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Effect of Surface Finishing Materials on the Moisture Conditions in Concrete: Vapor and Water Permeability of Finishing Materials Under Changing Environmental Conditions

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Abstract: Permeability to vapor and water among other performances required for finishing materials is dealt with in this study. The relative moisture content of concrete coated/covered with a finishing material was experimentally investigated while changing the environmental conditions including temperature, relative humidity, and rainfall. An organic paint (water-based urethane), organic synthetic resin emulsion-type film coating (film coating E), and inorganic porcelain tiles were selected as the finishing materials. When compared from the aspect of vapor and water permeability, the vapor permeability and water permeability of water-based urethane were high and low, respectively; those of film coating E were high and high, respectively; and those of porcelain tiles were low and low, respectively. This means that the moisture state of concrete structures is governed not only by the environmental conditions but also by the performance of finishing materials. It is therefore of paramount importance to appropriately select a finishing material to address the specific deteriorative factors involved in the concrete structure to be finished.

Keywords: finishing materials, temperature, relative humidity, rainfall, relative moisture content, concrete.

1. Introduction

In contrast to civil concrete structures, the surfaces of reinforced concrete buildings are generally coated/covered with a variety of finishing materials as measures to improve their durability under deteriorative external forces.

It has been pointed out, however, that the performance required of finishing materials to protect concrete varies depending on the type of external forces, such as chloride attack, carbonation, frost damage, and alkali-silica reaction (ASR).[1-4] In other words, when considering deterioration phenomena of concrete structures from the aspect of the mass transfer phenomenon, the deteriorative factors causing chloride attack, carbonation, frost damage, and ASR to be controlled are chloride ions and moisture, carbon dioxide and moisture, moisture, and moisture and alkalis, respectively, varying from one phenomenon to another. It is therefore particularly important for ensuring the resistance of concrete structures to these deteriorative phenomena to control moisture, which has a significant impact on most deteriorative phenomena.

The reason that different performance of finishing materials is required for different deteriorative factors is that not only the shielding effect against deteriorative factors (CO_2, Cl^-, O_2, and H_2O) but also the moisture state within concrete varies depending on the finishing material. Changes in the moisture state within concrete coated/covered with a finishing material should simultaneously be considered, as the diffusion speed of these deteriorative factors is also significantly affected by the moisture state within concrete.[5]

It has been pointed out that the effects of finishing materials (primarily against carbonation)[6] and defects of finishing materials such as delamination and blistering[7] are closely related not only to the permeability of the finishing materials but also to the high moisture content of the substrate concrete. However, there have been few data regarding the quantitative measurement of the moisture state of concrete with a finishing material under arbitrary environmental conditions.

With this as a background, this study took up the vapor and water permeability from performances required of finishing materials with the aim of elucidating the moisture state within concrete coated/covered with a finishing material under different environmental conditions including temperature, relative humidity, and rainfall. Changes in the moisture state of concrete with and without a finishing material were also experimentally investigated.

Note that the ratio of the actual moisture content in a specimen to the moisture content under the saturated condition was defined as the “relative moisture content” (RM) to be used as an index for comparison, as the saturated moisture content was found to vary from one specimen to another when measured by the electrode method.

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2. Outline of experiment and measurement procedure

2.1 Outline of experiment

Prismatic substrate concrete specimens 300 × 300 × 100 mm were fabricated with concrete having two levels of water-cement ratios (W/C) of 30% and 60%. Tables 1 and 2 give the factors and levels of experiment and the mixture proportions of concrete, respectively.

Electrodes and thermocouples were embedded at depths of 10, 30, 50, and 70 mm from the drying (open) surface. Specimens were demolded at an age of 1 day and water-cured at 60°C until an age of 30 days to prevent pore structure changes due to the progress of hydration during the measurement period.

The finishing materials used in the tests included organic and inorganic types, the former being a water-based urethane paint and synthetic resin emulsion-based film coating (film coating E), and the latter being porcelain tiles generally used for exterior finish as shown in Tables 3 and 4.

For organic finishes, a drying period is normally provided before application to prevent such defects as delamination and blisters. However, different views have been presented regarding this drying period. JASS 23 (Spray Finishing)[8] by the Architectural Institute of Japan requires the drying period to be 2 and 3 weeks in summer and winter, respectively, with the surface moisture content being not more than 10%, whereas BS 8203[9] requires the relative humidity (surface hygrometer measurement) to be not more than 75%. While one report states that the moisture content (relative humidity) actually increases again after finish application due to moisture equilibrium,[10] another states otherwise.[7] In this study, substrate concrete specimens after curing were dried in a dryer adjusted to 40°C for 7 days, with the five surfaces except the drying surface being wrapped with aluminum tape. The finish was then applied after applying a primer to ensure the performance required for the coating film and the specified finished condition. A water-based primer of the same specifications was applied in common with a roller to specimens.

