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An experimental and numerical study on water permeability of concrete

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HIGHLIGHTS

- Water transport behavior in concrete was simulated by a 3D FE algorithm.
- ITZ was modeled practically by the zero-thickness interface element.
- Laboratory experiment was conducted to provide parameters and validation data for numerical simulation.
- The effects of ITZ and coarse aggregates on water permeability were quantitatively studied.

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ABSTRACT

Durability of concrete depends largely on its water permeability, which is dominated by the composition and difficultly evaluated. This paper presents a three-dimensional (3D) FE algorithm to investigate the water transport performance in concrete. This FE model possesses three-phase mesostructure consisting of coarse aggregates, mortar matrix, and the interfacial transition zone (ITZ) which is practically modeled by the zero-thickness interface element. A series of numerical tests with regard to concrete samples containing different volume fractions of coarse aggregates are conducted. The calculated permeability coefficients are in reasonable accordance with the physical experiment data. Effects of aggregates and ITZ on the concrete permeability are also quantitatively studied by the numerical test. It is proved that the proposed algorithm is capable of modeling the permeable characteristics of concrete which is affected greatly by its heterogeneous mesostructure.

1. Introduction

Water permeability of concrete is believed as the key property related to the serviceability and durability of concrete structures (e.g., bridges, hydraulic structures and marine structures) subjected to aggressive environments, since water acts as either the major agent responsible for the deterioration of concrete or the transport medium for aggressive species like chloride or sulfate ions [1–4]. In general, higher permeable concrete, with more pores and voids, is less durable [5]. A good understanding of water transport characteristics of concrete will assist the progress in service-life prediction and optimum material design [6].

Physical experiment has been exercised for many years to measure water permeability [7–9] and to investigate different variables affecting water transport in cementitious materials [10–15]. Among these variables are the water–cement ratio [10,11], aggregate content [12,13], aggregate size distribution [14] and pore characteristics [15], etc. Particularly, it is revealed that the variations in the mixture proportions may exert a considerable impact on the permeability of concrete. Although the physical experiment method provides a direct means to look into these variables and their effects, it is subject to several inherent limitations. For example, due to the fact that concrete is a complex heterogeneous multi-phase composite, it is often difficult to exactly separate the effects of these variables. In addition, a large number of specimens should be prepared and tested to eliminate the stochastic variations aforementioned [16], which will be time-consuming and costly.

With the significant advance in computer technology and numerical methods, mesoscopic modeling becomes more and more widely accepted to study the composite behavior of concrete [17]. Many models have been proposed to simulate the mesostructure of concrete, which commonly takes into account of three phases: coarse aggregates, mortar matrix (or cement paste) and interfacial transition zone (ITZ) between them. Although these models are extensively employed to estimate the mechanical properties, such as elastic modulus, tensile strength, and fracture energy [18,19], thermal properties (e.g., thermal conductivity [16,20,21]), and diffusion properties (e.g., chloride diffusivity

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[22,23]), yet water transport properties of concrete has received relatively less attention. Recently, Wang and Ueda [24] develop a two-dimensional (2D) lattice network model to predict water penetration into concrete, whereby the three phases in concrete are discretized into lattice elements considered as conductive "pipes" with different transport properties. Their results show that the thickness of ITZ exhibits only a small influence on water absorption. Abyaneh et al. [25] utilize a mesoscale model to investigate water sorptivity of concrete with 3D lattice network and to study the effects of the amount, spatial distribution and shape of aggregate particles on capillary absorption, but the impact of ITZ is not taken into account. Zhou and Li [26] propose a 2D mesoscale model for simulating the steady permeation in concrete sample based on finite element method (FEM). Assuming concrete as a random three-phase composite, they have performed a numerical and statistical analysis to investigate its water permeability and to quantify the size of representative volume element (RVE). However, most of these models are 2D, which might not be used to predict the spatial 3D flow in reality. In addition, in the lack of a precise modeling of ITZ – the weakness zone in concrete [27,28], the simulated results may be questionable.

In this paper, a FE algorithm is established to evaluate the water permeability of concrete and to explore how the individual components of the concrete mixture influence its transport behavior. The model is built on the mesoscale level, whereby the concrete is idealized as a three-phase composite consisting of coarse aggregate, mortar and ITZ. The geometry entity of the 3D mesostructure is explicitly discretized by finite elements, in which the zero-thickness element is used for modeling ITZ. In order to validate the proposed algorithm, physical experiments are conducted in parallel. In the experiment, permeability coefficients of specimens with different aggregate volume fractions are measured, providing the material parameters and validation data for the numerical simulation. Finally, the effects of mesostructural heterogeneity such as the water transport property of ITZ and the volume fraction of aggregates on water permeability of concrete are investigated with the help of the numerical simulation algorithm proposed and validated in this paper.

