ARCHITECTURAL RESEARCH, Vol. 14, No. 4(December 2012). pp. 153-161 ISSN 1229-6163

Prediction of Temperature and Moisture Distributions in Hardening Concrete By Using a Hydration Model

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http://dx.doi.org/10.5659/AIKAR.2012.14.4.153

Abstract This paper presents an integrated procedure to predict the temperature and moisture distributions in hardening concrete considering the effects of temperature and aging. The degree of hydration is employed as a fundamental parameter to evaluate hydro-thermal-mechanical properties of hardening concrete. The temperature history and temperature distribution in hardening concrete is evaluated by combining cement hydration model with three-dimensional finite element thermal analysis. On the other hand, the influences of both self-desiccation and moisture diffusion on variation of relative humidity are considered. The self-desiccation is evaluated by using a semi-empirical expression with desorption isotherm and degree of hydration. The moisture diffusivity is expressed as a function of degree of hydration and current relative humidity. The proposed procedure is verified with experimental results and can be used to evaluate the early-age crack of hardening concrete.

Keywords: Degree of Hydration, Temperature Distribution, Moisture Distribution, Hardening Concrete, Modeling

1. INTRODUCTION

The continuously casting concrete may result in cracking propagation within structures. Researchers and engineers have noticed that high thermal stresses happen within mass concrete members when pouring a thick foundation base or constructing a dam. Preventive measures, such as using less quantity and low-heat cement, adding proper additives, cooling down, insulating surface and placing rebars, had been developed since the middle of the past century (Park et al. 2008). The cracking within early-age concrete relates with both the development of strength and early-age stress. For hardening concrete, the early-age stress relates with thermal variation, shrinkage and creep behavior. Thermal variation closely relates with the temperature history and temperature distribution in hardening concrete, and the shrinkage strain includes autogenous shrinkage strain and drying shrinkage strain, both of which closely relates with moisture distributions in concrete (Maekawa et al 2009). So the prediction of temperature and moisture distributions is a crucial step to control the early-age crack of hardening concrete (Mehta, 2006)

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This research was supported by Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (331-2008-D00661).

The prediction of temperature history in hardening concrete is essential to estimate the thermal stress as well as to prevent thermal cracking. The ability to predict the expected temperature history would thus be useful to structural engineers and designers interested in producing a durable concrete structure. In the past, several researchers (Cook and Aitcin 1993, Wang and Dilger 1994, and Bentz et al 1998) have attempted to predict the temperature rise occurring in hardening concrete, but the focus of these models has been on following the relationships between hydration heat rate and concrete maturity function under adiabatic conditions. The models did not take into account the effect of the water-cement ratio (w/c) on hydration heat release. The heat generation and varying mechanical properties of concrete at early ages are strongly related to the degree of hydration of each mineral compound consisting of cement. Thus, it is desired to consistently predict them with a single correlating parameter, that is, degree of hydration.

On the other hand, in concrete structures exposed to ambient air, the moisture content decreases due to moisture diffusion during drying (Kim and Lee 1998). In addition, self-desiccation due to hydration of cement causes an additional decrease of moisture content in concrete at early ages (Persson 1997). 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 (Kim and Lee 1999, Oh and Cha2003). Bazant and Najjar 1972, Luzio (2009a and 2009b) have modeled the moisture diffusion in hardened concrete. For early-age hardening concrete, due to the ignorance of the dependence of moisture diffusivity on aging of concrete, Bazant and Najjar (1972) and Luzio(2009a and 2009b)'s work are not valid. Yuan and Wan (2002) proposed a numerical procedure to evaluate the thermal, drying and creep behavior of young concrete. Yuan and Wan's work does not take into account the effects of temperature on the heat evaluate rate and development of mechanical properties. Moreover, the aging effect of moisture diffusivity in concrete with various temperature history has not been considered in Yuan and Wan's work.

In this paper, we proposed an integrated procedure to predict the temperature and moisture distributions in hardening concrete. The degree of hydration is employed as an intrinsic parameter to determine the heat evaluate rate, relative humidity decreasing due to self-desiccation, and moisture diffusivity of hardening concrete. The heat evolution rate is determined by degree of hydration and cement chemical composition, the self-desiccation is evaluated by using a semi-empirical expression with desorption isotherm and degree of hydration, and the moisture diffusivity is expressed as a function of degree of hydration and current relative humidity. Predicted temperature history and moisture distribution curves were compared with experimental data and good correlations were found.

