



Chloride diffusivity in saturated cement paste subjected to external mechanical loadings



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ABSTRACT

The chloride diffusivity in cement-based composite materials is mainly affected by the multi-scale pores, including gel pores, capillary pores, entrained and entrapped voids, etc. The pore-structure parameters, e.g. pore size, pore connectivity, pore surface roughness and pore volume fraction (porosity), will be changed under external mechanical loadings. And this leads to the change of the chloride diffusivity in cement paste. The porosity is regarded as the primary parameter of water-saturated cement paste, and the effect of the external mechanical loadings on the chloride diffusivity in cement paste is treated as the change of porosity on the chloride diffusivity. Saturated cement paste is regarded as a two-phase composite composed of intrinsic cement matrix and pore-water inclusion. A two-phase spherical model is developed, and the quantitative relationship between current porosity of cement paste and initial porosity as well as volumetric strain is evaluated based on the theory of elasticity. Moreover, a theoretical formula for the simulation of chloride diffusivity in cement paste is obtained. Finally, the effects of external mechanical loadings (herein i.e. the volumetric strain) and porosity variation on the chloride diffusion behavior of cement paste are explored based on the Fick's second law. It is found that chloride diffusion coefficient of saturated cement paste increases greatly with the increase of initial porosity. Furthermore, the diffusion coefficient decreases with the increase of compressive volumetric strain, and increases with the increase of the tensile volumetric strain.

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1. Introduction

Concrete is the most widely used man-made building material in the world owing to its versatility and relatively low cost, and it has also become the material of choice for the construction of structures exposed to marine environment (Shi et al., 2012). Chloride-induced corrosion of steel reinforcement is a major cause affecting the service life of reinforced concrete (RC) structures exposed to such conditions. Nowadays, more and more offshore buildings are constructed, it is thus of importance to know the chloride diffusivity in concrete to predict the initiation time of corrosion. So far, lots of efforts have been conducted to explore the chloride diffusivity in concrete. However, most of them mainly concentrate on the diffusivity of concrete at a stress-free state, i.e. without considering the effect of external mechanical loadings. In reality, almost all concrete structures work under the complicated stress conditions of tension, compression and torsion, etc (Jin et al., 2010). The structure and distribution of the pores and

micro-cracks within concrete change under external mechanical loadings, and new cracks may generate, which causes the change of the diffusivity and permeability of concrete.

Many efforts have been conducted to investigate the chloride diffusivity in concrete subjected to external mechanical loadings by using experimental methods, theoretical analysis methods and numerical simulations. In the experimental investigations, Konin et al. (1998) carried out a test to explore the effect of tensile loadings. In their experiment, three types of concrete with different compressive strengths (i.e. 45, 80 and 100 MPa) were exposed in a closed container at a loaded state, and they were subjected to a sequence of wetting by salt fog and drying, and then the chloride contents on the three prismatic specimens were measured. Their test data show that the apparent chloride diffusion coefficient of concrete increases with the increase of tensile loading level. The similar results also have been obtained in the work of Yang et al. (2008) (see Fig. 1a). Lim et al. (2000), Hong et al. (2013) and Wan et al. (2013) carried out a series of experiments to investigate the chloride diffusivity in concrete subjected to compressive loadings, and they found that chloride diffusion coefficient decreases with the increase of stress under a critical stress level, while the diffusion coefficient increases significantly when the stress level exceeds the critical value. This

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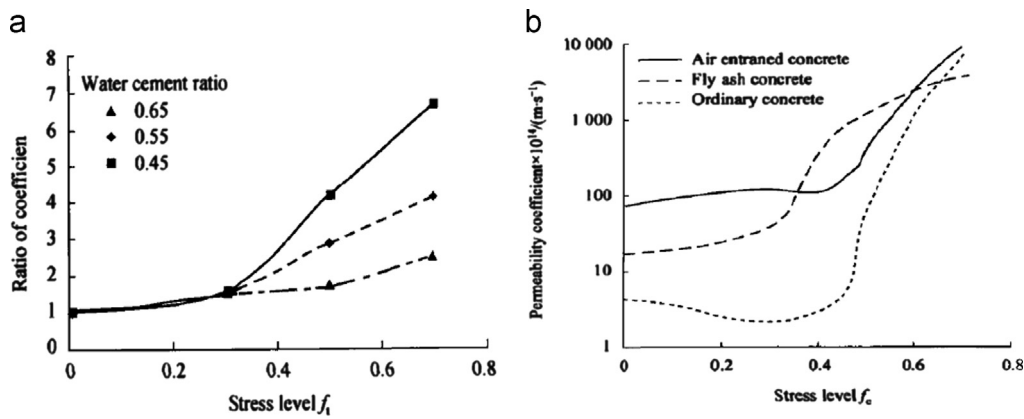


Fig. 1. Effect of loading level on permeability: (a) under tension (Yang et al., 2008) and (b) under compression (Kermani, 1991).

phenomena have also been examined by Kermani (1991) (see Fig. 1b). Francois and Maso (1988) and Gowripalan et al. (2000) carried out some tests to study the effect of flexural loadings on chloride diffusivity in concrete, and they found that the chloride ions diffuse much faster in the tensile areas than that in the compressive areas. When the compressive stress level is relatively lower, the porosity of concrete decreases with the increase of stress and it reduces the diffusion capacity of concrete. However, when the compressive stress level is high enough, new cracks will generate, causing the expansion of concrete. And then chloride diffusion will increase continuously with the increase of loadings.

