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# Effects of simulated environmental conditions on the internal relative humidity and relative moisture content distribution of exposed concrete

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ABSTRACT

Simultaneous measurement of the relative moisture content (RM) within concrete by the electrode method and the relative humidity (RH) within concrete using humidity sensors was conducted to elucidate the effects of cyclic daily changes in the environmental conditions (temperature and RH) and rainfall on the internal RH and RM distribution within exposed concrete.

The effects of the presence of cracking in concrete were also experimentally investigated in comparison with uncracked concrete. As a result, the changes of the internal RH and RM distribution within concrete due to external temperature/RH changes were found to occur only in the surface region of concrete, while moisture was found to decrease extremely slowly deeper inward. As for the effect of cracking on the RM distribution within concrete, a larger crack width tended to lead to a slightly higher drying rate. In regard to the effect of rainfall, the duration of rainfall and whether or not the concrete is directly exposed to rainwater were found to be more important than the amount of rainfall.



## 1. Introduction

Amid the current trend of durability design toward a shift from the prescriptive design to performance-based design of concrete structures, quantitative grasping and detailed modeling of their deterioration mechanisms are demanded [1]. It is essential to accurately predict the moisture condition in concrete in response to the environmental conditions for ensuring the durability design of concrete structures. This is because their deterioration phenomena, such as carbonation, chloride or sulfate attack, freezing and thawing, and alkali–silica reaction, are mostly caused by the mass transfer phenomenon mediated by moisture [2,3], and moisture condition significantly affects the rates of transfer and reaction of deteriorative factors [4].

In other words, for quantitative prediction of deterioration phenomena of concrete structures, the environmental conditions to which a concrete structure is to be exposed should be grasped in relation to the moisture transfer properties within concrete.

However, the surface tension, density, and viscosity of moisture that affect the physical properties of porous materials depend on the temperature [5], and their interaction directly affects the moisture transfer within concrete. Also, hysteresis due to inkbottle pores and partial saturation during wetting make the moisture transfer phenomenon in concrete extremely complicated, hampering accurate prediction.

Past studies on moisture transfer have tended to concentrate on drying shrinkage, because the moisture condition in concrete significantly affects the mechanical behavior of concrete, such as the elastic modulus, creep, and drying shrinkage [6–8]. Also, the diffusion coefficient of moisture in concrete depends on the state of existence of moisture in concrete, increasing as the moisture content increases and as the relative humidity increases as theoretically and experimentally proven [9–11].

There have been studies to elucidate the behavior of moisture in concrete by adopting physical adsorption theory and condensation theory. These studies have been comparatively analyzed by experiments using water vapor desorption and adsorption isotherms for various concrete [12–15].

However, the actual environmental conditions to which a concrete structure is exposed involve not only drying but also cyclic changes in temperature and humidity, causing repeated drying and wetting stages (water vapor desorption and adsorption). Moreover, direct penetration of rainwater in the form of liquid water during rainfall causes larger changes in the moisture content of concrete than drying and adsorption. Also, the coexistence of moisture transfer and heat transfer in actual concrete structures

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requires consideration of the effect of temperature on the moisture transfer, but few studies have examined moisture transfer under a temperature gradient. Such phenomenological models and theoretical studies on a macroscopic scale have been widely adopted for studies on the heat and moisture transfer in porous materials, which have been actively developed since the 1950s, in the field of soil science, rather than concrete engineering [16–20].

As stated above, it is essential to grasp the presence and fluctuation condition of moisture in concrete in use, in order to establish a quantitative prediction technique for a deterioration phenomenon and a durability design technique for reinforced concrete structures. Previous comprehensive studies on the moisture behavior of concrete under periodical changes in temperature and humidity and during rainfall are represented by those conducted by Andrade et al. [21].

Andrade investigated the effects of changes in the temperature and humidity, as well as rainfall, in actual environments on concrete and pointed out that irregular fluctuations of temperature in a natural environment prevents the vapor pressure in concrete from reaching equilibrium. Also, they pointed out the fact that the inside of concrete (with a w/c of 0.6 or less) is unsaturated even after immersion for a long time is highly relevant to the penetration of deteriorative factors [22,23].

Meanwhile, it has been pointed out that cracking mars the durability of concrete, because it facilitates the penetration of deteriorative factors into concrete [24], but the problem of cracking and durability (reinforcement corrosion primarily due to carbonation and chloride attack) is controversial. Some say there is a correlation between crack width and reinforcement corrosion in concrete [25], while others say the relationship is unclear [26].

Also, most studies on mass transfer in concrete assess its effect by air permeability testing or water permeability testing, scarcely relating it to moisture transfer through cracked regions. However, the mechanism of moisture transfer during air and water permeability tests conducted under high pressure is totally different from that of moisture transfer in actual environments driven by vapor pressure and capillary tension. It is also difficult to estimate the moisture distribution condition in cracked concrete from air and water permeability measurements.

While the state of moisture present in concrete fluctuates both annually (by seasons) and in the short terms (daily), short-term fluctuations are more important when considering deterioration factors associated with moisture transfer.

Accordingly, moisture content measurement by the electrode method and relative humidity (RH) measurement using humidity sensors were conducted in this study to elucidate the effects of cyclic daily fluctuations in the environmental conditions and rainfall on the RH and moisture content distribution in concrete. The effect of the presence of cracking on the moisture content distribution in concrete was also experimentally investigated.

In this study, the ratio of the actual moisture content to the saturated moisture content in a specimen is defined as a "relative moisture content (RM)" to be used as an index for comparison, since the moisture content in a saturated condition varies from one specimen to another.

## 2. Outline of experiment and measurement methods

### 2.1. Outline of experiment

As shown in Figs. 1 and 2, specimens consisted of prisms 300 × 300 × 100 mm in size. Two water–cement ratios were investigated; 0.3 and 0.6. Two types of specimens, with and without a bending crack, were prepared. The mass changes and moisture content in the drying process were determined from the mass

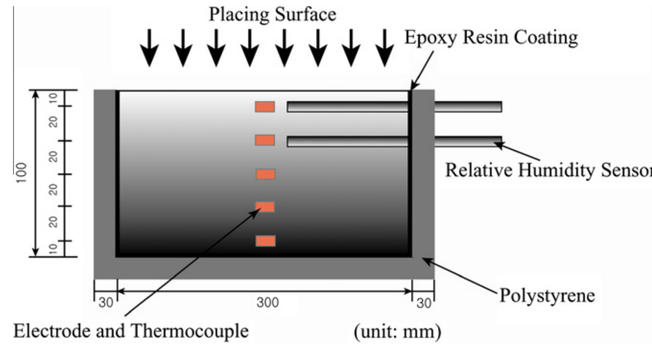


**Fig. 1.** Shape and dimensions of specimens.

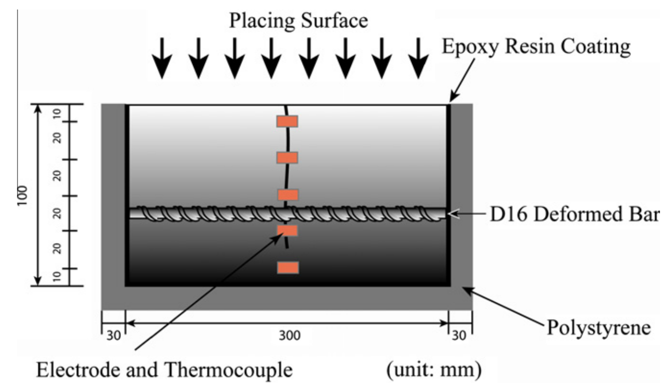


**Fig. 2.** Shape and dimensions of specimens with a bending crack.

differences using cylindrical specimens 100 mm in diameter and 100 mm in height. As for the measuring points, electrodes and thermocouples were embedded at depths of 10, 30, 50, 70 and 90 mm from the drying (open) surface, whereas humidity sensors were embedded at depths of 10 and 30 mm. The RH measurement was conducted only on uncracked specimens.

