WATER PERMEABILITY OF CRACKED CEMENTITIOUS COMPOSITES

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ABSTRACT

Cracking is one of the most severe problems facing the concrete industry worldwide. Of critical importance is the drastic decline of durability associated with these cracks, and the resulting cost of repair or replacement of concrete structures. This research examines the effect of crack width and crack frequency upon the durability of reinforced mortar, quantified by water permeability. Crack widths tested range from 0mm (for uncracked mortar) up to 2.7mm. In addition to mortar, the durability performance of Engineered Cementitious Composites, or ECC, are also investigated in the cracked state. This high performance fiber reinforced cementitious composite exhibits closely spaced microcracks with inherently tight crack widths, typically less than 80 micron, even when strained up to 5% in uniaxial tension. The advantages of closely spaced microcracks over a small number of large cracks are investigated and discussed. Results show that even with a large number of closely spaced microcracks, the inherently small crack width of ECC material exhibits a water permeability close to that of uncracked concrete when strained up to 1.5% in uniaxial tension.

1 INTRODUCTION

The durability of concrete structures is unarguably a major challenge facing the concrete community today. The rising cost of repair, retrofit, and replacement of concrete structures worldwide is staggering. In the United States alone, it has been estimated that it will cost $1.8 trillion (US) over the next 20 years to maintain the current state of dilapidated roads and bridges. To improve these infrastructure systems to adequate levels will require an additional $627 billion (US) over that same time period (AASHTO [1]). It is well known that the low durability of current concrete infrastructures is responsible for the poor condition of roads and bridges around the world and is causing a budget crisis among the transportation and governmental authorities responsible for maintaining them. Essentially, new technologies must be introduced to increase the durability of concrete infrastructure and relieve the mounting maintenance problems facing the transportation community.

Roughly 30 years ago the introduction of high strength concrete was thought to solve the dilemma of poor durability in concrete structures. With compressive strengths twice that of normal concrete and a low water permeability coefficient, these materials would appear to be effective in protecting against aggressive environments (Mehta [2]). However the main cause of deterioration in most concrete structures is cracking, resulting in ingress of corrosives down to the reinforcing steel bars and eventually spalling off concrete cover. High strength concretes, in comparison to normal strength concretes, show much higher levels of thermal shrinkage (Mehta [2]) and autogenous shrinkage (Wittmann [3]). Together with a high elastic modulus, low creep coefficient, and high brittleness, these materials are far more likely than normal strength concretes to crack at an early age, and produce a larger crack width, resulting in poor durability and shortened life spans (Li and Stang [4]). This was evident in a large number of bridge decks within the United States showing severe transverse cracking at a very early age during the mid 1990s (Rogalla [5]).

At the root of these durability problems is the permeability of concrete structures in the cracked state. Regardless of the reason for cracking, whether it be thermal loads, autogeneous or drying shrinkage, or mechanical loads, nearly all concrete structures crack during service life. Once this cracking takes place, the transport properties of the material change drastically and it is no longer reasonable to assume that durability life-spans based on uncracked properties will hold. Many studies have been conducted based on the uncracked transport properties of both air and water within concrete material, such as those by Claisse et al [6], and Abbas et al [7]. While these works remain important, they do not accurately represent the performance of most concrete structures in the cracked service state.

While less work has been done in the area of cracked concrete, a body of important work does exist. Much of this work has examined the impact of the width of single cracks on FRC and concrete permeability. Tsukamoto [8] studied the water flow rate in cracked fiber reinforced concrete, and found that the flow rate scales to the third power of crack width. This relationship is consistent for plain concrete and FRC. However, FRCs exhibit lower flow rates compared to plain concrete for a given crack width due to their higher crack tortuosity resulting from the fibers. For both concrete and FRC, the flow rate becomes negligible when crack width falls below 100 μm. Additionally, work has been done by Wang, et al [9] that focused on a single crack within concrete and measuring the permeability coefficient as a function of crack width. This study showed a similar result to that by Tsukamoto in that the permeability of cracked concrete with crack widths below 80 μm is nearly identical to that of sound, uncracked concrete.

