- Technical Paper -

ANALYSIS OF WATER TRANSPORT IN CONCRETE UNDER REAL ENVIRONMENT

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ABSTRACT

Transport of water in concrete under real environment was analyzed by the hybrid model of capillary suction and nonsaturated diffusion. While concrete surface was subjected to liquid water, the water transport phenomenon was modeled by capillary suction process into concrete pores. The water loss or gain, while concrete surface was exposed to the air, was described by nonsaturated diffusion model considering capillary condensation and diffusion of vapor and liquid water in concrete pores. The analytical results were verified with the experimental results under real environment.

Keywords: capillary suction, nonsaturated diffusion, exposure test

1. INTRODUCTION

Deterioration of concrete structures by environmental action is closely related with service life of structures. It is regarded that penetration of water into concrete plays great roles in deterioration process of concrete structures such as reinforcement corrosion, alkali-silica reaction and freeze-thaw action. Water content and its profile in concrete structure always changes due to the change of weather conditions: rainfall, sunshine and change of temperature and relative humidity. Transport of water in concrete has been experimentally and analytically studied by many researchers [1, 2]. However, prediction of water content in concrete under real environment is still difficult because of following reasons: difference in transport mechanisms between drying and wetting processes, complexity of concrete pore structure and difficulty in modeling of environmental conditions in nature.

In this study, the influential environmental factors on transport of water in concrete are considered, which are rainfall, sunshine and change of temperature and relative humidity of atmosphere. The authors' analytical method [3], a hybrid model of capillary suction and nonsaturated diffusion in concrete, is extended to concrete under real environment. While concrete surface is exposed to liquid water, capillary suction is considered as the dominant mechanism of transport of water into concrete. Transport of water content in concrete in this process is calculated by the capillary suction model [4]. On the other hand, transport of water in concrete while its surface is exposed to the air, is calculated by the diffusion model for nonsaturated concrete considering diffusion of vapor and liquid water [5]. Laboratory and field experiments were conducted to investigate the effect of real environmental condition on water content and its profile in concrete.

2. COMPUTATIONAL METHOD OF TRANSPORT OF WATER IN CONCRETE UNDER CYCLIC DRYING AND WETTING

2.1 Outline of Computational Flow

The computational flow of the proposed mathematical model for transport of water in concrete under real environmental condition including drying and wetting is shown in Fig. 1. In this model, characteristic of concrete is represented in terms of pore size distribution. Two different models are alternatively used depending on drying and wetting process: diffusion model for nonsaturated concrete and capillary suction model for partially saturated concrete.

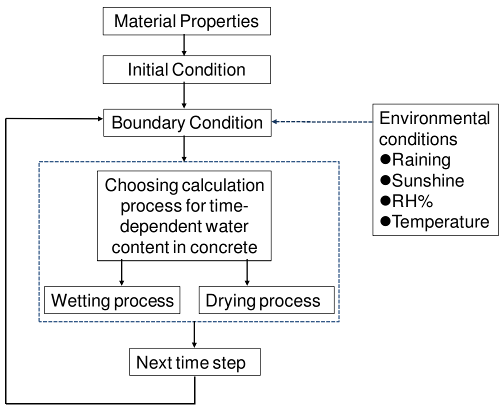

Fig. 1 Outline of computational flow

When concrete surface is subjected to the air, transport of water in concrete by drying and adsorption is calculated by diffusion model for nonsaturated concrete. On the other hands, when the concrete surface was wet due to rainfall, transport of water in concrete was calculated by the capillary suction model instead of diffusion model.

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2.2 Outline of Computational Method for Transport of Water in Concrete Under Drying and Wetting

In the first drying process, the diffusion model for nonsaturated concrete by the authors is adopted [5]. Capillary condensation of water in micro pores, diffusion of vapor and transport of liquid water within pore structure are taken into account in terms of pore size distribution function. Smaller pores are primarily filled with condensed water in this process.