As to the curing method, specimens were demolded at an age of one day and water-cured at 60 °C until an age of 30 days to prevent moisture loss and changes in the pore structure due to hydration during the measuring periods. Specimens were then allowed to naturally cool in water for 10 days until their internal temperature reached equilibrium (at 20 °C) without a thermal shock. The four sides and the bottom of each specimen were coated with epoxy and insulated with foamed polystyrene to reduce heat and moisture transfer through surfaces other than the open top 300 × 300 mm in size. Assuming that the moisture transfer occurs in an unsaturated condition in actual structures, specimens were then dried for 45 days in a thermo-hygrostatic room at 20 ± 1 °C and 60 ± 1% RH, as a pretreatment before testing.

On the other hand, specimens having a crack were fabricated by placing a D16 deformed bar at a depth of 50–70 mm from the open surface, water-curing at 60 °C, and then drying for 5 days in a dryer at 40 °C. These were loaded as shown in Fig. 3 to induce a non-through bending crack in the center where electrodes were located. In this process, loading was terminated when the average crack width reached 0.1 or 0.3 mm by $\pi$ displacement gauges. The bending crack width was controlled by inserting stainless steel shims having the same thickness as the crack at both ends of the crack.

However, there was a limit to the control of the crack width only from both ends after unloading, because of the long distance between ends across the open surface. Table 1 gives the ultimate width and depth of surface cracks. The average crack width and

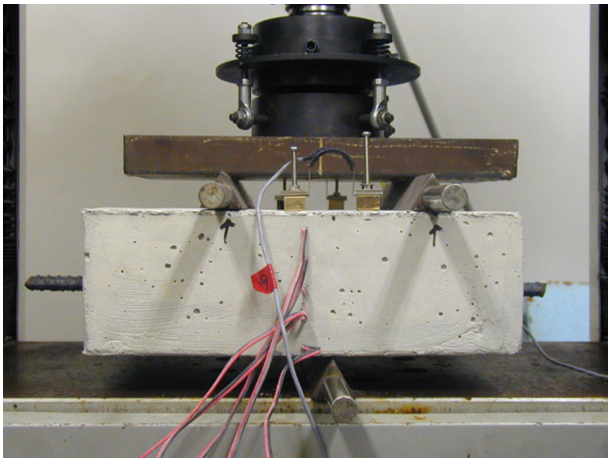

**Fig. 3.** Inducing a bending crack in specimen by three-point flexural loading.

**Table 1**
Average crack width and depth of bending crack specimens (in mm).

| W/C | Average crack width | Maximum crack width | Average crack depth |
|---|---|---|---|
| 0.3 | 0.11 | 0.15 | 59 |
| | 0.22 | 0.30 | 84 |
| 0.6 | 0.10 | 0.15 | 58 |
| | 0.18 | 0.25 | 86 |

**Table 2**
Types of specimens.

| Factors | Levels |
|---|---|
| W/C | 0.3, 0.6 |
| Crack type | Crackless specimens |
| | Crack specimens (width: ∼0.1 mm, ∼0.2 mm) |
| Measurement items | Temperature, relative humidity, relative moisture content |

**Table 3**
Materials of concrete.

| | |
|---|---|
| Cement | Normal portland cement (density 3.16 g/cm$^3$) |
| Aggregate | Crushed hard sandstone from Ohme (density 2.65 g/cm$^3$) |
| Fine aggregate | Land sand from Ohi river (density 2.59 g/cm$^3$) |
| Chemical admixture | Air-entraining and water-reducing admixture |

depth were calculated from the images captured by a digital camera using image processing software. The average crack width was determined from 10 equally spaced points on the cracked surface, whereas the average crack depth was the average of the crack depths measured at both ends.

Note that the cracked specimens were re-immersed in water for 10 days to examine their changes in moisture conditions during drying from the saturated condition similar to uncracked specimens.

Table 2 gives the factors and levels of the experiment. Tables 3 and 4 give the materials and mixture proportions of concrete, respectively. Also, the order of tests to evaluate the effects of environmental factors is shown in Fig. 4.

### *2.2. Measurement methods*

Humidity sensors 6 mm in diameter were embedded in specimens to directly measure the internal RH in concrete, as well as thermocouples and electrodes for measuring the moisture content to continuously monitor the temperature and interelectrode resistance in concrete using a data logger and LCR meter.

#### *2.2.1. Method of measuring internal RH*

Because it was difficult to measure the RH in the high moisture content ranges by the methods using humidity sensors, small humidity sensors 6 mm in diameter were waterproofed using a moisture permeable sheet to enable measurement in high moisture content ranges. Humidity sensors as shown in Fig. 5 were treated as follows: Insert the sensor in an acrylic pipe (8 mm external, 6 mm internal diameter), seal the clearance between the sensor and the pipe by inserting O rings to prevent humid air from leaking in and out through the clearance. Waterproof the tip of the pipe with a permeable sheet to prevent penetration of liquid water.

Preliminary tests revealed that the electronic circuit card deteriorated under high humidity (99.9% RH) sustained during long-term measurement in high moisture content ranges. For this reason, the card area excepting the humidity sensing probe was coated with nail polish to protect the card from being damaged by the high humidity. The relative moisture measurement range of the humidity sensors (Model TRH-7X: Shinyei Technology Co., Japan) used in this study is 10–95% RH, with the measurement accuracy being ±1.5 percentage points (in the ranges of 15–35 °C and 30–90% RH).

#### *2.2.2. Estimation of relative moisture content (RM)*

In this study, a method of measuring the moisture content of hardened concrete using electrodes proposed by Ichise et al. [28] was selected from among the methods proposed in a number of studies including those by Spencer [27].

The electrode bar comprised two SUS304 stainless steel bars 1.5 mm in diameter and 80 mm in length, with the distance between the bars being 8.3 mm as shown in Fig. 6. An impressed voltage of AC 1 V with a frequency of 1 kHz was selected to prevent polarization [29], and the interelectrode resistance was measured using LCR meters.

Calibration tests to estimate the RM were conducted using small specimens 40 × 40 × 160 mm in size made beforehand from similarly proportioned concretes. The target relative moisture content was set at six levels: 100%, 85%, 70%, 55%, 40%, and 25%. When the specified target level was attained, the specimens were immediately wrapped with aluminum tape, sealed with epoxy, and left to stand in a thermo-hygrostatic room at 20 ± 1 °C and 60 ± 1% RH for one month until the internal moisture reached equilibrium. Calibration tests were then conducted for different temperatures. In this study, the RM was calculated as follows:

**Table 4**
Mix proportions of concrete.

| W/C | Water (kg/m$^3$) | Cement (kg/m$^3$) | Fine agg. (kg/m$^3$) | Coarse agg. (kg/m$^3$) | S/A* (%) | Slump (cm) | Air (%) | AE water reducer (C × %) |
|---|---|---|---|---|---|---|---|---|
| 0.3 | 170 | 567 | 769 | 855 | 48 | 21.0 | 3.2 | 0.75 |
| 0.6 | 170 | 283 | 825 | 1035 | 45 | 14.5 | 3.7 | 0.5 |

* S/A = sand/coarse aggregate ratio.

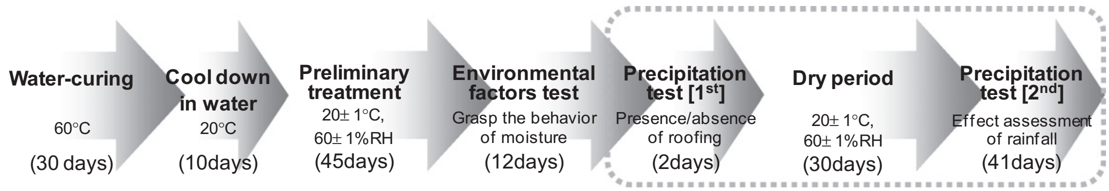


**Fig. 4.** Outline of environmental impact assessment tests.

**Fig. 5.** Treatment of relative humidity sensors.

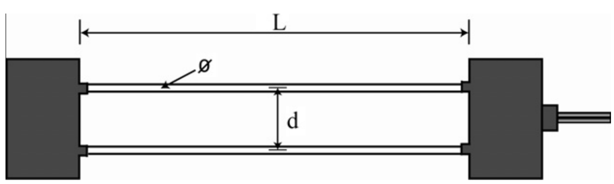


**Fig. 6.** Shape of electrode bars.

$$\mathrm{RM}(\%) = \frac{W - W_{\mathrm{dry}}}{W_{\mathrm{sat}} - W_{\mathrm{dry}}} \times 100 \quad (1)$$

where RM is the relative moisture content of specimen, $W$ the air-dry mass of specimen (g), $W_{\mathrm{dry}}$ the oven-dry mass of specimen (g), and $W_{\mathrm{sat}}$ the saturated mass of specimen (g).

