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Influence of micro-cracking on the permeability of engineered cementitious composites

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Engineered Cementitious Composites (ECC) forms multiple micro-cracks under tension when loaded to beyond the elastic stage. Unlike normal concrete, such tight cracks help to maintain low water permeability even in the cracked stage. Therefore ECC shows great potential for application in hydraulic structures, such as dams and levees for which water seepage control is critical for their performance. In this paper, the permeability of ECC under constant tensile load was experimentally studied using a specially designed displacement-control loading device, providing permeability data for ECC under realistic loading conditions. In addition, an analytical model capable of predicting permeability property of ECC composite based on tensile strain and crack patterns has been proposed and experimentally verified on two different ECC mixtures. The findings of this research are expected to support future design and application of ECC for hydraulic structures.

1. Introduction

Seepage in concrete dams poses a great threat to the safety of the structures. Approximately one third of all dam failures are caused by seepage problem [1]. Severe seepage results in loss of water in the reservoir, and is also responsible for water infiltration into the dam that may lead to freeze-thaw and frost-heaving damage in cold regions. More importantly, the structure may lose stability when such damage happens within the dam or dam foundation [2]. One example for dam failure caused by seepage problem is the collapse of Idbar Dam in Yugoslavia in 1960. Water seepage resulted in piping and erosion of the dam foundation, which then led to the collapse of the dam during its first filling [3].

In addition to dams, seepage control is also critical to other hydraulic structures such as levees, spillways and sluices. Severe seepage increases the risk of structural failure by reducing the effective stresses exerted on the foundation of these structures that may result in a loss of support stability. Additionally, excessive pore water within concrete material may also result in piping and internal erosion, leading to damage of the structure. For example, the spillway collapse of a reservoir in Qinghai Province, China in 2005 is due to the seepage between the dam and spillway, which resulted in internal erosion of the foundation [4]. Therefore, seepage needs to be carefully controlled to ensure the safety and durability of these hydraulic structures.

Current seepage control methods include applying waterproof concrete panels/curtain grouting (with low water permeability) on the upstream side of the hydraulic structure, or installing drain pipes/drain holes on the downstream side. Among these, waterproofing concrete panels is considered one of the most effective and most commonly used methods nowadays [5,6]. However, the effectiveness of this method depends critically on the performance of the waterproofing concrete material which tends to form large cracks under structural and/or environmental loads [7,8]. As an example, Fig. 1 shows cracks formed on the upstream concrete surface of the Los Angeles Dam. Such large cracks increase the water permeability of the concrete panels under hydraulic pressure and reduce the effectiveness of the seepage control. In order to ensure desirable dam performance, the cracking of the concrete panels needs to be carefully controlled.

Extensive studies have been conducted to establish the correlation between the permeability and cracking condition of cement-

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based materials. Picandet et al. [10] reported that the major part of water flow through a water containing structure is conveyed by cracks. Wang et al. [11] found that the permeability increases slowly from uncracked condition up to crack opening of 50 μm, followed by a sharp increase of the permeability as crack width increases from 50 μm to 200 μm. Wang et al. and Tsukamoto [12] pointed out that the water permeability of concrete scales with the 3rd power of crack width when the crack width is larger than 50 μm. Shah and co-workers [13–15] also observed similar trend for cracked normal strength concrete (NSC) and high strength concrete (HSC). Based on these studies, crack width less than 200 μm, and preferably less than 50 μm, is desirable for maintaining low water permeability in hydraulic concrete structures.

Engineered Cementitious Composites (ECC), a high performance fiber reinforced cementitious composites (HPFRCC) with controlled tight crack widths, is a promising alternative to concrete for the upstream waterproof application in hydraulic structures. Unlike normal concrete, ECC shows strain-hardening behavior with high ductility under tension and bending. The tensile strain capacity of ECC ranges from 2 to 5%, which is about 200–500 times larger than that of normal concrete or conventional fiber reinforced concrete (FRC) [16–19]. More importantly, the high tensile ductility of ECC is achieved by forming multiple tight micro-cracks (typically less than 100 μm wide) instead of localized large cracks, allowing the material to accommodate large deformation (caused by mechanical, environmental loads, or uneven settlement) while maintaining low water permeability at the same time. Therefore, using ECC as upstream waterproofing material for dams seems a plausible solution to enhance the performance of seepage control [20].