When concrete surface touches with water, concrete pores near the surface are immediately saturated and capillary suction from the surface begins. Since capillary suction water is considered to fill greater pores earlier [4], it is assumed that two kinds of liquid water temporally exist in concrete pores during wetting process: capillary condensed water and capillary suction water as illustrated in Fig. 2. In reality, capillary suction water will locally transit from greater pores to smaller pores and be gradually combined with condensed water. In addition, diffusion also takes places even during wetting process. It is assumed, however, that capillary condensed water does not change and only capillary suction occurs during wetting process because capillary suction is rapider phenomenon and transports greater amount of water compared with diffusion process.

When concrete is subjected to drying condition again, two kinds of liquid water are combined together and accounted as condensed water. Then, drying process is calculated again.

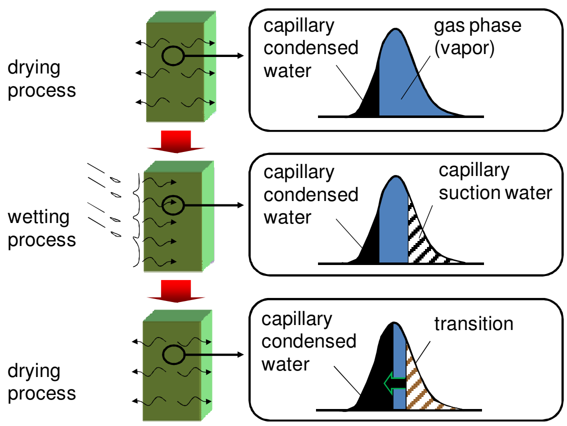


Fig. 2 Computational method for transport of water in concrete under cyclic drying and wetting

2.3 Formulation

(a) Pore size distribution of concrete

Pore size distribution of concrete is represented by following function [5].

$$V(r) = V_0\{1 - exp(-Br^c)\} \qquad (1)$$

where, $V(r)$ is accumulated pore volume having smaller radius than r, V_o is the total volume of pores per unit concrete volume (m^3/m^3), B and C are parameters for pore size distribution.

(b) Capillary suction

It is assumed that the pore structure of concrete is expressed in terms of parallel straight vessels having various radii as shown in Fig. 3. Referring capillary suction in a horizontal straight vessel, the length of liquid water by capillary suction in each pore is formulated as:

$$x = K_{cap}\sqrt{\frac{r\gamma}{2\mu}t} \qquad (2)$$

where, x is the length of absorbed water (m), K_{cap} is nondimensional mean friction factor depending on concrete pore structure, γ is the surface tension (N/m), μ is viscosity of liquid water (Pa・s) and r is radius of concrete pore (m). In case of actual concrete, however, pore structure is not straight vessel, but complex and tortuous mesh. Therefore, mean friction coefficient for concrete pores should be greater that for glass vessel. To express overall frictional effect of concrete pores comprehensively, K_{cap} is introduced. K_{cap} is one for ideal laminar flow in straight vessel and between zero and one for actual concrete.

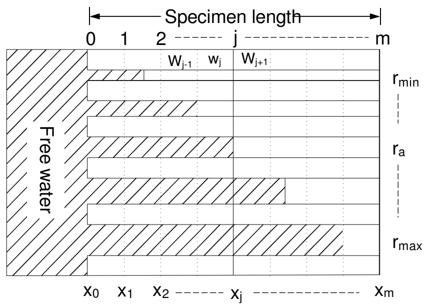


Fig. 3 Capillary suction model

Since concrete pores are considered enough small to neglect effect of gravity on transport of water within concrete, one-dimensional capillary suction in horizontal direction is considered here. In the computation procedure, concrete specimen is discretized into finite volume as shown in Fig. 3. Based on the assumption of capillary suction of water in straight vessel, pore having greater radius is filled with absorbed water prior to smaller ones at each section as illustrated in Fig. 4[4]. Therefore, at time "t", if we look at a certain element "w_j" locating at the distance "x_j" from the surface, there is a threshold pore radius "r_a". In the element "w_j", pores whose radius is greater than "r_a" are filled with water by capillary suction and pores whose radius is smaller than "r_a" are still empty. The threshold pore radius "r_a" is calculated as:

$$r_a(x_j,t) = \frac{2\mu}{\gamma t}\left(\frac{x_j}{K_{cap}}\right)^2 \qquad (3)$$

In the element "w_j", volume of water by capillary suction can be calculated as:

$$V_{cap}(x_j,t) = V_0 - V_{(r_a)}$$
$$= V_0\, exp(-Br_a^C) \qquad (4)$$

The total absorbed water in the specimen mass of absorbed water is calculated as:

$$w(t) = \rho_L \int_v V_{cap}\ dV \quad (5)$$

where, ρ_L is density of liquid water.

