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Moisture diffusion of concrete considering self-desiccation at early ages

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Abstract

In concrete structures exposed to the ambient air at early ages, the moisture content in concrete decreases due to moisture diffusion. In addition, self-desiccation due to hydration of cement causes an additional decrease of moisture content in concrete at early ages, especially for high-strength concrete. In this study, the internal relative humidity in drying concrete specimens was measured at early ages. Furthermore, the variation of relative humidity due to self-desiccation in sealed specimen was measured. The moisture distribution in low-strength concrete with high water/cement ratio was mostly influenced by moisture diffusion due to drying rather than self-desiccation. In high-strength concrete with low water/cement ratio, however, self-desiccation had a considerable influence on moisture distribution. The results obtained from the moisture diffusion theory were in good agreement with experimental results.

Keywords: Drying; Humidity; Diffusion; Finite element analysis; Permeability

1. Introduction

Concrete material properties change with time. These material properties of concrete (i.e., concrete strength, elastic modulus, creep, and shrinkage) are significantly influenced by the heat of hydration and moisture content in the concrete at early ages. Consequently, it is very important to predict the heat of hydration and moisture distribution in concrete structures [1].

In concrete structures exposed to ambient air, the moisture content decreases due to moisture diffusion during drying [2]. In addition, self-desiccation due to hydration of cement causes an additional decrease of moisture content in concrete at early ages [3]. Especially for high-strength concrete using the high unit cement content, the relative humidity distribution is considerably affected by self-desiccation at early ages. Thus the variation of relative humidity may be obtained by considering the effect of self-desiccation and moisture diffusion in concrete. But in some previous investigations, the moisture variation due to self-desiccation was ignored or not considered [4,5].

In this study, the internal relative humidity in concrete was measured for drying specimens at early ages. The variation of the internal relative humidity due to self-desiccation was also measured using sealed specimens. The effect of water/cement ratio and initial moist-curing time on relative humidity distribution in concrete was also investigated. The effect of moisture diffusion and self-desiccation on relative humidity at each location of concrete is discussed. In addition, the validation of moisture diffusion theory was verified by comparing experimental results with the results obtained from the moisture diffusion model.

2. Moisture diffusion of concrete at early ages

If concrete is exposed to ambient air at early ages, water movement takes place due to moisture diffusion. Therefore, the moisture distribution of a cross-section becomes nonuniform. In addition, self-desiccation in concrete occurs due to hydration of cement. Therefore, the variation of relative humidity in young concrete is a result of both moisture diffusion and self-desiccation. The self-desiccation phenomenon is especially significant for high-strength concrete with low water/cement ratio at early ages.

Fig. 1 shows a schematic illustration of the variation of relative humidity in concrete exposed to the ambient air at early ages. At time t_0 when drying is allowed to begin, the internal relative humidity already has decreased partially, due to self-desiccation. After concrete is exposed to the ambient air, however, the internal relative humidity decreases due to moisture diffusion also. The rates of moisture diffu-

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sion and self-desiccation are mainly dependent on material properties of the concrete, such as water/cement ratio and microstructure of concrete, and the outer drying conditions. Assuming that the inner variation of relative humidity due to self-desiccation in drying specimens is the same as that in sealed specimens, the total variation of internal relative humidity can be represented as in Eq. (1):

$$\Delta h = \Delta h_d + \Delta h_s \tag{1}$$

where Δh is the total inner variation of relative humidity, Δh_d is the variation of relative humidity due to moisture diffusion at each location, and Δh_s is the variation of relative humidity due to self-desiccation. In Fig. 1, the relative humidity (h_d) due to moisture diffusion can be obtained only by Eq. (2):

$$h_d = h + \Delta h_s \tag{2}$$

where h represents the internal relative humidity in the concrete at time t.