Fig. 7 shows the relationship between the RM and interelectrode resistance at different temperatures. Based on these relationships, the measured interelectrode resistance at the electrodes was converted to relative moisture content for evaluation.

*2.2.3. Simulated environmental conditions*

Meteorological conditions in Tokyo in the summertime were simulated (21.9–28.3 °C, 57–89.7% RH) as shown in Fig. 8 referring to the statistics of the Japan Meteorological Agency over the past 30 years [30]. In view of the statistics, the temperature and RH at around 1:00 p.m. when the daytime temperature peaks were set at 28.3 °C and 57% RH, whereas those at 4:00 to 5:00 a.m. when the temperature bottoms out were set at 21.9 °C and 89.7% RH One cycle was therefore 24 h similarly to the meteorological conditions of the atmosphere. The simulated rainfall conditions were created using an environment simulating apparatus shown in Fig. 9 with a temperature of 20 °C and rainfall of 30.1 mm/h for 24 h.

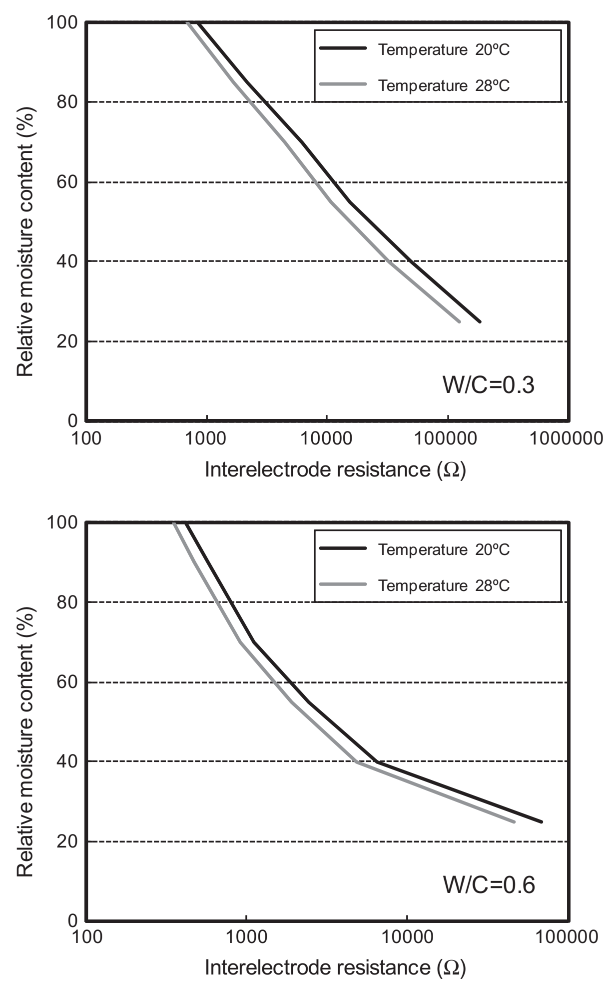


**Fig. 7.** Calibration curves.

## 3. Results and discussion

*3.1. Changes in the RM profile in concrete during drying*

Fig. 10 shows the changes in the RM profile in concrete specimens dried from the saturated state in a thermo-hygrostatic room at 20 ± 1 °C and 60 ± 1% RH over 45 days. When saturated concrete is subjected to drying, moisture in concrete evaporates through the concrete surfaces.

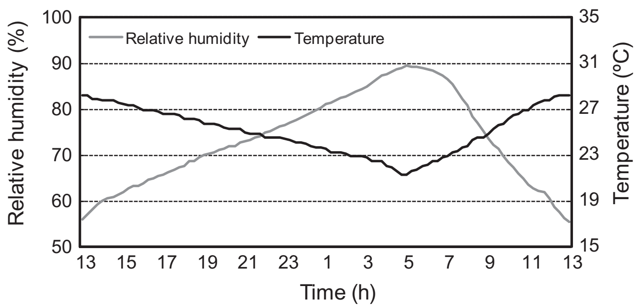


**Fig. 8.** Simulated environmental conditions.

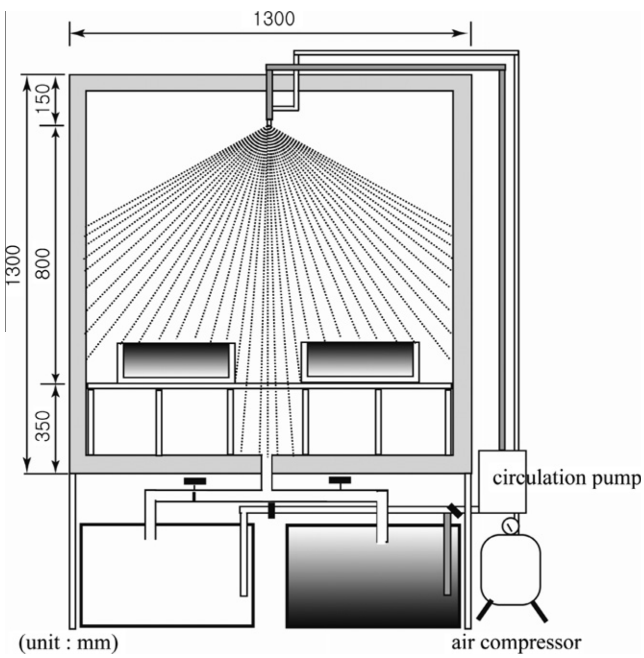


**Fig. 9.** Precipitation simulator.

From a thermodynamic aspect, an unstable liquid phase tends to change to the gas phase when the RH of the atmosphere is less than 100%. Such evaporation is therefore a phenomenon in which the liquid phase spontaneously vaporizes from its surface [31]. The amount of such evaporation progressively decreases as the rate of moisture supply from the inside decreases depending on the given environmental conditions, while drying proceeds in the surface region of concrete. This means that the area of gas–liquid phase change gradually recedes inward as the evaporation proceeds, and the transfer of liquid water, which is predominant at early stages of drying, is predominated by vapor migration in the unsaturated region where capillary water becomes discontinuous [11,32]. The rate of such moisture supply (or the rate of evaporation) is considered to be significantly affected by the capillary pore structure, which is the path of moisture transfer, and the continuity of capillary pores [33,34].

This concept is illustrated by Figs. 10 and 11. As shown in Fig. 10, the RM tended to more rapidly decrease, as soon as drying began, at points nearer to the surface, regardless of the specimen type [35]. Also, the reductions in the RM of all specimens were significant at early stages of drying and tended to converge to specific values thereafter. Similar tendencies are observed in the relationship between the drying period and the amount of moisture evaporation shown in Fig. 11. In consideration of the fact that the diffusion coefficient of moisture depends on the moisture content, the obtained results agree with the test results by Sakata [10], in which the moisture diffusion coefficient of concrete with a w/c of 0.6 significantly decreases when the moisture content decreases to below 80 to 70%.

Before the beginning of drying, the RM of an uncracked specimen with w/c of 0.6 was 100% at all depths excepting 90 mm, whereas with a w/c of 0.3, the RM did not reach 100% at any of the depths. This is presumably due to a phenomenon in which the curing water permeates only to the surface regions despite water-curing, leaving the concrete deeper inward in a state of self-desiccation due to hydration [36,37]. Also, the reduction in the RM due to drying tended to be smaller in specimens with a w/c of 0.3 than in specimens with a w/c of 0.6. This is presumably because the amount of free water (amount of evaporable water) was smaller and because the dense microstructure inhibited the escape of moisture [13].