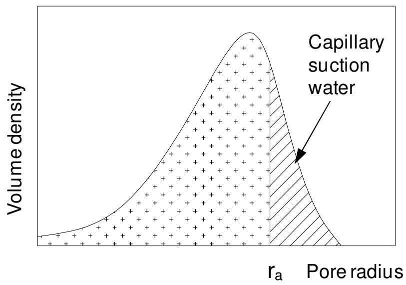


Fig. 4 Capillary suction water in concrete pores under wetting process

(c) Capillary condensation

The mechanisms of water diffusion in nonsaturated concrete are molecular diffusion of vapor and, in addition, transport of liquid water due to pressure gradient at high water content state. The gas phase is regarded as an ideal gas mixture composed of vapor and air. The partial pressure of vapor in nonsaturated concrete pore is assumed to be described by Kelvin equation for ideal capillary condensation,

$$ln \frac{p_v}{p_{vo}} = -\frac{2\gamma M_w}{RT\rho_L}\frac{1}{r_s} \quad (6)$$

where, p_v is partial pressure of vapor (Pa), p_{vo} is saturated partial pressure of vapor (Pa), Mw is molecular mass of water (kg/mol), R is gas constant (J/mol K), T is absolute temperature (K), ρ_L is density of liquid water (kg/m^3), r_s is radius of a curved liquid-gas interface (m).

According to the ideal capillary condensation theory, the pore whose radii are smaller than r_s, which is determined by Eq. 6, is filled with liquid water under the given relative humidity. The volume of liquid and gas in pore structure can be illustrated as Fig. 5.

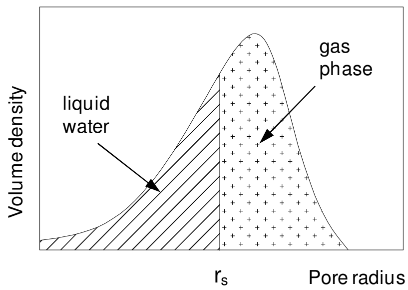


Fig. 5 Gas and liquid phase in nonsaturated concrete under drying process

(d) Diffusion of vapor and liquid water in nonsaturated concrete

The mass conservation equation of water is expressed as:

$$\frac{\partial w}{\partial t} = -div(j_v + j_l) \quad (7)$$

where, w is mass concentration of water per unit concrete volume (kg/m^3), t is time (sec), j_v is mass flux of vapour (kg/m^2 s), j_l is mass flux of liquid water (kg/m^2 s).

Both of vapor flux (j_v) and liquid water flux (j_l) are calculated based on the pore structure of concrete and thermodynamic behavior of water in porous media and can be express as Eqs. 8 and 9 respectively. The term $V(r)$ is pore size distribution function representing the pore structure of concrete which has been already mentioned as Eq. 1. K_v and K_l are non-dimensional material factor representing resistance of pore structure to transport of vapor and liquid water respectively.

$$j_v = \int_{r_s}^{\infty} \left\{\frac{dv(r)}{dr}(-K_v D_{vo} grad\rho_v)\right\} \quad (8)$$

$$j_l = \int_0^{r_s} \left[\rho_L \frac{dv(r)}{dr}\left\{-K_L \frac{r^2}{8\mu} grad\left(-\frac{2\gamma}{r_s}\right)\right\}\right] dv \quad (9)$$

where, r is pore radius in concrete (m), $v(r)$ is pore size distribution function (m^3/m^3), D_{vo} is diffusivity of vapor in the air (m^2/s), ρ_v is density of vapor (kg/m^3), ρ_L is density of liquid water (kg/m^3).

