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Influence of Microcracking on the Transport Properties of Engineered Cementitious Composites

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ABSTRACT

Durability of concrete structures is one of the most significant problems currently facing the engineering community. The use of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) may greatly enhance the durability and long term performance of concrete structures. However, prior to designing HPFRCC materials into practical applications, their durability performance must be shown equal or superior to concrete over long durations in service environments. In this article, the transport properties under mechanical loading of a class of HPFRCC called Engineered Cementitious Composites (ECC) is summarized. The research results indicate that due to intrinsic self-control tight crack width, many durability challenges confronting concrete can be overcome by using ECC. The superior performances of ECC under mechanical and environmental loads are expected to contribute substantially to improving civil infrastructure sustainability by reducing the amount of repair and maintenance during the service life of the structure.

INTRODUCTION

Increased durability of reinforced concrete is typically associated with a dense concrete matrix, i.e. a very compact microstructure expected to lower permeability and reduce transport of corrosives to the steel [1,2]. This can be achieved with a well-graded particle size distribution [3], fly ash and silica fume [4], or low w/c ratios [5]. These concepts, however, rely upon the concrete to remain uncracked within a structure throughout its expected service life and resist the transport of water, chloride ions, oxygen, etc. In this presumed uncracked state, numerous concrete materials have shown promising durability in laboratory tests [6,7].

In reality, however, reinforced concrete members crack due to both applied structural loading, shrinkage, chemical attack and thermal deformations, which are practically inevitable and often anticipated in restrained conditions [8,9]. The durability of concrete structures is intimately related to the rate at which water is able to penetrate the concrete. This is because concrete is susceptible to degradation through leaching, corrosion, sulfate attack, freezing-and-thawing damage, and other mechanisms that depend on the ingress of water. Because cracks significantly modify the transport properties of concrete, their presence greatly accelerates the deterioration process. To solve this serious problem, a fundamental solution which reduces the brittle nature of concrete is needed.

Through the use of High Performance Fiber Reinforced Cementitious Composites (HPFRCC), which display significantly higher ductility than reinforced concrete (R/C) and very tight crack width (generally less than 80 μm), durability problems resulting from cracking may be solved. A new class of HPFRCC materials, called Engineered Cementitious Composites (ECC), addresses many of these needs presented above. Recent years, increasing work has been done in investigating the relationship and interaction between Engineered Cementitious Composites cracking and transport properties. This paper provides an overview of the recent research in ECC cracking and transport properties. The subjects include ECC cracking and permeability, absorption and diffusion properties. The research results indicate that due to intrinsic self-control tight crack width, many durability challenges confronting concrete can be overcome as a result of improved transport properties. The superior performances of ECC under mechanical and environmental loads are expected to contribute substantially to improving structure sustainability by reducing the amount of repair and maintenance during the service life of the structure.

ENGINEERED CEMENTITIOUS COMPOSITES

During the last decade concrete technology has been undergoing rapid development. The effort to modify the brittle behaviour of plain cement materials such as cement pastes, mortars and concretes has resulted in modern concepts of high performance fiber reinforced cementitious composites (HPFRCC) that exhibit ductile behaviour under uniaxial tension load. In plain concrete, after the crack there is no load carrying capacity (Figure 2). In conventional fiber reinforced cementitious composites, matrix cracking is followed by a reduction in load carrying capacity known as tension softening (lower curve in Figure 2). For HPFRCC, after the formation of the first through crack, the fibers themselves are able to carry additional load. On further loading, multiple micro cracks with crack width less than 100 µm will form along the member, leading to a significant increase in strain capacity. The tensile stress-strain curve will hence exhibit a post-cracking hardening branch similar to that of ductile materials, such as aluminium (upper curves in Figure 2). The quantitative criterion for the achievement of ductility (inelastic straining), in terms of various material and geometric parameters (such as properties of fiber, matrix [composite without fiber], fiber-matrix interface, fiber geometry and volume fraction, etc.), was proposed by Li and Leung [10] and further developed by Li [11], and Kanda and Li [12]. With proper selection of parameters to fulfill the criterion, ductile composites with different strengths can be made with fiber volume from 1.5% to 5%. The actual 'ductility' of the HPFRCC, which can be defined as the strain at maximum tensile stress, depends on the effectiveness of fibers in transferring stress back into the matrix (which in turn depends on the ***microstructural parameters***) as well as the toughness of the matrix itself [13]. Normally, the higher the matrix toughness, the lower will be the ductility achieved with a certain fiber volume fraction. Depending on the particular application, the material design can be varied to produce an optimal tensile stress vs. strain relation that satisfies the strength and ductility requirements. In the literature, HPFRCC's have been given different names by various researchers.