Table 1 Factors and levels of experiment.

Factors	Levels
W/C	30%, 60%
Types of specimens	No finishing, Organic coating materials (water-based urethane, synthetic resin emulsion-type film coating), Inorganic finishing material (porcelain tiles)
Measurement items	Temperature, relative moisture content

The water-based urethane paint was also applied with a roller. Film coating E was sprayed in two layers by a skilled workman. After being stripped of the aluminum tape, all coated specimens were re-immersed in water at 20°C (to a level 95 mm from the bottom), leaving a depth of 5 mm from the drying surface above water, for another 30 days so as to examine the changes in the moisture state following the environmental changes from the saturated condition similarly to uncoated specimens.

On the other hand, tiles were laid on specimens in accordance with JASS 19 (Ceramic tile Work).[11] Job-mixed mortar conventionally used for tile setting was used as the setting bed.

After setting tiles on cured substrate concrete, tiled specimens were seal-cured in an environment of 20°C for one day and then water-cured at 60°C for 14 days for curing the setting mortar. The specimens were then allowed to cool in water for 10 days until the internal temperature reaches a state of equilibrium (20°C). The five surfaces excepting the open surface (the top surface in the placing position 300 × 300 mm in size) of each specimen were coated with epoxy and insulated with foamed polystyrene to prevent heat and moisture transfer. Fig. 1 shows the shape and dimensions of a tile specimen.

2.2 Measurement procedure

The temperatures and relative moisture content (RM) within substrate concrete were continuously monitored using thermocouples and electrodes for measuring the moisture content embedded in the concrete and connected to a data logger and LCR meter.

2.2.1 Estimation of RM

An electrode for estimating the moisture content comprises stainless steel electrode bars made of two SUS304 bars 1.5 mm in diameter and 80 mm in length set at a distance of 8.3 mm as shown in Fig. 2. An AC voltage of 1 V with a frequency of 1 kHz was impressed to avoid polarization.[12]

Calibration tests for estimating the RM were conducted for each temperature using small specimens 40 × 40 × 160 mm in size. The RM used in this study was calculated by Eq. (1).

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

Table 2 Mixture proportions of concrete.

W/C (%)	Water (kg/m³)	Cement (kg/m³)	Fine aggregate (kg/m³)	Aggregate (kg/m³)	s/a (%)	Slump (mm)	Air (%)	AE water reducing agent (C×%)
30	170	567	769	855	48	210	3.2	0.75
60	170	283	825	1,035	45	145	3.7	0.5

Table 3 Type and spread of organic coatings.

Types	Application method	Spread (kg/m²)
Water-based urethane	Roller	0.13 ~ 0.15
Synthetic resin emulsion-type film coating	Spray	1.2
Water-based primer	Roller	0.1 ~ 0.15

Table 4 Type and setting method of inorganic finishing.

Tile type	Shape and size (mm)	Setting material	Ratio by volume	Setting method	Standard joint width (mm)
Porcelain	Brick side size (227 × 60 × 11)	Job-mixed mortar	cement : sand = 1 : 2	Pressure method with mortar on both substrate and tile back	10

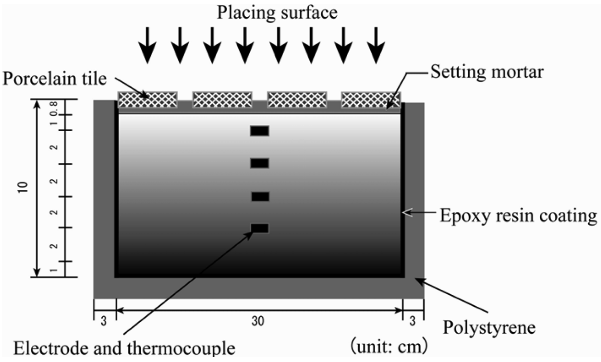

Fig. 1 Geometry of tile specimen.

Photo. 1 Specimen spraying.

where, W = air-dry mass of specimen (g), W_{dry} = oven-dry mass of specimen (g), and W_{sat} = saturated mass of specimen (g).

Figure 3 shows the relationships between the RM and the interelectrode resistance at two temperature levels. Using these relationships, the interelectrode resistance measured by the electodes was converted to the RM for evaluation.

