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External sulfate attack to reinforced concrete under drying-wetting cycles and loading condition: Numerical simulation and experimental validation by ultrasonic array method

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HIGHLIGHTS

- Moisture transfer takes the consideration of saturation degree, chemical reactions and loading condition.
- The numerical model is capable of predicting the degradation process of concrete subjected to sulfate attack and loading.
- Ultrasonic array method is used to detect the elastic modulus field change of reinforced concrete.
- The elastic modulus variation of the tested RC beam exhibits a two-stage evolution process.

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ABSTRACT

In this paper, an innovative mathematic model dealing with the hysteresis effect of evaporation of pore solution and the nonlinear relationship between diffusivity of moisture and saturation degree of pores solution is established to describe the sulfate attack to reinforced concrete with drying-wetting cycles. The coupling effects of sulfate attack and external loading condition are investigated using a four-point-bending experiment on a reinforced concrete beam and compared with the model predictions. In the experiments, ultrasonic array method is employed to detect the change of the field of modulus of elasticity due to the damage in concrete under sulfate attack coupled with loading condition. The external loading, resulting in tensile strain inside concrete matrix, accelerates the degradation process of concrete subjected to sulfate attack. The modulus variation of concrete under sulfate attack with loading exhibits two apparent stages: (1) the enhancing stage of ettringite crystallization and (2) weakening stage due to overexpansion. The experimental results verified the rationality and validity of the diffusion model proposed in this study, considering the coupling effects of external sulfate attack and loading condition.

1. Introduction

With the fast development of construction in civil engineering nowadays, tons of reinforced concrete structures are being built all over the world, in which marine concrete structures occupy a significant position due to the promising direction toward the fast developing ocean engineering. Carbonation, sulfate attack, acid attack, alkali-silica reaction as well as permeability and diffusivity of concrete materials in marine environments have drawn great attentions from both researchers and engineers [1–6]. The intrusion of negative ions, such as chloride and sulfate ions, causes deterioration in structures and great loss in economy, restraining the development of marine engineering [7–10]. It has reached a conclusion that chloride ions mainly cause the threat to the steel bars, which eventually reduce both the working condition and durability of the reinforced concrete structures [11]. Although there is no apparent evidence showing that sulfate ions will interact with the steel bars, the interaction between sulfate ions and cement hydration product, calcium hydroxide (CH) first and then remaining C_3A will result in the formation and development of ettringite (also called secondary ettringite), which causes volume expansion

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and subsequent cracks eventually [12,13]. The generated cracks in concrete matrix pave more paths for the ingress of other harmful ions, which accelerates the degradation of concrete materials and structures [14–16].

In the theoretical aspect, empirical models based on chemistry have been put forward to estimate the influence of temperature and concentration of the sulfate solution in the expansion process of cement mortars that are subjected to external sulfate attack [17]. As with what other researchers start with [18–20], assumptions are made that the cement or concrete are mainly immersed to be subjected to the external sulfate intrusion, neglecting the fact that almost all the structures in the practical engineering are under loading condition. Thus, those simulation models may lead to inaccuracy when applied in practice. On the other hand, similar to chloride intrusion situation, since exposure to environmental water or saturated air causes swelling or crystal growth of ettringite which will lead to subsequent damage of the concrete element, drying-wetting cycling zones of reinforced concrete structures are always under the highest risk of deterioration [21]. Traditionally, the Fick's second law with reaction term is assumed to govern the transport of the sulfate ions in various assumption situations [22,23]. Although some numerical simulation results which are only based on the governing equation of Fick's second law satisfied well with the experimental degradation data [18,19], they cannot theoretically simulate the accelerating process caused by the drying-wetting condition.

In the theoretical part of this paper, a mathematic model based on the relationship between moisture transfer and saturation degree of the pores solution, which is the main characteristics of drying-wetting cycles similar to the severe marine environment, is proposed to investigate the degradation of reinforced concrete structures caused by the sulfate attack and external loading.

In the experimental aspect, the prediction of erosion based on the Fick's second law was made in the aspect of sulfate ion concentration, and experiments on testing the mechanical property and porosity were conducted to detect the influence of sulfate intrusion and erosion [24]. In order to estimate the sulfate attack, various detection methods have been used on the investigation of sulfate attack. To investigate the influence of cement type, water-to-cement ratio and aggregate on Portland cement paste under sulfate attack, X-ray microtomography (microCT) and spatially resolved energy dispersive X-ray diffraction (EDXRD) were applied to detect both physical and chemical distress in non-destructive way [25]. However, this method cannot be directly applied to the field practice, which calls for a practical and accurate detection method for the damage evaluation. Due to its advantage of in-situ-convenience and non-destructive specialty, ultrasonic detection method has been utilized to investigate the degradation caused by sulfate attack [26,27].

