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ORIGINAL ARTICLE

Influence of microcracking on water absorption and sorptivity of ECC

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Abstract This paper presents the results of an experimental investigation on the water absorption and sorptivity properties of mechanically loaded Engineered Cementitious Composites (ECC). ECC is a newly developed high performance fiber reinforced cementitious composite with substantial benefit in both high ductility and improved durability due to tight crack width. By employing micromechanics-based material design, ductility in excess of 3% under uniaxial tensile loading can be attained with only 2% fiber content by volume, and the typical single crack brittle fracture behavior commonly observed in normal concrete or mortar is converted to multiple microcracking ductile response in ECC. In this study, water absorption (ASTM C642) and sorptivity tests (ASTM C1585) were conducted to determine absorption capacity and sorptivity of microcracked ECC. The experimental program described in this paper indicated that microcracks induced by mechanical loading increases the sorptivity value of ECC without water repellent admixture. However, the use of water soluble silicone based water repellent admixture in the production of ECC could easily inhibit the sorptivity even for the mechanically loaded ECC specimens. Moreover, the incorporation of the water repellent admixture reduced the absorption capacity of the resulting ECC mixture. Based on this study, the risk of water transport by capillary suction in ECC, cracked or uncracked, is found to be low compared with that in normal sound concrete. The incorporation of water repellent admixture further lowers this risk.

Keywords Cracking · Engineered cementitious composites (ECC) · Sorptivity · Water absorption

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1 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 corrosive agents to the steel [1, 2]. This can be achieved with a well-graded particle size distribution [3], supplementary cementitious materials such as 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, sulfate attack, freezing-and-thawing damage, and other mechanisms such as steel corrosion in reinforced concrete structures 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.

Engineered Cementitious Composites (ECC) is a family of ductile fiber reinforced cementitious composites micromechanically designed to achieve high damage tolerance under severe loading and high durability under normal service conditions [10–12]. Unlike ordinary concrete materials, ECC strain-hardens after first cracking, similar to a ductile metal, and demonstrates a strain capacity 300–500 times greater than normal concrete (Fig. 1). Cracking in ECC is also fundamentally different from that which occurs in concrete or reinforced concrete. ECC develops multiple micro-cracking in a strain-hardening response as a result of the bending preload (Fig. 1). Even at large imposed deformation, crack widths of ECC remain small, less than 80 μm. With intrinsically tight crack width and high tensile ductility, ECC represents a new concrete material that offers a significant potential to naturally resolving the corrosion related durability problem of R/C structures.

Normally, the formation of cracks increases the transport properties of concrete, so that water, oxygen and chloride ions easily penetrate and reach the reinforcing steel and accelerate the initiation of steel corrosion in concrete. However, recently, Lepech and Li [13] found that cracked ECC exhibits nearly the same water permeability as sound concrete, even when strained in tension to several percent. Further, when normalized by number of cracks within the specimen, the comparable permeability of cracked ECC with sound material becomes even more apparent.

In addition to water permeability, the relation between chloride diffusion coefficient of ECC and reinforced mortar, and deformation resulting from flexural load was examined by Şahmaran et al. [14]. Under high imposed bending deformation, the preloaded ECC beam specimens reveal microcracks less than 50 μm and an effective diffusion coefficient significantly lower than that of the similarly preloaded reinforced mortar beam because of the intrinsic tight crack width control in ECC. In contrast, cracks larger than 150 μm in reinforced mortar beams under the same imposed deformation result in significant increase in the effective diffusion coefficient.

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 [15]. Capillary transport may also be a concern for ECC since the crack width is so small.