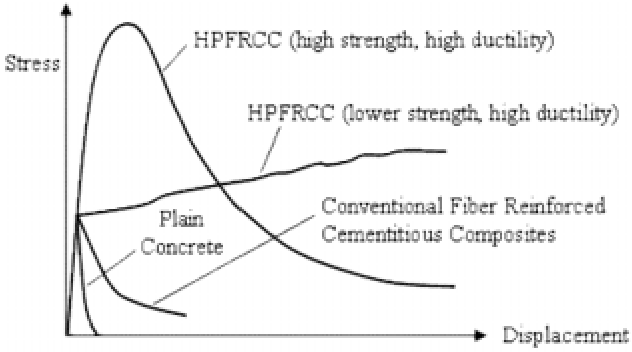

Figure 1. Tensile behavior of plain and fiber reinforced cementitious materials

Engineered Cementitious Composites (ECC) is a unique type of high performance fiber reinforced cementitious composite (HPFRCC) which features high tensile ductility [25-28]. By employing micromechanics-based material design, maximum ductility in excess of 3%

under uniaxial tensile loading can be attained with only 2% fiber content by volume. This moderate amount of short discontinuous fibers allows flexibility in construction execution, including self-consolidation casting [14] and shotcreting [15]. Structural products have also been manufactured by extrusion of ECC [16]. Recent research indicates that ECC holds promise in enhancing the safety, durability, and sustainability of infrastructure.

The composition of ECC is similar to many other FRCs, such that it is a mixture of cement, sand, water, fibers, and a small amount of commercial admixtures. Typical mix proportions for ECC using a poly-vinyl-alcohol fiber are shown in Table 1. Coarse aggregates are not used due to their adverse effect on performance. These large aggregates are found to dominate the micromechanical properties of the composite leading to poor fiber dispersion and lower overall performance. While most HPFRCCs rely on a high fiber volume to achieve high performance, ECC uses low amounts, typically 2% by volume, of short, discontinuous fiber. This low fiber volume, along with the common components, allows for conventional mixing in a gravity mixer or conventional mixing truck. Many HPFRCCs with fiber fractions exceeding 5% cannot conform to conventional mixing practices.

Table 1. Typical mix design of ECC material

Cement	Water	Sand	Fly Ash	SP	Fiber (%)
1.00	0.58	0.80	1.20	0.013	2.00

SP = superplasticizer; all ingredients proportion by weight except for fiber.

Figure 1 shows a typical uniaxial tensile stress-strain curve of ECC containing 2% poly-vinly-alcohol fiber. The characteristic strain-hardening after first cracking is accompanied by formation of multiple micro-cracks which eventually saturate the material. The crack width development during inelastic straining is also shown. Even at ultimate load (5% strain), the crack width remains at a maximum of 60 μm, and even lower at strains below 1%. Unique to ECC material, this tight crack width is self-controlled and, regardless of use in combination with conventional reinforcement, it is a material characteristic independent of steel rebar reinforcement ratio. In contrast, normal concrete and fiber reinforced concrete rely on increasing large amounts of steel reinforcement for effective crack width control. This is possible through the formation of steady-state "flat cracks" in ECC which exhibit a constant width independent of crack length, in contrast to Griffith-type cracks present in most R/C and FRC materials which widen as the crack length grows. This tight crack width of ECC is as essential to the serviceability limit state of ECC structures as the tensile ductility is to the structural safety at ultimate limit state.

