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Coupled heat and moisture transport in damaged concrete under an atmospheric environment

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HIGHLIGHTS

- A model was proposed and solved for coupled heat and moisture transport in concrete.
- A method to determine thermogradient and hygrogradient coefficients was presented.
- Moisture transport, temperature and humidity distributions were obtained in damaged concrete.
- Coupled heat and moisture has a significant effect on moisture transport in concrete.
- Effects of heat transfer and concrete damage on moisture transport should be considered.

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ABSTRACT

This paper presents thermogradient and hygrogradient coefficients as indicators for evaluation of coupled effects of heat and moisture transport in concrete. A numerical model for coupled heat and moisture transport was established and solved as well as a method to determine thermogradient and hygrogradient coefficients. Effects of temperature and humidity gradients were investigated through experiments, which covered also the effects of damage on moisture transport, temperature and humidity distributions along with coupled transport. The experimental results showed that temperature and humidity gradients accelerated moisture transport along with increased damage. In addition, the effect of temperature gradient on temperature distributions was significant, while the effect of humidity gradient was small. However, both temperature and humidity gradients had significant effects on relative humidity distributions. Hence, coupled heat and moisture transport in concrete had a significant effect on moisture transport, and the effect of damage on moisture transport must be considered when determining humidity field in damaged concrete.

1. Introduction

In a natural environment, the air temperature and humidity always vary with time, and the temperature and humidity inside of concrete change accordingly [1–4]. Previous studies reveal that concrete carbonation, chloride penetration in concrete, freeze-thaw damage and corrosion of embedded steel bars, which cause durability problems for concrete structures, are closely related to temperature and humidity fields in concrete [5–9].

In a time-dependent temperature environment, concrete structures are not only subjected to loads but also affected by temperature stresses. When the tensile stresses caused by loads and temperature actions exceed the tensile strength of concrete, cracks will generate, leading to durability degradation of concrete structures.

A change in ambient humidity is also an important factor leading to concrete cracking, particularly the occurrence of surface cracks. For example, in a cold region, the saturated surface concrete is prone to freeze-thaw damage. In fire, the free water, capillary water and even some adsorbed water in concrete will be evaporated; when the vapor pressure reaches a certain extent, it will lead to concrete cracking [10]. Since temperature and humidity gradients inside and outside of the concrete shell of nuclear reactors are great, and the conversions between vapor and liquid water occur continuously causing more and more capillary tubes to form, which may lead to the concrete shell eventually losing its radiation protection [11].

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Generally, the heat transfer and moisture transport in porous media are highly coupled and not equivalent, i.e., the heat transfer has a greater effect on moisture transport, while the moisture transport has a smaller effect on heat transfer [12]. During coupled heat and moisture transport in porous media, the moisture in the form of liquid water transports to the surface of the porous media and vaporizes [13]. Actually, coupled heat and moisture actions will produce higher temperature and humidity gradients in porous media, which easily cause drying defects, such as cracking and warping.

In order to improve transport properties of materials and structures, coupled heat and moisture transport was studied and analyzed in fiberglass insulation [14,15], fibrous insulation [16], wood slabs [17], mortar [18–20], sandstone [20–22], concrete at elevated temperatures [23], and whole-buildings [24,25]. In real concrete structures, concrete is always damaged by loads, leading to a change in pore structure, which may affect coupled heat and moisture transport in concrete. In order to predict accurately thermophysical properties and durability of concrete, it becomes necessary to investigate further coupled heat and moisture transport in damaged concrete.

In this paper, a coupled heat and moisture transport model for concrete was established and solved based on the Luikov's model [26], and thermogradient and hygrogradient coefficients were analyzed in depth. Then, the corresponding computational formulas were proposed for thermogradient and hygrogradient coefficients. Through coupled heat and moisture transport tests in damaged concrete under an atmospheric environment, effects of temperature and humidity gradients as well as damage on moisture transport, temperature and humidity distributions in concrete were investigated along with coupled heat and moisture transport, and thermogradient and hygrogradient coefficients of concrete were then obtained. Finally, the coupled heat and moisture transport model for concrete was verified by tests.

2. Coupled heat and moisture transport in concrete

2.1. Coupled heat and moisture transport model for concrete and its solution

Based on the characteristics of concrete, the following basic assumptions were proposed: (1) Concrete was seen as the porous media which were continuous, homogeneous and isotropic on the macroscale; (2) The main factors affecting coupled heat and moisture transport in concrete were vapor and liquid water, and the vapor was seen as the ideal gas.