2.3 Simulated environmental conditions

Tests were conducted under the following four sets of simulated environmental conditions: thermo-hygrostatic conditions (20 ± 0.5°C, 60 ± 1% R.H.), cyclic temperature/humidity changes (21.9 ~ 28.3°C, 57~89.7% R.H.), rainfall (20°C, rainfall intensity: 30.1 mm/h), and cyclic temperature/humidity changes after rainfall. The cyclic temperature/humidity changes were intended to simulate the meteorological environment of Tokyo referring to the statistics at the Japan Meteorological Agency over the past 30 years.[13] As shown in Fig. 4, one cycle lasted 24 h similarly to the atmosphere. Rainfall tests were conducted using a precipitation simulator under constant conditions of a temperature of 20°C and rainfall intensity of 30.1 mm/h for 24 h. In regard to the effect of the presence of roofing, tests were conducted with roofing, immediately followed by tests without roofing.

3. Results and discussion

3.1 Time-related changes in the RM distribution in coated/tiled concrete under drying

Figure 5 shows the variations over time in the RM in coated/tiled concretes that were allowed to dry under thermo-hygrostatic conditions at 20 ± 0.5°C and 60 ± 1% R.H. for 45 days. In the case of organic finishes, the reductions in the RM of concrete with

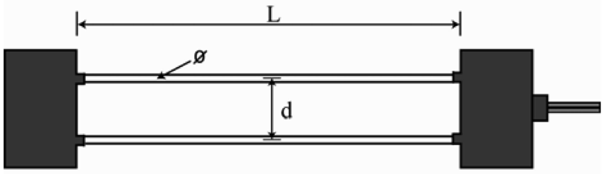

Fig. 2 Shape of electrode bars.

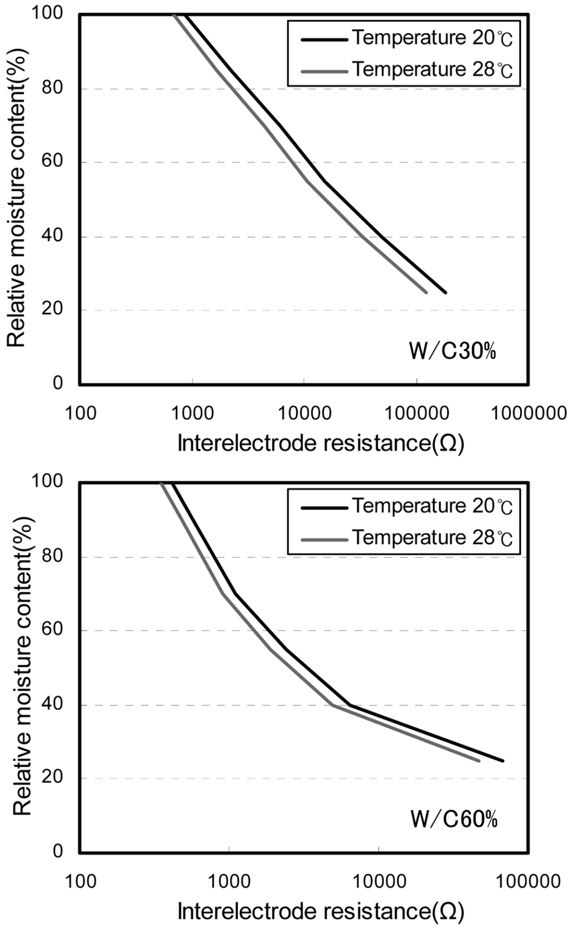

Fig. 3 Calibration curves.

a W/C of 60% during drying were moderate when compared with the significant reductions observed in uncoated concrete. Similar tendencies were observed in concrete with a W/C of 30%, but the differences between coated and uncoated concretes were smaller than in the case of 60% W/C, presumably because the dense pore structure of substrate concrete restricted the moisture loss of both

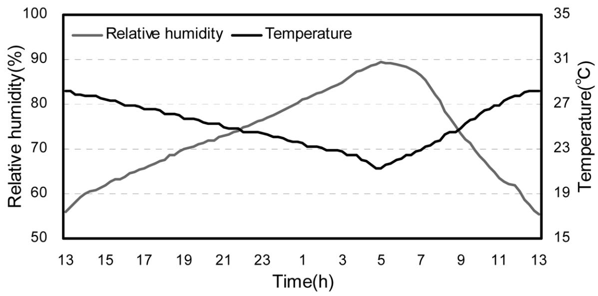

Fig. 4 Simulated environmental conditions.