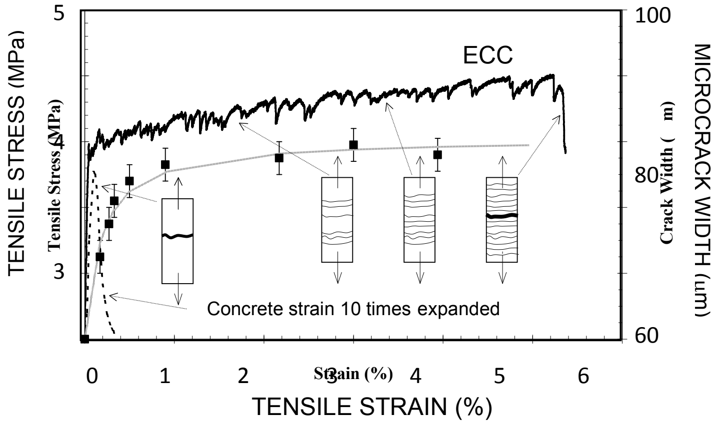

Figure 2. Typical tensile stress-strain curve and crack width development of ECC

TRANSPORT PROPERTIES OF MICROCRACKED ECC

Depending on the driving force, the transportations of liquids, gases and ions through hardened concrete can occur chiefly through three different mechanisms; permeation, absorption, or diffusion. Depending upon the conditions, transport of liquids, gases and ions may be driven by one or a combination of these three mechanisms. The main driving force behind permeation is the presence of a pressure gradient. Permeation is very important for concrete structures under water such as offshore structures. Absorption, driven by capillary pore suction, is the predominant transport process when the unsaturated concrete is exposed to liquids. Diffusion is the most commonly studied transport process of ions, such as chloride, which accelerates the initiation of steel corrosion in concrete. When the saturated concrete is exposed to a chloride solution, a chloride concentration gradient is created between the concrete element surface and the pore solution. In this case, diffusion will be the predominant driving mechanism of chloride transport.

Water Permeability

Typically, the formation of cracks increases the permeability, allowing water, oxygen and chloride ions to easily penetrate and reach the reinforcing steel and accelerate the initiation of steel corrosion in concrete. Lepech and Li studied the water permeability of mechanically loaded ECC and reinforced mortar [17]. Within this study, both ECC and reinforced mortar specimens were stretched in tension to identical deformation, 1.5% uniaxial deformation in this case, resulting in a variety of crack widths and number of cracks among the various specimens. Under high imposed uniaxial deformation, the preloaded ECC beam specimens reveal microcracks less than 60 μm, and cracked ECC exhibits nearly the same water permeability as sound concrete, even when strained in tension to several percent (Figure 5). In contrast, cracks larger than 150 μm are easily produced under the identical imposed uniaxial deformation, and have significant effects on the water permeability of reinforced mortar. Further, when normalized by number of cracks within the specimen, the comparable permeability of cracked ECC with sound material becomes even more apparent.

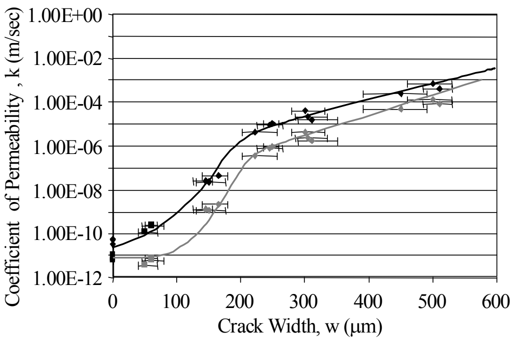

Figure 3. Permeability of cracked and uncracked ECC and Reinforced Mortar Specimens

