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Indirect assessment of hydraulic diffusivity and permeability for unsaturated cement-based material from sorptivity

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ABSTRACT

The hydraulic diffusivity, water permeability and relative gas permeability for cement-based materials are indirectly evaluated from measured sorptivity and water vapor sorption isotherms (WVSIs). The dependence of sorptivity on initial saturation degree is first established to help calculate hydraulic diffusivity and other transport properties. An experimental program with a self-scaled preconditioning strategy is also carefully designed and conducted on three concretes to measure their sorptivity, WVSIs as well as permeability to various fluids. It's found that hydraulic diffusivity of ambiguous physical significance may be not a good durability indicator. The predicted water permeability is larger than measured value but at the same order of magnitude. This overestimation is attributed to the required drying preconditioning. The predicted relative water permeability agrees well with reported data. However, the predicted relative gas permeability agrees with the measured data from classical CEMBUREAU method better than that from tri-axial permeameter with higher inlet gas pressure.

1. Introduction

The transport properties of water, the main controller of degradation under various actions including cyclic freezing–thawing, carbonation, and steel reinforcement corrosion, are significantly important in the quantitative analysis on the deterioration of cement-based materials [1–3]. Under real service, most cement-based materials are rarely saturated in engineering practice. In most cases, the water transport in unsaturated porous material is usually described by Darcy's law in terms of either hydraulic diffusivity or permeability [4,5], which strongly depend on the water saturation degree with very high non-linearity [6]. The models for these two significant properties are fundamentally central in the quantitative analysis of durability and service life for cement-based materials under various aggressive environments [1].

The direct measurements of hydraulic diffusivity and permeability for modern cement-based materials with low water to cement ratio, which are much denser and stiffer than porous soils, will face great practical problems [7,8]. The direct testing of hydraulic diffusivity usually employs the non-destructive detecting of instant water content profile in one-dimension capillary suction process, which requires special equipment like Gamma Ray Attenuation, Neutron Radiography and Nuclear Magnetic Resonance (NMR) [3,9]. Several methods indirectly deriving the hydraulic diffusivity from sorptivity, another transport property very easy to measure, have also been proposed [10,11]. Based on the assumed model of specific law for hydraulic diffusivity function, the hydraulic diffusivity can be obtained with certain empirical parameters, which are dependent on the pore structure of concerned materials [11]. In another aspect, although several advanced experimental techniques or facilities have been developed [12–14], the direct measurement of saturated water permeability for dense cement-based material is still a big problem, not mentioning the unsaturated situation [3]. Indirectly, another conceptual model has been proposed to derive unsaturated water permeability from only pore size distribution but limited to rocks in petroleum industry [15]. In addition, another implicit model giving relative permeability to water and gas from only water retention curve have been also initially deduced for soil materials [16,17]. It is further extended to cement-based materials [8,18] and calibrated mainly by gas permeability [19,20], which is much easier to measure over water permeability. However, the fundamental parameters like tortuosity factor in the critical models for water retention curve and relative permeability, which are originally developed for soils [21,22], vary in a great range and are rather hard to accurately determine for cement-based material with pore structure obviously different from soil materials [16,19,23,24]. Moreover, the hydraulic diffusivity and water permeability, different transport properties deducing from the unique Darcy's law for water migration, may be not consistent and contradict with each other on some specific characteristics [25]. It makes

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the indirect methods unconvincing and even questionable in evaluating unsaturated permeability from only water retention characteristics for cement-based materials.

Recently, several unified models for hydraulic diffusivity, unsaturated water permeability as well as relative gas permeability are well established and verified [25–27]. Provided that hydraulic diffusivity observes exponential law with the shape parameter representing relative tortuosity of overall transport path for unsaturated porous material, the hydraulic diffusivity can be determined from sorptivity measurement [26]. Furthermore, after determination of water retention curve for specific cement-based material, the water permeability and relative gas permeability can be explicitly and neatly calculated [25]. The model for permeability can be further extended for relative ion diffusivity with clear physical meaning [27]. As a result, all these important mass transport properties can be consistently characterized with only two measurable fundamental quantities, the water retention curve and shape parameter. For cement-based materials, the water retention characteristics are usually measured by the water vapor sorption experiments, which is rather time-consuming but relatively straightforward [18,28–30]. Then, how to conveniently determine the shape parameter is attractive but still needs further investigation. On another hand, it should be noted that these unified models are established and individually validated by pieces of experimental data grasped from the literature [25,27], which are measured on different cementitious materials by different authors. Importantly, the newly proposed models for saturated water permeability and relative water permeability have not been validated yet by experimental data in previous studies. Further research work is still needed to put forward the comprehensive verification of these unified models.

Based on the established consistent models for various transport properties, an indirect method assessing hydraulic diffusivity and permeability from sorptivity is proposed and verified for unsaturated cement-based materials. The theoretical relationships between sorptivity for initially unsaturated cement-based material and other transport properties are firstly analyzed in Section 2. In Section 3, a thorough experimental program is introduced to measure water vapor sorption isotherms (WVSIs), capillary sorptivity and permeability for concrete materials with various saturation degrees. Based on the measured WVSIs and capillary sorptivity, the unsaturated permeability to water and gas are further calculated and verified with experimental results in Section 4. Finally, some concluding remarks are given in Section 5.