Thus, variations of internal relative humidity in concrete are expressed as the variation of relative humidity due to moisture diffusion and self-desiccation of concrete, as shown in Eq. (3).

$$\frac{\partial h}{\partial t} = \frac{\partial h_d}{\partial t} + \frac{\partial h_s}{\partial t} \tag{3}$$

Fick's second law type of equation must be written to represent $\partial h_d/\partial t$ of Eq. (3), as shown in Eq. (4) [1,2].

$$\frac{\partial h_d}{\partial t} = \mathrm{div}(D(h_s, h, w/c)\,\mathrm{grad}\ h) \tag{4}$$

Combining Eqs. (3) and (4) yields Eq. (5):

$$\frac{\partial h}{\partial t} = \mathrm{div}(D(h_s, h, \mathrm{w/c})\,\mathrm{grad}\ h) + \frac{\partial h_s}{\partial t} \tag{5}$$

where D denotes the moisture diffusion coefficient. In CEB-FIP (1990) model code [6], the moisture diffusion coefficient for isothermal conditions is expressed as a function of the pore relative humidity as seen in Eq. (6):

$$D(h) = D_1\left(\alpha + \frac{1-\alpha}{1 + [(1-h)/(1-h_c)]^n}\right) \tag{6}$$

where D_1 is the maximum of $D(h)$ for $h = 1.0$, $\alpha = D_0/D_1$, D_0 is the minimum of $D(h)$ for $h = 0.0$, h_c is the pore relative humidity at $D(h) = 0.5D_1$, and n is an exponent. $\alpha = 0.05$, $h_c = 0.80$, and $n = 15$ are approximately assumed [6].

Eq. (5) can be used for the determination of relative humidity when both moisture diffusion and self-desiccation are active. In this research, the term $\partial h_s/\partial t$ of Eq. (5) is directly obtained from experiments. The nonlinear moisture diffusion equation, as shown in Eq. (5), was formulated by finite element method, considering the boundary condition in previous study [2]. As the boundary condition of moisture, it is necessary to correlate the surface moisture with the humidity of the environmental atmosphere. On the exposed surface S, the boundary condition is shown in Eq. (7):

$$D\left(\frac{\partial h}{\partial n}\right)_s = f(h_{en} - h_s) \tag{7}$$

where f is the surface factor, h_{en} is the environmental humidity, and h_s is the relative humidity on the exposed surface. Bazant and Najjar dealt with this problem by assuming an additional thickness to the specimen (i.e., the equivalent surface thickness) [1]. Comparing analytical results with experimental ones, Bazant and Najjar reported that the value of the equivalent surface thickness is 0.75 mm. In Eq. (5), $\partial h_s/\partial t$ denotes the rate of self-desiccation due to hydration of cement. This term is generally neglected. However, for high-strength concrete prepared with a high unit cement content, the rate of self-desiccation affects the total variation of relative humidity of concrete, especially at very early ages.

In this study, experiments on relative humidity distribution due to moisture diffusion and self-desiccation were carried out at early ages. The experimental results were analyzed by using the relations shown in Eq. (2) and Eq. (4).

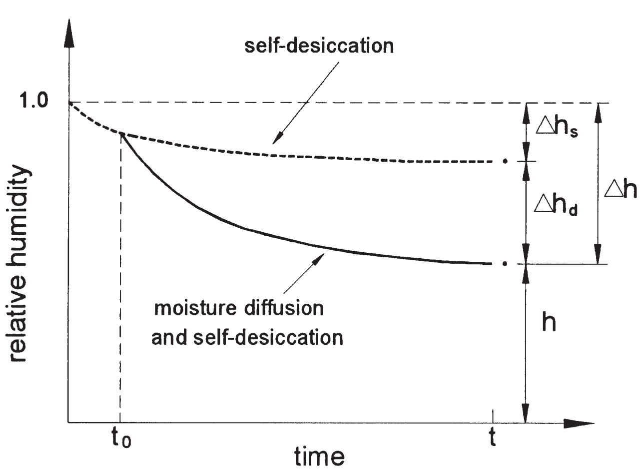


Fig. 1. Variation of relative humidity in concrete at early ages.

3. Experimental program

3.1. Test variables

To study the effect of self-desiccation on moisture distribution in concrete, concrete with three levels of compressive strength (f_c') was selected, and test specimens were moist-cured for 3 and 28 days, as shown in Table 1. After moist-curing, the internal relative humidity in concrete was

Table 1
Test variables

28-day compressive strength of concrete (MPa)	22, 53,76
Initial moist-curing time (day)	3, 28
Depth from exposed surface (cm)	3, 7, 12

Table 2
Mix proportions of concrete

Specimen	w/c (%)	S/A[a] (%)	Unit weight (kg/m^3)				S.P.[b] (C × %)	f_c' (MPa)
			Water	Cement	Sand	Gravel		
H[c]	28	38	151	541	647	1055	2.0	76
M[c]	40	42	169	423	736	1016	0.5	53
L[c]	68	45	210	310	782	955	–	22

[a] Sand (S) + gravel (G).
[b] Superplastizer.
[c] H, M, and L denote high-, medium-, and low-strength concrete, respectively.

measured at the distance of 3, 7, and 12 cm from the exposed surface.