As for specimens with a crack, the reductions in the RM in specimens with a w/c of 0.3 tended to be greater with a larger crack width and nearer to the surface, because the crack faces served as new paths for moisture transfer, readily releasing moisture into the atmosphere. With a w/c of 0.6, however, the effect of cracking on the reductions in the RM due to drying was not as significant as that in specimens with a w/c of 0.3, though the reductions tended to be slightly quicker at points nearer to the surface. This can be attributed to the rapid escape of moisture from the surface, as moisture transferred not only through the crack faces but also through percolated capillary pores under the dry environment.

When comparing the RM of specimens with a w/c of 0.6 at the same depths, the changes in the RM over time in specimens with a crack width of 0.2 mm were similar to those of uncracked specimens. However, the RM of specimens with a crack width of 0.1 mm was higher at depths of 50–70 mm. When cracked specimens were re-immersed in water to be saturated similarly to uncracked specimens, it is inferred that moisture permeated deeper into cracked specimens than uncracked specimens regardless of the crack width, but that its transfer outward was slower in specimens with a crack width of 0.1 mm than in specimens with a crack width of 0.2 mm. This is presumably the cause of the higher RM at depths of 50–70 mm.

Accordingly, though the specimens with 0.2 mm cracking showed behavior similar to that of uncracked specimens, their drying was actually quicker than uncracked specimens, as they had more water to lose.

It is likely that specimens having a higher w/c and wider cracking are more prone to such a phenomenon.

### 3.2. Effects on environmental factors on the internal RH and RM distribution in concrete

Figs. 12–17 show the changes in the internal RH and RM distribution in concrete over time under the following three sets of conditions: (1) constant temperature and changing RH (20 °C and 57–89.7% RH); (2) constant RH and changing temperature (60% RH and 21.9–28.3 °C); and (3) changing temperature and RH.

Generally speaking, the moisture state within concrete exposed to a natural environment becomes unstable (in a non-equilibrium condition) following the changes in the atmospheric conditions, while continuously changing at the meniscus-forming point to reach a local equilibrium with the in situ vapor pressure. However, equilibrium is never reached as long as the external temperature keeps changing.

In other words, at concrete surfaces in contact with the atmosphere, moisture exchange with the external environment by diffusion (adsorption/desorption ↔ condensation/evaporation) occurs

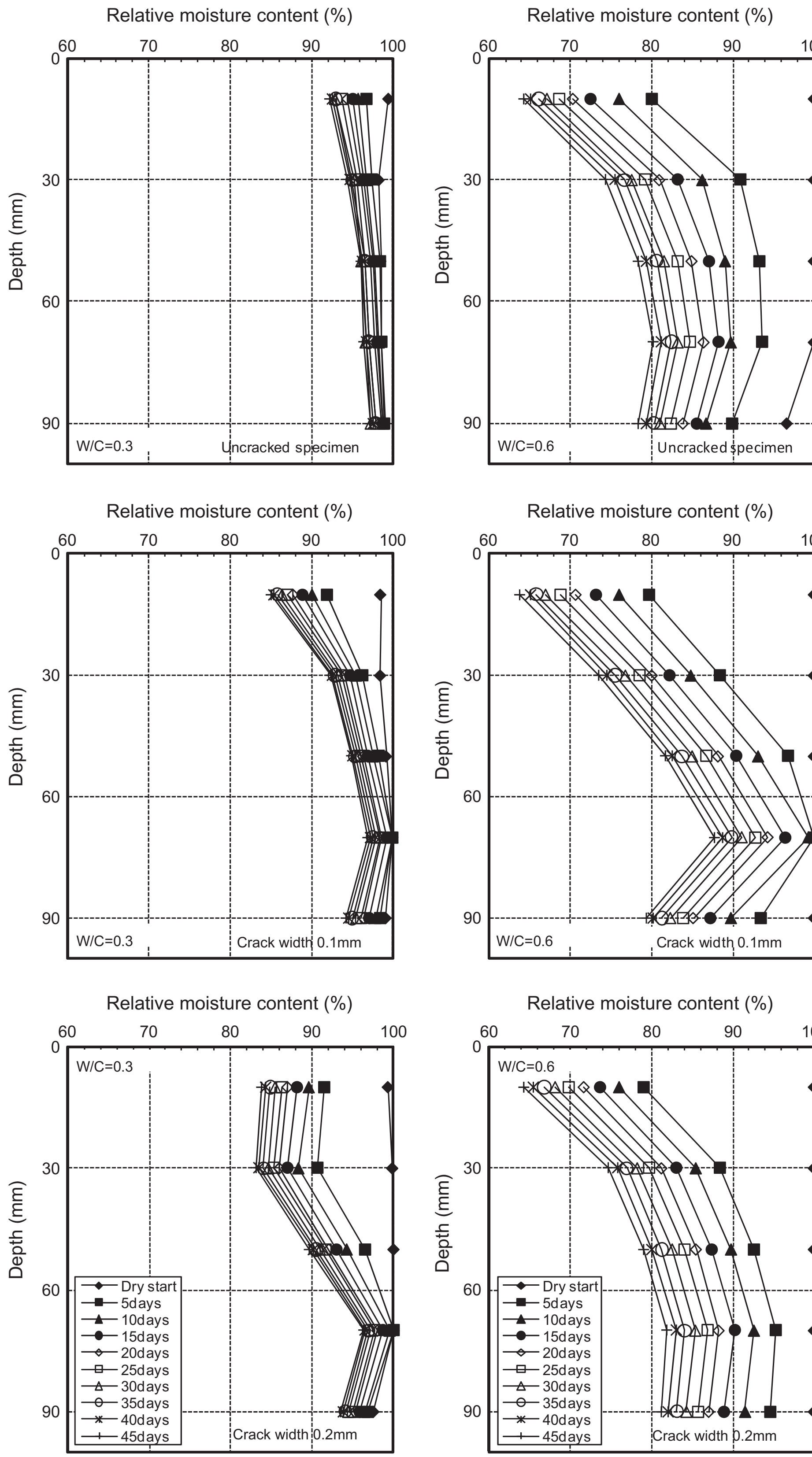


**Fig. 10.** Time-related changes in the RM profile in concretes under drying.

[5,21]. The resulting moisture content and temperature gradients work as driving forces that cause the transfer of water vapor and liquid water. A porous medium such as concrete has hydrophilic surfaces with a large specific surface area. For this reason, the physical adsorption/desorption of moisture on the surfaces has a decisive effect on the moisture transfer in concrete, such as a predominant part of evaporable moisture being present in the form of an adsorbed water film on solid surfaces [38,39].

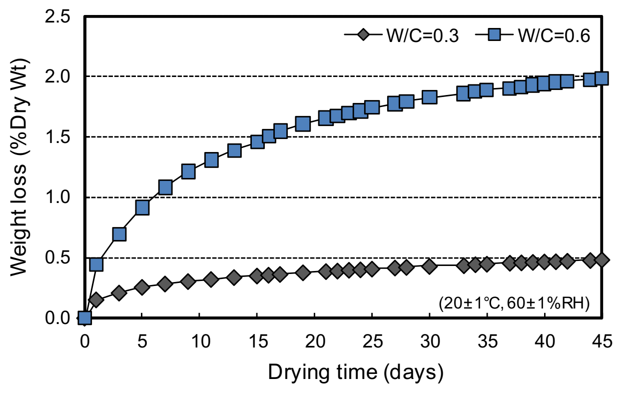


**Fig. 11.** Changes in mass during the drying period.

Fig. 12 shows the changes in the internal RH and RM distribution in concrete over time with cyclic changes in the RH while the temperature was kept constant. Figs. 12 and 15 reveal a phenomenon in which the internal RH and RM slightly increased only in the range of 10 mm from the surfaces in all specimens. Whereas the changes in the RM distribution of specimens with a crack width of 0.1 mm were nearly the same as those of uncracked specimens, those of specimens with a crack width of 0.2 mm were marginal.

