The hygro-thermal coupling model of concrete with water absorption characteristics is considered

Weijie You¹, Youzhi Wang, Fengping Zhang, Lei Zhou, Jiahao Han
School of Civil Engineering, Shandong University, Jinnan, China
²81087323@qq.com

Abstract. Basing on the theories of compound mixtures, considering the development of the microscopic pore structure of concrete at early age, and the dynamic balance of adsorbed water, free water, and water vapor within the pores, the thermo-hygro-mechanical coupling model was established with temperature, humidity, hydration degree and capillary pressure as main variables.

1. Introduction
Deformation of concrete is a kind of temperature and humidity deformation [1], therefore, after the initial setting, the main concrete deformation at early age is temperature deformation, chemical shrinkage and drying shrinkage. Among them, the drying shrinkage is a change in the pore pressure in the concrete caused by the loss of moisture, and it can be considered that the concrete solid phase is deformed by the pressure. Therefore, the study about hygro-thermal coupling of concrete can't be separated from its mechanical properties. Some scholars [2] [3] believe that the mechanical properties of concrete and the temperature and humidity changes are weakly coupled. In the simulation process, the influence of mechanical properties on the hygro-thermal coupling effect is usually ignored, and the influence of temperature and humidity changes on the mechanical properties of concrete is simply considered. Powers [4] thought that the stress would affect the balance of free energy inside the concrete, thus affecting the distribution of moisture. Gawin [5] thought that the solid-phase deformation had a certain influence on the moisture transport and conducted in-depth research through experiments. When subjected to external forces, the deformation of the microstructure of the concrete will change the distribution of bound water, adsorbed water, and free water, leading to significant changes in the humidity inside the concrete [6].

This paper is based on the Hybrid Mixture Method, considers the change of pore growth and the characteristics of water adsorption in early age of concrete, establishes a multi-parameter thermo-hygro-mechanical coupling model with temperature, humidity, hydration, and capillary pressure as the main variables, and verifies the correctness of the model through experimental data.

2. Constitutive relationships for early-age concrete
2.1. Hydration model of concrete
Degree of hydration is a measure of the degree of hydration of cement colloids, and its changes are closely related to various mechanical performance parameters of concrete [7]. Cervera considered the
influence of temperature and humidity on the hydration reaction process, and established a formula for calculating the hydration rate of concrete at early age:

\[ \dot{\alpha} = A(\alpha)\beta(H)\exp\left(-\frac{E_a}{RT}\right) \]

\[ A(\alpha) = A_1\left(\frac{A_2}{a_u} + \alpha(\alpha_u - \alpha)\exp\left(-\eta\frac{\alpha}{a_u}\right)\right) \]

In the formula: \( A(\alpha) \) is Chemical affinity, \( A_1, A_2, \eta \) are Material parameters; \( \beta(H) \) is Humidity coefficient; \( E_a \) is Apparent activation energy; \( R \) is Ideal gas constant; \( a_u \) is final degree of hydration.

2.2. Early-age concrete saturation and porosity

Internal pore adsorption characteristics of concrete in early age are closely related to temperature, humidity, and capillary pressure, and adsorption characteristics have a significant effect on shrinkage deformation of early-age concrete [8]. The calculation method about the saturation of early-age concrete considering the influence of capillary pressure and temperature and humidity given in the relevant literature [9] can well simulate the adsorption characteristics of the early-age concrete:

\[ S(\alpha, T, H) = 1 - \exp\left[B - \frac{2\gamma M_v}{\rho_i R T \ln H}\right] \]

In the formula: \( B \) is Material parameters.

The development of pores in early-age concrete is accompanied by hydration reactions, and relevant literature establishes a calculation method for parameter \( B \) related to the development of hydration degree:

\[ B = m e^{n_\alpha} \]

In the formula: \( m \) and \( n \) are Material parameters which are determined by experiment.

3. Control equation

Hassanizadeh and Gray [10] [11] [12] developed a new average method, this method uses a unified standard and gives a general form of the balance equation using the mixture method. The macroscopic equilibrium equations for mass, energy, momentum, and entropy consisting of solid, liquid, and liquid components are established by averaging methods. The method that combines the averaging method with the classical mixture method is the Hybrid Mixture Method [13]. The concrete components in practical projects are mostly in the state of restraint and stress. Based on the Hybrid Mixture Method and Darcy law, Fick law, Fourier law, the equation of temperature and humidity coupled equilibrium can be established:

Energy balance equation:

\[ \rho C_T \frac{dT}{dt} + \left(\rho_w C_w v_{ws} + \rho_g C_g v_{gs}\right)\nabla v - \nabla q = -\dot{m}_{hydr}\Delta H_{hyd} - \dot{m}_{vap}\Delta H_{vap} \]

