As shown in Fig. 7, compensated strains at all the depths proportionally increased with time up to about 150 days, and then the rate of increase in strain started to decrease. Compensated strains in the near-surface and central portions ceased to increase around 200 days and 230 days, respectively. Taking into consideration the fact that expansion increased up to about 270 days in concrete prism tests (Fig. 3) and high relative humidity values (80–97%) giving assurances for ASR expansion at depths of 50, 100 and 200 mm were still maintained even after 200 days (Fig. 4), the cease of increase in compensated strains is due to the restraint of expanding central portions by the non-expansive layer and/or gradual decreases in relative humidity with time at all the depths (Fig. 4). It will be discussed afterward whether the tensile strains measured in near-surface regions are associated with ASR expansions.

In order to estimate a critical free ASR expansion at the first surface cracking, it is significant to know a thickness of non-expansive layer formed by that time. However, since compensated strains measured include both ASR expansions and strains induced by internal stresses, it seems impossible to deduce a thickness of non-expansive layer from the compensated strains.

Expansion of concrete is considered to be caused by absorption of moisture by ASR gel. If moisture in the concrete is strongly held by the cement paste matrix, expansion will not occur even if much ASR gel has been produced. R.H. values, which reflect the free energy levels of the moisture, have been used as a measure for indicating moisture availability for ASR expansion [6]. As reported by Stark [1], ASR expansion does not occur at a R.H. value lower than 80%. Therefore, plotting the compensated strains against R.H. values at various depths can differentiate tensile strains due to expansions of the interior concretes from ASR expansions of concrete itself.

Relations between the compensated strain and R.H. value are presented in Fig. 8. As shown in this figure, tensile strains at depths of 100 and 200 mm continued to increase in the range of high R.H. values of about 90% to >95%; those at a depth of 50 mm at which R.H. values were kept above the threshold R.H. of 80% over the period up to 280 days (Fig. 4), increased with decreasing R.H. value up to about

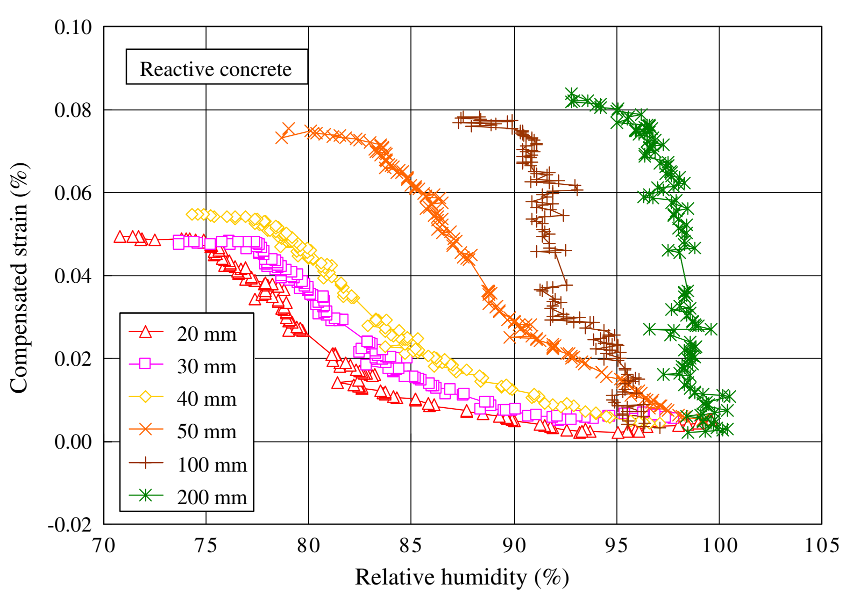

Fig. 8. Relations between compensated strain and R.H. value measured at various depths in a reactive concrete cylinder in the drying process.

