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Modeling water absorption in concrete and mortar with distributed damage

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HIGHLIGHTS

- The results of numerical simulations of sorption is corroborated with experiments.
- The effect of distributed damage on moisture flow is studied.
- The effect of moisture isotherm hysteresis is considered in modeling.
- Experimentally obtained modeling parameters for mortar and concrete are reported.
- The simulations well agree with experiments at early stages of moisture ingress.

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ABSTRACT

The deterioration rate of concrete structures is directly influenced by the rate of moisture ingress. Modeling moisture ingress in concrete is therefore essential for quantitative estimation of the service life of concrete structures. While models for saturated moisture transport are commonly used, concrete, during its service life, is rarely saturated and some degree of damage is often present. In this work, we investigate whether classical isothermal unsaturated moisture transport can be used to simulate moisture ingress in damaged mortar and concrete and we compare the results of numerical simulations with experimental measurements of water sorption. The effect of hysteresis of moisture retention is also considered in the numerical simulations. The results indicate that the unsaturated moisture transport models well simulate early stages of moisture ingress at all damage levels, where capillary suction is the prominent mechanism. At later stages of moisture transport, where air diffusion and dissolution have a more significant contribution, simulations that consider moisture hysteresis compare most favorably with experimental results.

1. Introduction

The rate of freeze-thaw deterioration, chemical attack, corrosion of reinforcement, and many other deleterious processes in concrete structures are strongly dependent on the rate of moisture ingress. The rate of moisture ingress is heavily influenced by the degree of saturation and the presence of damage. Concrete, during its service life, is rarely saturated and some degree of damage is often present (e.g. due to freeze-thaw) [46]. Distributed damage in concrete significantly increases the rate and the amount of moisture ingress [17,72,73,24,1]. While unsaturated moisture transport in concrete material has been studied (e.g. [23,33,37,21]), limited research exists on unsaturated moisture transport in *damaged* concrete [35,69,39,75,76,19]. Specifically, modeling studies on unsaturated moisture transport in damaged cementitious material are very scarce [63,20,7,11]. In this paper, we investigate the accuracy of the classical model (including hysteresis) for simulating unsaturated water absorption in damaged mortar and concrete.

The majority of the previous studies on moisture transport in damaged cementitious material were experimental in nature. These studies have shown that, for example, chloride migration (as tested by Rapid Chloride Permeability Testing) increases in concrete after subjecting concrete to compressive loading above 75% of its compressive strength [54,68]; found that water permeability generally increases with damage [1]; found that discrete cracks have a significant effect on water permeability [53]; found that chloride penetration increases in damaged samples, irrespective of the presence of mineral admixtures [45]; found that the permeability of discrete cracks increases proportional to the cube of the crack opening displacement in specimens. They also showed that

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the use of fiber reinforcement increases the crack tortuosity. In a recent study, the effects of distributed damage on mass transport was shown to be dependent on the mechanisms of transport considered ([18]).

The previous experimental studies have offered significant insights as to the effect of damage on the mass transport properties of damaged cement-based material. While a significant amount of experimental data for damaged cement-based materials are available in the literature, the numerical simulation of unsaturated moisture flow in damaged cement-based material is not well studied. In contrast, numerous studies have simulated moisture flow in undamaged materials (e.g. [25,59,47,41,4]). Numerical simulations are of significant interest since many service-life prediction models need to account for the effects of damage – characteristics which significantly affect moisture flow in concrete structures ([57]).

Recent examples studying moisture flow simulations in damaged cementitious material include the followings. Grassl [20] developed a lattice model, modeling 2D fractured materials, to simulate moisture flow in concrete with distributed cracks. Pour-Ghaz et al. [47,48] compared simulations of unsaturated moisture flow from saw-cuts, an idealized crack, to X-ray radiography images. Van Belleghem et al. [63] compared flow regimes from numerical simulations of unsaturated moisture flow in discrete cracks with X-ray images, showing good comparison between the numerical model and X-ray images. These numerical investigations demonstrated the feasibility of numerical simulations of unsaturated moisture flow in cement-based materials. However, neither the effects of varying degrees of damage in the form of distributed cracks nor the effect of moisture retention hysteresis have been studied.

