Ocean Engineering 127 (2016) 144–157

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Prediction of mass transport in cracked-unsaturated concrete by mesoscale lattice model

Licheng Wang[a], Jiuwen Bao[a,*], Tamon Ueda[b]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China
[b] Division of Engineering and Policy for Sustainable Environment, Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan

ARTICLE INFO

Keywords:
Mass transport
Cracked-unsaturated concrete
Mesoscale lattice model
Drying-wetting (D/W) cycles

ABSTRACT

The ingress of mass in a harsh chloride environment leads to the corrosion of reinforcing steel bars and deterioration of the structural performance. This paper deals with a two-dimensional (2D) numerical model for water and chlorides transport in the cracked-unsaturated concrete on the mesoscale level, in which concrete is modeled as a composite material with impermeable coarse aggregates embedded in the porous matrix which is separated by vulnerable interfacial transition zone (ITZ). Coupled with the unsaturated flow theory and the cubic law of water through a single crack, the transport coefficients for water and chloride ions in a single crack are developed by treating the crack as a parallel-plate configuration. The lattice network developed on the basis of Voronoi tessellation is presented to investigate mass transport process in the cracked-unsaturated concrete subjected to drying-wetting (D/W) cycles. The above proposed transport model coupled with the mesoscale lattice approach is validated by comparison with the available experimental findings from the literature. The numerical results indicated that the computational models are able to well represent the mass (water and chloride) movement within the cracked-unsaturated concrete. Furthermore, the cyclic D/W action and crack width/length within concrete are crucial for the transport properties of unsaturated concrete.

1. Introduction

The mass transport in concrete when exposed to harsh marine environment or deicing salt has been increasingly recognized as the major concern to the durability of reinforced concrete structures (Ababneh et al., 2003; Şahmaran and Li, 2009; Du et al., 2015). Chloride-induced corrosion of steel bar is generally considered as one of the main deterioration mechanisms of structural performance. Over the past few decades, a variety of models to predict the chloride ingress into concrete have been introduced, and in terms of them, some service life prediction methods are now available under certain conditions (Wang and Ueda, 2011a, 2011b; Ishida et al. 2009). Currently, many deterministic and probabilistic studies on chloride diffusion adopt the classical Fick's second law to depict mass transport process, which can be assumed that both the diffusion coefficient and chloride surface concentration are invariable and the material is under saturated state. Therefore, according to the initial and boundary conditions, the chloride ion concentration $C(x, t)$ at a given time t and position x can be estimated by an error function complement solution as the formulation follows:

$$C(x,t) = C_0 + (C_s - C_0)\left[1 - erf\left(\frac{x}{2\sqrt{D_c t}}\right)\right] \tag{1}$$

where C_0 is the initial chloride concentration within concrete; C_s is the chloride concentration at the surface of the concrete; D_c is the chloride diffusivity; $erf(x)$ denotes the error function. However, concrete in the real environment is always found under the unsaturated state or cracked due to various mechanisms (e.g. plastic or autogenous/drying shrinkage, thermal and mechanical loading). Moreover, water penetration and chloride ingress into cracked concrete imply a complex interaction concerning many physical and chemical processes. Meanwhile, the mass transport mechanisms may influence the durability of concrete structures indirectly by controlling the penetration rate of aggressive agents.

Since free water usually acts as the carrier of chlorides ions into the bulk concrete, the effect of water movement on chloride ingress into unsaturated concrete should not be ignored, especially undergoing the D/W cycles (Li et al., 2009 and 2013; Nielsen and Geiker, 2003; Saetta et al., 1993; Wang and Ueda, 2011b). Moreover, it has been well recognized that cracks or microcracks caused by mechanical loading or environmental action may result in a higher rate of water or chloride

* Corresponding author.
E-mail address: baojiuwen55@126.com (J. Bao).

http://dx.doi.org/10.1016/j.oceaneng.2016.09.044
Received 28 September 2015; Received in revised form 2 August 2016; Accepted 29 September 2016

ingress into concrete than that of the sound concrete, since cracks can provide preference pathways to allow more water along with chlorides to easily penetrate (Djerbi, 2008; Šavija et al., 2013; Wang et al., 2008). Regarding to the above consideration, if the methods treat concrete as a sound, uncracked and saturated material, the durability and service life of concrete structures cannot be realistically evaluated. Thereafter, it is indispensable to clarify the mass transport mechanism and mass distribution result in the cracked-unsaturated concrete.

In the past few decades, some attempts have been attracted attention on water penetration or chloride ingress into concrete/cracked concrete. Li et al. (2009) adopted the diffusion-absorption model of moisture transport to numerically calculate the influential depth of the sound concrete surface subject to D/W cycles. They found that the initial saturation and the D/W time ratio mainly determine the moisture influential depth. Saetta et al. (1993) and Ababneh et al. (2003) simulated chloride penetration into unsaturated concrete by considering the effect of material parameters on the environmental conditions, chloride binding capacity, moisture capacity, and diffusion coefficient by means of convection-diffusion equation. According to the Fick's second law, Nielsen and Geiker (2003) modified the chloride diffusion coefficient by experimental method and developed a simplified model for predicting chloride ingress into partially-saturated (i.e. unsaturated) concrete. However, due to the complexity in representation of the cracking of concrete, in the previous studies the effect of cracking on transport properties of unsaturated concrete was rarely clarified Although the characteristics of chlorides penetration in cracked concrete have been reported (Wang and Ueda, 2011a; Djerbi, 2008; Šavija et al., 2013; Wang et al., 2008; Boulfiza et al., 2003; Grassl, 2009; Bentz et al., 2013), the transport process is regarded to be in saturated condition and it is not always coincide with the actual state of concrete. Particularly, the mass transport characteristic through a single crack has not yet been made clear.