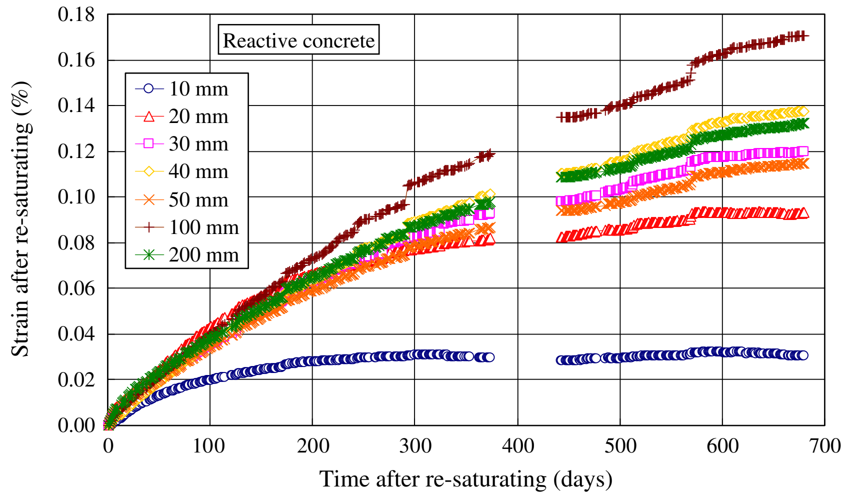

Fig. 9. Strain vs. time curves at various depths in a reactive concrete cylinder in the re-saturating process.

83%. At depths of 20, 30 and 40 mm, tensile strains slowly increased with decreasing R.H. value up to 85%, and then the rate of increase in strain gradually rose with decreasing R.H. value in the range of 85% to 78%. It should be noted that tensile strains at depths smaller than 40 mm continued to increase even below the threshold R.H. value of 80%.

Fig. 4 indicates that R.H. values at depths smaller than 40 mm had fallen to the range of 83% to 86% by the time concrete began to rapidly expand (60 days) (Fig. 3). Thus, from these results of R.H. values and trends of the compensated strains with decreasing R.H. value in the exterior concretes, it is conjectured that most tensile strains measured at depths smaller than 40 mm after the initiation of rapid ASR expansion were not ASR expansions of concrete itself, but caused by ASR expansions of the interior concretes.

It is also found from Fig. 4 that R.H. values at a depth of 50 mm slowly reduced with time and were kept greater than 92% up to the beginning of rapid expansion of concrete (60 days). However, R.H. values at depths smaller than 40 mm rapidly decreased with time, reaching R.H. values of 83% to 86% at 60 days. A great difference in the compensated strain vs. R.H. value curves between a depth of 40 and 50 mm (Fig. 8) reflects the drastic change in R.H. value vs. time relations with only a small increase of depth from 40 mm to 50 mm. These results suggest that ASR expansions more actively occurred at depths greater than at least 50 mm.

3.3. Strains and R.H. values within the concrete cylinders in the re-saturating process

As seen in Fig. 4, 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 after raising the environmental humidity to >95% R.H. Transfer of moisture through micro- and macro-cracks produced by ASR expansive pressures during the drying process may contribute to the rapid increases in R.H. value in the near-surface regions. R.H. values at a depth of 100 mm gradually increased with time. However, those measured at a depth of 200 mm still decreased with time for about 100 days after re-saturating, followed by slow increases toward >95% R.H. Thus, a sudden rise of the environmental humidity increased R.H. values at a depth of 100 mm even at early

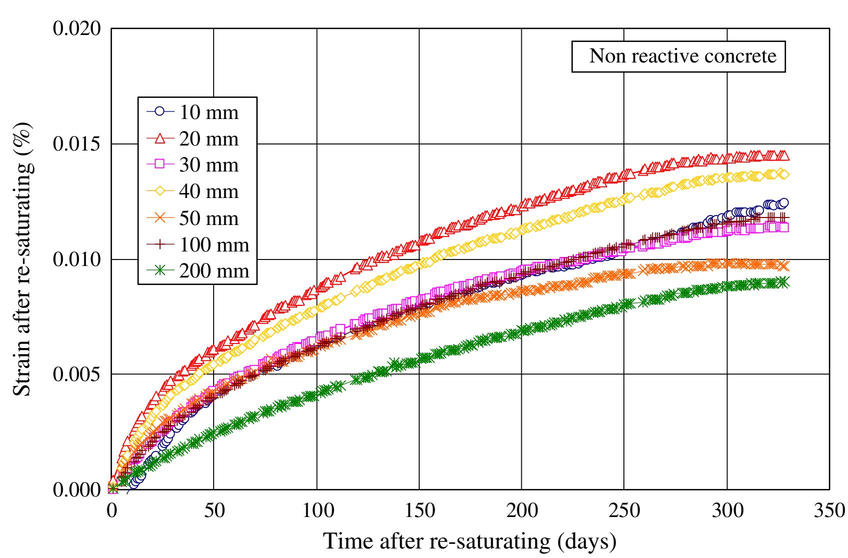

Fig. 10. Strain vs. time curves at various depths in a non-reactive concrete cylinder in the re-saturating process.