Recently, a new high performance cementitious composite, or HPFRCC, has been developed by Li [10] called Engineering Cementitious Composites (ECC). This class of composites, designed from micromechanical concepts, has been tailored to exhibit pseudo-strain hardening up to a strain capacity of between 4% and 5%, far beyond that of ordinary concrete. This high level of strain capacity allows the material to undergo large deformations while maintaining load capacity. Of interest to this study are the tight crack widths inherent within ECC material. Previous studies conducted by Weimann and Li [11] have shown that even as ECC undergoes large strains, the crack widths remain constant at approximately 60μm, depending on the exact composition of the material. This unique performance is shown by the stress-strain-crack width plot in Figure 1 and the ECC specimen surface photograph in Figure 2.

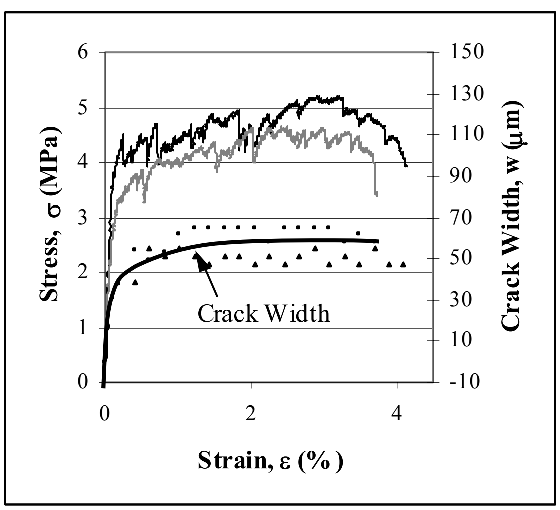

Figure 1: ECC Tensile Stress-Strain Response

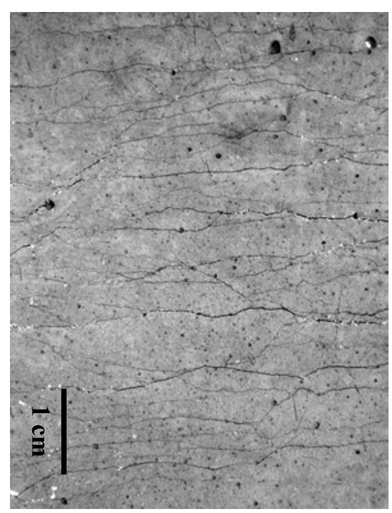

Figure 2: ECC Specimen Surface

This type of performance is possible due to the formation of closely spaced microcracks within ECC which allow the material to "strain" under uniaxial tension. Below a strain of roughly 0.8%, a small number of cracks form within the material and their widths grow to approximately 60 μm. Once this crack width is reached, further deformation is accomplished though formation of additional closely spaced microcracks, all of which exhibit the same maximum crack width of approximately 60 μm. This leads to the designation of crack width in ECC as a material property, similar to compressive strength or fracture toughness, rather than a structural property as in reinforced concrete. While crack width in reinforced concrete is know to be a function of steel reinforcing ratio, crack widths in ECC are a result of the composition of the fibers and cementitious matrix, along with the interfacial properties between these components. Regardless of the amount of reinforcing bars used in ECC, if any at all, the crack widths in ECC material remain constant. Similarly crack widths within ECC are independent of structural dimensions.

One of the concerns of ECC is its crack pattern of closely spaced cracks in relation to transport properties. This concern is addressed directly in this paper by measuring the permeability of multiply cracked ECC material.

2 EXPERIMENTAL PROCEDURES

The objective of this work is to examine the water permeability of both cracked and uncracked ECC and reinforced mortar. Rather than examining the effect of a single crack within the specimens as done in other studies, reinforced mortar plates were fabricated with varying reinforcement ratios to produce multiple cracks of uniform width and spacing throughout each specimen. By altering the amount of reinforcement among specimens, the crack width present in each mortar specimen was varied. The performance of reinforced mortar with multiple cracks is compared with that of ECC with multiple cracks deformed to the same tensile elongation.