Based on the Luikov's model [26], the model for coupled heat and moisture transport in concrete was established as follows [27]:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + \rho c_m \kappa h_v \frac{\partial RH}{\partial t} \tag{1}$$

$$\rho c_m \frac{\partial RH}{\partial t} = D_m \frac{\partial^2 RH}{\partial x^2} + D_m \delta \frac{\partial^2 T}{\partial x^2} \tag{2}$$

where T is the temperature (K); RH is the relative humidity (%); t is the time (s); x is the distance from the concrete surface (m); λ is the thermal conductivity of concrete ($W \cdot m^{-1} \cdot K^{-1}$); D_m is the moisture conductivity of concrete ($kg \cdot m^{-1} \cdot s^{-1}$); κ is the phase change coefficient of water; h_v is the latent heat of vaporization of water ($J \cdot kg^{-1}$); ρ is the density of concrete ($kg \cdot m^{-3}$); c_p is the specific heat capacity of concrete ($J \cdot kg^{-1} \cdot K^{-1}$); c_m is the specific moisture capacity of concrete ($kg \cdot kg^{-1}$), and δ is the thermogradient coefficient of concrete (K^{-1}), characterizing the effect of temperature gradient on moisture transport.

Previous studies reveal that between heat transfer and moisture transport in concrete has a significant coupling effect [10–12]. In fact, the effect of heat transfer on moisture transport is considered in Eq. (2), although the effect of moisture transport on heat transfer was not considered in Eq. (1). In order to reflect the effect of moisture transport on heat transfer, Eq. (1) can be written as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + \lambda \xi \frac{\partial^2 RH}{\partial x^2} + \rho c_m \kappa h_v \frac{\partial RH}{\partial t} \tag{3}$$

where ξ is the hygrogradient coefficient of concrete (K), characterizing the effect of humidity gradient on heat transfer.

According to the latent heat of vaporization of water under a normal atmospheric pressure [28], the relationship between the latent heat of vaporization of water and temperature is as follows:

$$h_v = [2501 - 2.289(T - 273.15) - 1.448 \times 10^{-3}(T - 273.15)^2] \times 10^3 \tag{4}$$

When one-dimensional coupled heat and moisture transport in concrete has the length of L, the initial temperature and relative humidity are T_0 and RH_0, respectively. Meanwhile, the ambient temperature and relative humidity on both sides of the concrete are respectively T_1, RH_1 and T_2, RH_2. At the boundaries of concrete, the latent heat of vaporization is the part of energy balance, and the mass diffusion caused by the temperature and humidity gradients also affects the energy balance [17]. Then, the boundary conditions can be written as follows:

$$\begin{cases} \lambda \frac{\partial T(0,t)}{\partial x} + \lambda \xi \frac{\partial RH(0,t)}{\partial x} = h_{c1}[T(0,t) - T_1] + (1-\kappa) h_v h_{m1}[RH(0,t) - RH_1] \\ -\lambda \frac{\partial T(L,t)}{\partial x} - \lambda \xi \frac{\partial RH(L,t)}{\partial x} = h_{c2}[T(L,t) - T_2] + (1-\kappa) h_v h_{m2}[RH(L,t) - RH_2] \\ D_m \frac{\partial RH(0,t)}{\partial x} + D_m \delta \frac{\partial T(0,t)}{\partial x} = h_{m1}[RH(0,t) - RH_1] \\ -D_m \frac{\partial RH(L,t)}{\partial x} - D_m \delta \frac{\partial T(L,t)}{\partial x} = h_{m2}[RH(L,t) - RH_2] \end{cases} \tag{5}$$

where h_{c1}, h_{c2} are the surface heat transfer coefficients of concrete ($W \cdot m^{-2} \cdot K^{-1}$), and h_{m1}, h_{m2} are the surface moisture transfer coefficients of concrete ($kg \cdot m^{-2} \cdot s^{-1}$).

According to Henry's transformation method [29], the partial differential equations of Eqs. (2) and (3) can be transformed into two equivalent homogeneous partial differential equations as follows:

$$\begin{cases} \frac{\partial u_1}{\partial t} = a_1 \frac{\partial^2 u_1}{\partial x^2}, \ (0 < x < L, t > 0) \\ \frac{\partial u_2}{\partial t} = a_2 \frac{\partial^2 u_2}{\partial x^2}, \ (0 < x < L, t > 0) \end{cases} \tag{6}$$

where

$$a_i = \frac{\lambda(1-\zeta)}{\rho c_p \mu_i^2}, i = 1,2 \tag{7}$$

$$m_i T + n_i \cdot RH = u_i, \ i = 1,2 \tag{8}$$

$$\mu_i^2 = \frac{(1 + Fe + \frac{1}{Lu}) \pm \sqrt{(1 + Fe + \frac{1}{Lu})^2 - \frac{4(1-\zeta)}{Lu}}}{2}, \ i = 1,2 \tag{9}$$

$$\begin{cases} m_1 = 1, m_2 = \mu_1^2 - 1 \\ n_1 = \frac{1}{\delta}(1 - \mu_1^2), n_2 = \frac{Fe}{\delta} + \frac{\xi}{Lu} \end{cases} \tag{10}$$

$$\begin{cases} Lu = \frac{D_m c_p}{\lambda c_m}, & \text{Luikov number} \\ \zeta = \xi \delta, & \text{Interference number in coupled heat and moisture transport} \\ Fe = \frac{\delta c_m \kappa h_v}{c_p}, & \text{Fedolov number} \end{cases} \tag{11}$$