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Numerical and experimental study of moisture and chloride transport in unsaturated concrete

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HIGHLIGHTS

- A prediction model for chloride transport in unsaturated concrete was proposed.
- A new device was developed to simulate marine tidal and splash zones.
- The chloride content in concrete under drying-wetting cycles was measured.
- Numerical simulation and tests of moisture and chloride transport were carried out.

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ABSTRACT

Based on the establishment of a moisture transport model, a prediction model for chloride transport in unsaturated concrete was developed. The moisture transport model considers both the diffusion of water vapor and seepage of liquid water in concrete under drying-wetting conditions. The moisture transport model was verified by wetting and drying tests. In the transport model of chloride ions, both diffusion and convection were considered. Tests of specimens under drying-wetting cycles with four types of cycles were carried out to verify the chloride transport model. Furthermore, a new device was developed to mimic tidal and splash zones of a marine environment to achieve different time ratios of drying-wetting. The measured results of chloride content corresponded with the simulated results. The results showed that the chloride content in concrete displayed no relationship with the ratio of drying and wetting times. The chloride content of concrete in mimicked tidal and splash zones significantly varied with height, especially in the surface layer of concrete, and the chloride content of concrete at the junction of the splash and tidal zones was the highest.

1. Introduction

Reinforcement corrosion induced by chloride attack is one of the major causes of deterioration of concrete structures [1–4], especially when exposed to seawater or deicing salts. Concrete in tidal, splash, and salt-spray zones is subjected to drying-wetting cycles, which comprise the most extreme corrosion environments for concrete structures [5–7]. In these environmental conditions, concrete is commonly in an unsaturated state [8–10], and the chloride transport mechanisms in concrete become more complex, depending mainly on capillary suction and diffusion [11]. During the wetting process, chloride ions transfer to concrete with moisture transport by capillary, whereas during the drying process, moisture evaporates from the concrete, leaving chloride ions inside the concrete, accumulating in the surface layer and being transported into concrete by diffusion [12]. In this way, a local maximum chloride concentration occurs near the exposed surface. The area between the exposed surface and the depth of local maximum chloride concentration in concrete is called the convection zone, and the area between the depth of local maximum chloride concentration and the maximum depth of chloride diffusion in concrete is named as the diffusion zone. An obvious convection zone was found in mortar under salt-fog drying-wetting cycles [13].

In view of the more universal and serious corrosion problems caused by chloride ions under drying-wetting cycles, the study of chloride transport in unsaturated concrete is urgently needed to predict the service life and durability of concrete structures.

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Previous studies have tended to describe the chloride transport in unsaturated concrete by Fick's second law [6,11,14]. The chloride content in a diffusion zone can be predicted, but the chloride content in a convection zone cannot be described accurately by this model [11,14,15]. In practical applications, the reliability-based theoretical model is recommended by Dura-Crete and the International Federation for Structural Concrete (fib) Model Code [16], but it is difficult to obtain the chloride contents and the depth of the convection zone.

To better describe the chloride content in both the convection and diffusion zones, several prediction models of chloride transport in concrete have been developed [15,17]. A chloride transport model based on a moisture transport model in unsaturated concrete was proposed to more accurately predict the chloride content in the convection zone [18]. To study chloride transport in unsaturated concrete, testing is essential in addition to theory. A new automatic experimental setup was developed to more accurately simulate the drying-wetting condition [9]. Many studies of chloride transport in unsaturated concrete have been conducted recently. However, most of the results could not be used in a practical concrete structure, so more advanced theory and practice are still needed.

Previous studies indicate that chloride transport in partially saturated concrete is significantly accelerated by moisture transport [7,8], which should be considered when describing chloride transport in cement-based materials [19]. Moisture transport in concrete under drying-wetting cycles has been extensively studied. Li [20] proposed a diffusion model for the global process of moisture transport under drying-wetting conditions, and different diffusion coefficients were assigned to the drying and wetting processes. Based on pore-size distribution, a numerical approach was proposed to simulate moisture transport in concrete [21]. Studies of moisture transport have laid the foundation for the establishment of a chloride transport model in unsaturated concrete.

Previous studies lack a comprehensive characterization of moisture transport and chloride transport in concrete subject to drying-wetting cycles. This study attempts to develop a moisture transport model based on Fick's law and Darcy's law, regarding the water-saturation degree as the basic variable, and our predicted results were compared with the measured results in tests of wetting and drying. Based on a moisture transport model, a prediction model of chloride transport in unsaturated concrete has been proposed. To verify the chloride transport model, a new simulation of the tidal and splash zones of a marine environment was developed.