3.2. Materials and mix proportions

The cement used in the experiments was ordinary portland cement (ASTM Type I). River sand was used as fine aggregate and crushed granite gravel passing the 19-mm sieve was used as coarse aggregate. Detailed mix proportions of concrete specimens are given in Table 2. A superplastizer meeting ASTM C 494 requirements for Type F admixture was used to obtain a good workability in Mixes M and H.

3.3. Specimen preparation

As shown in Table 3, three types of concrete specimens were prepared for experiments on moisture diffusion and self-desiccation. For measuring the internal relative humidity in concrete, both drying specimens and sealed specimens were used. Another specimen was prepared for measuring the total moisture loss of concrete during drying. For each condition, two identical specimens were tested.

At the age of 1 day, the mould was removed from test specimens. The specimens were submerged into water until the tests were started. After moist-curing, test specimens were exposed to a constant temperature of 20 ± 1°C and constant humidity of 50 ± 2% relative humidity.

3.4. Experimental method

The internal relative humidity in concrete was measured using a Vaisala HMP44 probe and a Vaisala HMI41 indicator [7,8]. After drilling a hole at various distances from the exposed surface, plastic sleeves were placed at each location as shown in Fig. 2. The relative humidity probe was inserted with a rubber plug in the plastic sleeve. The relative humidity within the sleeve was measured using the HMI41 indicator as soon as the equilibrium between the concrete and the air in the plastic sleeve was obtained.

Table 3
Type and size of specimen

Objective	Type of specimen	Size of specimen (cm)
Measurement of relative humidity in concrete	Drying specimen	10 × 10 × 20
	Sealed specimen	10 × 10 × 10
Measurement of moisture loss	Drying specimen	10 × 10 × 20

3.5. Experimental details and procedure

As shown in Fig. 3, the exposed area of the drying specimen is 10 × 10 cm. The total depth of specimen is 20 cm. Five sides of the specimen were sealed with paraffin wax to ensure that only uniaxial moisture diffusion took place during the drying process. The plastic sleeves in which the relative humidity was measured were placed at distances of 3, 7, and 12 cm from exposed surface.

To measure the variation of relative humidity due to self-desiccation only, totally sealed specimens were also used. The size of these specimens was 10 × 10 × 10 cm.

4. Results and discussion

4.1. Moisture distribution in concrete

Figs. 4 and 5 show the distribution of relative humidity of the specimens subjected to drying and self-desiccation. Specimens used to obtain the results in Fig. 4 where moist-cured for 3 days before testing. In the case presented in Fig. 5, 28 days of moist-curing were employed. The variation of relative humidity due to self-desiccation in sealed specimens is also shown in Figs. 4 and 5. At time t_0 when drying begins, the initial internal relative humidity in specimens with low water/cement ratio decreased due to self-desiccation despite of the earlier moist-curing. This is due to the

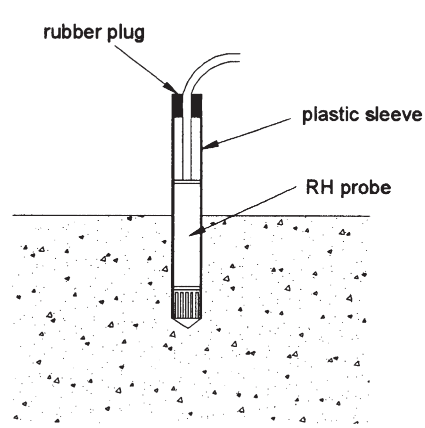


Fig. 2. Measuring device for the internal relative humidity in concrete.