In the experimental part, a four-point-bending experiment is conducted on a reinforced concrete beam accompanied by drying-wetting cycles of sodium sulfate solution. Ultrasonic array method is employed to detect the elastic modulus field change of damaged concrete under sulfate attack coupled with loading condition, which is rarely considered in the previous research.

2. Numerical modeling

2.1. Moisture diffusion under unsaturated condition

When assuming that the concrete is saturated without considering the chemical reactions between the sulfate ions and concrete, the diffusion process holds the dominant position, the Fick's second law has often been adopted to describe the quantitative relationship. However, normally the concrete cannot be saturated all the time in a practical situation, especially in the typical drying-wetting cycles. The diffusion of sulfate ions is accompanied with the process of moisture movement under unsaturated situation, so the moisture diffusion and capillary saturation would be the point cuts to modify the traditional simulation models.

To figure out the transportation of moisture (in both liquid and vapor phase), the representative elementary volume (Fig. 1) in the microscopic scale would be used to illustrate this problem [28]. In the process of drying-wetting cycles, moisture transportation behaves in both liquid and vapor phase. The revised Fick's law considering these two phases can be used to describe the total moisture diffusion process [29]

$$\frac{\partial \theta_w}{\partial t} = \operatorname{div}(D_v \cdot \nabla \rho_v + K_l \cdot \nabla P_l) = \operatorname{div}[D(\theta_w) \cdot \nabla \theta_w] \quad (1)$$

where $\theta_w \approx \varphi \rho S$ is the total mass of water per unit volume of concrete (kg/m^3), φ is the porosity of concrete. It has to be noted that chemical reactions of sulfate ions accompany the diffusion process which would cause the expansion in the pores inner the concrete [22,30]. So the porosity can be expressed in the form of $\varphi = \varphi(x,y,z,t)$ in three dimensions, which would make sense in the degradation process in the following parts of this paper. ρ is the bulk density of the liquid water. S is the degree of saturation in the micro pores inside the concrete (m^3/m^3), D_v is the vapor phase diffusivity, K_l is the permeability parameter representing the property of water to flow through the porous medium. P_l is the liquid phase pressure inner the pores. $D(\theta_w)$ is the total diffusivity parameter combining the moisture transfer in both liquid and vapor phase, which can be expressed as

$$D(\theta_w) = \left(\rho_s D_v + K_l \frac{\partial P_l}{\partial h}\right) \frac{\partial h}{\partial \theta_w} \quad (2)$$

where ρ_s is the saturated vapor density such that $h = \rho_l/\rho_s$, h is the ambient relative humidity. However, the vapor phase pressure can be set as zero inner the pores when compared to the liquid phase pressure, namely $P_l \approx P$. P is the total moisture pressure inner the pores. So the total diffusivity parameter can be simplified as

$$D(\theta_w) = \left(D_v \frac{\partial \rho_v}{\partial P} + K_l\right) \frac{\partial P}{\partial \theta_w} = (K_v + K_l) \frac{\partial P}{\partial \theta_w} \quad (3)$$

where K_v is the vapor phase permeability parameter.

The permeability property depends on the pores which are saturated and linked together, so for simplification and numerical calculation, the liquid phase permeability parameter K_l can be expressed as [31]

$$K_l = \frac{\rho \varphi^2}{50\eta} \left(\int_0^{r_c} r dV\right)^2 \quad (4)$$

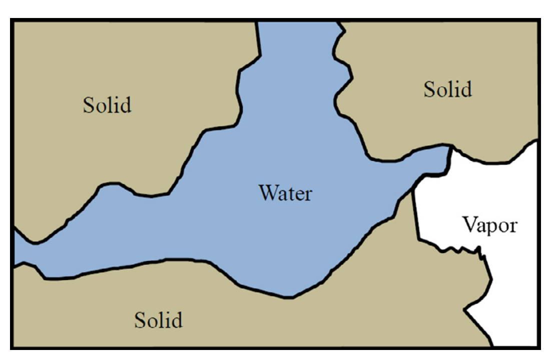

Fig. 1. The schematic of representative elementary volume (REV) [28].