2. HYDRATION MODEL OF PORTLAND CEMENT

2.1 Hydration Mechanism

At the beginning of the hydration simulation, cement particles are randomly cast into the representative unit cell space, as shown in Figure 1. It is assumed that cement hydration will start when cement and water come into contact, and the hydrate formed by the hydration adheres spherically to the cement particles.

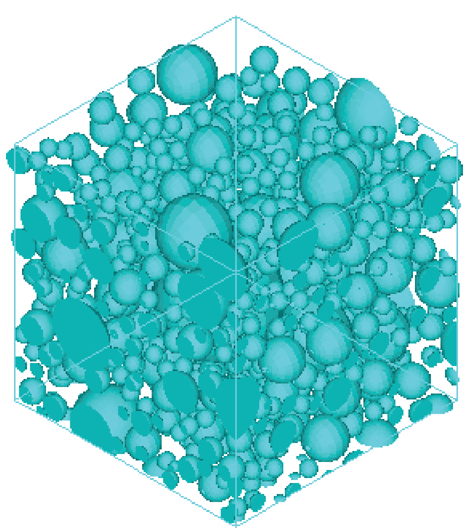


Figure 1. Cement particles distribute randomly in the cell space.

The basic hydration equation is described in Equation (1), which was developed by Tomosawa (1997) to describe the hydration of a single cement particle. His model divided the hydration of cement into three processes: the initial dormant period, phase boundary reaction process and diffusion period.

$$\frac{d\alpha^j}{dt} = \frac{3C_{w\infty}}{(v+w_{ag})r_0^j\rho}\frac{1}{(\frac{1}{k_d}-\frac{r_0^j}{D_e})+\frac{r_0^j}{D_e}(1-\alpha^j)^{\frac{-1}{3}}+\frac{1}{k_r}(1-\alpha^j)^{\frac{-2}{3}}} \quad (1)$$

In the equation above, α^j denotes the degree of hydration of cement particles; j refers to an individual cement particle; v is the stoichiometric ratio of the masses of water to cement; w_{ag} is the physically bound water; ρ is the density of cement; r_0^j is the radius of anhydrate cement particles; D_e is the effective diffusion coefficient of water in the hydration product; $C_{w\infty}$ is the concentration of water at the outer region of the gel; k_r is the coefficient of the reaction rate of cement; and k_d is the reaction coefficient in a dormant period and is expressed in Equation (2):

$$k_d = \frac{B}{(\alpha^j)^{1.5}} + C(r_0^j - r_t^j)^4 \quad (2)$$

where B and C are the rate determining coefficients of cement hydration and r_t^j is the inner radius of the hydrating cement particle.

The effective diffusion coefficient of water is affected by the tortuosity of the gel pores as well as the radii of the gel pores in the hydrate. This phenomenon can be described as a function of the degree of hydration shown in Equation (3):

$$D_e = D_{e0}\ln(\frac{1}{\alpha^j}) \quad (3)$$

where D_{e0} is the initial diffusion coefficient.

The influence of temperature on cement hydration is considered by the Arrhenius law in Equations (4)-(6):

$$B = B_{20}\exp(-\beta_1(\frac{1}{T}-\frac{1}{293})) \quad (4)$$

$$D_e = D_{e20}\exp(-\beta_2(\frac{1}{T}-\frac{1}{293})) \quad (5)$$

$$k_r = k_{r20}\exp(-\frac{E}{R}(\frac{1}{T}-\frac{1}{293})) \quad (6)$$

where B_{20}, D_{e20}, and k_{r20} are the values of B, D_e, and k_r at 293 K, respectively, and β_1, β_2, and E/R are the activation energies of B, D_e, and k_r respectively. In this paper, the values of hydration reaction coefficients are obtained from the calibration of experimental results of degree of hydration of cement by using predictor-corrector methods (Tomosawa 1997).

The degree of hydration of cement can be calculated from the hydration degrees of individual cement particles as follows:

$$\alpha = \sum_{j=1}^{j=n}\alpha^j g^j \quad (7)$$

where g^j is the weight fraction of the individual particle j and n is the total number of cement particles in the cell space.

Furthermore, by considering the development of microstructure of hydrating cement and the reduction of capillary water during hydration process, Equation (1) can be modified to form Equation

$$\left(\frac{d\alpha^j}{dt}\right)' = \frac{d\alpha^j}{dt} * (\frac{freesurface}{totalsurface})^j * \frac{w_0 - 0.42 * Ce_0 * \alpha}{w_0} \quad (8)$$

where $(\frac{freesurface}{totalsurface})^j$ is the ratio between the free surface area (the area which contacts water) and the total surface area that is determined by Navi's proposed method (1996); w_0 is the total water mass; Ce_0 is the cement mass in a mixing proportion, and $\frac{w_0 - 0.42 * Ce_0 * \alpha}{w_0}$ describes the decrease in the capillary water available for cement hydration.