2.4 Boundary conditions

In this study, boundary condition in nonsaturated diffusion is treated in a similar way to heat transfer between a solid and a fluid. The mass flux of water on the boundary surface is evaluated by the following law:

$$J_B = \propto_B (w_L - w_{LB}) \quad (10)$$

where, J_B is mass flux of water at the boundary surface (kg/m^2 s), $\propto_B$ is moisture transfer coefficient (m/s), w_L is water content of concrete at the surface (kg/m^3) and w_{LB} is water content in equilibrium with atmosphere (kg/m^3). When the concrete surface subjected to splash water, concrete at the boundary surface is immediately saturated, while inside of concrete is still nonsaturated. Capillary suction mechanism will dominate during wetting process and the mass flux of water will be Eq. 5. As formulated in section 2.3, calculation of capillary suction water is based on the concept to regard concrete as gather of straight vessels. Capillary suction in concrete is simulated as total motion of water in each vessel.

3. VERIFICATION OF THE PROPOSED METHOD BY LABOLATORY TEST

3.1 Preparation of Test

Laboratory tests were conducted with the purpose of verifying the applicability of the proposed model to ideal conditions. Two types of concrete mix whose w/c was 50% and 30% were prepared. Three specimens of 100x100x200mm in size were prepared for each concrete mix. The mix proportions of concrete mix are shown in Table 1. Specimens were cured in water for 14 days. After curing, four side surfaces of 100x200mm were coated with coal tar to avoid moisture transfer through these surfaces.

Table 1 Mix proportions of concrete

Specimen	Unit weight (kg/m^3)					
	W	C	S	G	Ad	w/c
N-1,2,3	158	334	778	1046	3.3	50%
H-1,2,3	151	591	714	762	10.6	30%

Experimental cases are shown in Table 2. Monotonic drying-wetting and cyclic drying-wetting were conducted. For the monotonic case, water absorption in both horizontal and vertical direction was tested. For the cyclic drying-wetting case, only horizontal water absorption was tested.

Table 2 Experimental cases

Specimen	Monotonic/ Cyclic	Direction	Concrete
N-1	Cyclic drying-wetting	Horizontal	w/c 50%
H-1			w/c 30%
N-2	Monotonic drying-wetting	Horizontal	w/c 50%
H-2			w/c 30%
N-3		Vertical	w/c 50%
H-3			w/c 30%

The experimental setup are illustrated in Fig. 6(a) and Fig. 6(b). All specimens were tested in temperature controlled room of 20°C. The period of drying was 6 days for cyclic case and 14 days for monotonic case. The period of wetting was 1 day for cyclic case and 28 days for monotonic case. The weight change of specimens was measured every day.

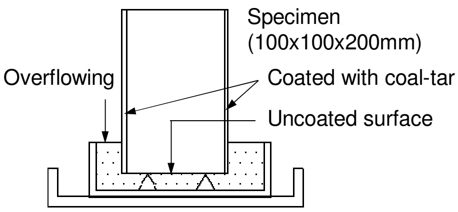


Fig. 6(a) Experimental setup for vertical direction of water absorption in laboratory

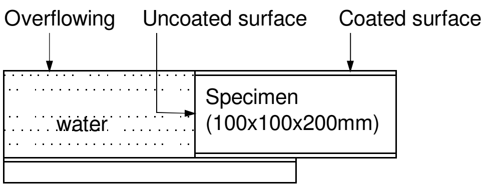


Fig. 6(b) Experimental setup for horizontal direction of water absorption in laboratory

3.2 Test Results and Analytical Results

The comparison of experimental results and analytical results for monotonic drying-wetting of w/c 50% and 30% concrete are shown in Figs. 7 and 8 respectively. In Figs. 7 and 8, analytical results and experimental results well agree in drying process: descending part of the graph. In ascending part of the graph that is under wetting process, the analytical results are close to the experimental results of horizontal water absorption. The reason why experimental results of wetting process in the horizontal and vertical directions were slightly different may be a gravity effect that had been assumed to be negligible. Fig. 9 shows the comparison of analytical and experimental results of cyclic dying-wetting cases for 69 days of w/c 50% and 30% concrete. The analytical results and the experimental results are close to each other in both normal and high strength concrete from the beginning to the end. It is verified that the proposed model has good applicability for both monotonic and cyclic drying-wetting process under laboratory test condition.