Note that the internal RH within concrete with a w/c of 0.6 tended to follow the changes in the cyclic changes in the external RH with a certain lag of approximately 5–6 h, in contrast to those in concrete with a w/c of 0.3. This is presumably because the moisture adsorption/desorption of concrete with a w/c of 0.6 is faster than that of concrete with a w/c of 0.3, since the time-dependent rate of moisture adsorption/desorption is higher in concrete with a higher w/c, which has a more open pore structure [40,41]. Also, the increase in the internal RH and RM can be attributed to the amount of adsorption being greater than the amount of desorption in the medium- to high humidity region simulated in this study, which resulted in accumulation of moisture through the hysteretic repetition of drying and wetting [42].

In regard to changes in the RM (internal RH) distribution within concrete when the temperature of the environment cyclically changes as shown in Figs. 13 and 16, a decreasing tendency of the RM (internal RH) in the surface region is evident when compared with the case where only the RH of the environment cyclically changes. Temperature is a factor that has the strongest

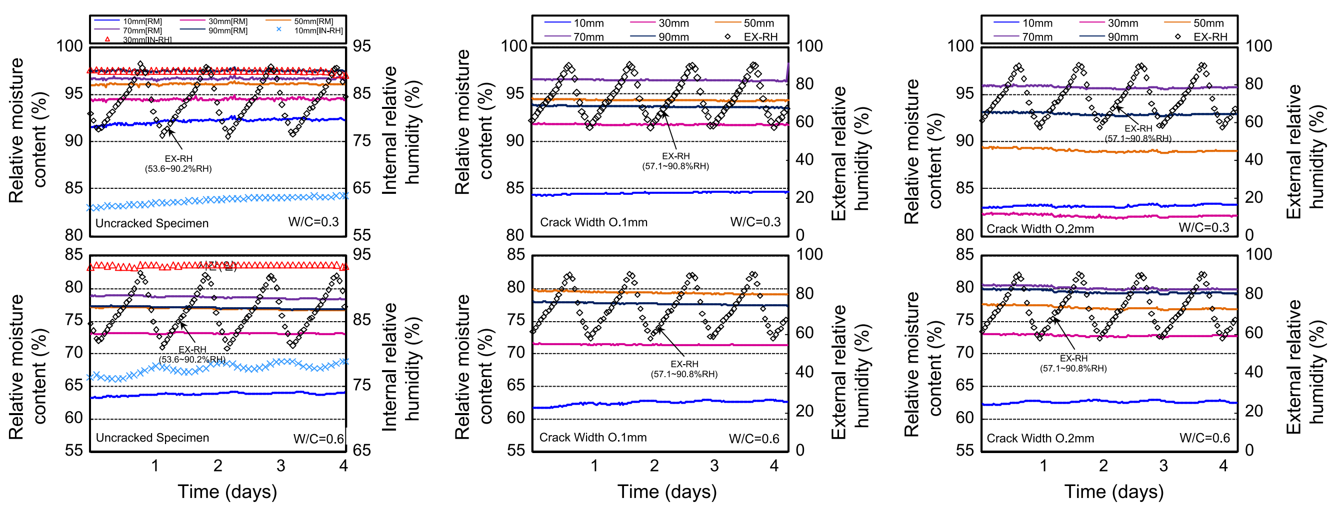


**Fig. 12.** Time-related changes in the internal RH and RM distribution in concretes under cyclic humidity changes.

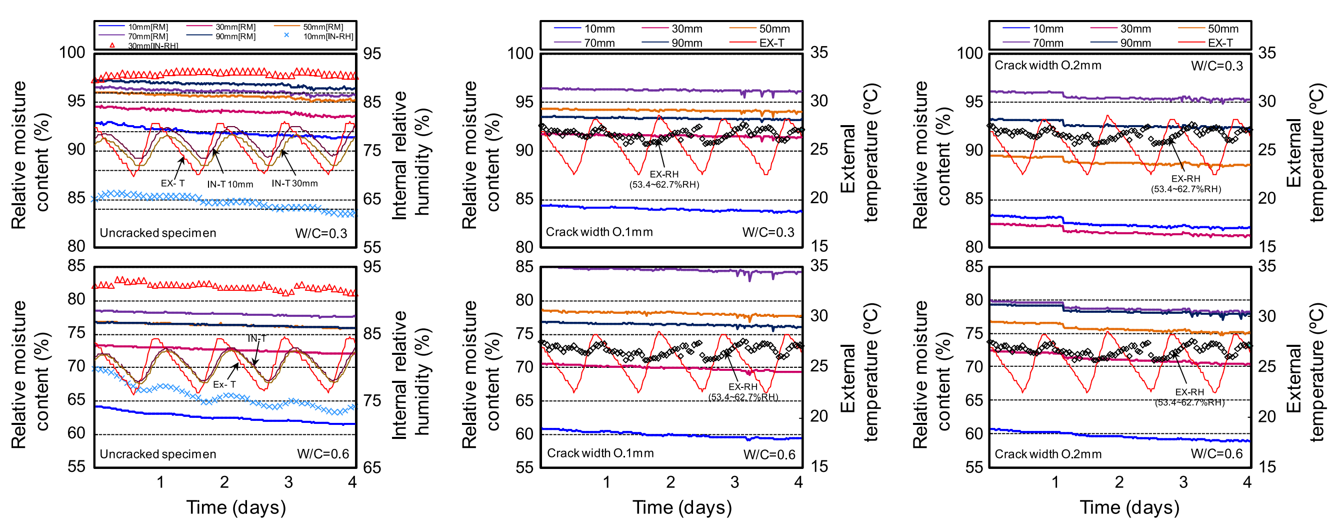


**Fig. 13.** Time-related changes in the internal RH and RM distribution in concretes under cyclic temperature changes.

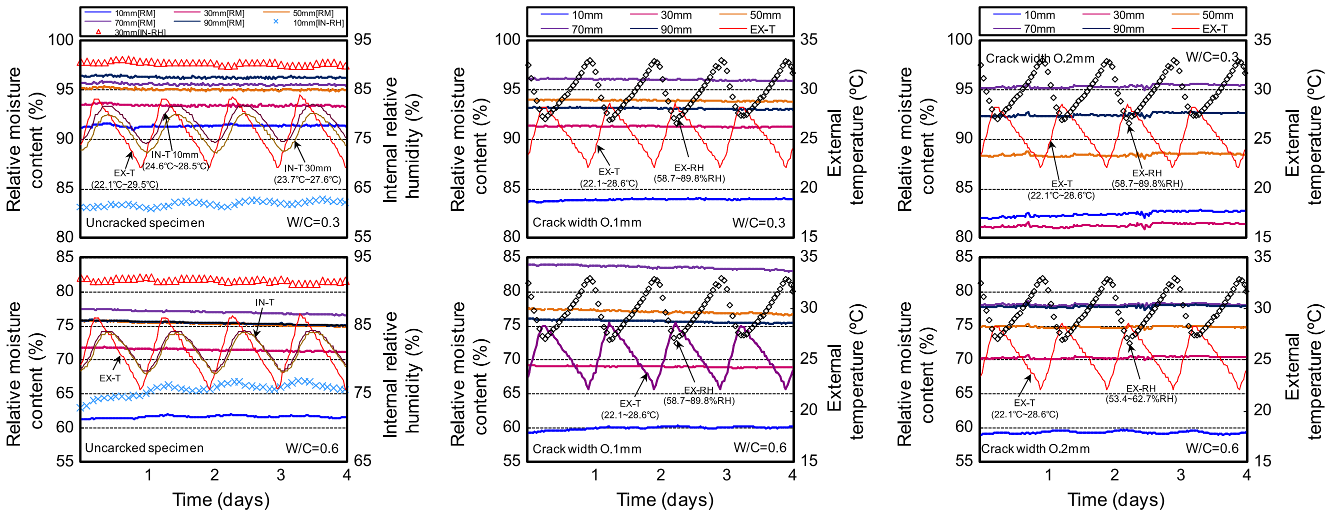

**Fig. 14.** Time-related changes in the internal RH and RM distribution in concretes under cyclic temperature–humidity changes.

