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Numerical simulation on time-dependent mechanical behavior of concrete under coupled axial loading and sulfate attack

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ABSTRACT

This paper numerically simulates time-dependent mechanical behaviors, such as stress redistribution and bearing capacity degradation, of concrete subjected to the coupled axial loading and sulfate attack. Based on Fick's law and chemical reaction kinetics, a diffusion-reaction model was proposed to obtain the spatial and time-dependent concentration distribution of sulfate ion, gypsum and ettringite. From previous study, a chemical damage, characterized by the volumetric expansion from ettringite formation, is introduced to reflect the influence of sulfate attack on concrete performance. Furthermore, using the plasticity theory and damage mechanics, a coupled chemo-mechanical damage constitutive model was determined by introducing the chemical damage. Finally, a concrete prism is regarded as a research object, to investigate the time-dependent stress and bearing capacity degradation of concrete structures subjected to the coupled axial compression and sulfate attack.

1. Introduction

Concrete used in piers and piles, made of concrete, and coastal power stations in marine environment, while bearing external load actions like wind and gravity, are also subjected to chemical attack, such as chloride and sulfate (Du et al., 2015; Gao et al., 2013a; Liu et al., 2016; Medeiros-Junior et al., 2015), whose concentrations in sea water are about 550 mol/m^3 and 30 mol/m^3 respectively. Chloride ion mainly attacks the reinforcement to decrease its effective area and leads to the reduction of bearing capacity of concrete structures (Val et al., 2009; Amleh and Ghosh, 2006), which plays an indirect role in the destruction of concrete. However, sulfate ion penetrates into concrete and directly reacts with the cement hydration products to generate expansive crystals such as gypsum, ettringite and other phases (Taylor et al., 2001; Yang and Luo, 2012). The growth of these crystals results in the chemical damage of concrete such as volumetric expansion, cracking and spalling, which leads to the degradation of mechanical properties such as strength, elastic modulus and ultimate strain in concrete, (Bassuoni and Nehdi, 2009; Idiart et al., 2011; Khelifa and Guessasma, 2013; Neville, 2004). Also, the stresses resulting from the load action cause the development of micro-cracks in concrete, which not only creats mechanical damage but also changes the transport mechanism (Sun and Zuo, 2012), and accelerates both the transport of sulfate ions and chemical damage of concrete under sulfate attack (Bassuoni and Nehdi, 2009; Gao et al., 2013a). Hence, there is need to analyze the coupled behavior of sulfate-induced chemical damage and load-induced mechanical damage for concrete subjected to sulfate attack and external loading.

The chemical damage of concrete caused by sulfate attack is a complex physico-chemical process, which involves the transport of sulfate ions, microstructure damage and degradation of macro-mechanical properties (Güneyisi et al., 2010; Yu et al., 2016). Researchers have carried out corrosion experiments to investigate the transport of sulfate ions in concrete specimens immersed into sulfate solutions, and applied EDTA titration method and X-ray Energy Dispersive Spectral (EDS) to quantitatively analyze the distribution of sulfate ions in the specimens (Sun et al., 2013; Zuo et al., 2012a). Combined with the experimental data, a diffusion model of sulfate ions in concrete was developed using Fick's law and the transport theory in porous media (Nie et al., 2015; Samson and Marchand, 2007; Sun et al., 2013; Zuo et al., 2012a). Based on SEM and Computed Tomography (CT) microscopic observation on the concrete sample immersed into sulfate solutions at varying concentrations, the influence of sulfate concentration on the damage process of concrete was investigated (Nehdi et al., 2014; Schneider and Chen, 1998; Yuan et al., 2016), and the evolution of its microstructure, caused by the formation and growth of gypsum and ettringite crystals, was also studied to obtain its damage mechanism (Liu et al., 2012b; Neville, 2004; Santhanam et al., 2003). The change in concrete mechanical properties with time were studied and analyzed to obtain the complete stress-strain curve associated with

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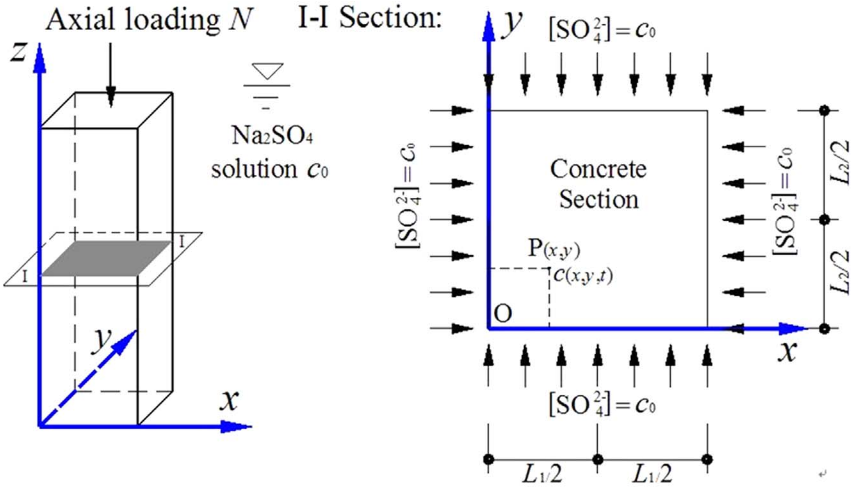

Fig. 1. Diffusion-reaction model of sulfate ion in concrete under axial loading.

sulfate concentration and corrosion time (Liu et al., 2012a; Thidar and Chiaki, 2011; Zhou et al., 2016). Results show that the shape of the stress-strain curve of corroded concrete in sulfate solution is similar to that without sulfate attack (Liu et al., 2012a; Zhou et al., 2016).