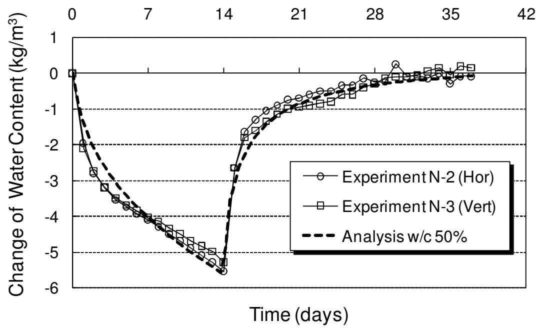


Fig. 7 Experimental and analytical results of monotonic drying-wetting of w/c 50% concrete

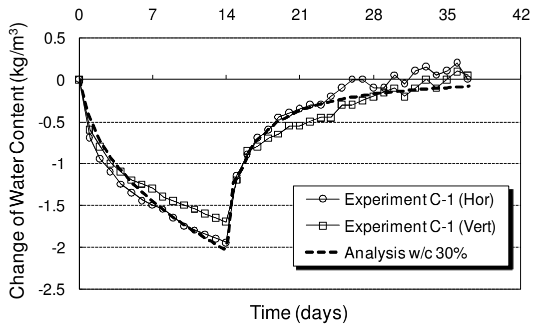


Fig. 8 Experimental and analytical results of monotonic drying-wetting of w/c 30%

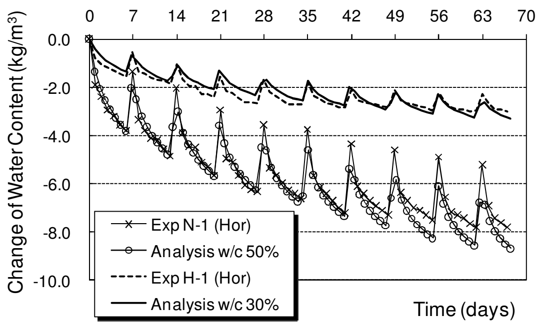
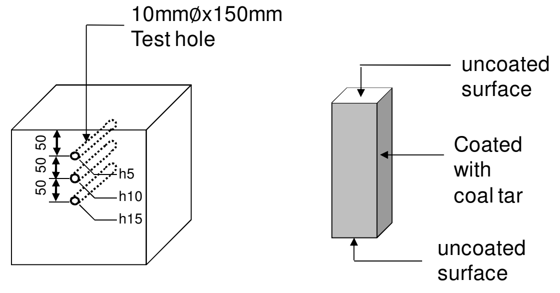


Fig. 9 Experimental and analytical results of cyclic drying-wetting of w/c 50% and 30% concrete

4. LONG TERM EXPOSURE TEST UNDER VARIOUS ENVIRONMENTS

4.1 Specimen Preparation

Time-dependent change of water content and its profile in concrete specimen under various environmental conditions, both of field and laboratory experiment were measured. Two kinds of concrete specimen as shown in Fig. 10 were prepared. The mix proportions of concrete are shown in Table 3. All specimens were cured under moist condition for 28 days. After curing, four side surfaces of type "B" were coated with coal tar as shown in Fig. 10(b), to avoid moisture transfer through these surfaces.



(a) Type "A" (300x300x300mm)   (b) Type "B" (100x100x300mm)

Fig. 10 Detail of specimens

Table 3 Mix proportions of concrete

Specimen type	Unit Weight [kg/m3]					
	W	C	S	G	Ad	w/c
A, B	170	340	799	980	3.4	50%

Ad.: Super plasticizer

4.2 Test Procedure

Table 4 shows the experimental cases. The condition of laboratory is controlled at 60% relative humidity and 20℃ temperature. Continuous drying (case 1) and cyclic drying-wetting (case 2) were conducted in laboratory.