Crack width development, water permeability and durability characteristics of ECC have been reviewed by van Zijl et al. [21]. The water permeability of cracked ECC has been first studied by Lepech and Li [20]. In their study, it was observed that the micro-cracks formed within ECC specimens under uniaxial tensile load were approximately 60 μm in width on average. Such tight crack width allows ECC to maintain low permeability similar to that of uncracked concrete or mortar even under high tensile strain. However, the previous experiments on permeability of ECC were conducted after unloading the specimen and the crack width used in that study was residual crack width instead of crack width under loading. In reality, the crack width of ECC under tension is generally larger (by about 15% [22]) than the residual crack width. Therefore, in the previous research, the measured permeability was not directly correlated to a specific loading condition. In order to make better correlations between the real service condition and water permeability and to obtain more conservative permeability data, it is necessary to investigate the permeability of ECC while the material is tension loaded.

Fig. 1. Large cracks formed on the upstream side concrete of the Los Angeles Dam [9].

In addition to measuring the permeability under load, it is also important to develop a reliable model for predicting and understanding the permeability property of ECC. In general, under a given tensile strain, ECC exhibits multiple cracking of varying crack widths. Previous studies (e.g. Ref. [20]) typically correlate permeability with the average crack width. However, given the non-linear relationship between permeability and crack width, this correlation may produce unconservative results. A permeability model that accounts for crack width distribution of ECC under a given tensile load or strain is needed.

In the present work, the permeability of ECC under tension was studied experimentally and analytically. The permeability behavior of two ECC mixtures under tensile load was experimentally measured using a specially designed displacement-controlled loading device. Permeability behavior of a single crack at various crack widths was also studied. Based on the crack pattern and single crack permeability behavior, an analytical model capable of predicting permeability of ECC at a given strain level has been derived and experimentally verified. The research findings documented in this paper are expected to support future design and application of ECC in hydraulic structures.

2. Experimental investigation

2.1. Materials

Two ECC mixtures were used for this experimental investigation. One is a normal ECC (denoted as N-ECC) as found in previous research [23], and the other one is a ECC mixture developed incorporating crumb rubber (CR-ECC). Both ECC mixtures consist of Type I Portland cement, fine silica sand, class F fly ash, water, high range water reducing agent (HRWRA), and poly-vinyl-alcohol (PVA) fibers. In addition to the above ingredients, CR-ECC also used crumb rubber to replace part of the silica sand. The detailed mix proportions of the two ECC mixtures are shown in Table 1. The properties of PVA fiber used in this study are listed in Table 2. Previous studies [24] suggest that ECC with crumb rubber tends to show more saturated multiple-cracking behavior with significantly tighter cracks than normal ECC. Since permeability is very sensitive to crack pattern, particularly crack width, using these two distinct ECC mixtures offer the opportunity to study the effect of different crack patterns on ECC permeability. The experimental results for these two mixtures can also be used to demonstrate the wide applicability of the proposed analytical model (Section 3.3).

The preparation of the ECC mixes follows a typical ECC mixing procedure [25]. After mixing, the fresh mixtures were cast into dogbone-shaped specimens. 31 and 34 specimens were prepared using N-ECC and CR-ECC mixtures, respectively. The detailed dimensions of the dogbone specimen are shown in Fig. 2. All specimens were covered with a plastic sheet for 24 h until demolding. Specimens for permeability characterization should be in the saturated condition, otherwise capillary absorption could significantly affect the water flow [26,27]. Therefore all specimens were immersed in water at a room temperature of 23 ± 3 °C after demolding until the age of 28 days to guarantee that they were saturated at the time when permeability tests commenced.

2.2. Experimental procedures

2.2.1. Composite tensile characterization

Uniaxial tensile tests were conducted on a set of 4 dogbone specimens (for each mixture) to characterize the tensile behavior of