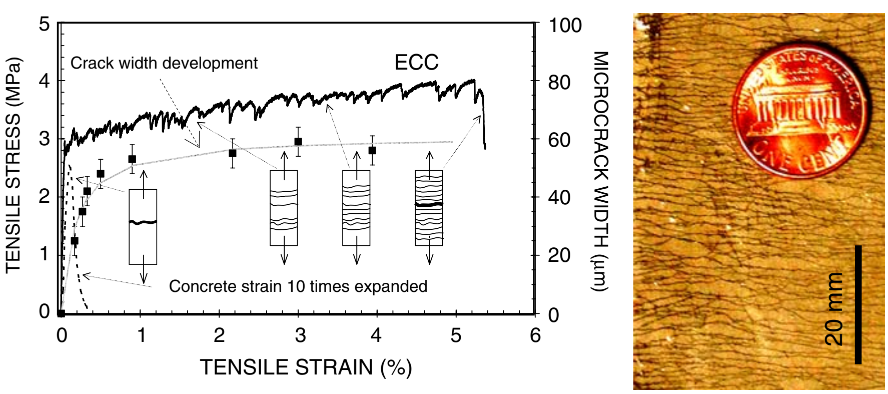

Fig. 1 Typical tensile stress–strain curve and crack width development of ECC

Therefore, reliable assessment of its absorption and sorptivity characteristics is essential. A recent study, however, has shown that capillary suction in ECC could be controlled by application of a water repellent agent [16]. It is known that an efficient water repellent surface treatment can act as an effective barrier against penetration of aqueous solutions and hence protect concrete elements from early degradation.

A first possibility for the improvement of the life span of ECC structures can be realized by impregnation of the covercrete with water repellent agents [17]. In this method the properties of the covercrete are optimized in a rational way. The most important parameter controlling the effectiveness of impregnating water repellent admixtures as means of protecting concrete from aggressive ions to cause concrete deterioration is the depth of penetration of the water repellent agents. However, when concrete structures experience cracking in field conditions, the depth of cracking can easily reach or exceed the full depth of penetration. Another possibility to reduce water transportation is to modify the ECC properties by adding a water repellent agent directly to the fresh mixture [18].

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 this paper by measuring the sorptivity and absorption properties of pre-cracked ECC material. 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. Further, an ECC mixture with water repellent admixture was also produced and the same experimental studies were done for material.

2 Experimental studies

2.1 Materials, mixture proportions, and basic mechanical properties

The materials used in standard ECC mixtures were ordinary portland cement (C), Class-F fly ash (FA) with a lime content of 10.44%, silica sand with average and maximum grain sizes of 110 and 200 μm, respectively, water, poly(vinyl alcohol) (PVA) fibers, and a high range water reducing admixture (HRWR). The PVA fibers are purposely manufactured with a tensile strength, elastic modulus, and maximum elongation matching those needed for strain-hardening performance. Additionally, the surface of the PVA fibers is coated with a proprietary oiling agent 1.2% by mass to tailor the interfacial properties between fiber and matrix for strain-hardening performance [19]. The mechanical and geometrical properties of the PVA fibers used in this study are shown in Table 1. In addition, a water-soluble silicone based water repellent chemical admixture (Dow Corning IE-6683) was also used to improve the water absorption characteristics of the ECC mixture. This water repellent chemical admixture was supplied by the manufacturer in liquid form with a solid content of 40%. This type of admixture does not provide an impenetrable physical barrier, but rather induces a chemical repulsion/repellency of the concrete to water [20].

Table 1 Mechanical and geometrical properties of PVA fiber

Nominal strength (MPa)	Apparent strength (MPa)	Diameter (μm)	Length (mm)	Young's modulus (GPa)	Elongation (%)
1,620	1,092	39	8	42.8	6.0

A standard ECC mixture (M45) was used in this investigation, details of which are given in Table 2. ECC mixtures were prepared in a standard mortar mixer with a constant cementitious material content and constant water to cementitious material (W/CM) ratio of 0.27. The ECC mixture had a fly ash–cement ratio (FA/C) of 1.2 by mass. In order to improve the water absorption and sorptivity characteristics, the same ECC mixture with water repellent admixture was also produced. Water repellent admixture at a medium dosage of 13.6 kg/m^3 (about 0.80% by weight of total dry materials) recommended by the manufacturer was added directly to the fresh mixture during the mixing process.