Table 4 Experimental Cases

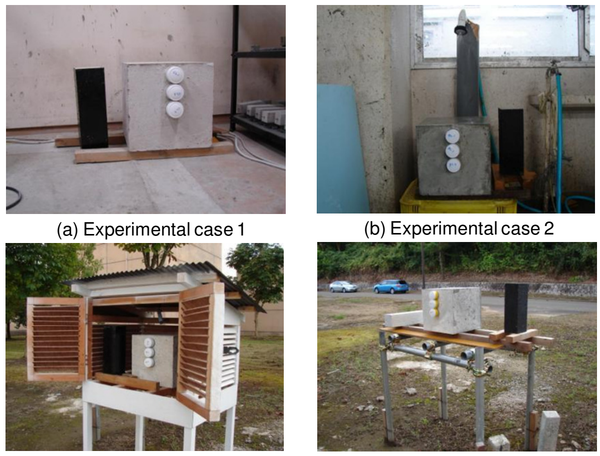
Case	Specimen type		Test place	Experimental conditions
1	A	B	laboratory	Continuously drying
2	A	B	laboratory	Cyclic drying-wetting (inside building)
3	A	B	Field	Not subjected to rainfall & sunshine
4	A	B	Field	Subjected to rainfall & sunshine

Experimental case 1 is a reference case under ideal condition. Specimens in case 1 were placed in the temperature and humidity controlled room. Time-dependent weight change of specimen type B and the humidity of test holes in specimen A were measured every day.

Specimens in case 2 were placed in the normal room conditions and subjected to periodical water shower which simulates rainfall. The length of one cycle of drying and wetting was 7 days: 6 hours (1/4 day) showering and 162 hours (6-3/4days) drying.

The specimens in case 3 were placed in the shelter in the field, in which specimens are subjected to natural atmosphere but not exposed to rainfall nor direct sunshine.

Specimens in case 4 were exposed to natural environment including change of temperature and humidity, rainfall and sunshine.



(a) Experimental case 1   (b) Experimental case 2   (c) Experimental case 3   (d) Experimental case 4

Fig. 11 Experimental set up for exposure test

4.3 Comparison of Analytical and Experimental Results

The material parameters used in the computational model were listed in Table 5, which were estimated from previous test data. Figs. 12, 13, 14 and 15 show the comparison of analytical and experimental results of time-dependent weight change of water content in concrete of specimen B in case 1, 2, 3 and 4 respectively. The environmental condition in case 3 and 4: rainfall and sunshine duration, relative humidity and temperature were imported from the recorded data of Japan Metrological Agency for Nagaoka, Niigata, Japan.

Table 5 Material parameters

V_o	B	C	K_v	K_l	K_{cap}
0.1301	16300	0.5	0.14558	0.00291	0.00291

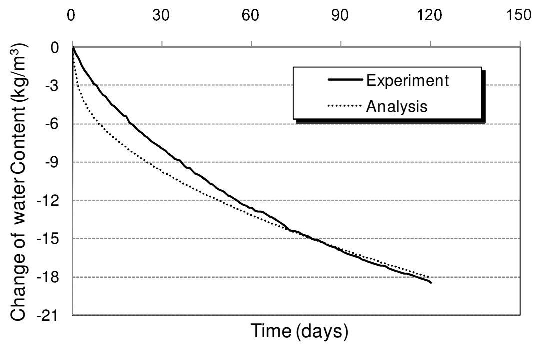


Fig. 12 Experimental and analytical results of specimen type B in the exposure test case1

In Fig. 12, experimental and analytical results of time-dependent weight change of water content in concrete specimen B in case 1 agrees with each other, decreasing smoothly.

In Fig. 13, the water content in concrete in case 2 immediately increases after showering, while it decreases during dry period. Although, the tendency of experimental and analytical curves is same, the absolute value of water content is different. This might be because the local RH% around the specimen surface is higher than room humidity due to periodical showering.