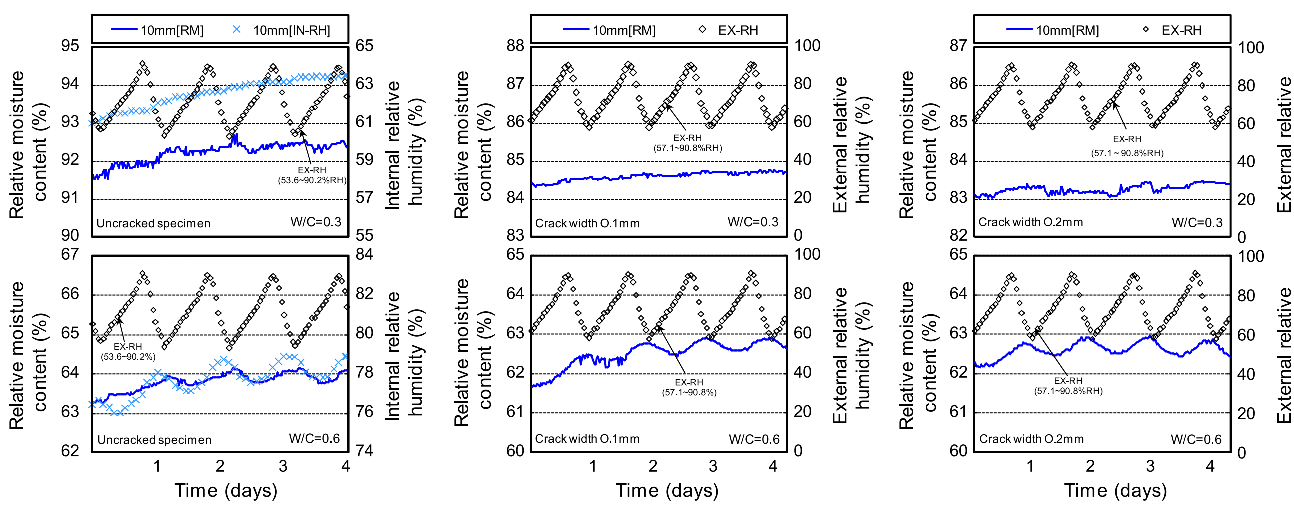

**Fig. 15.** Changes in the internal RH and RM over time at a depth of 10 mm in concrete under cyclic RH changes.

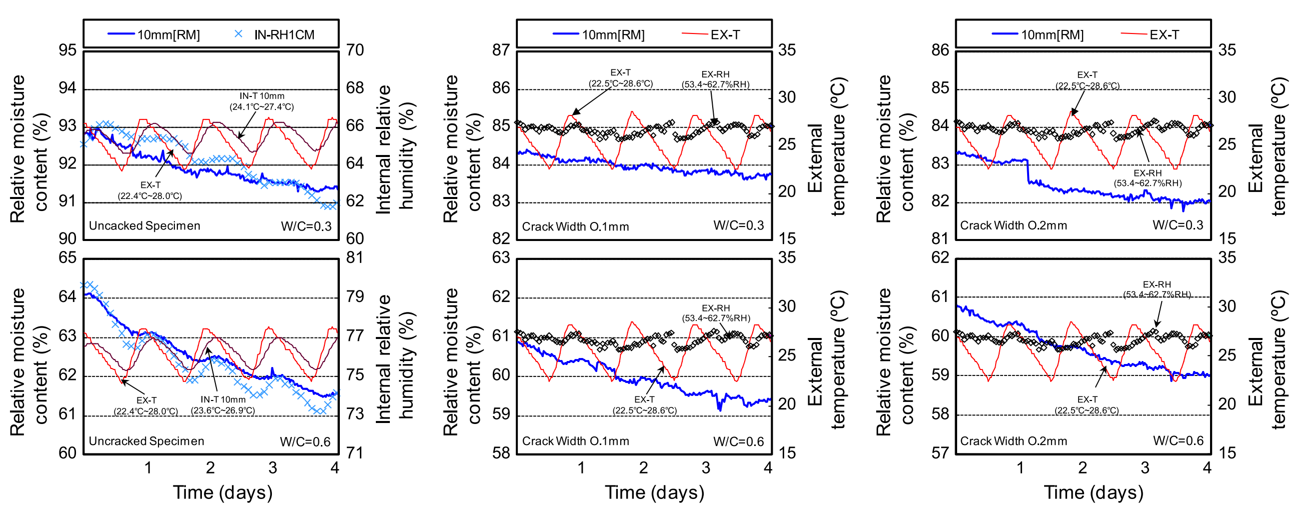

**Fig. 16.** Changes in the internal RH and RM distribution over time at a depth of 10 mm in concrete under cyclic temperature changes.

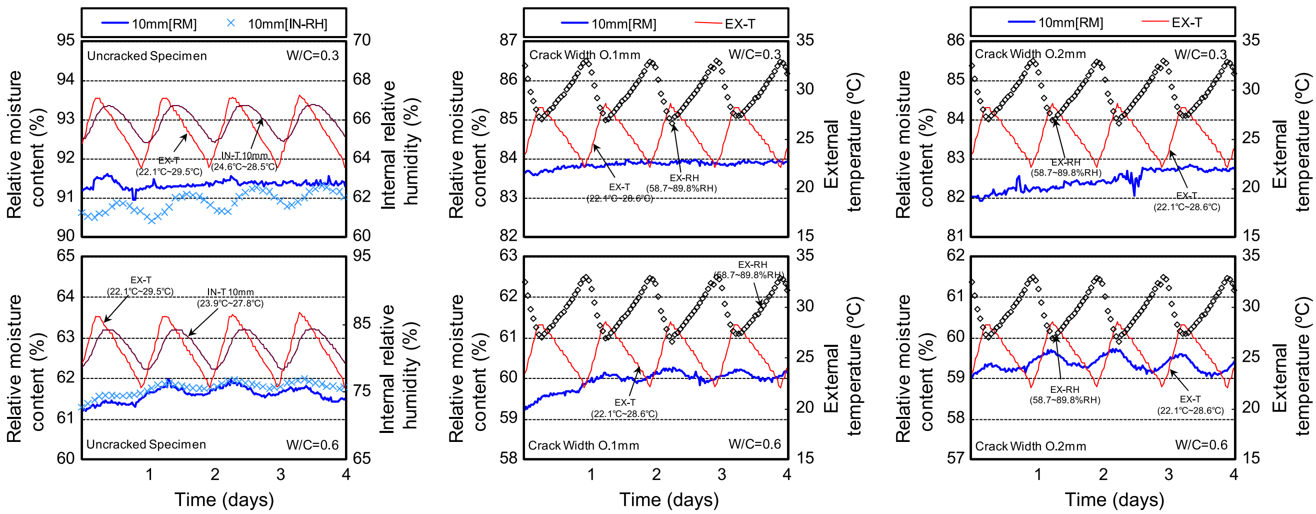


**Fig. 17.** Changes in the internal RH and RM distribution over time at a depth of 10 mm in concrete under cyclic temperature–humidity changes.

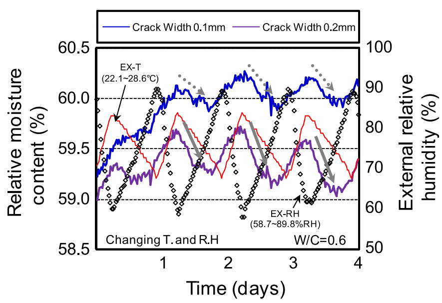


**Fig. 18.** Effect of cracking on RM behavior (at a depth of 10 mm).

direct impact on the moisture behavior in a porous medium. In other words, the viscosity, density, and surface tension of liquid water decrease and the saturated vapor pressure increases as the temperature increases [43,44]. Therefore, in consideration of the fact that the surface adsorption and capillary condensation of moisture result from surface tension, it is inferred that the increases in the amount of moisture escape were caused by the changes in the surface tension of moisture within concrete and the reductions in the external RH under high temperature conditions.