2.2 Heat Evolution Rate

The heat generation rate for cement paste, $\frac{dQ}{dt}$, is assumed to be proportional to hydration rate,

$$\frac{dQ}{dt} = Ce_0 * \sum P_i H_i \frac{d\alpha}{dt} \tag{9}$$

where H_i is the total heat generation of the individual components of the cement and P_i is the weight percentage of the individual components of the cement.

Based on the hydration model, the incremental temperature rise in one time step under adiabatic conditions can be calculated as in Equation (10):

$$\Delta T = \frac{dQ(t)}{Cp(t)} \tag{10}$$

where ΔT is the incremental temperature in one time step; $dQ(t)$ is the released heat that can be determined from Equation (9); and $Cp(t)$ is the heat capacity of the hydrating concrete that can be calculated as the sum of the individual components of the concrete (The heat capacities of cement, fly ash, slag, sand, aggregate, water, and chemically bound water are 0.84 J/g℃, 0.84 J/g℃, 0.84 J/g℃, 0.9 J/g℃, 0.9 J/g℃, 4.18J/g℃, and 2.2 J/g℃ respectively) (Tomosawa 1997; Tomosawa et al. 1997).

2.3 Prediction of Temperature Distribution and History in Quasi-adiabatic Concrete

At any time, the temperature distribution in a hardening concrete is in a dynamic heat balance between the heat generated inside the concrete and heat loss to the surroundings. The heat generation inside comes from hydration reactions of the cement and the mineral admixtures. The temperature distribution is determined by the following heat equation (Park et al. 2008):

$$Cp(t)\frac{\partial T}{\partial t} = div(k\nabla T) + \frac{dQ}{dt} \tag{11}$$

where k is the thermal conductivity of concrete; and $\frac{dQ}{dt}$ is the heat generation rate in hardening concrete, which can be calculated based on the degrees of hydration of the cement (Equation 9).

There exist two types of boundary conditions for Equation (11). The first is that the temperature along the boundary or around a portion of the boundary is known, and the second is that the energy transfer through the boundary is known. For ordinary engineering structures, the second type of boundary condition normally occurs. This boundary condition can be described by the following equation:

$$k\nabla T = \beta\left(T_s - T_a\right) \tag{12}$$

where β is the heat convection coefficient between the surface of the concrete and the surrounding environment; T_s is the temperature on the surface of the concrete; and T_a is the temperature of the surrounding environment.

The initial condition can be described by the following equation:

$$T|_{t=0} = T_0 \tag{13}$$

where T_0 is the initial temperature of the concrete member.

In this paper a finite element method is adopted both in time and in space to solve equation (11) numerically. The eight-node isoparametric element is built to discrete mass volume concrete in three dimensional space. After space discretization with a Galerkin procedure, equation (11) can be rewritten as following:

$$[B]\{T\} + [C]\frac{\partial\{T\}}{\partial t} = \{P\} \tag{14}$$

In equation (14), the global matrix $[B]$, $[C]$ and $\{P\}$ are obtained from the integration of element matrix.

Furthermore, based on time space discretization, the equation (14) can be written as

$$([B] + [C]\theta\Delta t)\{T\}_{n+1} = ([B] - [C](1-\theta)\Delta t)\{T\}_n + \{P\}_n \Delta t \tag{15}$$

Generally, the value of parameter θ should be higher than 0.5 to confirm the stability of numerical calculation. In this paper based on Galerkin procedure in time space, the value of parameter θ is adopted as 2/3.

2.4 Prediction of Moisture Variation in Hardening Concrete

In concrete structures exposed to ambient air, the moisture content decreases due to moisture diffusion during drying. 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 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.

For hardening concrete, the total variation of internal relative humidity relates with both self-desiccation and moisture diffusion, which can be represented as Equation (16) (Kim and Lee 1999):

$$\frac{\partial h}{\partial t} = \frac{\partial h_d}{\partial t} + \frac{\partial h_s}{\partial t} \tag{16}$$

Where $\frac{\partial h}{\partial t}$ is the total variation rate of relative humidity in concrete, $\frac{\partial h_d}{\partial t}$ is relative humidity variation rate due to moisture diffusion, and $\frac{\partial h_s}{\partial t}$ is relative humidity variation rate due to self-desiccation.