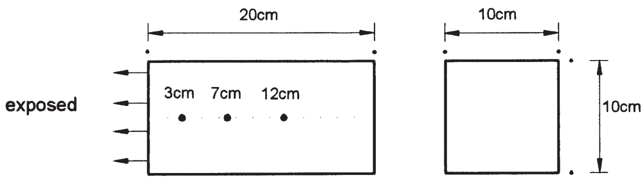
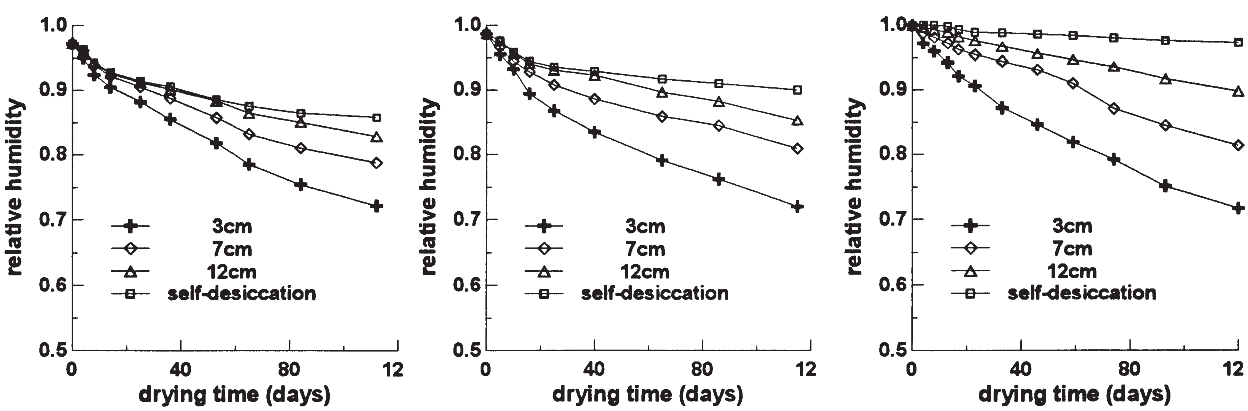


Fig. 3. Geometry and size of test specimens.

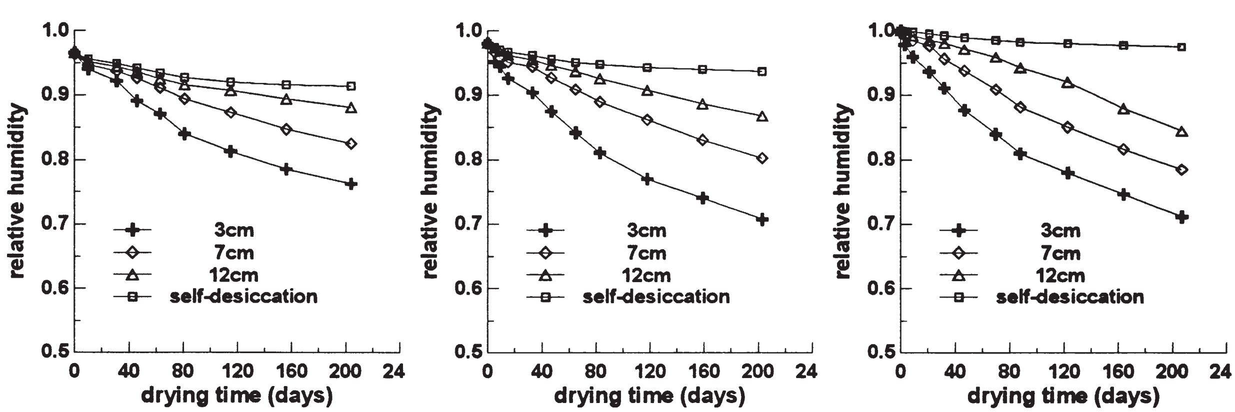
fact that although the specimens are subjected to moist-curing before drying, high-strength concrete with low water/cement ratio becomes so dense and impermeable that the moist-curing water will not fully penetrate the specimen. The self-desiccation may be more active in this case. However, in low-strength concrete with high water/cement ratio, the initial internal relative humidity was fully saturated at the start of the experiment. This trend is similar to experimental results of previous research [9].

