



Effect of cracks on concrete diffusivity: A meso-scale numerical study



Xiuli Du^a, Liu Jin^{a,b,*}, Renbo Zhang^a, Yue Li^a

^a Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China

^b Department of Civil Engineering, Tsinghua University, Beijing, China

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ABSTRACT

Concrete cover is often cracked due to e.g. shrinkage, thermal and mechanical loadings, making the service life of concrete structures severely reduced. The diffusivity are strongly dependent on the micro-/meso-structure of concrete. Considering the concrete heterogeneities, cracked concrete at meso-scale is treated as a four-phase composite composed of aggregate particles, cement paste matrix, the interfacial transition zone (ITZ) and crack phase. A meso-scale simulation model for the investigation on the chloride diffusivity into heterogeneous cracked concrete is proposed. In the model, each phase has its own mechanical and diffusion properties. The aggregate is set as impermeable, and the diffusion properties of the cement paste and the ITZs are determined by water-to-cement ratio. For the crack phase, the diffusion coefficient is obtained by fitting the available test data. The accuracy of the developed meso-scale simulation method is verified and discussed. The effect of artificial crack and tortuous crack on the chloride diffusivity is explored. The simulation results indicate that the developed meso-scale model can successfully describe the chloride diffusivity into cracked concrete. Moreover, it is found that the apparent chloride diffusivity in cracked concrete depends on not only the crack width but also the crack depth.

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1. Introduction

For concrete structures, deteriorating mechanisms are of great concern for both safety and economy reasons. One such important mechanism is that of chloride ion ingress. As known, chloride ions are harmful for concrete structures because they can initiate corrosion of embedded reinforcement bars at a certain level of concentration. Concrete covers often crack unavoidably when they are subjected to chemical shrinkage, drying shrinkage, autogenous shrinkage or external mechanical loadings. Then chloride ions will penetrate into concrete through the cracks and pore systems, and the deterioration of concrete properties will therefore be accelerated. Accordingly, it is of paramount importance to investigate the chloride diffusivity in cracked concrete.

Numerous studies have been devoted to determine the chloride diffusivity in cracked concrete by using experimental and numerical methods. Some laboratory tests, for instance, the splitting tensile tests (Wang et al., 1997; Aldea et al., 1999; Djerbi et al., 2008), flexural tests (Win et al., 2004; Sahmaran, 2007), artificial notches (Marsavina et al., 2009; Ye et al., 2012) or mechanical expansive cores

(Ismail et al., 2004, 2008) are usually introduced to generate cracks in concrete. The concrete specimens with cracks were then subjected to the traditional ponding tests or rapid diffusivity tests designed to allow the chloride ions to diffuse along the generated crack paths. Chloride concentrations or diffusion coefficients can be measured. Aldea et al. (1999) studied the relationship between cracking and concrete diffusivity, and they found that chloride diffusivity was sensitive with respect to cracking for only high-strength concrete with a very low water-to-cement ratio. Djerbi et al. (2008) found that, the chloride diffusion coefficient increased with the increase of crack width when the crack width is in the range of 30 μm –80 μm , and the diffusion coefficient through the crack was not dependent on material parameters and it became constant when the crack width is larger than 80 μm . The study of Ismail et al. (2008) showed that crack width significantly affects chloride diffusion along a crack. In detail, a crack with a width of 30–200 μm has a great influence on chloride diffusivity; and the diffusion of chloride in the solution filling cracks with a width greater than 200 μm is not a limiting factor controlling the diffusion process perpendicular to the crack wall. Jang et al.'s (2011) studies indicated that the diffusion coefficient did not increase with increasing the crack widths up to the so-called “threshold crack width” and its corresponding magnitude was found to be around 55–80 μm . However, due to the differences of the test methods to generate cracks, the ways to expose the specimens and the means to measure the diffusion coefficients, the above conclusions cannot

* Corresponding author at: Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China. Tel.: +86 15811171018.

E-mail address: kinglew2007@163.com (L. Jin).

correspond to each other. Furthermore, there are some other disadvantages in these experimental studies, for instance, too much time is required and the independent effects of some parameters cannot be determined.

There are few studies about theoretical analysis on the chloride diffusivity into cracked concrete, owing to the discontinuity and heterogeneity of cracked concrete. Kato et al. (2005) proposed a model for chloride transportation in cracked concrete. In their model, the zone affected by cracking was treated as a region near the exposed surface of concrete where chloride transportation was assumed to be governed by the concentration of the chloride solution in the cracks. Furthermore, the quantitative effect of the crack width on the apparent diffusion coefficient were investigated.