In the simulations, a lot of computational approaches for the investigation on the chloride diffusivity in concrete subjected to external mechanical loadings have been developed. The mechanisms of the chloride penetration in concrete are very complex, and therefore lots of empirical formulas have been developed for the prediction of chloride diffusivity in concrete. For instance, Li et al. (2003) derived an analytical solution of the Fick's second law for the prediction of chloride diffusivity in concrete flexural members based on the combination of the Knudsen and the viscous flows. Boulfiza et al. (1999) proposed a method to establish the essentials of the dependence between the mechanical performances and the physic-chemical environment within the general framework of continuum thermodynamics of reactive porous media. Their analysis results indicate that the chloride concentration at a same depth of concrete specimen subjected to flexural loads is much larger than the one of the specimen without loadings. Lu et al. (2008) carried out some axial compressive and flexural-tensile tests of concrete, and they proposed a quantitative relationship between chloride diffusion coefficient and stress level based on their test data.

In recent years, the effect of external mechanical loads on chloride diffusivity in concrete has also been investigated by using numerical simulations. Wang et al. (2008) applied the rigid body spring model (RBSM) to carry out the mechanical analysis for the simulation of the distribution and the width of micro-cracks, and they also adopted the truss network model to evaluate the chloride diffusivity of cracked concretes. Moreover, the chloride diffusivities in mortar and the interfacial transition zone (ITZ) subjected to loadings were analytically clarified. Their results show that the chloride diffusivity depends on the stress level significantly. Xiang and Zhao (2007) conducted some efforts on the time-variant reliability of chloride diffusion in fatigue damaged concrete structures through integrating damage mechanics, nonlinear analysis, numerical simulation of diffusion processes, and reliability methods. The results demonstrate that the fatigue damage accumulation may have a significant influence on the time-dependent reliability of chloride concentration at the pre-stress tendon

position. Kamali-Bernard and Bernard (2009) explored the influence of tensile cracking on the diffusivity of mortar using a three-dimension meso-scale numerical method. Šavija et al. (2013) studied the chloride diffusion in sound and cracked concrete by using the lattice model, and they proposed a relation between the effective diffusion coefficient of cracked lattice elements and crack width. Moreover, the effect of transverse cracking on chloride penetration into concrete was also investigated by Bentz et al. (2013). And they found that cracking has a relatively larger impact on chloride penetration in high-performance concretes.

These studies promote the understandings of chloride diffusion behavior in concrete under external mechanical loads. Nevertheless, the micro-/meso-scopic mechanism of the effect of external mechanical loads on chloride diffusivity in concrete has not been totally solved. Moreover, the quantitative relationship between chloride diffusivity in cement-based composite materials and external mechanical loads has not been described either. And further work thus needs to be conducted.

Under a marine environment, concrete is often subjected to cycles of saturated and unsaturated (Ababneh et al., 2003). For the sake of simplicity, the focus of the paper is on the chloride diffusivity in water-saturated cement paste under external mechanical loads. The purpose of the present study, therefore, for one thing is to provide a theoretical formula for the simulation of chloride diffusivity in saturated cement paste, and for another thing is to examine the effect of external mechanical loads on chloride diffusivity. As known, under external mechanical loadings, the porosity of cement paste changes, causing the change of chloride diffusivity in cement paste (Hoseini et al., 2009; Jin et al., 2010). Accordingly, the influence of external mechanical loads on chloride diffusivity in cement paste can be equivalent as the effect of the change of porosity on chloride diffusivity.

In light of this, from the microscopic point of view, the saturated cement paste is considered as a two-phase composite material composed of intrinsic cement paste matrix (with zero porosity) and pore-water inclusion in this article. In Section 2, based on the theory of elasticity, the quantitative relationship between the current porosity of cement paste and initial porosity as well as volumetric strain is derived, and the macroscopic effective chloride diffusion coefficient of water-saturated cement paste is obtained. In Section 3, the effects of the related parameters are explored, including initial porosity and volumetric strain. In Section 4, the effects of external mechanical loadings (herein i.e. the volumetric strain) and porosity variation on the diffusion behavior of cement paste are investigated on the basis of the Fick's second law. Some concluding remarks on the proposed theoretical model are outlined in Section 5.

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