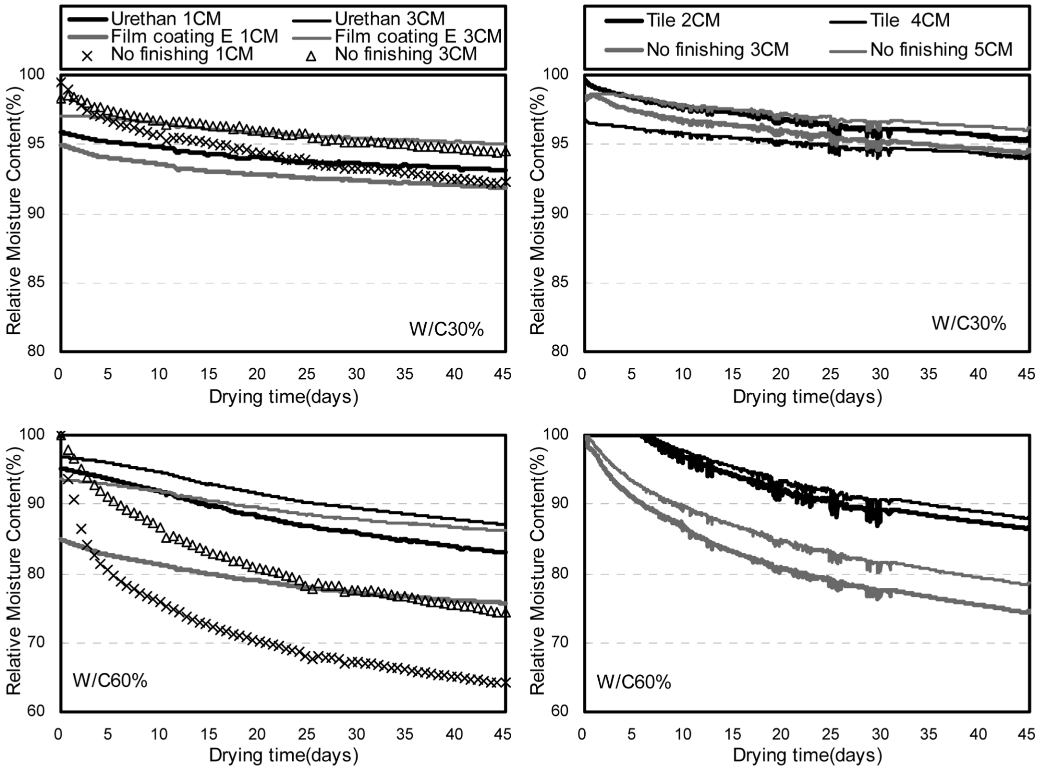

Fig. 5 Time-related changes in the RM distribution in coated/tiled concretes under drying.

coated and uncoated concretes.

When comparing the vapor permeabilities of water-based urethane paint and film coating E, the reductions in the RM under drying conditions were greater with water-based urethane. In consideration of only outward permeability to vapor, a high permeability means an increase in the unsaturated regions in the substrate concrete in the long run, possibly reducing the carbonation-inhibiting effect, but conversely can increase the effect of inhibiting chloride attack and AAR mediated by moisture.

In the case of tiles, the inorganic finish, the distances from the drying surface to the electrodes were 20 and 40 mm including the thickness of setting mortar. The results were therefore compared with those at depths of 30 and 50 mm of untiled concrete. The rates of decrease in the RM of tiled concretes were extremely slow despite the shorter distances from the drying surface. This can be attributed to the airtight characteristic of the porcelain tiles used in the tests with a water absorption of 1.0% or less, with which the outward passage of moisture loss was nearly limited to tile joints. In other words, moisture evaporation through the parts covered with tiles was completely blocked, while the evaporation through joints was marginal, resulting in the retention of a very high moisture content compared with untiled concrete.

Wilkins et al conducted a similar study,[14] although the measuring locations differed from the present study. They report as follows: when cylindrical concrete specimens 150 mm in diameter and 300 mm in height were partially wrapped with impermeable bands with different widths at different intervals to measure the changes in the moisture distribution in the concrete under drying at different depths, the moisture evaporation (drying) was more significantly affected by the band width than by the band intervals. In other words, a wider band width led to the retention of a higher humidity, and this tendency was weakened as the depth increased. It follows that the moisture state of tiled concrete is affected more by the tile area than by the joint width (tile intervals). With a W/C of 30%, the RM at depths of 20 and 40 mm reversed, presumably because autogenous drying occurred in the substrate concrete due to hydration.

3.2 Effects of environmental factors on the RM of coated/tiled concrete

Figures 6 to 8 show the changes in the RM within concrete over time under three sets of conditions to examine the effects of temperature and relative humidity on the RM distribution of substrate concrete with or without a finishing material: (1) constant temperature with changing humidity (20^{o}C, 57 to 89.7% R.H.); (2) constant humidity and changing temperature (60% R.H., 21.9 to 28.3^{o}C); and (3) changing temperature and humidity.

In these graphs, only the values at a depth of 1 cm are shown, as the changes in the RM within substrate concrete following the external environmental changes were limited to the surface region while the moisture reductions deeper inside were extremely slow similarly to those in concrete with no finishing material.