2. Permeability theory of concrete

2.1. Governing equation

Suppose that the flow of liquid in porous medium obeys Darcy's law, which may be written as [3,5]:

$$u = -k\nabla\phi \tag{1}$$

in which u ($\mathrm{L\,T^{-1}}$) is the flow velocity, k ($\mathrm{L\,T^{-1}}$) is the permeability coefficient, ϕ (L) is the hydraulic potential and ∇ ($\mathrm{L^{-1}}$) is the spatial gradient operator.

Introducing Darcy's law into continuity equation for incompressible and steady flow, water transport in perfectly saturated materials is governed by the following partial differential equation:

$$\nabla(k\cdot\nabla\phi) = 0 \tag{2}$$

Eq. (2) is subject to appropriate boundary conditions:

$$\phi|_{\Gamma_1} = \phi_0 \text{ (first type)} \tag{3}$$

$$k\cdot\partial\phi/\partial\{n\}|_{\Gamma_2} = -q \text{ (second type)} \tag{4}$$

in which $\{n\} = \{l_x, l_y, l_z\}^T$ are direction cosines of the external normal to the boundary, ϕ_0 and q are specified hydraulic potential at the first type boundary Γ_1, and the flow rate through the second type boundary Γ_2, respectively.

2.2. Permeability test

Water permeability characterizes the capability of saturated concrete to transport water when subjected to an applied hydraulic gradient [3,5]. It is usually measured in the laboratory by permeability tests based on the Darcy's law (Vide Eq. (1)), which can be written as follows:

$$k = \frac{QL}{\Delta\phi S} \tag{5}$$

in which $\Delta\phi$ (L) is the hydraulic potential difference, S ($\mathrm{L^2}$) is the cross-sectional area perpendicular to flow direction, L (L) is the length of flow path and Q ($\mathrm{L^3\,T^{-1}}$) is the flow rate.

However, laboratory based permeability tests for modern dense concrete or high performance concrete may encounter practical difficulties: a high pressure and a long time are required to drive the steady state flow through the concrete specimen, and there is high risk of leaking around the specimen if the surface sealing is not guaranteed. There seems still no widely or fully accepted techniques for measuring the permeability of concrete [9,29], though some advanced experimental methods [8,30,31] have been proposed. Given the limitations of experimental test, numerical simulation might be an applicable and effective approach.

3. Mesostructure modeling of permeable concrete using FE algorithm

The FE algorithm is formulated to investigate the water transport behavior of concrete with a heterogeneous mesostructure, in which coarse aggregates, mortar matrix and ITZ are modeled as distinct phases with different material properties assigned.

3.1. Numerical sampling of concrete with mesostructure

The 3D random aggregate structure (RAS) is established for numerical samples of concrete. Spherical particles are used to model coarse aggregates for simplification. The size distribution of aggregates is determined following a certain given grading curve (such as Fuller curve or Bolomey curve [18,32]). In most concretes, the volume fraction of coarse aggregates is between 0.4 and 0.5 [18,19]. The prescribed volume fractions of aggregate particles are randomly arranged and placed in a cube, cylinder or frustum shaped sample, which depends on the type of concrete specimen to be tested. The approach of "occupation and removal method" [33,34] is employed to conduct this packing process. In order to produce the geometrical configuration which resembles the real concrete, the random sampling principle of Monte Carlo (MC) simulation method is used for both the spatial distribution and size distribution of aggregates. The detailed procedure for generating the geometrical models can be referred to literature [17]. Fig. 1 shows three concrete samples in different shapes with constant aggregate volume fraction of 0.4.

An important phase in the mesostructure is ITZ, which has long been regarded as a zone of weakness in concrete composite, both in terms of strength and the permeation [15,28]. So the ITZ is included in the numerical sample as a bonding layer structure surrounding the coarse aggregates.

3.2. FE algorithm

It is still a challenge for the mesh generation of such a complex 3D mesostructure in presence of the unique layer structure of ITZ, which is extremely thin and rather small compared to the normal size of coarse aggregates. Therefore, many efforts have been made to model ITZ structure [17,22,24,35]. An elegant FE model is devel-