stages, but its influence on R.H. values at a depth of 200 mm was greatly delayed.

In order to understand the tendency of strain vs. time curves in the re-saturating process in full detail, strains were plotted against time from the beginning of the process in Figs. 9 and 10. In Fig. 9 it is seen that after a rise of the environmental humidity to >95% R.H., strains rapidly increased with time at depths greater than 20 mm in the reactive cylinder. Differences in strain between different depths gradually increased with time from about 100 days after re-saturating. However, as seen in Fig. 10, tensile strains (swelling) at each depth as well as differences in strain between different depths in the reactive aggregate-free concrete cylinder were very small.

Comparing strains measured in the concrete with and without reactive aggregate, ASR expansion in the reactive aggregate-containing concrete cylinder was found to start progressing immediately after the environmental humidity had been raised to >95% R.H. (Figs. 9 and 10). Shortly after ASR expansion and primary swelling of concrete started in the re-saturating process, residual internal stresses induced within the concrete cylinder during the drying process are supposed to be relieved. However, it is difficult to refer to internal stresses newly induced in the re-saturating process in the concrete cylinder with many surface cracks.

In Fig. 9, it is seen 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 after re-saturating. 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 depths of 100 and 200 mm appears to result from differences in time-dependent changes in R.H. value between both depths after re-saturating (Fig. 4). These results also suggest that internal stresses were newly induced by differences in ASR expansion between different depths in the re-saturating process and stress distributions became complicated.

Carefully seeing Fig. 9, it is found that strains jumped up about 120, 170, 240, 290 and 570 days after re-saturating in a strain vs. time curve at a depth of 100 mm. Abrupt smaller increases in strain were also intermittently found at other depths except a depth of 10 mm. The greater increases in strain at a depth of 100 mm suggest that the production and growth of cracks were especially active in the middle areas between the center and surfaces in the concrete cylinder.

Fig. 9 demonstrates that strain vs. time curves at all the depths started to level off about 600 days after re-saturating. The ultimate compensated strain at depths of 100 and 200 mm in the concrete cylinder with reactive aggregate was about 0.24% and 0.21%, respectively (Fig. 7). The potential expansions of concrete prisms with reactive aggregate were as high as 0.30% (Fig. 3). As described in the next paragraph, non-expansive near-surface layers in the concrete cylinder have been cracking to considerable extent during the drying and re-saturating process. Nevertheless, the rigidity of near-surface layers must be great enough to restrain inner portions to some degree. It is the restraint of non-expansive layers that reduced ASR expansions of central portions to levels lower than the potential ASR expansion of the concrete (Fig. 3). Considerable reductions in R.H. value in the central portions in the drying process must have also influenced the ultimate ASR expansion (Fig. 4).

Another conspicuous indication obtained from Fig. 9 is that strains measured at a depth of 10 mm in the re-saturating process were far smaller than those at the other depths. It should be noted that extension of cracks and their propagation in the radial direction influence the rate of increase in strain in the surface-near regions. The drastic reduction in strain at a depth of 10 mm may be due to growth of the surface cracks which have been formed during the drying process.