Chloride Diffusion

The corrosion of steel in concrete is one of the major problems with respect to the durability of reinforced concrete structures, and the penetration of chloride ions into concrete is considered to be the major cause of corrosion. Miyazato and Hiraishi was probably the first to show that the penetration depth of chloride ions into ECC cover was substantially lower than that in concrete cover, for both beams preloaded to the same level of flexural deformation deflection and subjected to accelerated chloride exposure [18]. In addition, a relation between flexural deformation levels and the chloride diffusion coefficient of ECC and reinforced mortar was examined by Sahmaran et al [19]. Under high imposed bending deformation, the preloaded ECC beam specimens reveal multiple microcracks with width of less than 50 μm and an effective diffusion coefficient significantly lower than that of the similarly preloaded reinforced mortar beam because of the tight crack width control in ECC (Figure 6). In contrast, cracks larger than 150 μm are easily produced in reinforced mortar specimens under the same imposed deformation, producing significant effects on effective diffusion coefficient. The effective diffusion coefficient of ECC was found to be linearly proportional to the number of cracks, whereas the effective diffusion coefficient of reinforced mortar is proportional to the square of the crack width. Therefore, the effect of crack width on chloride transport was more pronounced when compared to that of crack number.

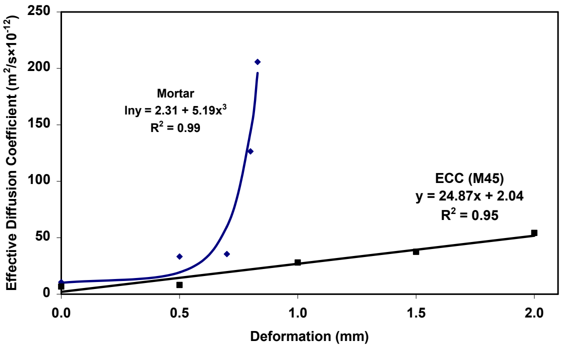

Figure 4. Diffusion coefficient versus pre-loading deformation level for ECC and mortar

Absorption

Transport of liquids in porous solids due to surface tension acting in capillaries is called water absorption. Absorption is related not only to the pore structure, crack density and crack size, but also to the moisture state of the concrete. Since concrete structures in exposed conditions are always subjected to the drying actions of wind and sun, they are rarely fully saturated when in service. Under this condition, therefore, permeability and diffusion may not be the dominant transport processes in concrete materials. Under dry or partially saturated conditions, the movement of water into concrete is controlled by capillary suction forces existing in the evacuated capillary cavities within the matrix [20].

As mentioned above, cracking in ECC is fundamentally different from that which occurs in concrete or reinforced concrete. One of the concerns of ECC is its crack pattern of closely spaced cracks with tight crack width in relation to capillary suction. This concern is addressed directly in the study conducted by Sahmaran and Li by measuring the sorptivity and absorption properties of pre-cracked ECC material [21]. After various numbers of microcracks were introduced by mechanical loading, water absorption and sorptivity tests were performed to develop an understanding of how microcracks accelerated the deterioration process. Figure 8 shows the relationship between the sorptivity (mm/min$^{1/2}$) over six hours and the number of cracks, for ECC specimens. Corresponding values for virgin ECC specimens (data points with zero number of cracks) are also included in this plot. As seen from the figure, the presence of micro-cracking in ECC significantly alters the transport properties measured as a function of the number of micro-cracks. The water absorption increase is fairly high as the number of cracks on the surface of the ECC specimens increases. Therefore, the sorptivity test shows that micro-cracked ECC specimens would be more vulnerable to attack than virgin specimens. As the number of cracks along the specimen grows, the sorptivity of ECC increased exponentially. Even so, the sorptivity values of pre-loaded ECC specimens up to a strain representing 1.5% on the exposed tensile face is not particularly high when compared to that of normal concrete, probably due to higher amount of cementitious materials, lower water-cementitious materials ratio, high fly ash content and the absence of coarse aggregate. Moreover, in the same study, Şahmaran and Li [21] also studied the absorption rate in cracked ECC, and found that the use of water repellent admixture in the production of ECC could easily inhibit the sorptivity even for the mechanically pre-loaded ECC.