The classical model describing unsaturated mass transport in porous media is Richards' equation ([52]), modeling capillary suction. Richards' equation has been identified as a valid model for mass transport in building materials [71]. Analytical solutions to Richards' equation have been developed for simple geometries [8,44,43,70]. Analytical solutions are generally feasible in simple geometries subjected to simple boundary conditions. Practical applications, however, often requires numerical solution to Richards' equation using, for example, the Finite Element Method. The Finite Element Method solutions of Richards' equation have been used previously to analyze unsaturated moisture transport in concrete (e.g. [63,47,48]. However, these studies investigated cementitious material with discrete cracks. Therefore the feasibility of using classical isothermal unsaturated moisture transport to model moisture ingress and moisture hysteresis in mortar and concrete with distributed damage remains an open question.

2. Numerical methods

2.1. General

In this paper, moisture absorption is modeled using the Richards' Equation (Eq. (1)) [52] for unsaturated moisture flow. Eq. (1) is the classical governing differential equation for isothermal unsaturated flow

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K(h)\left(\frac{\partial h}{\partial x_j} + \delta_{ij}\right)\right] \tag{1}$$

where $K = K(h)$ (mm/hour) is the unsaturated hydraulic conductivity, θ (mm^3/mm^3) is the volumetric moisture content, h (mm) is the capillary suction, x_i (mm) is the spatial coordinate (i,j = 1, 2, 3 for three dimensional space) and δ_{ij} is the Kronecker Delta function which accounts for the gravitational effect. Eq. (1) is generally solved using a numerical methods such as finite element method. In this work we have used a commercially available software (HYDRUS 3D) for this purpose and the details of modeling methods are discussed in Section 2.4.

2.2. Material model

The unsaturated hydraulic conductivity (K) in Eq. (1) is a function of capillary suction (i.e., $K = K(h)$). Experimental measurements of unsaturated hydraulic conductivity are generally difficult and time consuming. These measurements are especially challenging for cement-based materials due to the fine pore size distribution resulting in high capillary suction at low water contents [47,48]. Alternatively, the unsaturated hydraulic conductivity can be expressed as a product of the saturated hydraulic conductivity, K_s, and the relative hydraulic conductivity, $0 < K_r < 1.0$ (i.e., $K = K_s K_r$). Such a model, commonly used in soil physics, has been shown to well-represent the unsaturated hydraulic conductivity in cement-based materials [59,50,55]. The value of K_s can be experimentally measured using Darcy's law. The relative hydraulic conductivity is related to water content and capillary suction by Mualem's model [38] (Eq. (2))

$$K_r = \Theta^I \left[\frac{\int_0^{\Theta} \frac{1}{h(x)}\,dx}{\int_0^{1} \frac{1}{h(x)}\,dx}\right]^2 \tag{2}$$

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{3}$$

where $0 \leqslant \Theta \leqslant 1.0$ is the effective material saturation, and θ_s and θ_r are the saturated moisture content and the residual moisture content, respectively. In this work, θ_s is experimentally obtained for each degree of damage and $\theta_r = 0$ [47,48]. Further discussion of determining θ_s is provided in Section 2. I is an empirical parameter which has been described as accounting for tortuosity and connectivity of pores [38]. Mualem proposed $I = \frac{1}{2}$ as an optimal value for 45 undisturbed soils; however, he noted that values for I can take positive or negative values. Values for soil have been shown to range from -8.83 to 100 [56,74,58]. Kosugi argued that I has no physical significance and should be interpreted as a fitting parameter ([28]). Values of I for cementitious materials and especially for damaged cementitious materials are not readily available [59]. reported values of -3.0 and 35.2 for mortar and concrete, respectively [50]. concluded that the values of I can take positive or negative values, but are generally negative.

It should be noted that the choice of $\theta_r = 0$ is mainly for convenience since it does not introduce a significant modeling error and does not require elaborate measurements. In theory, the value of θ_r should correspond to the water content of the material at equilibrium with 11% relative humidity. This condition results in the formation of a monolayer of physically adsorbed moisture on calcium silicate hydrate [2,13–15], which can be only achieved under extreme drying conditions. In this work, we choose $\theta_r = 0$ following [47,48] to also avoid inconsistency in modeling between mortar and concrete since the actual value of θ_r for concrete is unknown for our materials.

In this study, values of I are estimated by model training using maximum likelihood approach [29]. For such an approach the data need to be split into two sets: training and validation set. In this study only limited supply of experimental data is available. In such situations, using cross-validation methods may provide more accurate solutions of I. However, cross-validation methods can be very computationally expensive due to the computational cost of moisture transport simulations. We therefore use the maximum likelihood least squares fitting approach by splitting the experimental data into training and validation set using random number generators. Training set consisted of 33% of the data and validation set