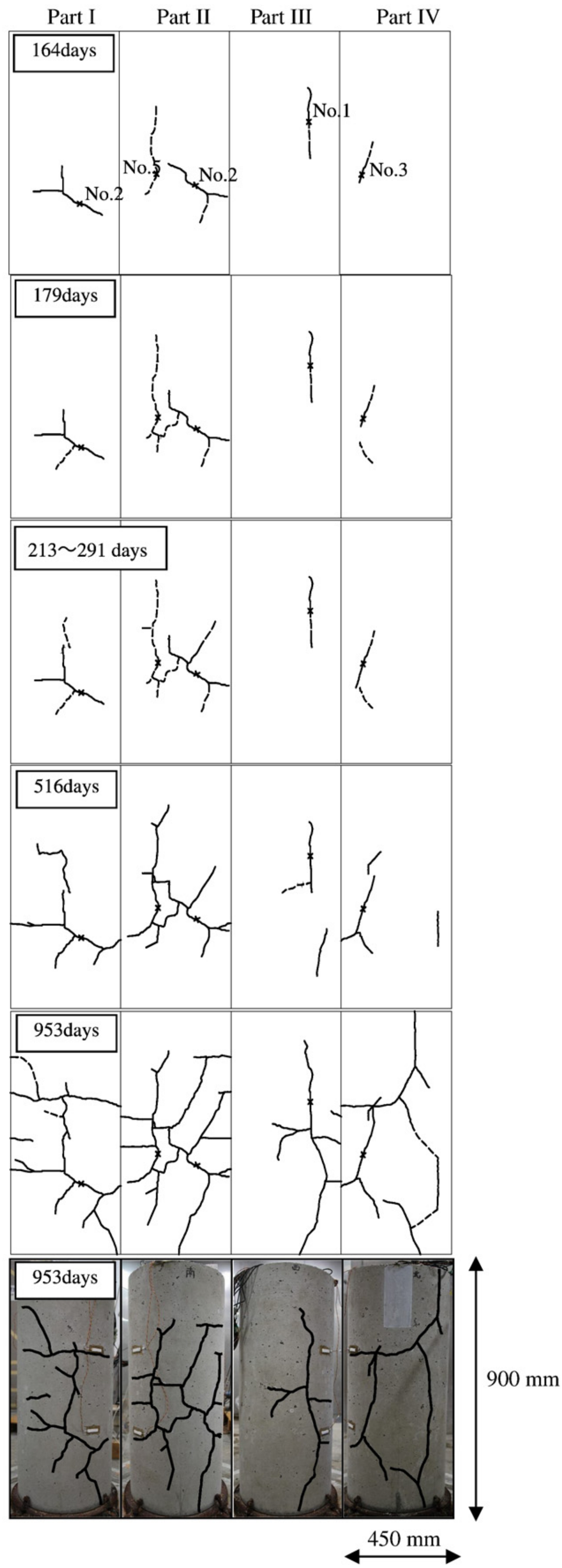

Fig. 11. Sketches of surface cracks on a reactive concrete cylinder in the drying and re-saturating process.

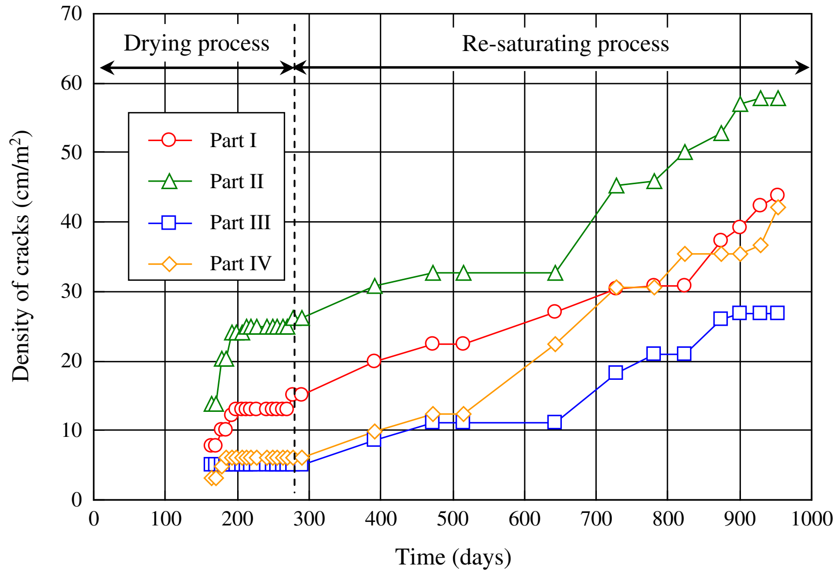

Fig. 12. Changes in the width of cracks with time on the surface in a reactive concrete cylinder throughout the drying and re-saturating process.