The compressive strength and the ultimate tensile strain capacity of ECC mixtures at 7 and 28 days are listed in Table 2. The companion cylinders with 75 mm diameter and 150 mm height were tested in compression using the standard ASTM C39

Table 2 Mixture properties of ECC

	ECC (M45) without water repellent	ECC (M45) with water repellent
FA/C	1.2	1.2
W/CM[a]	0.27	0.27
Water (W) (kg/m^3)	331	320
Cement (C) (kg/m^3)	570	570
Fly ash (FA) (kg/m^3)	684	684
Sand (S) (kg/m^3)	455	455
Fiber (PVA) (kg/m^3)	26	26
HRWR (kg/m^3)	4.9	4.9
Water repellent (kg/m^3)	–	13.6
Air content (%)	8.4	8.0
7-day compressive strength (MPa)	37.4	39.6
28-day compressive strength (MPa)	48.2	51.2
7-day tensile strain capacity (%)	3.48	3.29
28-day tensile strain capacity (%)	3.16	2.97

[a] CM, cementitious materials (Cement + Fly ash)

procedures. A minimum of three compression cylinders was used to obtain the average compressive strengths. As seen from Table 2, the compressive strength of ECC mixtures with water repellent admixture is slightly higher than that of ECC mixtures without water repellent admixture. The reason of slightly higher compressive strength of ECC mixtures with water repellent admixture may be attributed to the polymerization of the water repellent admixture [16].

To characterize the direct tensile behavior of ECC, 152 × 76 × 13 mm coupon specimens were used. Direct tensile tests were conducted under displacement control at a loading rate of 0.005 mm/s. The tensile stress–strain curves of ECC mixtures at 7 and 28 days are shown in Fig. 2. As seen from Fig. 2, the strain capacity of the ECC mixture with water repellent admixture is slightly lower than that of the ECC mixture without water repellent admixture, and the tensile strength is slightly higher than that of the ECC mixture without water repellent admixture; nevertheless the observed ∼3.0% strain capacity remains acceptable for an ECC. The reason for the slight differences in tensile properties of ECC mixtures with and without water repellent admixture may be attributed to the fact that the polymerization of the water repellent admixture may lead to a denser microstructure, and a denser microstructure may result in higher interfacial bond between fiber and matrix, especially frictional bond, and therefore higher fiber bridging capacity and ultimate tensile strength of the composite. However, more experimental studies on a micro-mechanical scale are necessary to clearly understand the mechanisms behind the slight increase in the ultimate tensile strength and reduction in the tensile strain capacity, and are beyond the scope of this paper.

2.2 Specimen preparation for water absorption and sorptivity testing

From each mixture 355 × 75 × 50 mm (length × depth × width) beam specimens were prepared for absorption and sorptivity tests. All specimens were demolded at the age of 24 h, and moisture cured in plastic bags at 95 ± 5% RH, 23 ± 2°C for 7 days. The beam specimens were then air-cured in laboratory air at 50 ± 5% RH, 23 ± 2°C until the age of 28 days for testing.

At 28 days, except for the control specimens, all ECC beams were pre-cracked by applying different deflections up to 2.0 mm using a 4-point bending test to obtain different crack frequencies. The 2.0 mm

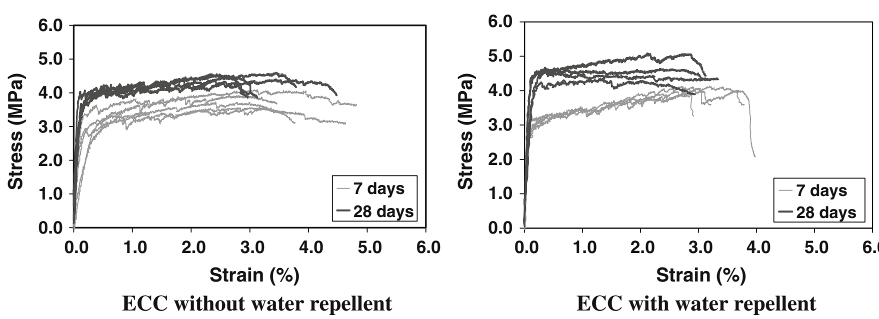

Fig. 2 Tensile behavior of ECC mixtures

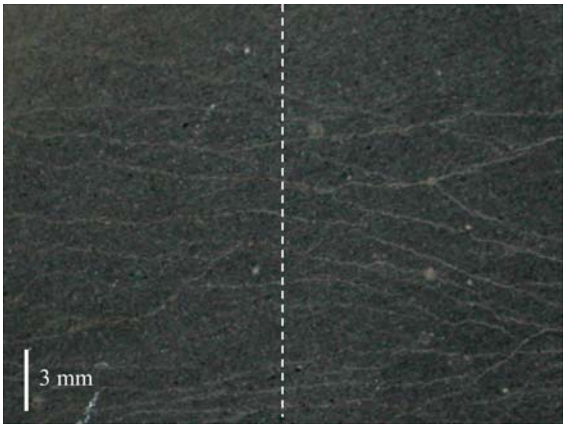

Fig. 3 Typical crack pattern on tensile surface of ECC beams after bending load application