2. Theoretical background

2.1. Relationship between sorptivity and hydraulic diffusivity

Sorptivity S ($\mathrm{L \cdot T^{-0.5}}$), which is strongly dependent on initial water saturation degree, is an important durability indicator easily to measure from one-dimensional water suction test [5]. To facilitate the following analysis on sorptivity, hydraulic diffusivity as well as permeability for partially saturated cement-based materials, the water saturation degree ω (−) and initial water saturation degree ω_i (−) are first defined as,

$$\omega = \theta/\theta_s, \omega_i = \theta_i/\theta_s \tag{1}$$

in which θ (−) is the volumetric water content. Subscripts "i" and "s" denote the initial unsaturated state and fully saturated state, respectively. For an isotropic porous material with initial water saturation degree ω_i, the cumulative volume of water suction per unit area of the inflow surface V_w (L) will linearly increase with the square root of the suction time span t (T),

$$V_w = S(\omega_i)\sqrt{t} \tag{2}$$

from which the sorptivity $S(\omega_i)$ for initially unsaturated cement-based materials can be easily regressed. Actually, sorptivity $S(\omega_i)$ is usually obtained by fitting the measured V_w at different times t to the below relationship [5,31]

$$V_w = S(\omega_i)\sqrt{t} + B \tag{3}$$

in which B (L) is a correct term accounting for the filling of open porosity on the inflow surface (surface effect). This measurement can be conducted in general laboratory.

In essence, the water suction process in unsaturated concrete material can be also described by unsaturated flow theory, which employs the extended Darcy's law to quantify the water transport in terms of hydraulic diffusivity $D(\omega)$ ($\mathrm{L^2/T}$) [4,5]. In another words, the water transport can be quantified by either sorptivity $S(\omega_i)$ or hydraulic diffusivity $D(\omega)$, which determines the implied intimate relationship between them. In another paper published by the corresponding author, the relationship between sorptivity S and hydraulic diffusivity $D(\omega)$ has been strictly derived, provided that the hydraulic diffusivity $D(\omega)$ obeys exponential law [26]. For cement-based materials, the hydraulic diffusivity usually observes exponential law [5,32], which is also recommended over power law from the viewpoint of relative permeability to water and gas [11,27],

$$D(\omega) = D_0 \exp(n_0\omega) \tag{4}$$

in which D_0 ($\mathrm{L^2/T}$), n_0 (−) are named as initial hydraulic diffusivity and shape parameter in accordance with saturation degree $\omega = 0$, respectively. After measuring sorptivity S for totally dried material, the initial hydraulic diffusivity D_0 thus $D(\omega)$ can be determined by either General Solving Approach (GSA) [26] or another approximate method [33] with known shape parameter n_0. More generally, for an unsaturated porous material with initial water saturation degree ω_i, if the hydraulic diffusivity observes exponential law in terms of reduced water saturation degree Θ (−) with shape parameter n_i (−),

$$\Theta = \frac{\theta - \theta_i}{\theta_s - \theta_i}, D(\Theta) = D_i \exp(n_i\Theta) \tag{5}$$

where D_i and n_i denote the hydraulic diffusivity and shape parameter corresponding to $\theta = \theta_i$ ($\Theta = 0$). From the General Solving Approach (GEA) proposed by the corresponding author [26], the relationship between hydraulic diffusivity D_i and sorptivity $S(\omega_i)$ may write

$$D_i = \tau(n_i)\left[\frac{S(\omega_i)}{\theta_s(1-\omega_i)}\right]^2 \tag{6}$$

in which τ (−) is a coefficient determined only by the shape parameter n_i. For more detailed information, one can refer to reference [26]. Theoretically, the calculation of coefficient τ from GEA is very complicated and time-consuming, provided that the shape parameter n_i is known. Approximately, the relationship between coefficient τ and shape parameter n_i, which is tabulated in reference [26], can be well approximated by the following function Eq. (7) with very high correlation coefficient $R^2 = 0.9999$, as shown in Fig. 1.

$$\tau(n_i) = \exp\left(-0.1153 - 0.7341 n_i - 0.0069 n_i^2\right) \tag{7}$$

Another approximate calculation of τ from shape parameter n_i, suggested by Parlange and his co-authors [11,33], yields

$$\tau(n_i) = \frac{1}{\left(2n_i^{-1} - n_i^{-2}\right)\exp(n_i) - n_i^{-1} + n_i^{-2}} \tag{8}$$

In Fig. 1, the approximate relationship between coefficient τ and shape parameter n_i in Eq. (8) above is also presented. From Fig. 1, one can see that the fitting function (7) can well approximate the coefficient τ strictly calculated through GEA. When shape parameter n_i is relatively