To make up for deficiencies of experimental studies and theoretical analyses, recently, some efforts have been conducted to explore the diffusion behavior of chloride into cracked concrete by numerical simulations. For instance, Ishida et al. (2009) simulated the movement of chloride in the cracked concrete using the Finite element (FE) method. In their studies, the transport of chloride in cracked concrete was modeled by introducing large void spaces in a control volume to represent the crack. In the work of Marsavina et al. (2009) and Bentz et al. (2013), considering the cracked zone as an exposed surface, the chloride diffusivity in cracked concrete was simulated based on the FE method. In addition, Kwon et al. (2009) predicted the quantitative relationship between the chloride diffusion coefficient and crack width, and they investigated the service life of the cracked concrete in the probabilistic framework of Monte Carlo simulation. It is worthy to note that the concretes were considered as a homogeneous media in the above research work. In reality, the concrete conductivity and diffusivity, as well as the mechanical behavior are strongly dependent on the microstructure of concrete (Garboczi and Bentz, 1998). To consider the heterogeneities of concrete, Ye et al. (2012) elaborated a finite-difference model to describe the transport of chloride ions in cracked concrete. Moreover, Wang et al. (2008, 2011) and Šavija et al. (2013, 2014) established meso-scale models to simulate chloride diffusivity in cracked concrete based on the Rigid Body Spring Model and the Lattice network model, respectively. In their studies, the concrete was considered as a three-phase composite, i.e., aggregate particles, cement paste matrix, the interfacial transition zone (i.e. the ITZ). However, there are some deviations between their simulation results and the available experimental observations. In Šavija et al.'s (2014) work, the penetration front obtained by the simulation is much narrower than the test. They attributed the potential cause to be the wall effect which could have caused a more porous zone close to the notch. And, it is possible that the crack introduces a change in the electrical field locally due to the high conductivity of the solution in the crack, resulting in somewhat high penetration of chloride ions in the lateral direction than expected (Šavija et al., 2014).

The aim of the present study is to explore the effect of crack dimensions (i.e. crack depth and crack width) on chloride diffusivity in concrete. Taking the concrete heterogeneities in account, the cracked concrete in the present work was treated as a multi-phase composite. The cracking herein this work was set as an independent phase having its own independent diffusion characteristic. The cracks including artificial cracks (notches), and tortuous cracks generated from the fracture simulation of a concrete specimen, were utilized. The meso-scale material constituents, therefore, involve four phases, namely the cement paste matrix, aggregates, the ITZ and cracks. The aggregates were treated as inclusions with random spatial distribution enfolded by an interface layer of ITZ, and the cement paste matrix was considered to be homogeneous. It was assumed that the aggregate is relatively impermeable compared with the ITZs and the cement paste matrix. The chloride diffusion coefficient of aggregate was thus

taken to be zero in the present study. The chloride diffusion was assumed to take place in the cement paste matrix, the ITZs and the crack phases. A quantitative relationship between chloride diffusion coefficient of crack and crack width was derived by fitting the available test data. The transport equations were then solved using the finite element method, in which the four components were meshed separately and continuity in fluxes at interfaces between them was applied.

After the introduction, the paper is organized as follows: In Section 2, the basic theory on chloride diffusivity is described firstly, and chloride diffusivity in heterogeneous sound concrete is introduced briefly. Section 3 presents the meso-structure of concrete and the diffusion properties of the meso components. In Section 4, the influence of aggregate distribution pattern on chloride diffusivity is examined, and the proposed model is validated against the available test data. The influences of cracking on chloride penetration into concrete are explored based on the meso-scale computational method. Finally, some concluding remarks are presented in Section 5.

2. Method

2.1. Chloride diffusivity theory

2.1.1. Governing equation

The governing equations for mass diffusion are an extension of Fick's equation (Crank, 1979): they allow for non-uniform substance in the base material and mass diffusion driven by gradients of temperature and pressure. The basic solution variable (used as the degree of freedom at the nodes of the mesh) is the "normalized concentration" (often also referred to as the "activity" of the diffusing material), $\phi = C/s$, where C is the mass concentration of the diffusing material and s means its solubility in the base material.

The weak form of the governing equation is

$$\int_V \left[\delta\phi \left(\frac{dC}{dt} \right) - \mathbf{J} \cdot \frac{\partial \delta\phi}{\partial \mathbf{X}} \right] dV + \int_S \delta\phi \mathbf{n} \cdot \mathbf{J} dS = 0 \quad (1)$$

in which V is any volume whose surface is S , $\delta\phi$ is an arbitrary, suitable continuous and scalar field, \mathbf{n} is the outward normal to S , \mathbf{J} is the flux of concentration of the diffusion phase, and $\mathbf{n} \cdot \mathbf{J}$ is the concentration flux leaving S .

As known, the diffusion is assumed to be driven by the gradient of a chemical potential, which gives the general behavior as

$$\mathbf{J} = -s\mathbf{D} \cdot \frac{\partial \phi}{\partial \mathbf{X}} \quad (2)$$

where $\mathbf{D}(c, \theta, \mathbf{f})$ denotes the diffusivity; ϕ is the normalized concentration; $s(\theta, \mathbf{f})$ means the solubility; θ is the temperature; and \mathbf{f} are any predefined field variables.

The detailed derivation of the weak form of the governing equation refers to the previous work (Du et al., 2014a).

2.1.2. Discretization and time integration

Equilibrium in a finite element model is approximated by a finite set of equations through the introduction of appropriate interpolation functions. Discretized quantities are indicated by uppercase superscripts (e.g., ϕ^N). The summation convention is adopted for the superscripts. These represent nodal variables, with nodes shared between adjacent elements and appropriate interpolation chosen to provide adequate continuity of the assumed variation. The interpolation is based on material coordinates S_i , $i = 1, 2, 3$.

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