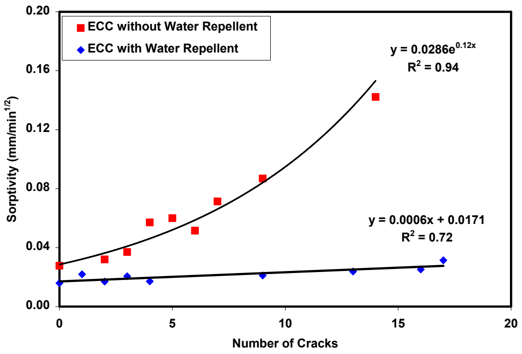

Figure 5. Sorptivity versus number of crack for ECC mixtures

SELF-HEALING OF MICROCRACKS IN ECC

The reason for the relatively low permeation and diffusion cracked ECC specimens are not only due to the tight crack width but also the presence of self-healing of the microcracks. The self-healing of cracks becomes prominent when crack width is small. Based on experimental results, Evardsen [22] and Reinhardt and Jooss [23] proposed that cracks with width below 0.1 mm can be closed by a self-healing process. In the case of precracked ECC specimens exposed to water or salt solution or under wet and dry cycles, micro-cracks in ECC were found to close due to self-healing [24] even after 30 days exposure period, thus slowing further water intake, reducing the rate of water absorption and diffusion. For example, an environmental scanning electron microscope (ESEM) observation of the fractured surface of ECC across a healed crack after exposed to salt solution is shown in Figure 11. The present ESEM observations show that most of the products seen in the cracks were newly formed C-S-H gels. This can be attributed primarily to the large fly ash content and relatively low water to binder ratio within the ECC mixture. The continued pozzolanic activity of fly ash cause is responsible for the self-healing of the crack and then which reduces the ingress of the chloride ions.

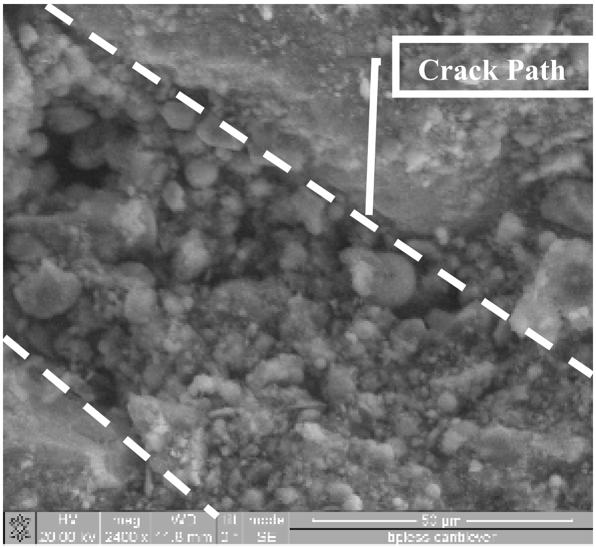

Figure 6. ESEM micrograph of rehydration products in a self-healed crack

CONCLUSION

Engineered Cementitious composites (ECC) have benefits including high tensile ductility and very tight crack width (generally less than 80 µm) under applied loads. In terms of transport properties, these reduced, finely-distributed micro-cracks can provide good resistance to transport of water and/or aggressive substances from the environment even under extensive straining. The risk of water transport by permeability and capillary suction, and chloride transport by diffusion in ECC, cracked or uncracked, is found to be comparable or lower with that in normal sound concrete without any cracks. Moreover self-healing in terms of transport properties of pre-damaged (by pre-cracking) ECC is revealed in a variety of transport mechanisms; permeation, absorption, or diffusion exposure. The superior performances of ECC are expected to contribute substantially to improving civil infrastructure sustainability by reducing the amount of repair and maintenance during the service life of the structure.

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