The internal relative humidity significantly differed according to the depth from the exposed surface, and the change of relative humidity was greater at the depth close to exposed surface than at an inner region of the concrete. In concrete with high water/cement ratio, the variation of relative humidity due to self-desiccation was very small. The difference of relative humidity at each location in the specimen with high water/cement ratio increased more rapidly with drying time than that of high-strength concrete with low water/cement ratio. However, for concrete with low water/cement ratio, self-desiccation had a considerable influence on moisture distribution in concrete, especially at t_0 = 3 days. That is, the moisture distribution in concrete with low water/cement ratio at early ages was affected by self-desiccation as well as by moisture diffusion. On the other hand, the difference in internal relative humidity with drying time due only to moisture diffusion was small in concrete with low water/cement ratio. This is due to the fact that the dense microstructure of high-strength concrete de-



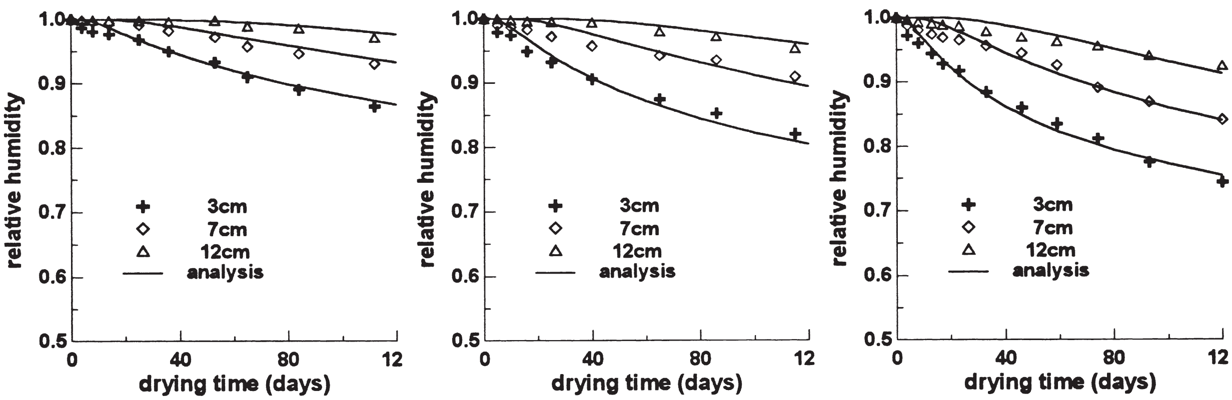
(a) H (W/C=0.28) (b) M (W/C=0.40) (c) L (W/C=0.68)

Fig. 4. Relative humidity distribution in concrete due to moisture diffusion and self-desiccation (t_0 = 3 days).



(a) H (W/C=0.28) (b) M (W/C=0.40) (c) L (W/C=0.68)

Fig. 5. Relative humidity distribution in concrete due to moisture diffusion and self-desiccation (t_0 = 28 days).



(a) H (W/C=0.28) (b) M (W/C=0.40) (c) L (W/C=0.68)

Fig. 6. Calculated relative humidity values compared to modified experimental values (t_0 = 3 days).

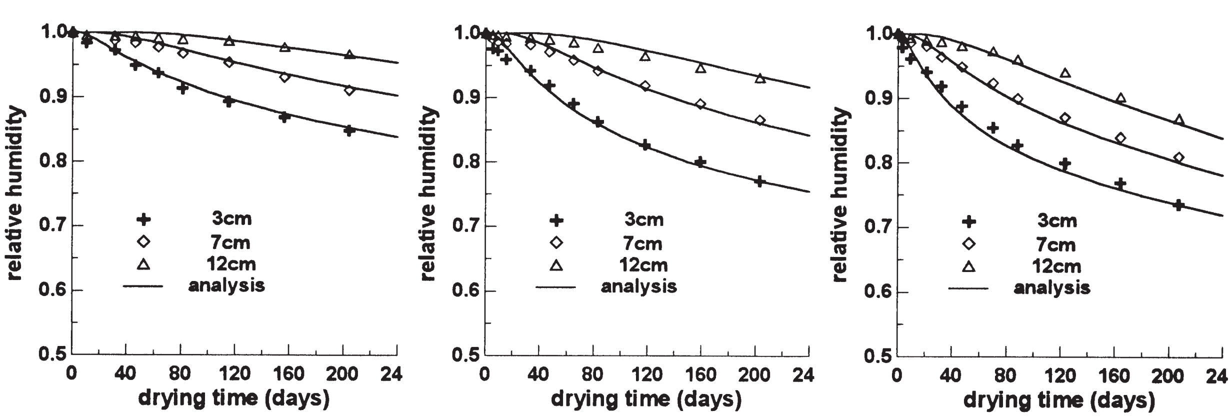
creases the rate of moisture diffusion, and the higher cement content increases self-desiccation.