Such a phenomenon is explained by water vapor adsorption/desorption isotherm curves in the literature [18], though the retained moisture content in the drying process differs from that in the wetting process (the moisture content in a drying process always exceeds that in a wetting process). In regard to the behavior of liquid water during the drying process, an increase in the temperature under the same humidity condition increases the escape of moisture confined by the inkbottle effect [44,45], causing a rapid reduction in the degree of saturation (RM). In other words, an increase in the temperature under the same RH condition means a reduction in the Kelvin's radius in which capillary condensation can occur, requiring a higher RH to keep the same degree of saturation.

Figs. 14 and 17 show the changes in the internal RH and RM distribution in concrete over time when both the external temperature and RH change. Slight increases in the internal RH and RM are observed only to a depth of 10 mm from the surfaces in all specimens, similar to the case where only the RH in the environment changes. Fig. 18 shows typical changes in the RM of cracked specimens with a w/c of 0.6 at a depth of 10 mm from the surface under changing external temperature and RH conditions shown in Fig. 17. This figure reveals that the drying rate of the specimen with a crack width of 0.2 mm (indicated by solid arrows) is higher than that of the specimen with a crack width of 0.1 mm (indicated by dotted arrows).

As stated above, the effects of external temperature and RH on the internal RH and RM distribution in concrete were investigated for each factor. As a result, the moisture of uncracked specimens was found to change only in the surface regions, while the moisture deeper inward decreased extremely slowly. In regard to the effect of cracking, wider cracks were found to tend to slightly increase the drying rate.

### 3.3. Changes in the RM distribution in concrete over time due to rainfall

As to the effect of rainfall, the duration and direct exposure are important factors [21]. Water sorption occurs in concrete segments that come into direct contact with rainwater, whereas moisture sorption occurs in segments under cover not in direct contact with rainwater.

Figs. 19 and 20 show such time-related changes in the RM in concrete during and before/after rainfall, respectively.

Without cracking, the effect of the presence of roofing was smaller in concrete with a w/c of 0.3 than in concrete with a w/c of 0.6 as shown in Fig. 19a and d, but the RM tended to increase in the surface region when exposed to rainwater, regardless of w/c. In concrete having a dense microstructure with a w/c of 0.3, the RM slowly increased in the surface region only to a depth of 10 mm from the surface, whereas the RM tended to increase over time to a depth of 30 mm in concrete with a w/c of 0.6, with particularly rapid increases in the range to a depth of 10 mm from the surface. This is presumably because the amount of water absorbed by capillary tension was overwhelmingly greater than the amount of adsorbed water vapor. Also, the RH in the surface region reached 100%, but the RM did not reach 100% at least by the rainfall for 24 h (no roofing, w/c 0.6) as shown in Fig. 20.

Such a phenomenon may have resulted from the differences between the moisture supply rate and concrete's absorption rate, as well as the time dependence of moisture conductivity (absorption rate) in the process of concrete sorption. In other words, because of the upper limit of the sorption rate due to the formation of a film of water on the concrete surfaces by surface tension [46], the water supply rate exceeds the sorption rate in most cases, excepting very

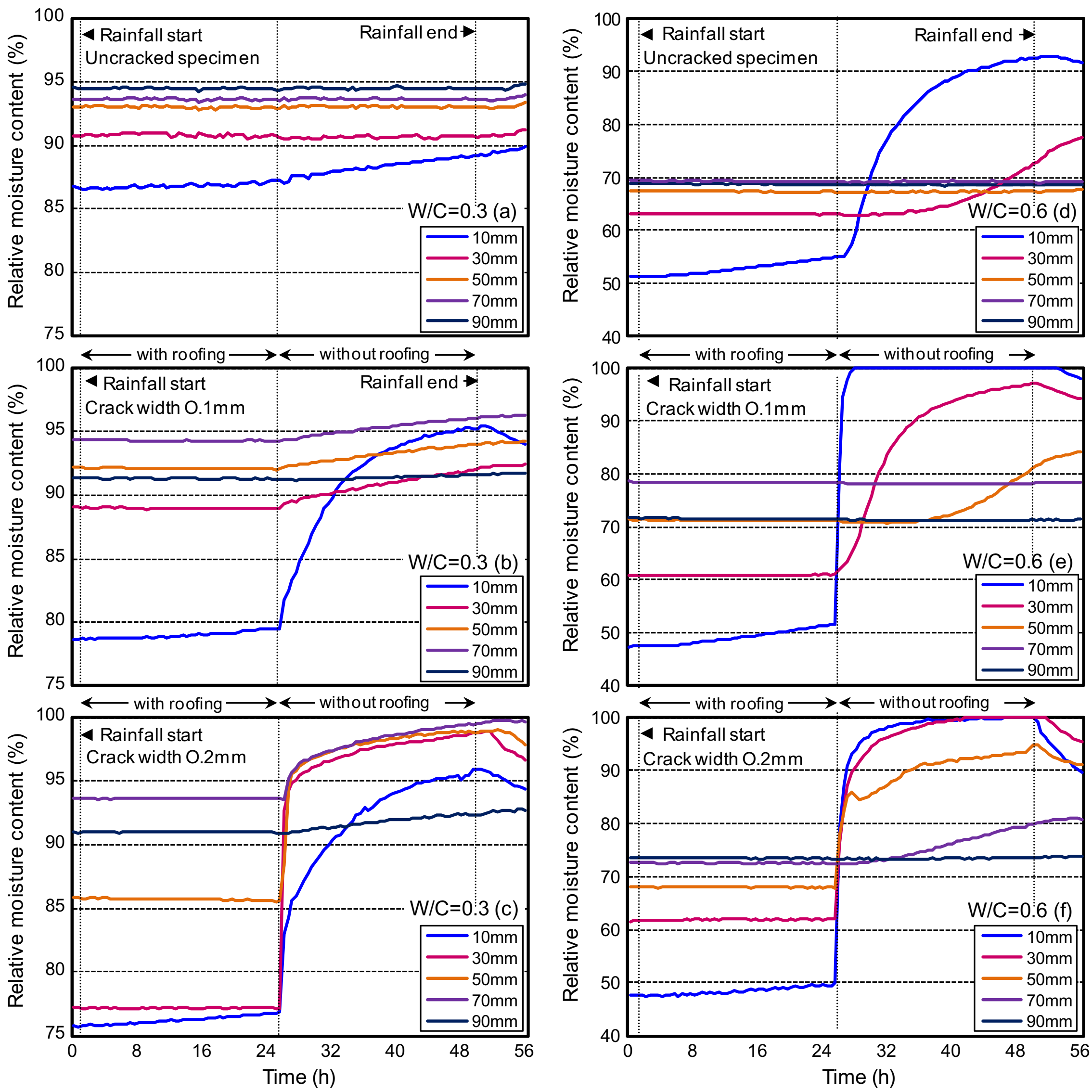


**Fig. 19.** Time-related changes in the RM of concrete under different exposure conditions during the raining period.

light rain. Also, the distance from the sorption surface to the meniscus increases over time, increasing the resultant forces of the frictional resistance of capillary tube walls, thereby reducing the moisture conductivity over time [47].

It can therefore be said that the effect of the duration of rainfall is more important than the amount of rainfall as the impact of rainfall on the moisture state within concrete, and that the sorption rate is high in the beginning but decreases over time.

On the other hand, cracked specimens were strongly affected by rainfall. The water permeation rate increased as the crack width increased, with rainwater reaching deep into concrete with relative ease regardless of w/c.