The relative humidity variation rate due to moisture diffusion can be determined through Fick's second law as the following Equation (17) (Bazant and Najjar, 1972):

$$\frac{\partial h_d}{\partial t} = div(D(h)\nabla h) \tag{17}$$

Where $D(h)$ denotes the moisture diffusion coefficient. As proposed by Bazant and Najjar(1972), the moisture diffusion coefficient can be expressed as a function of relative humidity as equation (18-1):

$$D(h) = D_I\left(m + \frac{1-m}{1+\left[\frac{1-h}{1-h_c}\right]^n}\right) \tag{18-1}$$

Where D_I is the maximum $D(h)$ when h=1, h_c is the pore relative humidity at $D(h) = 0.5D_I$, $m = \frac{D_0}{D_I}$, D_0 is the minimum relative humidity at h=0. n is the exponent. m=0.05, n=15, and h_c =0.8 were approximated assumed (Yuan and Wan,2002). The value of D_I relates with the compressive strength of concrete and may be estimated as follows:

$$D_I = \frac{D_{1.0}}{f_c(t)/f_{c0}} \tag{18-2}$$

Where $D_{1.0}$=3.9*10-6m2/h, f_{c0}=10 MPa and the the development of compressive strength of hardening concrete $f_c(t)$, can be evaluated through Powers' strength theory, as:

$$f_c(t) = A{x_{pc}}^n \tag{18-3}$$

where A is the intrinsic strength of cement gel, or the strength at zero capillary porosity, and can be regarded as the final strength of concrete; n is a constant (usually between 2 and 3); and x_{pc} is gel/space ratio of hydrating cement paste which is approximately given by

$$x_{pc} = \frac{v(T)(1/\rho)\alpha}{(1/\rho)\alpha + \frac{w_0}{Ce_0}} \tag{18-4}$$

$$v(T) = \frac{\text{volume of hydration products at T}}{\text{volume of reacted cement at T}} = v_{293}\exp(-28\times10^{-6}(T-293)^2) \tag{18-5}$$

where $v(T)$ is the ratio between the volume of hydration products and that of reacted cement. As shown in Equation (18-5), with the increasing of curing temperature, this ratio will decrease ($v_{293} \approx 2.2$) (Wang and Lee, 2012)

In this paper, we assumed that the intrinsic strength will increase with the decreasing of the curing temperature, which can be written as follows:

$$A = aT^{-b} \tag{18-6}$$

In our former research (Wang and Lee, 2012), based on analysis of mechanical properties of concrete with various temperature, the intrinsic strength of concrete was estimates as a function of chemical composition of cement shown as follows:

$$a = 115 * \frac{g_{C_3S}}{g_{C_3S} + g_{C_2S}} + 172 * \frac{g_{C_2S}}{g_{C_3S} + g_{C_2S}} \tag{18-7}$$

Where g_{C_3S} and g_{C_2S} are the mass percentage of C3S and C2S in mineral composition of cement respectively, b=0.238, and n=2.118.

For hardening concrete, the development of compressive strength depends on a trade-off among some competing effects: when the curing temperature increases, the rate of cement hydration will increase. This factor will contribute to the trend that with the increase of curing temperature, at a certain age, the compressive strength will increase. On the other hand, with the increase of curing temperature, the ratio between the volume of hydration products and that of reacted cement will decrease. In addition, the relative strength of concrete will decrease with the increase of curing temperature. These factors will weaken the increasing trend of compressive strength. Summarily, based on Equations from (18-3) to (18-7), it is possible to model the trend that concrete subjected to a lower early-age temperature attained a lower early-age strength and a higher later-age strength than concrete subjected to a higher early-age temperature (Wang and Lee, 2012). Furthermore, as the development of compressive strength can be determined from the proposed hydration model, the aging effect of hardening concrete on the moisture diffusivity also can be calculated.

On the exposed surface, the boundary condition can be written as

$$D\left(\frac{\partial h}{\partial n}\right)_s = f(h_{en} - h_s) \tag{19}$$

Where $\left(\frac{\partial h}{\partial n}\right)_s$ is the gradient of moisture on the exposed surface of concrete, f is the surface factor, h_{en} is the environmental relative humidity, and h_s is the relative humidity on the exposed surface.