Numerical analysis of mass transport in concrete by mesoscale method, in which concrete is described as a three-phase composite consisting of the coarse aggregate, hardened cement mortar and the interfacial transition zone between aggregate and mortar, not only may enhance understanding of the non-homogeneous characteristic of concrete but also can represent influence of material composition and cracking on transport properties. According to cracking mechanism of the anisotropic concrete, there are two groups of approaches within the finite element framework to account for the cracking effect on mass transport process in concrete, i.e. smeared and discrete approaches (Boulfiza et al., 2003; Grassl, 2009). In smeared approaches, the effect of cracking on mass transport processes can be considered by transport properties spatially varied in the whole domain. For example, Ožbolt et al. (2010) adopted a damage variable to describe the increase of diffusivity and permeability of concrete in the cracked area, and presented a 3D numerical chemo-hygro-thermo-mechanical model to simulate the corrosion of reinforcement. Similarly, a uniform scalar damage variable “*d*” employed by Rahman et al. (2012), which is dependent on the magnitude of strain, was regarded as the intermediate link of coupled mechanical cracking and chloride diffusion, realizing numerical simulation of rapid chloride-migration test. According to the smeared crack concept, the numerical model developed by Ishida et al. (2009) has realized the effect of cracking on chloride diffusivity coupled with non-linear binding capacity by treating cracks as a group of large voids. In comparison, in discrete approaches the crack is explicitly represented by two surfaces with flow occurring between the surfaces, and an exchange of water and chloride ions is allowed between the crack and surrounding bulk concrete (Boulfiza et al., 2003; Wang et al., 2008). On mesolevel, Sadouki and Van Mier (1997) indicated that the lattice-type approach, in which the lattice elements can be treated as conductive “pipes”, can be used to accurately describe continuous unidirectional flow between the two nodes of the element. On the basis of Voronoi tessellation, Grassl (2009) developed the dual-lattice model in which one can be used for flow simulation and the other for mechanical response. Likewise, Šavija et al. (2013) proposed a 3D dual-lattice model to numerically simulate chloride diffusion in saturated sound and cracked concrete. Wang and Ueda (2011a, 2011b) developed the mesoscale lattice network model, in which concrete is discretized as a set of lattice elements by connecting the Voronoi nuclei and the intermediate points of the particle boundaries, and assumed that cracks occur and propagate along the particle boundaries. As a result, the diffusion coefficient and cross sectional area can be varied in terms of the crack width. However, on the whole, it is necessary to investigate the influence of cracking on transport properties of unsaturated concrete.

This paper focuses on developing the 2D numerical mesoscale method that could systematically investigate the mass transport of concrete by the coupling of capillary water absorption and diffusion-convection of chloride, including the influence of crack and the saturation degree of concrete. The objective lies on determination of the water content distribution and chloride profiles within concrete samples. The transport governing equations are implemented by the Galerkin weighted residual method in space and the Crank-Nicholson approach in time domain. The water diffusivity through a single crack is formulated in terms of the unsaturated flow theory, and the rate of chloride penetrating through cracks with variable width and water content is addressed. Based on the mesoscale lattice network model, the above proposed transport equations are validated by comparison with the available experimental works from the literature. Additionally, application of transport analysis for concrete undergoing drying-wetting cycles as well as the sensitivity analysis is carried out.

2. Mass transport mechanisms in unsaturated concrete

Mass transport processes in unsaturated concrete, which implies a complex interaction between the nonlinear dynamic phenomena and physical-chemical process, are mainly categorized into four types: (i) diffusion, where it occurs due to concentration difference of non-uniform distribution of media, moving from zones with higher concentration to lower ones; (ii) convection or capillary absorption, where mass transport is driven by capillary pressure gradient due to surface tension in the capillary pores; (iii) electro-migration, where it is driven by electrical potential gradient under additional electric-field action; (iv) pressure permeation, where it is produced by hydraulic pressure gradient. In practice, the ingress of mass transport (water or chlorides) into the unsaturated concrete can be governed by any of these mechanisms or a combination of them.

2.1. Water movement driven by capillary absorption

Unsaturated flow theory, which is widely adopted to describe water uptake in soil, can be utilized to explain water transport in partially saturated concrete (Carpenter et al., 1993; Hall, 1989, 2007; Leech et al., 2003; Lockington et al., 1999). According to the following assumptions: i) concrete being taken as the porous and semi-infinite media; ii) ignoring gas phase of water; the equation for unsaturated flow through porous media is expressed by combination of the extended Darcy's equation due to capillary pressure gradient and the mass balance equation (Hall, 1989; Lockington et al., 1999):

$$\begin{cases} u = K(\theta)\cdot\nabla p_c \\ \frac{\partial\theta}{\partial t} + div\ u\ = 0 \end{cases} \tag{2}$$

where u is the flow rate of water, (m/s); p_c is capillary pressure; $K(\theta)$ is the hydraulic conductivity function; the dimensionless variable θ is defined as the relative water content, usually normalized by $\theta=(\Theta-\Theta_i)/(\Theta_s-\Theta_i)$, in which Θ_i and Θ_s is the initial and saturated volumetric water content (i.e. volume of water/bulk volume of concrete). Obviously, θ takes the value 0 at initial water content (whatever it is)