A vapor blocking property to impede vapor permeation into concrete is one of the general performances required for finishing materials. Though the required performance naturally varies depending on the relevant deteriorative mechanism, moisture control is crucial, as moisture in concrete is involved in all deteriorative phenomena.

Figure 6 shows the changes in the RM distribution in concrete over time when the external relative humidity changed while the external air temperature remained constant. For specimens with water-based urethane, the RM of concrete with a W/C of 60% decreased regardless of the external relative humidity but that with a W/C of 30% nearly remained constant. For specimens with film coating E, the changes were irregular but tended to slightly increase over time. When tiled, the RM tended to decrease regardless of the W/C.

Figure 7 shows the changes in the RM distribution of concrete when the external temperature cyclically changed. The reductions in the RM in the surface regions were greatest with water-based urethane, followed by film coating E, and tiles, regardless of the finish type.

Figure 8 shows the changes in the RM distribution within concrete when both the external temperature and humidity cyclically changed. The RM of concrete with water-based urethane or film coating E showed a slightly increasing phenomenon excepting urethane-coated concrete with a W/C of 60%, in which the values were nearly constant. The slight increases were greater with film coating E than with urethane. In the case of tiles, the RM conversely tended to decrease, with the reductions being smaller as the depth from the surface decreased. These results can be regarded as natural in consideration of the fact that the measurement depth in tiled concrete was 20 mm from the surface and that only the surface regions are affected by the changes in the environmental conditions.

Figure 9 schematically shows the vapor permeability of finishing materials in the above-mentioned environment with changing temperature and humidity.

3.3 Effects of rainfall on the RM of concrete with a finishing material

As for moisture transfer in actual structures, vapor transfer in an

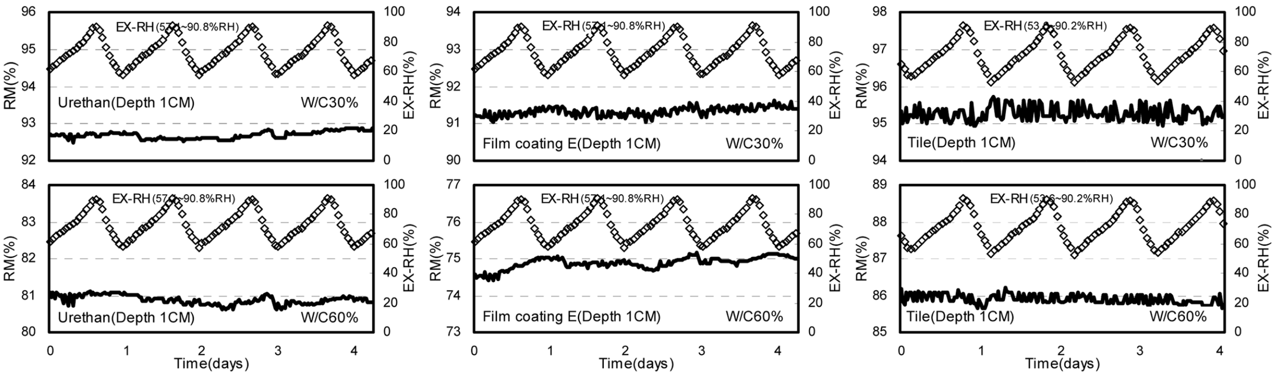

Fig. 6 Time-related changes in the RM distribution in coated/tiled concretes under cyclic humidity changes.

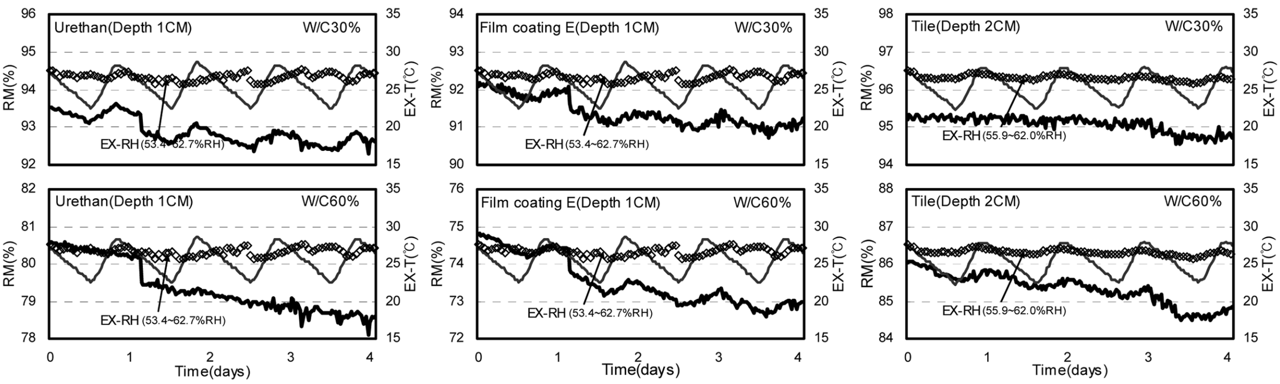

Fig. 7 Time-related changes in the RM distribution in coated/tiled concretes under cyclic temperature changes.