Norling Mjonell (1997) proposed a model on self-desiccation for high performance concrete. In this model, the desorption isotherm was used to describe the self-desiccation. The desorption isotherm is decomposed into two parts: gel isotherm and capillary isotherm. The self-desiccation $\frac{\partial h_s}{\partial t}$ can be determined as follows:

$$h_s = \frac{1}{b-10\alpha}((\sqrt{W_e^2 + 2W_e(W_{cap} - W_{gel}) + W_{gel}^2 + 2W_{cap}W_{gel} + W_{cap}^2} + W_e - W_{gel} + W_{cap})/2W_{cap}) \tag{20}$$

Where b is the shape factor of desorption isotherm and the range of b is from 0.8 to 1.2 (Norling Mjonell (1997)); W_e is the amount of evaporable water in hydrating concrete; W_{cap} is the amount of capillary water in hydrating concrete; and W_{gel} is the amount of gel water in hydrating concrete.

Summarily, in this section, the dependence of moisture diffusivity on the age of concrete is considering is considered through equations from (18-2) to (18-7). With the development of compressive strength of concrete, the porosity of concrete will reduce and the moisture diffusivity will decrease correspondingly. On the other hand, by using the semi-empirical desorption isotherm, the self-desiccation of high performance can be described. Furthermore, by using finite element method, the variation of moisture in hardening concrete can be calculated as a function of time. In this paper, to get the stability in numerical calculation, the Galerkin's procedure is used in the time domain.

3. VERIFICATION OF PROPOSED MODEL

3.1 Prediction of Temperature Distribution in Hardening High Strength Concrete

In this part, the experimental results from Maekawa et al.(2009) on quasi-adiabatic temperature tests are adopted to verify the proposed model. The chemical composition of ordinary Portland cement is shown in the Table 1. As shown in the Table 2, the water to cement ratio is 0.32, which is typical for high performance concrete in the construction sites. The sizes of the block specimens are 400 mm in length, 600 mm in width, and 400 mm in height. The temperature measurement at the center points are carried out on blocks that are completely covered in styrofoam to a depth of 8 cm. Water migration was prevented around the measurement points. The experiments were conducted in an room with no wind and a constant temperature of 20 ℃. The thermal conductivity of concrete is 41 kcal/(m·day·℃), and the heat transfer coefficient is 18 kcal/(m^2·day·℃). For the quasi-adiabatic test of hardening concrete, the release of hydration heat and the thermal convection between specimens and surrounding environment will occur simultaneously. The experimental results of temperature history are shown in Fig.2. From casting time to about 5 hours, the temperature increases very slowly. This period is the initial dormant period of hydration of cement. From 5 hours to 1 day, the phase boundary reaction process which presents a higher hydration rate is the dominant process (Wang and Lee, 2012), hence the concrete temperature in this period will increase rapidly. The temperature peak will occur at about 1 day. In the following age after 1 day, with the changing of hydration kinetic process from phase boundary reaction to diffusion-controlled process, the heat evolution rate become lower and the convection is the dominant. So the concrete temperature will decrease gradually. The Finite element modeling with 3D elements was used for the temperature analysis. Because of the symmetry of the geometry, boundary conditions, and initial conditions, the FEM mesh and calculation is only performed on one-eighth of the specimens. A comparison between the experimental results and the calculated results is shown in Figure 2. As shown in this figure, the calculated results generally agree with experimental results. Because the proposed model has taken into account the effect of low water to cement ratio on the heat evolution, the model can be used to predict the temperature distribution in high strength concrete and high performance concrete.

Table 1. Mineral compositions of cement

Mineral composition (mass %)					Blaine(cm^2/g)
C_3S	C_2S	C_3A	C_4AF	$C\bar{S}_2H$	
47.2	27.0	10.4	9.4	3.9	3380

Table 2. Mix proportions of concrete

Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	Water to cement ratio	Water reducing agent (C×%)
174	550	857	827	0.316	0.25

Table 3. The coefficients of the hydration model

B_{20} * (cm/h)	C (cm/(cm^4·h))	k_{r20} * (cm/h)	D_{e20} * (cm^2/h)	β_1 (K)	β_2 (K)	$\frac{E}{R}$ (K)
7.92× 10-9	1×1015	7.84× 10-6	9.28× 10-8	1000	7500	5400

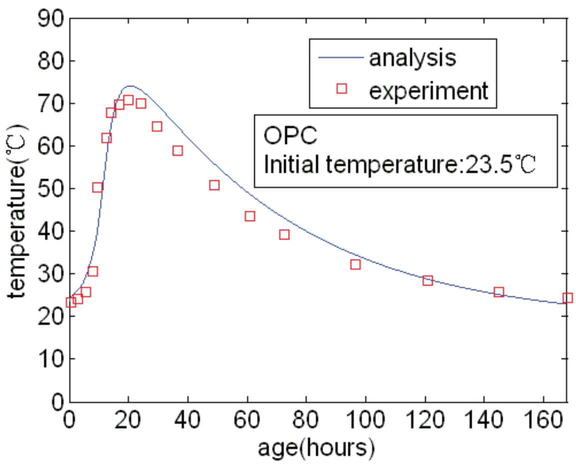


Figure 2. Temperature history of OPC concrete.

