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Modeling moisture transport at the surface layer of fatigue-damaged concrete

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HIGHLIGHTS

- New theoretical model to predict the surface factor of drying concrete is proposed.
- Experimental studies on the effects of fatigue damage on moisture diffusion.
- New insights regarding the concrete damage on drying process are provided.

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ABSTRACT

This study investigates the moisture transport at the surface layer of concrete damaged by uniaxial tensile fatigue loading. In particular, a theoretical model for calculating the *surface factor* of drying concrete was established and verified with laboratory testing. The effect of mix proportion (e.g. water-to-binder ratio, supplementary cementitious materials) and level of fatigue damage on the moisture desorption at the concrete surface were studied. The results show that the surface factor of drying concrete increases as the environmental temperature or wind speed increases, but seldom changes with the mix proportion and fatigue damage. However, the fatigue loads (up to 30% of the ultimate tensile load) can accelerate the concrete surface water transfer by a factor of 1.05–1.60 times in the initial drying process, mainly due to enlarged surface mass transfer area.

1. Introduction

Water movement is involved in most of the deterioration processes in concrete, including chloride- and carbonation-induced steel corrosion, acid and sulfate attacks, freeze-thaw attack, and alkali-silica reaction [1,2]. As such, tremendous amount of work has been conducted over decades to characterize the water transport in concrete. In the meantime, many theoretical models have been established to predict the moisture movement and profiles in concrete [3,4,5]. Among all of these predictive models, the governing equations describing the physics of water movement in the interior of concrete, as well as the initial values and boundary conditions of drying/wetting concrete, were established [6].

While significant efforts have been made to understand the thermodynamics of water transport within the non-saturated concrete, few studies have ever exclusively investigated the boundary conditions of drying concrete. According to the previous studies, the *surface factor* is the most widely-used mathematical coefficient to predict the water evaporation at the concrete surface [7,8,9,10]. The *surface factor* is a convective water-transfer coefficient between air and concrete surface, which is dependent on the ambient temperature, surface temperature, relative humidity (RH) at the surface of concrete, wind speed, roughness at the surface of concrete, and diffusion coefficient of vapor in the air [11–15]. For instance, Yuan et al. used the modified Menzel's equation to give out surface factor based on an empirical coefficient and wind speed [16]. Shimomura et al. used the moisture diffusivity within the concrete and a factor representing the state of humidity distribution in the atmosphere near the surface to calculate the surface factor [9]. Wong et al. [7] and Sakata et al. [10] found that the surface factor for water evaporation increases with increasing *w/c* for concrete and mortar. However, Akita et al. [8] found the surface factor for water evaporation decreases with increasing *w/c* for concrete. Nevertheless, few studies have ever systematically investigated

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the evolution of *surface factor* for concrete exposed to a broad range of environmental conditions. Moreover, few theoretical models have ever been proposed to predict the surface factor of concrete.

On the other hand, there is an increasing need to understand the effect of mechanical loading on the moisture transport in concrete [17–20]. As a structural material, concrete serves under different types of loads, leading to micro-cracking [21,22], microstructural alteration [23] and macro-cracks [24], which in turn affect the transport properties. The formation of additional void or cracks at the surface of concrete due to mechanical loading would also affect the moisture transport at the surface layer of concrete. For example, the openings of new micro-cracks at the concrete surface may increase the quantity of moisture being lost when exposed to a low RH condition. However, little information is available to quantitatively determine the effect of mechanical loads, especially fatigue loads, on the moisture transport at concrete surface. In addition, the effect of mechanical loads on the surface factor of drying concrete is rarely studied.

To fill the aforementioned knowledge gap, this study proposes a new theoretical model to calculate the surface factor of concrete based on fluid dynamics. In parallel, experimental testing regarding the effect of temperature, wind speed, mix proportion (e.g. water-to-binder ratio, supplementary cementitious materials (SCMs)), and level of fatigue damage, on surface factor in concrete was conducted. In addition, a new expression for the surface mass transfer area was proposed to quantify the effect of fatigue damage on the moisture transfer at the surface of concrete.