3.4. Observations of surface cracks

We carefully observed surfaces of the reactive concrete cylinder 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. 11. Widths of visible cracks sketched in Fig. 11 were greater than 0.05 mm. It is found from this figure that cracks extended and branched off with time. Little extension of cracks was seen after 213 days in the drying process. Simultaneously, strains measured at all the depths ceased to increase about 200 days (Fig. 5). Furthermore, it is interesting to see that cracks separately formed in Part II coalesced to form tortoise shell-like patterns occasionally found in ASR-affected field concrete structures.

The growth of surface cracks was evaluated by measuring the width and density of cracks (the sum total length of cracks per meter squared) in the four parts at various times in the drying and re-saturating process, as shown in Figs. 12 and 13. In these figures, it is clearly seen that the width and density of cracks changed little for the period of 200 days to 300 days after the cease of increase in strain in the drying process (Fig. 5).

As seen in Fig. 12, the width of cracks did not increase with time smoothly, but intermittently jumped up several times. These results suggest that the cracks grew in the radial direction during the time. As shown in Fig. 13, the sum total length of cracks per meter squared in each part also continued to increase with time up to at least about 950 days. The continuous growth of surface cracks during the re-saturating process denotes that tensile stresses induced in near-surface regions increased with time during the period.

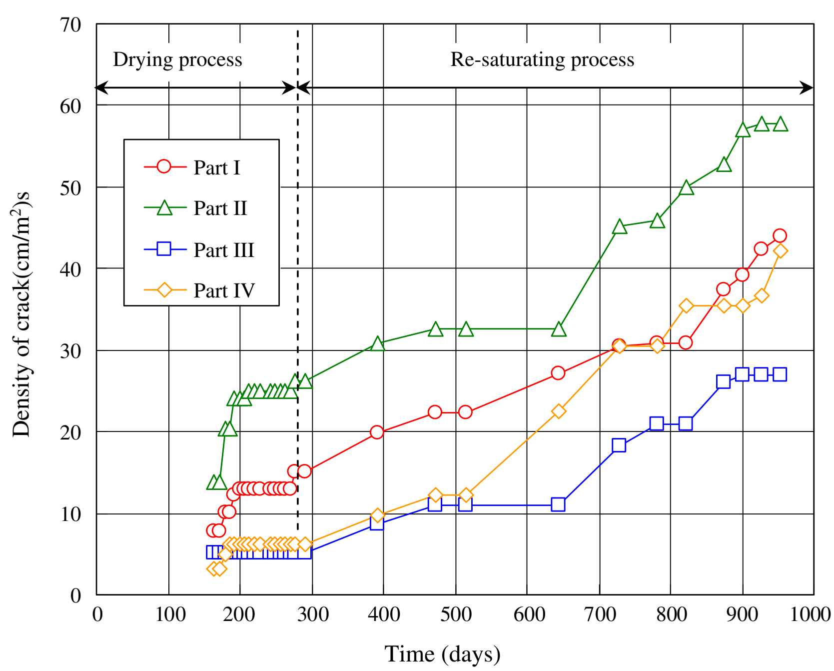

Fig. 13. Changes in the density of cracks with time on the surface in a reactive concrete cylinder throughout the drying and re-saturating process.

Multon and Toutlemonde [7] reported that a supply of water to ASR-affected concretes in which the maximum potential expansion has not been reached because of lack in available water, newly caused ASR expansions. Lenzner and Ludwig [5] demonstrated that mortar bars stored in a dry environment (60% R.H.) for 42 days in the early stage followed by the storage under >95% R.H. showed expansions higher than those stored from the beginning under >95% R.H. In the former study, the upper and bottom faces in concrete beams were dipped in water for long times. The results in the latter were obtained by the use of mortar specimens (10×40×160 mm). The present study has been carried out using relatively massive concrete cylinders placed under a dry and a moist environment. Since R.H. values in the near-surface regions have been reduced to 70–75% in the drying process (Fig. 4), we cannot declare that ASR expansion was generated in the exterior concretes in the re-saturating process. However, consistent growth of surface cracks (Fig. 13) convinces evidence that, even if ASR expansions occurred in near-surface regions, the expansions must have been smaller than those in the interior concretes.