3.2 Prediction of Moisture Variation in Hardening Concrete

In this part, the experimental results from Kim and Lee (1999) are adopted to verify the proposed model. To study the effect of self-desiccation on moisture distribution in concrete, concrete with three levels of compressive strength was selected, and test specimens were moist-cured for 3 and 28 days, as shown in Table 4. After moist-curing, the internal relative humidity in concrete was measured at the distance of 3, 7, and 12 cm from the exposed surface. The mixing proportions of concrete are shown in Table 5. The 28 days compressive strengths for high strength concrete (HC), middle strength concrete (MC) and low strength concrete (LC), were 76MPa, 53MPa, and 22MPa respectively. The water to cement ratios for high strength concrete (HC), middle strength concrete (MC) and low strength concrete (LC), were 0.28, 0.4 and 0.68 respectively. The cement used in the experiments was ordinary Portland cement (ASTM Type I).

Two 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. 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 ℃ and constant humidity of 50% relative humidity.

The analysis of self-desiccation of concrete is shown in the Fig.3. In the simulation, when the specimens were moist-cured, the imbibition of water from surroundings into specimens is approximately considered through the amount of imbibed capillary water. Fig.3 represents the analysis of self-desiccation for different curing conditions, i.e. continuously moist-curing, and moist-curing followed by sealed curing. The dashed line in Fig.3 represents the analysis results of the evolution of relative humidity in the continuously moist-curing specimens, while the solid line represents the analysis results of the evolution of relative humidity in the specimens firstly moist-curing and followed by sealed curing. The square points in the Fig.3 represent the experimental results of the decreasing of relative humidity in concrete specimens firstly moist-curing and followed by sealed curing. As shown in this figure, the analysis results generally agree with experimental results. At time t0 when drying begins, the initial internal relative humidity in specimens with low water/cement ratio (Fig.(3-a) and Fig. (3-b), water to cement 0.28) decreased due to self-desiccation despite of the earlier moist-curing. This is due to the 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 (Fig.(3-e) and Fig. (3-f), water to cement ratio 0.68), the initial internal relative humidity was fully saturated at the start of the experiment. With the decreasing of water to cement ratios, the self-desiccation effect becomes more serious (Kim and Lee,1999).