Liquid phase balance equation:

\[ \frac{d(\varphi \rho_w S_w)}{dt} + \nabla j_w = \dot{m}_{hydr} - \dot{m}_{vap} \]

Dry air balance equation:

\[ \frac{d(\varphi \rho_g S_g)}{dt} + \nabla j_g = 0 \]

Water vapor balance equation:

\[ \frac{d(\varphi \rho_v S_v)}{dt} + \nabla j_v = \dot{m}_{vap} \]

In the formula: \( \rho, \rho_w, \rho_g \) are concrete density, liquid phase density, gas phase density of porous multiphase media, respectively; \( C_T, C_w, C_g \) are Concrete heat, liquid heat, gas heat of porous multiphase media, respectively; \( q \) is Concrete heat flux; \( \Delta H_{hyd} \) and \( \Delta H_{vap} \) are the specific enthalpies of hydration and evaporation of unit mass concrete, which is generally considered as constant; \( \dot{m}_{hydr} \) and \( \dot{m}_{hyd} \) are the hydration reaction water consumption rate and evaporation diffusion water.
consumption rate, respectively; $\phi$ is porosity; $v_s$ is deformation speed of solid skeleton, set the solid phase skeleton to $u$, then $v_s = \frac{du}{dt}$; $J_w = \phi \rho_w S_w v_w$ is the diffusion flux of liquid water; $v_w$ is the flow speed of liquid water; $J_a = \phi \rho_a S_a v_a$ is the diffusion flux of dry air; $v_a$ is the flow speed of dry air; $J_v = \phi \rho_v S_v v_v$ is the diffusion flux of water vapor; $v_v$ is the flow speed of water vapor.

4. Boundary conditions
The initial values of the parameters in the entire solution area $\Omega$ and boundary $\Gamma$ are:

1) Dirichlet boundary conditions

\[ T(t) = T_0,\quad P_c = P_{c0},\quad P_g = P_{g0},\quad v_s = v_{s0},\quad \alpha = \alpha_0 \]

2) Cauchy boundary conditions

\[ (-\lambda \nabla T) \cdot n = q_T + h_T(T - T_{atm}) \text{ on } \Gamma_T \]

\[ (\phi S_v \rho_v v_v + \phi S_w \rho_w v_w) \cdot n = q_v + q_w + \beta_c(\rho_v - \rho_{v,atm}) \text{ on } \Gamma_c \]

\[ (\phi S_a \rho_a v_a + J_a) \cdot n = q_a \text{ on } \Gamma_g \]

In the formula: $n$ is unit vector; $q_T, q_v, q_w$ and $q_a$ are the flux of temperature, water vapor, liquid water and dry air. $h_T$ is exchange coefficient of temperature; $\beta_c$ is exchange coefficient of moisture; $T_{atm}$ and $\rho_{v,atm}$ are ambient temperature and humidity density.

5. Result and discussion
Hou Dongwei [14] tested the early-age temperature and humidity changes in the center of concrete with a water-cement ratio of 0.3 and a section size of 200mm x 200mm. The boundary conditions are sealed on both sides and the bottom, and the top surface is in free contact with the environment.

Figure 1. Comparison of relative humidity calculated values and experimental values
As can be seen from Fig. 1, the relative humidity calculated values are saturated in the 2d instar, and it decline after 2d instar, and then gradually become stable. During the period from 2d to 19d, the relative humidity calculated values were slightly larger than the experimental values, mainly because the uneven distribution of moisture due to aggregate sinking was not considered. From Fig. 2, it can be seen that the temperature of the center of the concrete rises to the maximum temperature within 3 days after the completion of the pouring, and then gradually decreases until it conforms to the change law of the ambient temperature. The overall trend of the temperature calculated values are basically the same as the experimental value, and the temperature values curve is smoother than the experimental value curve. The main reason is that the ambient temperature change during the test is difficult to control and cannot be maintained.
From Fig. 3 to Fig. 5, it can be seen that the upper surface of the model is in free contact with the environment, its humidity value is low, and the internal and sealing surfaces have relatively high humidity; the center temperature of the model is greater than the boundary temperature, and the center capillary pressure is greater than the boundary capillary pressure. The maximum values of temperature and capillary pressure are far from the upper surface, which indicates that the diffusion and evaporation of humidity affects the distribution of the internal temperature and capillary pressure of the model, and the temperature and capillary pressure near the surface are relatively low. The relative humidity calculated and temperature agree well with the experimental results.
6. Conclusion

The change of temperature and humidity in early age of concrete is obvious. The model established in this paper can well simulate the evolution of temperature and humidity in the early age of concrete. The temperature change of the concrete during the completion of the pouring to the 3d age is significant, and the moisture content of the concrete drops significantly after 2 days of age. The distribution of temperature, humidity, and capillary pressure is related to the model boundary conditions.

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