2.1 Tensile Specimens

Tensile plate specimens measuring 300mm x 75mm x 12mm were prepared of ECC and a standard mortar mixture. Mixing proportions of both materials are shown in Table 1. The sand used in ECC had an average grain size of 0.11mm while the sand used for mortar was larger with an average size of 0.6mm. As mentioned before, various reinforcement ratios were used in the reinforced mortar tests to achieve uniformly spaced cracks of varying widths among specimens. Various levels of reinforcement were fabricated by using multiple layers of different steel wire mesh reinforcement made of 0.2mm to 1mm diameter wire in a 2mm to 6mm grid. The various reinforcement ratios, along with the crack widths and spacings produced are shown in Table 2.

Table 1: Mixing Proportions

Component	ECC	Mortar
Cement	1.0	1.0
Sand	0.8	2.5
Fly Ash	1.2	-
Water	0.53	0.35
Superplasticizer	0.03	-
PVA Fiber (vol)	0.02	-

Table 2: Tensile Specimen Characteristics

Specimen Series	Reinforcement Ratio	Crack Width (μm)	Crack Spacing (mm)
R/M - 1	0.009	750 - 2500	50 +
R/M - 2	0.019	200 - 500	10 - 30
R/M - 3	0.028	125 - 200	5 - 15
ECC	0.000	40 - 80	2 - 5

Note: R/M - # denotes reinforced mortar series with # levels of reinforcement

2.2 Tensile Testing

Tensile tests were carried out at 28 days to ensure that full maturity had been achieved by both ECC and mortar samples. Using a displacement controlled uniaxial tension regime, both the ECC and reinforced mortar samples were deformed to a uniaxial elongation of approximately 2.7mm. In the ECC samples, this corresponds to a pseudo strain of approximately 1.5%. While this is far below the maximum strain capacity of the material, at this level the crack widths have attained their maximum width and will continue to saturate the specimen at higher strain levels. When elongated to this level, the reinforced mortar samples exhibited various patterns of crack spacing and width. Once cracked, the tensile load was relaxed and the permeability of the specimens was tested in the unloaded state. While after unloading the specimens do exhibit an elastic relaxation shortening, the crack width versus permeability relation developed from these tests still holds since the crack widths are also measured in the unloaded state.

2.3 Water Permeability Testing

Water permeability testing was conducted on both uncracked and cracked ECC and concrete samples immediately following tensile testing. Due to the large range of crack widths tested, and therefore large range of possible specimen permeabilities, two test setups were used. For the lower permeability materials a falling head test setup was used, similar to that used by Wang et al [9], and shown schematically in Figure 3. For the higher permeability materials, a constant head test was used and is shown schematically in Figure 4.

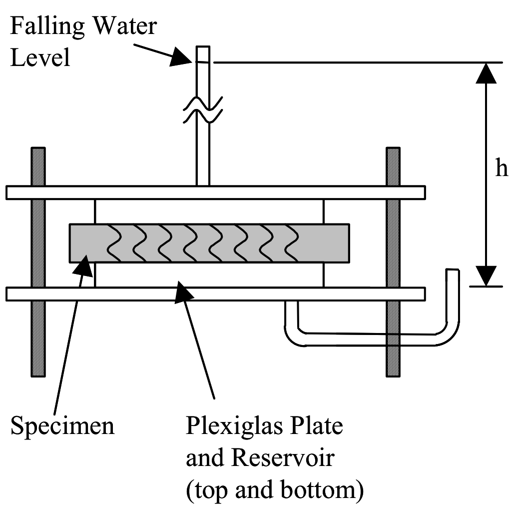

Figure 3: Falling Head Test

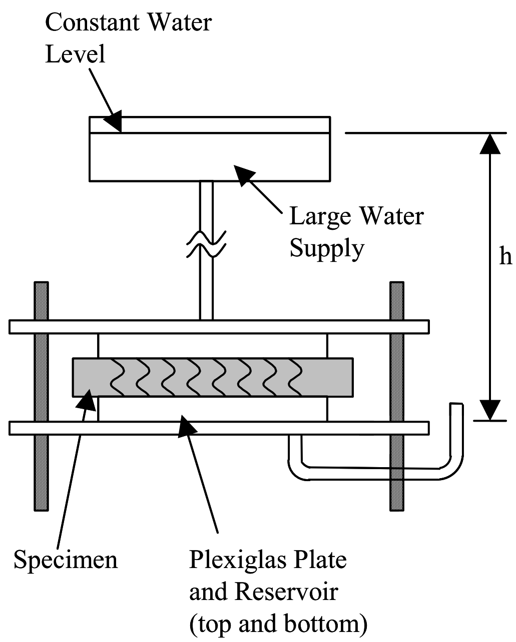

Figure 4: Constant Head Test

Formulations for calculating the water permeability from each of these setups, falling head and constant head, are summarized in eqns (1) and (2) respectively, derived in Cernica [12].