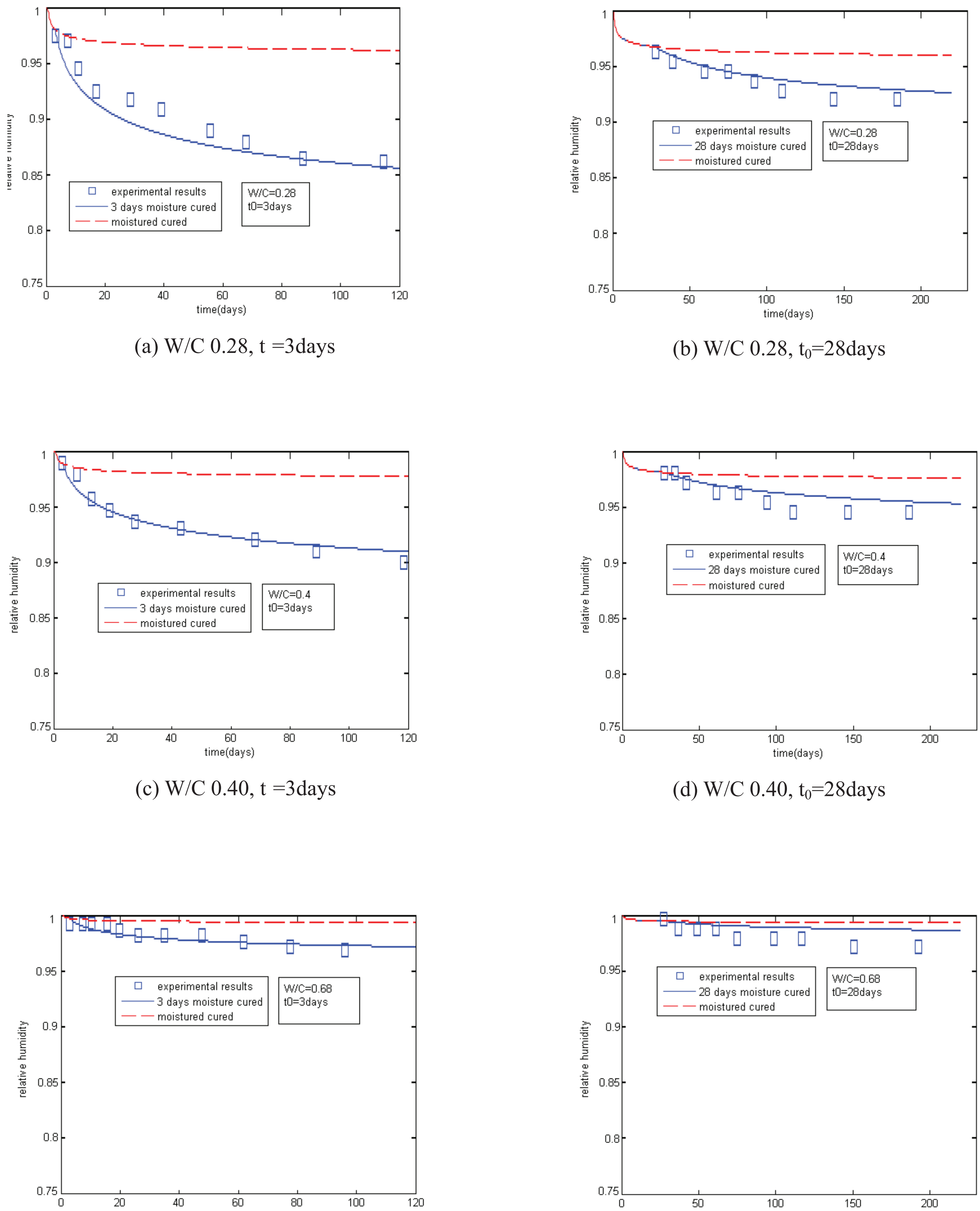
Table 4. Test variables

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

To analysis the moisture variation due to both self-desiccation and moisture diffusion, a finite element method is employed to solve equation (14). A one dimensional linear element is used to discrete the geometrical body. The decreasing of the relative humidity due to self-desiccation is treated as a sink term. As shown in the Fig.4, the analysis results generally reproduce experimental results. As shown in this figure, 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. 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. This is due to the fact that the dense microstructure of high-strength concrete decreases the rate of moisture diffusion (Kim and Lee, 1999). For high strength concrete, the shrinkage, such as autogenous shrinkage and drying shrinkage, relates closely with the variation of relative humidity. The proposed model is valuable for the prediction of shrinkage crack of concrete.

Table 5. Mix proportions of concrete for moisture permeability test

Specimen	W/C	Sand/(sand +gravel)	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Superplasticizer (cement*%)	fc (MPa)
HC	0.28	38	151	541	647	1055	2.0	76
MC	0.40	42	169	423	736	1016	0.5	53
LC	0.68	45	210	310	782	955	-	22