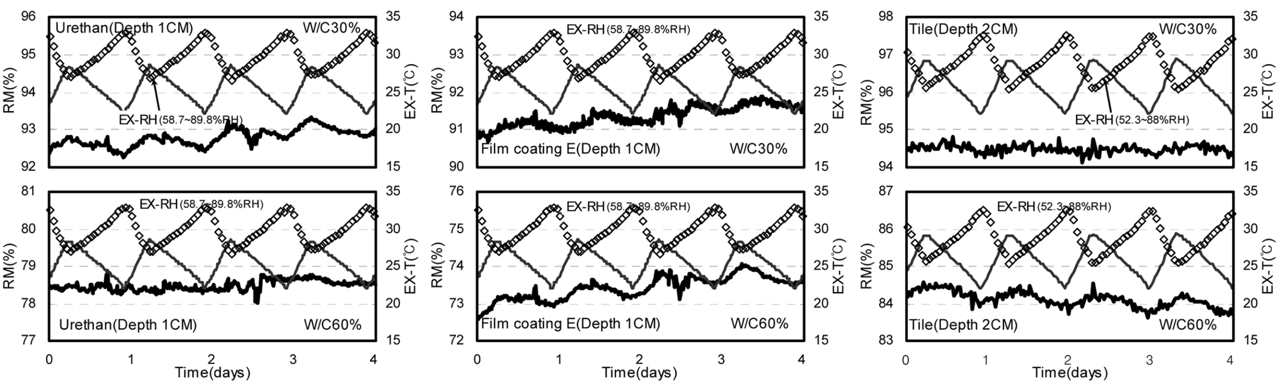

Fig. 8 Time-related changes in the RM distribution in coated/tiled concretes under cyclic temperature-humidity changes.

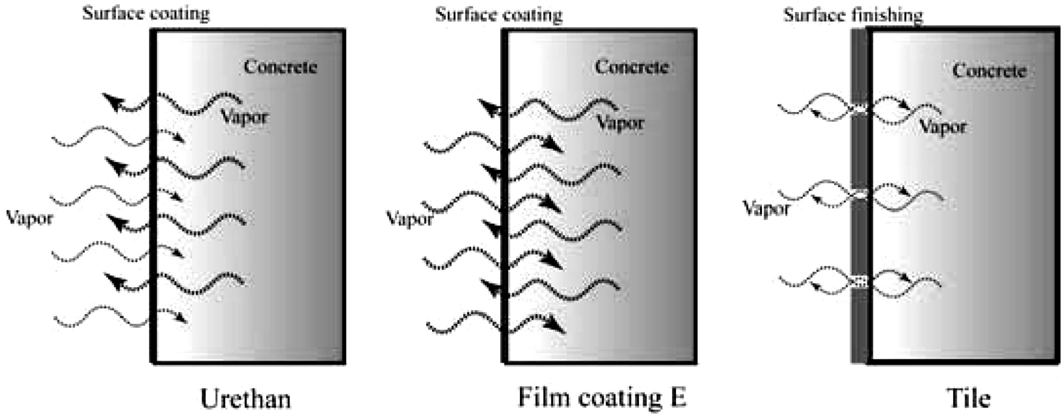

Fig. 9 Schematic expression of the vapor permeability of finishing materials.

unsaturated condition is predominant over liquid water transfer in the saturated condition. When it rains, rainwater directly permeates into concrete, significantly changing the moisture content of concrete.

Such changes in concrete structures coated/covered with a finishing material should vary depending on the permeability of the finish. It is therefore necessary to investigate the vapor permeability and water permeability, when exposed to rainwater, of finishing materials, which could affect the RM of substrate concrete. The effect of rainfall through finishing materials with different permeabilities on the moisture content of substrate concrete was therefore experimentally investigated by simulating rainfall in the natural environment.

Figure 10 shows the changes in the RM of concrete coated/covered with a finishing material with and without roofing during rainfall. When coated with water-based urethane, the presence of roofing scarcely affected the RM regardless of the W/C. In other words, water-based urethane was found to scarcely allow vapor permeation into concrete even in a high humidity conditions under a roof. It was also found to completely block moisture permeation from outside with no roof, though the moisture content slightly tended to increase after the end of rainfall. Since water-based urethane is a repellent-type waterproofing coating that inhibits the permeation of liquid water from outside while allowing the escape of vapor from the inside, it is highly probable that the drying of substrate concrete is accelerated from a long-term perspective.