$$k = \frac{a \cdot T}{A \cdot t} \ln\left(\frac{h_o}{h_f}\right) \tag{1}$$

$$k = \frac{V \cdot T}{h \cdot A \cdot t} \tag{2}$$

Where: k = water permeability coefficient (m/sec)
a = cross sectional area of stand pipe (m^2) = $2.84 \times 10^{-5} m^2$
T =specimen thickness in direction of flow (m) = 0.012m
A = cross sectional area of specimen exposed to flow (m^2) = $8.93 \times 10^{-3} m^2$
t = time duration of the test (sec) = varies
h = constant water head in constant head test (m) = varies
h_o = initial water head in falling head test (m) = varies
h_f = final water head in falling water test (m) = varies

Falling head tests were conducted continuously over a period of three weeks until a steady state value of permeability had been reached. Constant head tests were conducted twice every week for three weeks until a steady state value of permeability has either been validated or reached. The reported permeability values are final steady state value exhibited.

3 DISCUSSION

As was seen in previous work, the water permeability of cracked concrete, or mortar in this case, increased dramatically after cracking. Of interest however, is the performance of cracked ECC specimens, while elongated to the same deformation level as the reinforced mortar samples, showed a water permeability coefficient on the order of uncracked mortar or ECC. These results are summarized in Figure 5.

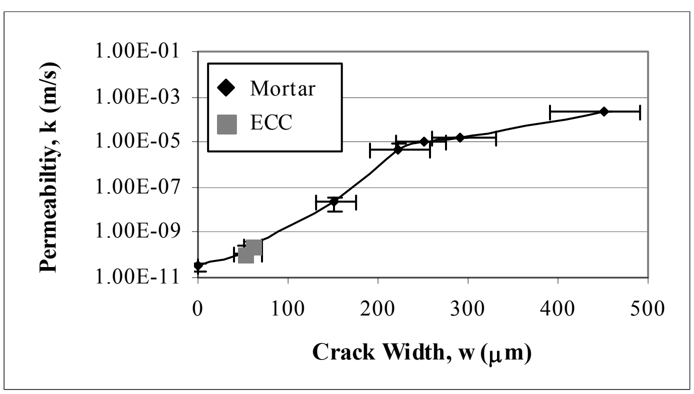

Figure 5: Water Permeability of Cracked ECC and Concrete (See Table 2 for crack widths)

When examined on "per crack" basis, these results relate well to findings of previous researchers. Since the number of cracks in ECC specimens far outnumbers those in the mortar specimens, the permeability coefficient on a per crack basis is similar to that of uncracked mortar. Even when taken as a whole, due to the inherently tight crack widths of ECC, when loaded to high levels of deformation the permeability, and therefore durability of the material, is not diminished.

Current concrete codes in the United States are calibrated to allow for a crack width of 300 μm within properly reinforced concrete structures. From a durability standpoint, this minimum crack width exhibits a permeability nearly 5 orders of magnitude larger than exhibited by cracked ECC. The use of ECC material to minimize crack widths in highly corrosive environments will likely lead to more durable concrete structures, and significantly longer service lives.

4 CONCLUSIONS

When subjected to identical tensile deformation, ECC and reinforced mortar specimens exhibited very different cracking patterns and widths. This study looked to determine the influences of this difference on water permeability and material durability. When elongated to a "strain" of 1.5%, ECC specimens showed closely spaced microcracks with crack widths of approximately 60μm, while reinforced mortar with varying reinforcement ratios showed crack widths from 150μm to over 2.5mm. In the cracked state, the small crack widths within ECC maintained a water permeability similar to uncracked mortar, while cracked reinforced mortar specimens exhibited higher water permeability with larger crack widths. As durable building materials are continuously sought for longer lasting constructed facilities, the type of highly durable performance shown by ECC in comparison to reinforced mortar in this study is very promising.

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