(a) W/C 0.28, t =3days

(b) W/C 0.28, t_0=28days

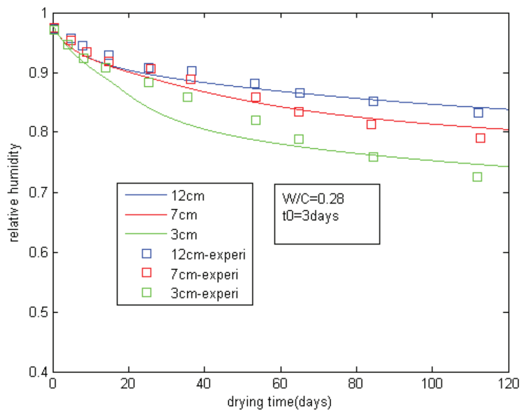
(c) W/C 0.40, t =3days

(d) W/C 0.40, t_0=28days

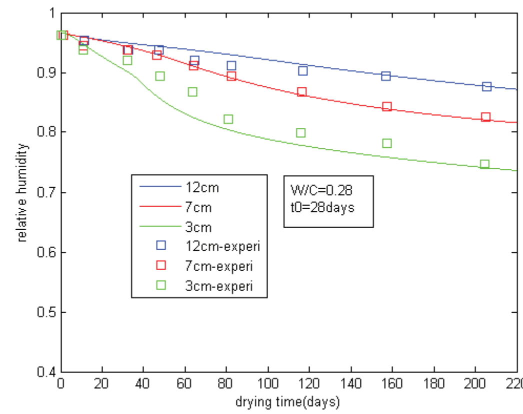
(e) W/C 0.68, t_0=3days

(f) W/C 0.68, t_0=28days

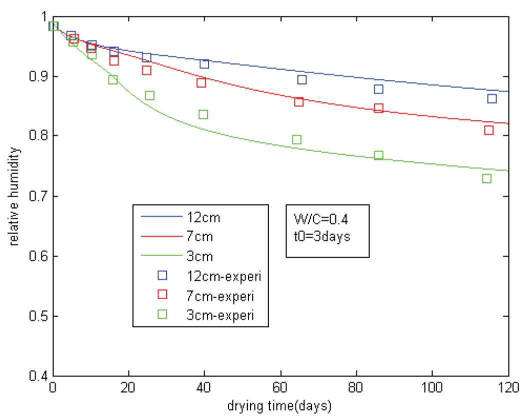
Figure 3. The analysis of relative humidity variation due to self-desiccation.



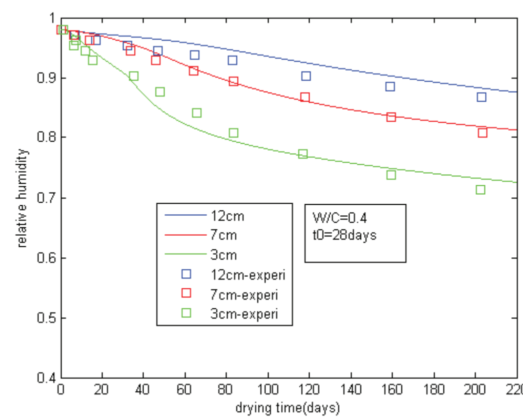
(a) W/C 0.28, t_0=3days



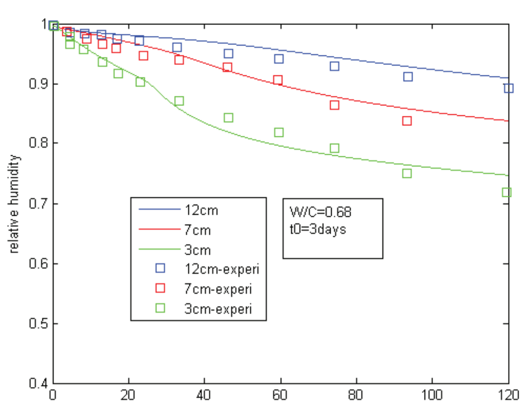
(b) W/C 0.28, t_0=28days



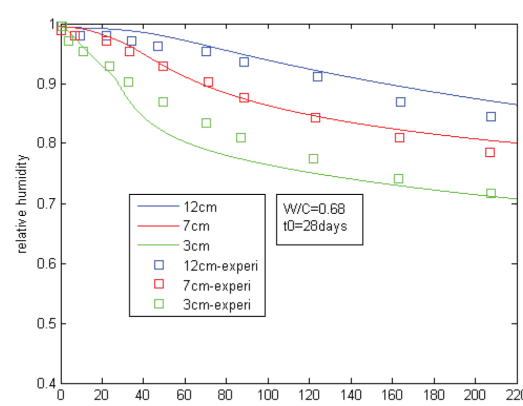
(c) W/C 0.40, t_0=3days



(d) W/C 0.40, t_0=28days



(e) W/C 0.68, t_0=3days



(f) W/C 0.68, t_0=28days

Figure 4. The analysis of relative humidity variation due to both moisture diffusion and self-desiccation.

4. CONCLUSION

In this paper, by using a hydration model which has considered the water-reducing effect for high strength concrete with a low water-to cement ratio, the temperature and moisture distributions in hardening concrete are evaluated. First, the heat evolution rate is determined from degree of hydration and mineral compositions of cement. Furthermore, by using finite element method, the temperature distribution and temperature history is calculated. Second, the self-desiccation of high strength concrete is evaluated through the desorption isotherm of hydrating cement. Third, by using degree of hydration and gel-space ratio, the development of compressive strength of hardening concrete is evaluated considering the effects of temperature and aging. Furthermore, the aging effect of moisture diffusivity is considered through the development of compressive strength. The proposed model has taken into account the influences of self-desiccation and moisture diffusion on the moisture variation of concrete. The proposed model is verified with experimental results of temperature distribution, self-desiccation and moisture variation for hardening concrete.

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(Received September 10, 2012/Accepted December 14, 2012)