2. Model establishment

2.1. Governing equations

As the concrete surface is exposed to a lower relative humidity (RH), the evaporation process occurs at the gas-liquid interface within the pore structure of concrete. Meanwhile, the evaporation reduces the local vapor concentration near the interface, which induces a vapor diffusion process from the interface to the concrete surface [25]. Therefore, the following nonlinear diffusion equation can be used to describe the moisture transfer in concrete during the drying process [3,8]:

$$\frac{\partial\theta}{\partial t} = \nabla[\boldsymbol{D}(\theta)\cdot\nabla\theta] \tag{1}$$

where $t(s)$ is the time, θ (–) is the volumetric water content (volume of water per unit volume of porous medium), and $\boldsymbol{D}(\theta)$ $(\mathrm{m}^2/\mathrm{s})$ is the diffusion coefficient for moisture (also called moisture diffusivity) in concrete, which depends strongly on the volumetric water content θ. The governing Eq. (1) for one-dimensional moisture transfer can be simplified as [26]:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\cdot\frac{\partial\theta}{\partial x}\right] \tag{2}$$

in which x (m) denotes the distance from the concrete surface. The consideration of one-dimension is reasonable to the circumstance that the concrete (e.g. sound concrete or concrete with homogenous level of damage) can be modeled as a homogenous media.

Moreover, the one-dimensional flow velocity $J_{\mathrm{m}}(\mathrm{m/s})$ can be expressed in terms of water content θ as [27]:

$$J_{\mathrm{m}} = -D(\theta)\cdot\frac{\partial\theta}{\partial x} \tag{3}$$

To determine the moisture profiles in concrete, it is necessary to solve Eq. (2). However, such a solution depends on the physical conditions existing at the boundaries of the medium and, if the situation is time-dependent, on initial conditions.

During the drying process of concrete, the flow of water in concrete may be divided into two parts: (i) moisture transfer in the internal concrete, defined as m_1 (kg); (ii) moisture transfer between the concrete and the ambient air, defined as m_2 (kg).

Based on Eq.(3), the moisture transfer, m_1, can be expressed as [6,28]:

$$m_1 = -D(\theta)\cdot\frac{\partial\theta}{\partial x}A_s\Delta t\rho \tag{4}$$

where A_s (m^2), ρ $(\mathrm{kg/m}^3)$, and Δt (s) are the projection area of the concrete surface pore, the density of water and the unit time, respectively.

The moisture transfer, m_2, can be expressed as [6,28]:

$$m_2 = f(H_s - H_0)A_s\Delta t\rho_s \tag{5}$$

where f (m/s), H_s (–), H_0 (–), ρ_s $(\mathrm{kg/m}^3)$ are the *surface factor* for water evaporation, the RH at the drying surface of concrete, the ambient RH, and the density of saturated water vapor, respectively.

According to the mass conservation of water, when $x = 0$, m_1 is equal to m_2. Substituting from Eq. (4) for the m_2 in Eq. (5) we obtain:

$$D(\theta)\frac{\partial\theta}{\partial x} + f(H_s - H_0) = 0 \tag{6}$$

Eq. (6) is the third boundary condition for the drying concrete. To obtain the moisture profiles in concrete, the moisture diffusivity $D(\theta)$ and surface factor f, need to be known. Since the moisture diffusivity $D(\theta)$ can be derived out and have been extensively studied by numerous investigators [7,27], the main objective of this study is to model and analyze the *surface factor* f.

2.2. Modeling of surface factor

In this study, the moisture convection and diffusion processes at the concrete surfaces were simplified as the convective mass transfer of incompressible fluid in the one-dimensional flat wall. The concrete surface is regarded as an infinite plane and wind direction is parallel to the surface. Water vapor velocity boundary layer and the concentration boundary layer of concrete surface are shown in Fig. 1. When the fluid flows through the flat wall, there is a gradient between the concentration of water vapor and that of flat wall. Thus, it is reasonable to believe that the mass transfer is mainly concentrated in a layer of fluid having a concentration gradient

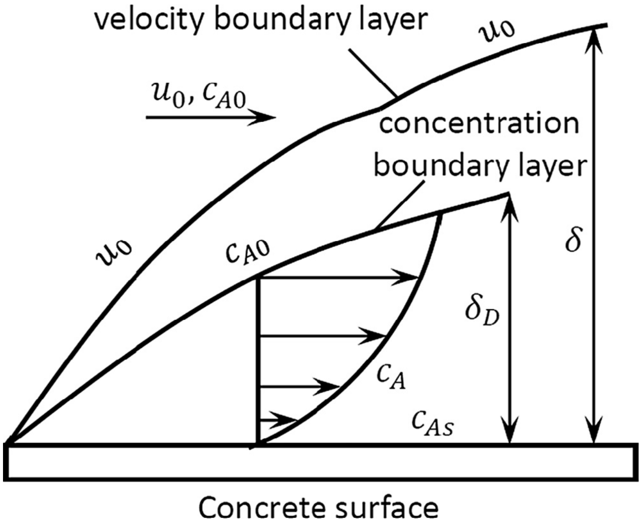

Fig. 1. Velocity boundary layer and concentration boundary (The physical meanings of the symbols can be found in the text).