The moisture distribution in concrete with high water/cement ratio was mainly influenced by moisture diffusion. Therefore, the variation of internal relative humidity of concrete with high water/cement ratio can be described by the term $\partial h_d/\partial t$ in Eq. (3), and $\partial h_s/\partial t$ can be assumed to be negligible. In concrete with low water/cement ratio, however, $\partial h_s/\partial t$ as well as $\partial h_d/\partial t$ must be considered. Thus, to evaluate the experiments on moisture diffusion in concrete at early ages, the effect of self-desiccation on internal relative humidity of concrete must be considered.

4.2. Results of internal relative humidity due to moisture diffusion

Figs. 6 and 7 show the predicted relative humidity at the distances of 3, 7, and 12 cm from exposed surface due to moisture diffusion only. These values are obtained from the experimental results presented in Figs. 4 and 5 by simply separating the internal relative humidity due only to moisture diffusion from the measured moisture distribution in concrete. This clearly shows that the effect of water/cement ratio on moisture diffusion is very significant. Therefore, the rate of moisture diffusion in concrete with high water/cement ratio is concluded to be much higher than that in concrete with low water/cement ratio. The relative humidity near the exposed surface decreased rapidly at the early stage of drying, but inside the concrete, the relative humidity varied very slowly.

The relative humidity distribution in the test specimens was analyzed by the nonlinear moisture diffusion equation shown in Eq. (4). The calculated values of moisture distribution obtained by using this nonlinear moisture diffusion equation were compared with experimental results in Figs. 6 and 7. A finite element program capable of solving nonlin-



(a) H (W/C=0.28) (b) M (W/C=0.40) (c) L (W/C=0.68)

Fig. 7. Calculated relative humidity values compared to modified experimental values (t_0 = 28 days).

Table 4
Maximum moisture diffusion coefficient used in the analysis (unit: m^2/h)

Specimen[a]	t_0 = 3 days	t_0 = 28 days	CEB-FIP (1990)
H (w/c = 0.28)	1.45×10^{-6}	1.12×10^{-6}	0.53×10^{-6}
M (w/c = 0.40)	1.60×10^{-6}	1.26×10^{-6}	0.80×10^{-6}
L (w/c = 0.68)	2.65×10^{-6}	2.62×10^{-6}	2.57×10^{-6}

[a] H, M, and L denote high-, medium-, and low-strength concrete, respectively.

ear moisture diffusion equation, developed previously [2], was used in this analysis. The input data used in the finite element program (i.e., the geometric conditions, mix proportions, and the atmospheric conditions) are the same as those used in these experiments. The input data (α, h_c, n) related to moisture diffusion coefficient was the values recommended by the CEB-FIP (1990) model. The maximum moisture diffusion coefficient used, denoted D_1, was calibrated for best fits between experimental and theoretical results. Table 4 shows the maximum values used in the moisture diffusion analysis. The values of D_1 used were higher than those recommended by the CEB-FIP (1990) model.

As shown in Figs. 6 and 7, the predicted values were in good agreement with the modified experimental results. It seems that moisture diffusion can be well predicted by the nonlinear moisture diffusion theory in 3-day moist-cured concrete exposed to ambient air at early ages, as well as in 28-day moist-cured concrete.

4.3. Effect of moist-curing time on moisture diffusion of concrete

The effect of moist-curing time on moisture diffusion in concrete is presented in Fig. 8. This figure shows that the initial moist-curing time has a considerable effect on moisture diffusion in concrete. At each location, the variation of internal relative humidity with drying time in 28-day moist-cured concrete was smaller than that of 3-day moist-cured concrete. Because the moist-curing time influences the microstructure of concrete, the moisture diffusion is also affected.