3.5. Calculation of a critical free expansive strain at the first cracking

It is difficult to calculate the maximum tensile stress induced within reactive concrete cylinders at the first cracking from the measured strains in the drying process. A simple calculation method of a critical free expansive strain for ASR surface cracking in concrete cylinders has been proposed by the second author [4]. In the simple calculation method, non-expansive near-surface layers formed in concrete cylinders in the drying process are assumed to act as restraint against uniform expansion of the interior concretes. Namely, the non-expansive cylindrical region is simplified as an elastic hollow cylinder on the inner surface of which uniform pressures corresponding to an ASR expansive pressure act. Generally, expansive pressures induced in ASR-affected concrete depend on the degree of restraint. Creep and shrinkage of concretes also influence the expansive pressure. Therefore, even in the simplified model, it is not easy to determine an expansive pressure for a free ASR expansion to be restrained. However, relations between expansive pressure and free expansion under various degrees of restraint in reactive concretes can be experimentally determined [4]. The degree of restraint is assumed to be estimated from the thickness of non-expansive layer and the modulus of elasticity of concrete.

In the model, surface cracks are assumed to form when the maximum circumferential tensile stress produced at the inner surface of a hollow concrete cylinder reaches the tensile strength of concrete. A critical free expansion for surface cracking is given as a free expansion for an expansive pressure under which the maximum circumferential stress at the inner surface equals the tensile strength of concrete [4].

In this study, measurements of strains and R.H. values at various depths indicated that most tensile strains at depths smaller than 40 mm were attributed to expansions of the interior concretes. Namely, a non-expansive layer 40 mm thick formed in the concrete cylinder (ϕ450 mm×900 mm). The compressive strength and the modulus of elasticity obtained by the use of ϕ100 mm×200 mm concrete cylinders cured in a moist atmosphere for 180 days were 32.2 MPa and 28.8 GPa, respectively. Therefore, the tensile strength of the concrete was assumed to be 3.2 MPa.

A non-expansive layer 40 mm thick in the concrete cylinder was regarded as an elastic hollow cylinder with the outer and inner radii of 225 mm and 185 mm. An equation for obtaining the maximum circumferential stress at the inner surface in the cylinder submitted to an internal pressure is found in a book of the theory of elasticity [8]. A calculation made by the use of the equation indicated that the internal pressure to be acted to produce the maximum circumferential stress of 3.2 MPa at the inner surface was 0.62 MPa. From a relation between expansive pressure and free expansion experimentally obtained [4], it was deduced that an expansive pressure of 0.62 MPa had been induced for a free expansive strain of 0.16% under the degree of restraint to be equivalent to a 40 mm thickness of hollow concrete cylinder with the modulus of elasticity of 28.8 GPa. A free expansive strain of 0.18% was obtained at the first cracking (150 days) in the concrete prism tests (Fig. 3). Thus, a calculated critical free expansion (0.16%) for the first surface cracking was considerably close to a free expansion (0.18%) obtained in concrete prism expansion tests at 150 days.

4. Conclusions

It was found from measurements of strains and R.H. values within a massive concrete cylinder with reactive aggregate that the first surface cracks and their subsequent extension were caused by greater expansions in the interior concrete than in the near-surface portions throughout the drying and re-saturating process.

The major results obtained are summarized as follows;

(1) It is conjectured that most tensile strains measured at depths smaller than 40 mm after the initiation of rapid ASR expansion were not associated with ASR in this zone, but rather attributed to the swelling of inner portions in the concrete cylinder.
(2) Cylindrical zones showing strains greater than surrounding concretes were produced in the middle areas between the center and surfaces in the concrete cylinder shortly after the beginning of the re-saturating process.
(3) Surface cracks gradually extended, branched off and widened with time in both the drying and re-saturating process leading to the formation of tortoise shell-like crack patterns. The crack patterns will extend until an equilibrium between the potential expansion of the concrete and the degree of restraint given by the near-surface non-expansive layer will be attained.
(4) The results obtained in this study suggest that intercepting water from outside is effective for controlling the growth of ASR surface cracks in concretes.

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