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Capillary imbibition of water in discrete planar cracks

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HIGHLIGHTS

- Theoretical analysis of capillary imbibition was corroborated with experimental results.
- Effect of crack width on capillary rise height was studied.
- Effect of gravitational term considered in theoretical model was clarified.
- Cumulative water mass of cracked granite with various crack widths were reported.
- Theoretical results well agreed with experiments within a certain crack width.

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ABSTRACT

Knowledge of capillary imbibition of water in distributed microcracks within building materials plays a critical role in assessing and predicting the durability of reinforced concrete structures. This paper focuses on a comprehensive investigation of capillary imbibition of water in discrete planar cracks, involving both theoretical and experimental aspects. In view of dynamic capillary flow of liquid in discrete cracks, which is usually described by Lucas-Washburn (L-W) equation, the correlation between capillary rise height and crack width is theoretically established. A benchmark study to investigate capillary flow in a series of discrete granite cracks, artificially fabricated by means of ultrathin steel disc with various thicknesses, is reported, and this provides data to validate the theoretical model developed in the paper. The experimental results give out the measurement of discrete crack width with different sizes (23.64–240.38 μm) as well as the mass of absorbed water obtained by the traditional gravimetric method. The average cumulative water mass of specimen generally increases with an increase of crack width for the ranges studied. Moreover, the cumulative water mass rapidly increases at the initial stage of water absorption test while at later stage the variation of absorbed water mass is relatively less. The analysis shows that the influence of gravity on the variation of capillary rise height is remarkable when crack width is beyond a critical range. Finally, the comparison between experimental and theoretical results indicates that the L-W capillary imbibition model of porous capillary tube after taking into account the gravity effect can be applied to the case of discrete crack with a certain range of width.

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1. Introduction

The behavioral deterioration of reinforced concrete (RC) structures (i.e. swelling, spalling and cracking) is closely related to the role of water [1,2]. The rate of water absorption strongly depends on the degree of saturation, distributed damage, the connectivity of pores and microcracks, which may be caused by mechanical actions (external loading) or be a consequence of non-mechanical effect (drying shrinkage, thermal effect, freeze-thaw action, etc.) [3–6]. Concrete, during its service life, is rarely saturated and microcracks are often present within it. Therefore, knowledge of water or other liquids movement in fractures of unsaturated concrete is of significant importance for predicting the service life of RC structures exposed to the harsh environment of marine or deicing salt [7–10].

Water absorption by cracked concrete principally involves both the capillary imbibition of fractures and the simultaneous diffusion-like wetting of matrix [11]. Discrete cracks within concrete have a strong influence on the imbibition kinetics and significantly increase the rate and amount of water absorption due to the initial capillary invasion of cracks and later the matrix-fracture interaction [11–13]. The capillary pressure gradient occurring between matrix and fractures, which is associated with the

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saturation degree of matrix, may lead to water imbibition along the direction perpendicular to the fractures. Nevertheless, the dynamic properties of water uptake by a single discrete crack have a significant impact on the characterization of porous media by capillary rise. While a large body of literature exists documenting water absorption by building materials [14–19], surprisingly few studies have focused on capillary imbibition of water in fractures with a certain range of width. Specifically, in the absence of experimental data on the capillary imbibition in fine discrete cracks in building materials, the theoretical understanding of dynamic flow of water in fractures has not yet been made clear [12,20–23]. Therefore, a systematical investigation of dynamic capillary imbibition in discrete cracks of building materials is highly imperative for quantitative estimation of the service life of structures.

Capillary imbibition, which is ubiquitous in various fields of technological applications (i.e. soil physics, oil/gas production, building materials), is usually described by the classical Lucas-Washburn (abbreviated as L-W) equation on the basis of the momentum balance of dynamic flow in a capillary tube [12,24–27]. In terms of theoretical analysis, most previous studies focused on the dimensionless scaling methods for capillary rise [28], and the effect of phase change [29], tortuosity [30], nonuniform cross section [31], etc. Meanwhile, several studies on capillary water absorption in building materials, such as brick, stone and cement-based materials were subsequently conducted [12,32,33].

In the past decades, considerable efforts have been dedicated to the influence of cracking on water absorption by cement-based materials [6,11–13,34–38]. The work performed by Smyl et al. [39] indicated that the Electrical Resistance Tomography (ERT) could be a viable method of imaging three-dimensional (3D) unsaturated moisture flow in cement-based materials with discrete cracks. Although the advanced imaging technologies can significantly improve testing capabilities to visualize fracture flow in porous cementitious materials, most of them are still unpractical for testing in ordinary laboratory or an actual site inspection due to higher expenses. For example, by means of neutron imaging technology, the test performed by Zhang et al. [40] was conducted to visualize the rapid penetration of water into a single crack with the width of 0.35 mm in steel-reinforced concrete. Similarly, Tsuchiya et al. [20] detected the water penetration around concrete cracks under unsaturated conditions using neutron radiography. They found that water movement in a crack decelerates dramatically in minutes and the length of water migration in a crack dominated by diffusion is in proportion to the quadratic root of time. Moreover, microfocus X-ray computed tomography (CT) was applied to investigate the diffusivity and observe water migration in cracked concrete [37,41,42]. Van Belleghen et al. [37] adopted X-ray radiograph to investigate capillary water absorption in cracked mortar with the crack size of 0.3 mm-width and 20 mm-depth.