In the case of film coating E, concrete with a W/C of 30% was scarcely affected by the absence of roofing when compared with concrete a W/C of 60%, but the RM tended to increase when directly exposed to rainwater. This is not due to the effect of film coating E itself but due to the effect of the pore structure resulting from the low W/C. Note that the RM of concrete with a W/C of 60% with no roof rapidly increased, showing a tendency similar to uncoated specimens as shown in Fig. 10(e). Tiled concrete showed slight increases in the RM in the surface region due to the high relative humidity regardless of the W/C.

Figure 11 shows the long-range effect of rainfall for 24 h on the RM of coated/tiled concrete in a summery environment. The RM of concrete coated with water-based urethane slightly increased in the surface region immediately after rainfall but generally tended to decrease thereafter at all depths. A similar tendency was observed regarding the long-term RM behavior under cyclically

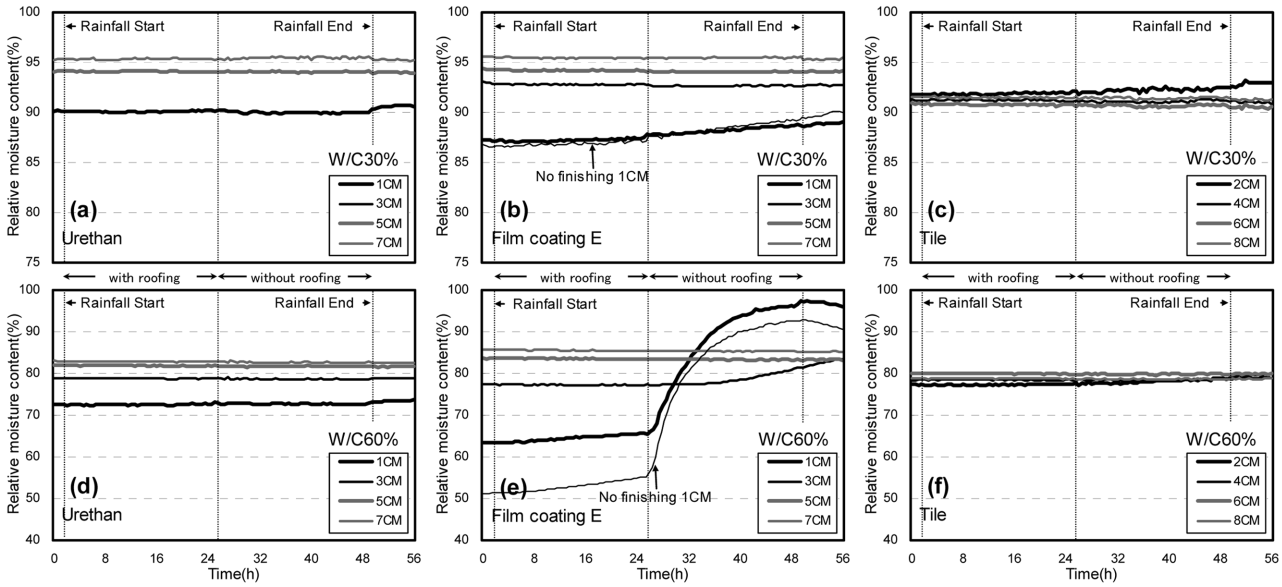

Fig. 10 Time-related changes in the RM distribution in coated/tiled concretes with and without roofing.