Mechanical damage of concrete caused by external load is another significant factor influencing the long-term, in-service behavior of concrete structures, and currently there are many achievements on studies in this aspect, which include the classical Mazars's damage model (Mazars and Pyaudier-Cabot, 1989), Borcelona's damage model (Lubliner et al., 1989), Faria's damage constitutive model associated with strain-rate dependent plasticity (Faria et al., 1998) and Wu's plastic-damage model based on damage energy release rate (Wu et al., 2006). However, these researches have mainly focused on modeling the mechanical damage process of concrete subjected to load actions, without considering the influence of sulfate-induced chemical damage, which also reduces the strength and elastic modulus of concrete materials. In order to obtain the chemical damage of concrete caused by sulfate attack, the concentration of sulfate solution and the immersion time can be used to characterize the chemical damage degree (Chen et al., 2016; Saetta et al., 1998; Schneider and Chen, 1998), based on the results of mechanical properties of concrete during sulfate attack. However, the chemical damage obtained by this method is an average value for the concrete specimen in which the damage degree actually has a gradient distribution from the surface to the interior of concrete. Therefore, other researches (Basista and Weglewski, 2009; Idiart et al., 2011; Ikumi et al., 2014; Tixier and Mobashe, 2003; Sarkar et al., 2010) associate the volume expansive strain, from the formation of ettringite, with the chemical damage to reflect its time-varying gradient distribution. Based on the mechanism of sulfate attack on concrete, they consider that when a fraction of pore volume in concrete is filled with ettringite (especially in a low sulfate concentration environment, ettringite is the main reaction product, and the expansive effect of gypsum formation is neglected), the strain of volume expansion will start to develop, which leads to cracking of concrete. However, the present researches rarely consider the coupled influence of sulfate-induced chemical damage and load-induced mechanical damage on the mechanical behaviors for concrete subjected to sulfate attack and external loading, which serves as the main focal point of this research.

Using an axially compressed concrete prism immersed in Na_2SO_4 solution as a case study, a numerical model is developed to investigate the time-dependent mechanical behavior of concrete under coupled axial loading and sulfate attack. A diffusion-reaction model is established to obtain the concentration of sulfate ion and reaction products in concrete, then, the sulfate-induced chemical damage is characterized by the volume expansive strain from the formation of reaction products. Based on the plasticity theory and damage mechanics, a coupled chemo-mechanical damage constitutive model, with stress-based plasticity and strain-driven damage, for concrete subjected to the coupled external loading and sulfate attack is determined by introducing the chemical damage degree to reflect the influence of sulfate attack. A concrete prism immersed into Na_2SO_4 solution is regarded as a research object, and the stress distributed in the concrete section and the bearing capacity of the concrete prism are obtained. Finally, a numerical simulation is performed, and the results of concrete damage process, including the sulfate ion concentration, sulfate penetration depth, chemo-mechanical damage, time-dependent stress and bearing capacity degradation are presented.

2. Sulfate-induced chemical damage

2.1. Diffusion-reaction model

The formation of reaction products (gypsum and ettringite), resulting in the chemical damage of concrete, is related to the diffusion and reaction of sulfate ions in concrete (Saetta et al., 1998). Therefore, modeling the diffusion process of sulfate ion is necessary for the characterization of chemical damage. A concrete prism subjected to the coupled actions of axial load and Na_2SO_4 solution, with two ends of which are sealed with epoxies, was used in this paper, as shown in Fig. 1. Due to the coexistence of ionic diffusion and chemical reaction, the diffusion process of sulfate ions in the specimen is modeled using Fick's second law and chemical reaction kinetics, which is expressed by

$$\begin{cases} \frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D_c^{\sigma}\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_c^{\sigma}\frac{\partial c}{\partial y}\right) + \frac{\partial C_d}{\partial t} \\ c\,(x,\,y,\,0) = 0, \quad (x,\,y) \in \Omega \\ c\,(x,\,0,\,t) = c_0, \quad c\,(0,\,y,\,t) = c_0 \\ c\,(L_1,\,y,\,t) = c_0, \quad c\,(x,\,L_2,\,t) = c_0 \end{cases} \tag{1}$$

where $c(x, y, t)$ refers to the sulfate ion concentration at the location (x, y) at sulfate penetration time, t; concrete specimen section area, Ω; c_0 is the concentration of Na_2SO_4 solution; C_d is the dissipated concentration of sulfate ion caused by chemical reaction; $D_c{}^{\sigma}$ is the diffusion coefficient of sulfate ion in concrete considering the effect of stress, referred in document (Zuo et al., 2010); L_1 and L_2 are the lengths of section along x and y directions respectively. Eq. (1) is a nonlinear partial differential equation, solved by the finite difference method with Alternating Direction Implicit (ADI) scheme (Zuo et al., 2017).

During the penetration process, part of the sulfate ions react with the dissolved calcium hydroxide (CH) in concrete to produce secondary gypsum ($C\bar{S}H_2$), as revealed in Eq. (2), and the secondary gypsum ($C\bar{S}H_2$), reacts with some calcium aluminate phases, such as tetra-