When the crack width was 0.1 mm, the surface region of concrete with w/c 0.6 was quickly saturated (100% relative moisture content), and the RM of the deeper region progressively tended to increase over time as shown in Figs. 19e and 20e. With w/c 0.3, however, the surface region did not reach a saturated state, while the increase in the RM in the deeper region almost simultaneously began as shown in Figs. 19b and 20b. This is presumably because, in the case of 0.6 w/c having highly continuous capillary voids, rainwater entering the crack was absorbed through the crack faces while migrating inward, whereas in the case of 0.3 w/c having a dense microstructure, rainwater was scarcely absorbed through the crack faces but permeated deeper at a higher rate. These results have also been reported by Roels et al. [48]. According to X-ray photography by Roels et al., the capillary rise of moisture in a crack occurs while saturating the surrounding matrix (Strictly speaking, moisture re-rises after saturating the matrix. The part filled with water in the crack becomes a new moisture source for the matrix.); The rate of capillary rise decreases as the water absorption coefficient of the matrix increases; also, the rise of moisture in a crack grows stagnant as the crack width decreases, since the amount of moisture absorption by the matrix through the crack faces exceeds the amount of liquid water inflow into the crack.

Specimens with a crack width of 0.2 mm showed tendencies similar to those with a crack width of 0.1 mm excepting the higher rate of moisture permeation as shown in Fig. 19c and f.

Fig. 20 shows the effect of rainfall for 24 h on the internal RH and RM distribution in concrete under environmental conditions in the summertime.

The reductions in the RM of the surface regions of specimens with no crack after rainfall were slow with a w/c of 0.3, but the reductions began immediately after the end of rainfall and were

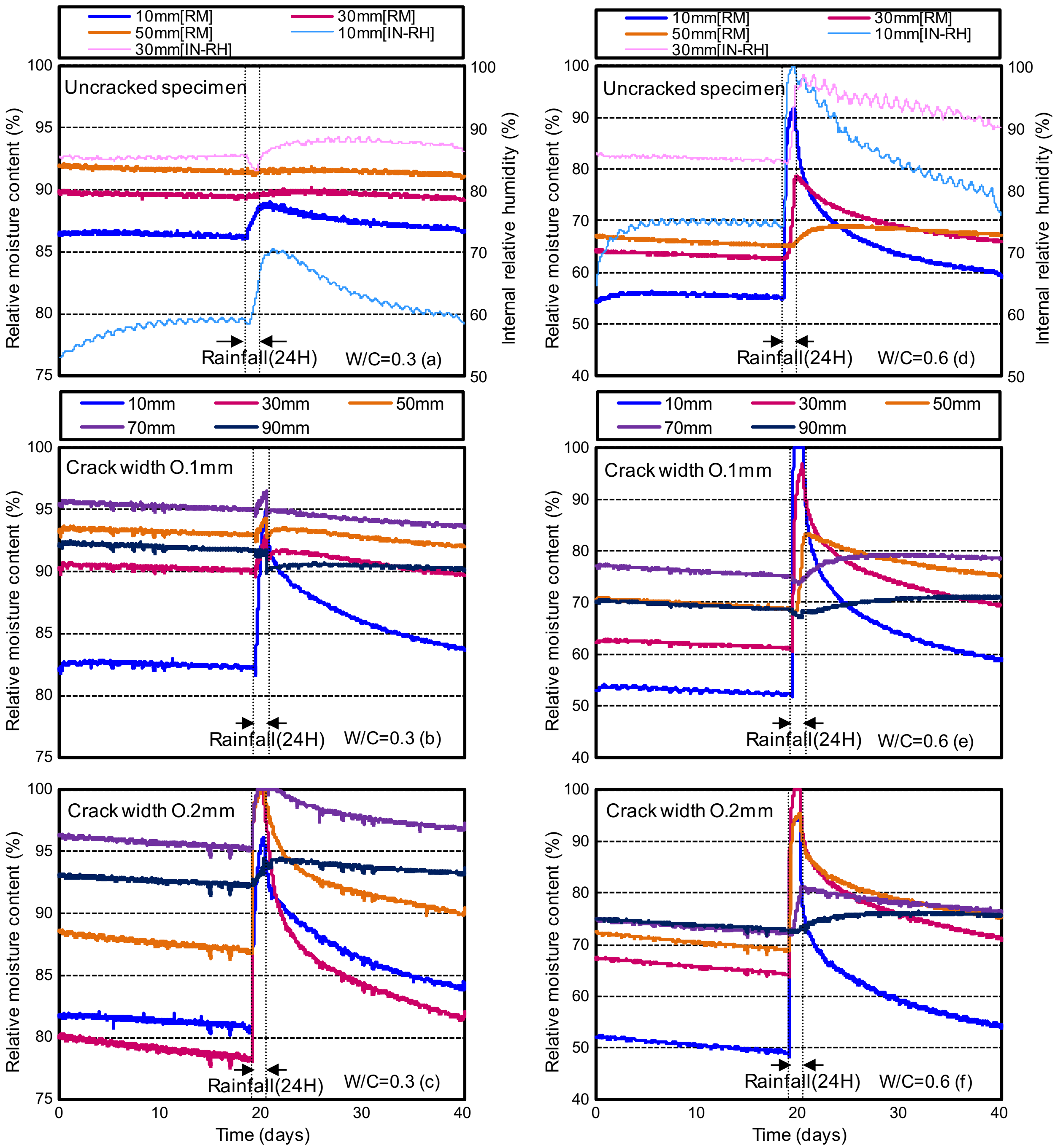


**Fig. 20.** Rainfall-induced changes in the internal RH and RM in exposed concrete over time.

rapid with a w/c of 0.6. This is because, in the surface region partially saturated by rainwater, moisture transferred inward due to the RM gradient and also escaped outward due to drying. Note that, with a w/c of 0.6, the effect of rainfall was evident to a depth of 30 mm from the surface as shown in Fig. 20, but the internal RH and RM distribution scarcely changed in the region deeper than 50 mm.

On the other hand, the RM in the surface region of cracked specimens tended to significantly decrease regardless of w/c due to repeated drying/wetting beginning immediately after the end of rainfall. Andrade et al. [21] have reported that, when concrete is exposed to rainwater, the internal RH increases only while the concrete is exposed to rainwater, and when the rain stops, it rapidly returns to the level before rainfall, canceling the gain in the internal RH during the rainfall period. In the present study, however, the RM of concrete did not decrease to the pre-rainfall level 480 h after the end of exposure to rainwater even at a depth as shallow as 10 mm, and the rate of moisture reduction was even slower at deeper levels. This suggests that moisture is kept within concrete when rainfall repeats at short intervals.

## 4. Conclusions

In this study, experimental research was conducted, simulating environmental conditions in the summertime, to elucidate the effects of cyclic daily changes in the environmental conditions (temperature and RH) and rainfall on the internal RH and RM distribution within concrete. The effects of cracking on the RM distribution within concrete were also investigated. As a result, the following were found:

(1) The RM of concrete decreased more rapidly at smaller depths from the beginning of drying at the specified ages, regardless of the specimen type. The reductions were particularly significant at an early stage of drying. In cracked specimens with a w/c of 0.3, the reductions in the RM were greater with a wider crack, but with a w/c of 0.6, the effect of cracking on the RM reductions was less appreciable.
(2) When investigating the separate and combined effects of external temperature and RH on the internal RH and RM distribution within concrete, the changes in the internal RH and RM distribution were found to occur only in the surface region, while the moisture reductions were extremely slow deeper inward. In regard to the effect of cracking, a wider crack width was found to lead to a slightly higher rate of drying.
(3) When there was no crack in the surface of concrete, rainfall caused the RM of concrete having a dense microstructure (w/c 0.3 in this experiment) to increase in the range of 10 mm from the surface, whereas it increased the RM in the range of 30 mm from the surface in concrete having a coarse microstructure (w/c 0.6 in this experiment). The RM was found to be scarcely changed by rainfall in the range deeper than 50 mm from the surface.
(4) When there was a crack in the surface of concrete, water permeated more quickly through a wider crack, regardless of w/c, reaching deep into the concrete with relative ease. However, whereas the RM of the deeper region began to increase after the surface region was saturated in concrete with a coarse microstructure (w/c 0.6 in this experiment), it tended to begin to increase before the surface region was saturated in concrete with a dense microstructure (w/c 0.3 in this experiment).

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