2. Theoretical analysis

2.1. Moisture transport model in unsaturated concrete

Moisture in concrete pores can be regarded as the transport medium of aggressive agents, e.g., chloride ions and CO_2 [21]. Most durability problems for concrete structures are associated with moisture transport [5,21]. The degree of water saturation is an important factor for moisture transport in concrete [10,21], which plays a significant role in the moisture transport model for unsaturated concrete in this paper.

Moisture transport in concrete occurs mainly in the forms of water vapor and liquid water. The transport of water vapor in concrete pores can be approximately described by Fick's law. At present, the diffusion coefficient of water vapor in concrete can be given based on the diffusion coefficient of water vapor in the atmosphere [22],

$$J_v = -D_{va} f \nabla \rho_v = -D_v \nabla \rho_v \tag{1}$$

where J_v is the diffusive flux of water vapor [kg/(m^2·s)], D_{va} is the diffusion coefficient of water vapor in air (m^2/s), D_v is the equivalent diffusion coefficient of water vapor (m^2/s), ρ_v is the water-vapor density (kg/m^3), and f is defined as the influence coefficient of a porous medium on air transport. The equivalent diffusion coefficient of water vapor can be written as [23,24]

$$D_v = 0.217 \frac{p_{atm}}{p_g} \left(\frac{T}{T_0} \right)^{1.88} \phi^a (1-\theta)^b, \tag{2}$$

where p_{atm} is the reference atmospheric pressure (Pa), p_g is the air pressure (Pa), T is the temperature (K), T_0 is the reference temperature (T_0 = 273 K), φ is the porosity of concrete, θ is the water-saturation degree in concrete pores, and a and b are fitting parameters. Li [24] obtained the values of a and b for ordinary silicate concrete as 2.7 and 10/3 by fitting the measured data [25].

A modified Darcy's law can be used for the transport process of liquid water in concrete pores under pressure gradients [26].

$$J_l = -K \nabla p_l, \tag{3}$$

where J_l is the penetrative flux of liquid water in concrete [kg/(m^2·s)], K is the permeability coefficient of liquid water [kg/(Pa·m·s)], and p_l is the pore solution pressure (Pa). According to capillary mechanical theory, for concrete under normal atmospheric pressure, the relationship between capillary pressure p_c and liquid water pressure p_l in pores is

$$p_c = -p_l. \tag{4}$$

Due to micro-sized concrete pores, the permeability coefficient is not easy to test directly, and it is defined in several ways. In general, the transport model of liquid water in concrete pores can be based on the theory of soil science. Previous study has shown that moisture transport in concrete mainly depends on open pores [27]. We assume that the pores in concrete are cylinders with varying diameters, and we neglect the transport of liquid water in unsaturated pores. Considering the effect of tortuosity of pores, the permeability coefficient can be simplified to [16,26]

$$K = \frac{\rho_l \phi^2}{50\eta} \left(\int_0^{r_c} r dV \right)^2, \tag{5}$$

where ρ_l is the density of liquid water (ρ_l = 1000 kg/m^3), η is the viscosity of liquid water (η = 8.01 × 10^{-3}Pa·s), and r_c is the Kelvin equilibrium radius (m). Pores with radius less than r_c are assumed to be saturated. We assume that the pore radius r in concrete follows a Rayleigh-Ritz distribution, i.e.,

$$dV = B\exp(-Br)dr, \tag{6}$$

where B is the parameter of the Rayleigh-Ritz distribution, which can be determined by mercury-intrusion porosimetry. The relationship between the saturation degree and the Kelvin radius can then be approximated as [21]

$$\theta = \int_0^{r_c} dV = 1 - \exp(-Br_c). \tag{7}$$

Substituting Eq. (6) into Eq. (5) and combining with Eq. (7), the approximate relationship between the permeability coefficient of liquid water and the water-saturation degree can be expressed as

$$K = \frac{\rho_l \phi^2}{50B^2\eta} [1 - [1 - In(1-\theta)] \cdot (1-\theta)]^2. \tag{8}$$

For simplicity, according to the local equilibrium relationship between the gas and liquid phases of moisture, based on the assumption of isothermal transport for moisture, the relationship between the pore-solution pressure and water-vapor density can be expressed as [28]