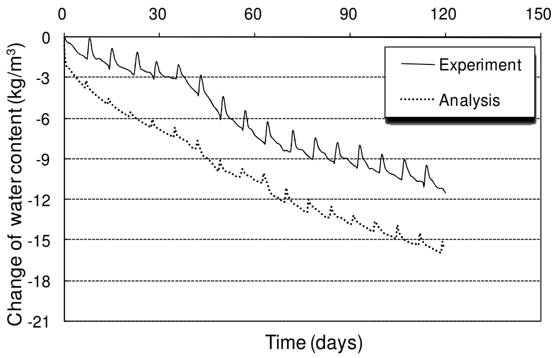


Fig. 13 Experimental and analytical results of specimen type B in the exposure test case 2

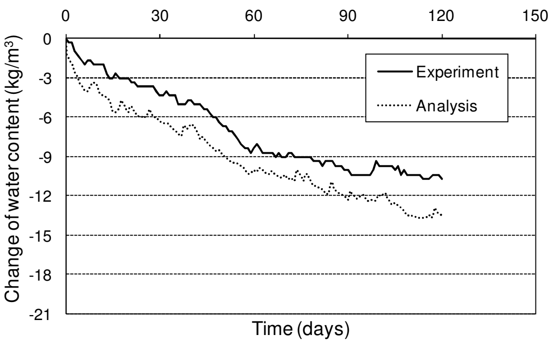


Fig. 14 Experimental and analytical results of specimen type B in the exposure test case 3

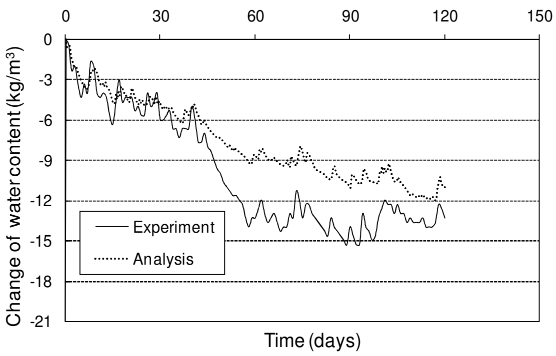


Fig. 15 Experimental and analytical results of specimen type B in the exposure test case 4

Fig. 14 shows the experimental and analytical results of case 3, in which specimens are placed in the shelter. The tendency of two curves is almost same. However, analytical result overestimates drying at the early stage.

The comparison of experimental and analytical results of case 4, in which specimens are exposed under natural environment, is shown in Fig. 15. For the first 40 days, the experiment and analytical curve are close to each other, but the rest part is noticeably different. This gap is probably attributable to the seasonal change in climate from summer to autumn. The experimental curve in case 4 is less smooth compared with case 3. This may be due to the influence of direct sunshine and rainfall.

5. CONCLUSIONS

(1) A hybrid computational model for capillary suction and diffusion in nonsaturated concrete was developed. It was verified that the proposed model can simulate cyclic drying and wetting process of concrete in the laboratory test.

(2) The proposed analytical method was applied to the prediction of change in water content of concrete in the laboratory and field test under various environmental conditions. It was shown that the boundary condition greatly affect the transport process of water in concrete. Therefore, in order to estimate time-dependent water content and its profile in concrete under real environment, it is of importance to properly assess boundary conditions including raining, time-dependent humidity and temperature.

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REFERENCES

[1] Kefei Li, Chunqiu Li.,"Influential depth of moisture transport in concrete subject to drying–wetting cycles," Cement and Concrete Composites, Vol.31, Nov., 2009, pp.693-698

[2] C. Andrade, J. Sarria, C. Alonso., "Relative Humidity in the Interior of Concrete Exposed to Natural and Artificial Weathering" Cement and Concrete Research, Vol. 29, 1999, pp.1249-1259

[3] Thynn, T.H. and Shimomura, T., Hybrid computational method for capillary suction and nonsaturated diffusion in concrete, 4th International Conference on Construction Materials (ConMat'09), Aug., 2009, pp.1075-1080

[4] Thynn, T.H. and Shimomura, T., "Modeling of Water Absorption from Concrete Surface by Capillary Suction," Proceedings of the 26th Annual Conference of Niigata-Kai, Japan Society of Civil Engineers, Nov., 2008, pp.222-225

[5] Shimomura, T., and Maekawa, K., "Analysis of the Drying Shrinkage Behavior of Concrete Using a Micromechanical Model Based on the Micro Pore Structure of Concrete," Magazine of concrete research, Vol.49, No.181, 1997, pp.303-322

[6] T.Nishi, "Modeling of moisture transport in cracked concrete," Master thesis, Nagaoka University of Technology, Feb., 1999.