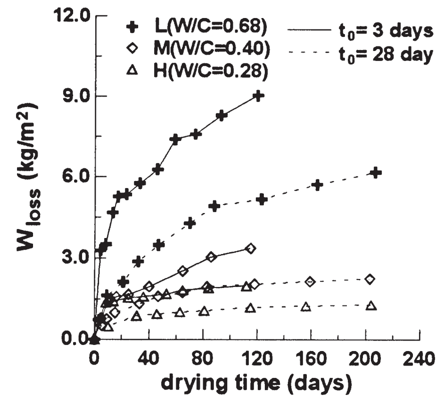
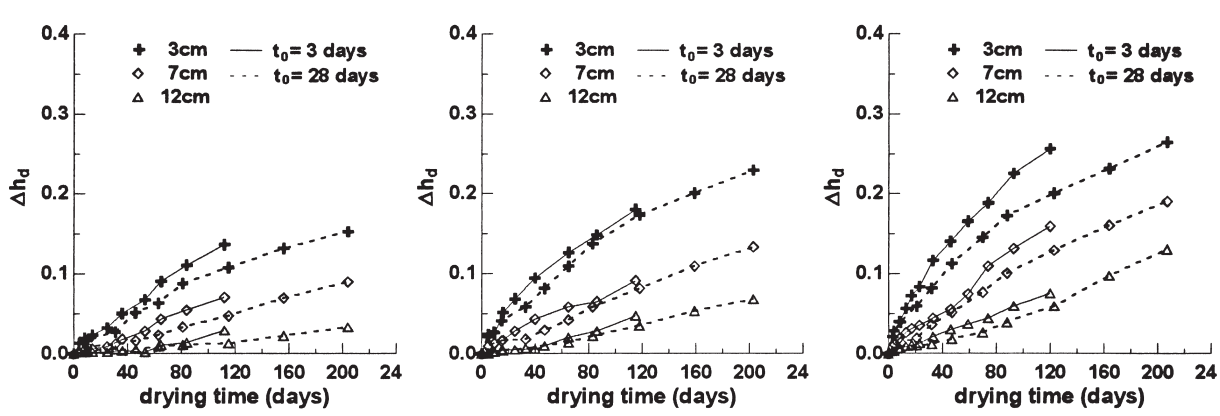


Fig. 9. Moisture loss of concrete.

4.4. Moisture loss of concrete

Moisture loss from concrete specimens to the surroundings is related directly to moisture diffusion and is not affected directly by self-desiccation. Fig. 9 shows the moisture loss of concrete with drying time. In Fig. 9, the moisture loss of the concrete is represented as moisture loss weight per unit exposed area (kg/m^2). As the water/cement ratio and unit water content increased, the moisture loss increased significantly. Fig. 9 also shows that the moisture loss of concrete was considerably influenced by initial moist-curing time. When exposed at t_0 = 3 days, the moisture loss of concrete was larger than that exposed at t_0 = 28 days. This is because the evaporable free water content in capillary pore of a 3-day moist-cured concrete is higher than that in a 28-day moist-cured concrete, and also because the rate of moisture diffusion in a 3-day moist-cured concrete is higher compared to a specimen cured for 28 days, as shown in Fig. 8.



(a) H (W/C=0.28) (b) M (W/C=0.40) (c) L (W/C=0.68)

Fig. 8. Effect of moist-curing time on moisture diffusion of concrete.

5. Conclusions

From this investigation on moisture diffusion and self-desiccation in concrete, the following conclusions can be drawn.

1. The moisture distribution in concrete with high water/cement ratio was influenced mostly by moisture diffusion, but little by self-desiccation. The rate of moisture diffusion in concrete with high water/cement ratio was much higher than that of concrete with low water/cement ratio.
2. In concrete with low water/cement ratio, self-desiccation had a considerable influence on moisture distribution in a cross-section of concrete. That is, the moisture distribution in concrete was affected by self-desiccation as well as moisture diffusion of concrete. On the other hand, the difference of relative humidity with drying time due to moisture diffusion in concrete with low water/cement ratio was small compared with concrete with high water/cement ratio.
3. To evaluate the experiments on moisture diffusion in concrete at early ages, it seems that the effect of self-desiccation on internal relative humidity must also be considered.
4. The results obtained by the proposed moisture diffusion theory were in good agreement with the modified experimental results.
5. The moisture diffusion and moisture loss of concrete were influenced by initial moist-curing time as well as water/cement ratio and unit water content.

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