In terms of theoretical analysis, Gardner et al. [21] presented a series of experimental studies on capillary flow of water in discrete cracks in cementitious materials using high speed video measurement. In order to establish the amended theoretical model of capillary flow in discrete cracks in cementitious materials, the correction factors, such as the stick-slip behavior of meniscus, frictional dissipation at the meniscus wall boundary and slip between the fluid and solid wall, were taken into account. Likewise, Cheng et al. [12] proposed a theoretical model for predicting nearly one-dimensional movement of water into a single air-filled fracture within a porous media, which was validated by the acquired quantitative data on spontaneous imbibition of water in unsaturated fractured sedimentary rock cores with different permeability classes ranging from 50 to 500 mD. In general, the fracture aperture width of above-mentioned investigations ranges from 0.11 mm to 1.17 mm. Furthermore, the majority of previous studies demonstrated the feasibility of theoretical model of capillary imbibition in larger fracture apertures. However, both theoretical and experimental studies on capillary imbibition in discrete cracks within the scope of 100-μm width are relatively scarce. Besides, the objective of most previous studies was mainly focused on cementitious materials, i.e. mortar or concrete. However, water migration in cracked cementitious materials may simultaneously occur in the vertical and parallel directions of a discrete crack due to the capillary invasion of crack and matrix-fracture interaction. This cannot ensure the simulated 1D movement of water in a discrete crack, and as a result it may influence the rate and amount of capillary imbibition in the crack.

This paper attempts to gain more insight into capillary imbibition of water in discrete cracks of building materials from the perspective of theoretical analysis and experimental investigation. The major objectives of this study are to: (i) develop a theoretical model of the dynamic capillary imbibition of water in air-filled discrete cracks with a certain range of widths, and (ii) provide new experimental data to analyze the proposed mathematical model of capillary imbibition of water in discrete cracks. The theoretical solution of L-W equation involving viscous and gravity terms is derived, and the influence of gravity term and crack width on the variation of capillary rise height in discrete planar cracks is discussed. The measurement of discrete crack width with different sizes (23.64–240.38 μm) as well as the experimental results of cumulative absorbed water mass obtained by the traditional gravimetric method recommended in ASTM C1585 [43] is presented.

2. Theoretical background

From the standpoint of the energy balance principle to the liquid column in a vertical capillary tube, the required total energy for raising capillary height in a vertical capillary tube is equal to the sum of the energy to overcome the gravity, the viscous energy dissipated by the fluid, and the inertial energy spent on accelerating the fluid and maintaining the capillarity speed [44]. Thus, the equation of energy balance for describing the liquid moving through a capillary tube can be obtained as follows

$$\varphi_{sd} dA_{sl} - \varphi_{sw} dA_{sl} = dE_g + dE_v + dE_k \tag{1}$$

in which φ_{sd} and φ_{sw} represent the surface energy of the dry and wetted surface, respectively; A_{sl} is the area of solid-liquid interface; E_g, E_v and E_k are the dissipative energy of gravity, viscous forces and inertial forces, respectively. Furthermore, for capillary imbibition of liquid in a tube as shown in Fig. 1, the capillary pressure can be given

$$P_c = \rho g h \sin\phi + \Delta P + P_k \tag{2}$$

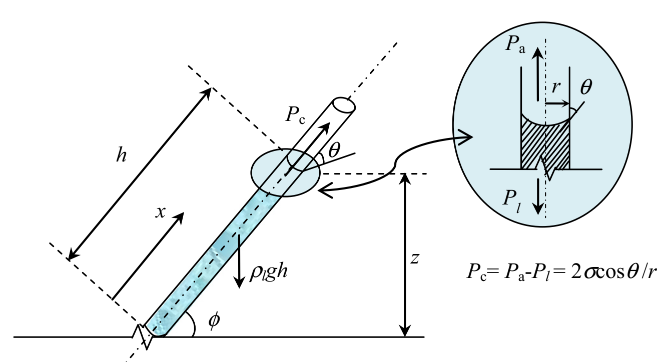

Fig. 1. Schematic diagram of capillary imbibition of water in a uniform tube.

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