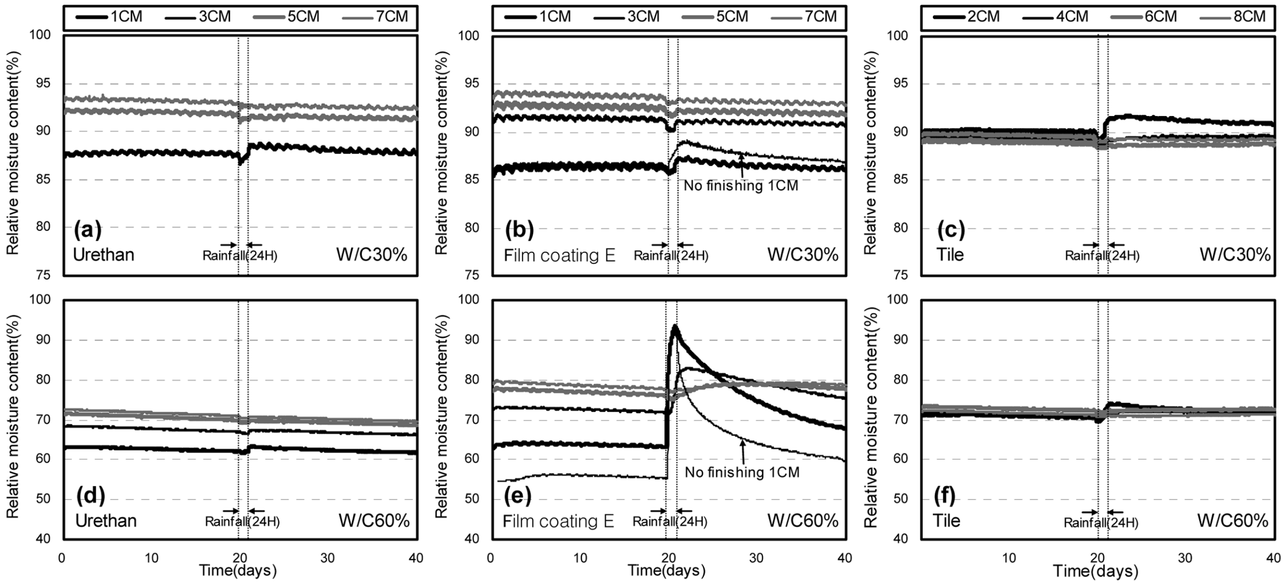

Fig. 11 Time-related changes in the RM distribution in coated/tiled concretes in rainfall.

changing temperature and humidity conditions after rainfall, with little effect of rainfall.

The RM of concrete coated with film coating E showed tendencies similar to uncoated specimens but was found to remain higher than that of uncoated concrete under long-range temperature-humidity cycles after rainfall. This is presumably because inward permeation of liquid water through film coating E is the same as uncoated concrete but outward escape of vapor through film coating E is slower as shown in Fig. 11(e).

In the case of tiled concrete, the RM tended to increase more by direct exposure to rainwater than by cyclic changes in the temperature and humidity, due to water absorption of joint mortar. It is thus inferred that permeation through water absorption by mortar is prompt, with the water amount being much greater than the amount of escape.

Figure 12 schematically shows the water permeability of finishing materials subjected to rainfall.

4. Conclusions

The authors considered that the moisture state of concrete structures was controlled not only by the environmental conditions but also internal factors, such as the performance of finishing materials, and investigated the effects of finishing materials on the moisture state of substrate concrete. The results are summarized as follows:

1) The rate of vapor escape under drying was highest with water-based urethane, followed by film coating E and tiles.

2) Changes in the relative moisture content of substrate concrete following the changes in the environmental conditions occurred only in the surface regions similarly to specimens with no finishing material, with the moisture reductions in the deeper regions being extremely slow. Also, the permeability to water and moisture varied from one finishing material to another. The inward vapor permeability of water-based urethane was low but its outward vapor permeability was high. Whereas film coating E was highly permeable to vapor both inward and outward, tiles showed very low vapor permeability both inward and outward.

3) The effect of rainfall on the relative moisture content of concrete varied depending on the type of finishing material. Rainfall scarcely affected the relative moisture content of concrete coated with water-based urethane. The relative moisture content of concrete coated with film coating E was similar to that of uncoated concrete but retained at higher levels than uncoated concrete under

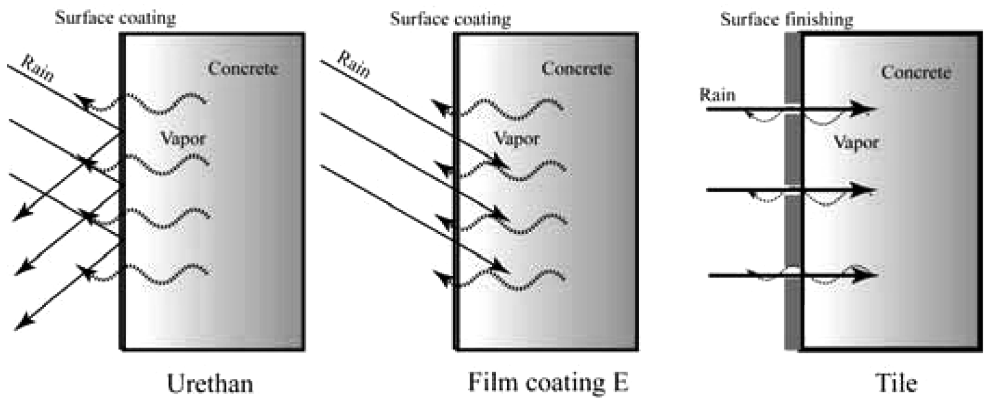

Fig. 12 Schematic expression of the water permeability of finishing materials.

cyclic changes in the temperature and humidity after rainfall. In the case of tiled concrete, rainwater promptly permeated through tile joints, and the absorbed moisture slowly escaped over a long time.

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