deformation is nearly equivalent to 1.5% strain on the tensile face of the beam. This represents a relatively large deformation in an actual structure. The different deflections resulted in a different number of cracks with different crack spacing (and therefore crack density) for each beam. The cracking behavior in ECC after bending test is fundamentally different from that which occurs in concrete or reinforced concrete. ECC develops multiple micro-cracking in a strain-hardening response as a result of the bending preload (Fig. 3). After bending load was applied, 75 × 75 × 50 mm (length × depth × width) prisms from the central portion of each beam specimen (as shown in Fig. 7) were cut for water absorption and sorptivity tests.

The absorption and sorptivity tests were carried out with the pre-cracked ECC specimens in the unloaded state. To account for the crack closure on unloading, all crack width measurements were conducted in the unloaded state. For each specimen, a line parallel to the longitudinal axis of the beam was drawn on the cracked surface (Fig. 3). The number of cracks and crack width were measured along this line using an optical microscope. The crack widths thus measured represent the maximum opening at the tensile surface of the beam. Even at large beam deformations crack widths of ECC remain nearly constant (below 70 μm), while the number of cracks on the tensile surface of the ECC specimens increased. Table 3 shows the average crack widths, and corresponding number of cracks over the gauge length of 75 mm for the ECC prism specimens used for the sorption/absorption tests. For each mixture, three virgin (with no preloading) prisms were also tested for control purpose.

The two test procedures used, water absorption and sorptivity tests, reflect different performance of the ECC mixtures. The sorptivity test method is used to determine the rate of water absorption by concrete by measuring the increase in the mass of a pre-dried specimen resulting from absorption of water as a function of time when only one surface of the specimen is exposed to water [21]. The exposed surface of the specimen is immersed in water and water ingress of unsaturated concrete dominated by capillary suction during initial contact with water. On the other hand, the absorption test method determines the percent voids in hardened concrete materials [22]. During the absorption test, the specimens are exposed to water on all six faces. Brief explanations of the water absorption and sorptivity test procedures are provided in the following sections.

Table 3 Crack widths and number of cracks in pre-cracked ECC prisms

ECC without water repellent			ECC with water repellent		
No. of cracks	Average crack widths (μm)	# of specimens	No. of cracks	Average crack widths (μm)	# of specimens
–	–	3	–	–	3
2	25	2	1	40	2
3	30	2	2	40	2
4	27	2	3	53	2
5	61	2	4	40	2
6	38	2	9	42	2
7	35	2	13	43	2
9	37	2	16	27	2
14	63	2	17	37	2

2.2.1 Sorptivity test

The sorptivity test was based on ASTM C1585 [21]. The test consisted of registering the increase in mass of a prism specimen (75 × 75 × 50 mm) at given intervals of time (1, 2, 3, 4, 6, 8, 12, 16, 20, 25, 36, 49, 64, 81, 120 and 360 min) when permitted to absorb water by capillary suction. The specimens were dried in an oven at 50 ± 5°C for 3 days. Only one surface of the specimen (negative moment surface—tensile face) was allowed to be in contact with water, with the depth of water between 3 and 5 mm (Fig. 4). The sides of the specimen were sealed with a silicone coating in order to have one-directional flow through the specimen. The rate of absorption (mm), defined as the change in mass (g) divided by the cross sectional area of the test specimen (mm^2) and the density of water at the recorded temperature (g/mm^3), was plotted against the square root of time ($min^{1/2}$). The movement of water into concrete is described by the square-root-time relationship, fully explained by Hall [23]. The slope of the obtained line defines the sorptivity of the specimen during the initial 6 h of testing. For all specimens (cracked and uncracked), this slope is obtained by using least-squares, linear regression analysis of the plot of the rate of absorption versus the square root of time. This test was chosen as it measures the rate of ingress of water through unsaturated concrete. Moreover, Gummerson et al. found that the sorptivity test is a useful test for establishing the effectiveness of any water repellent treatment [24].

2.2.2 Absorption test

The absorption test is based on ASTM C642 for determination of voids in hardened concrete [22].

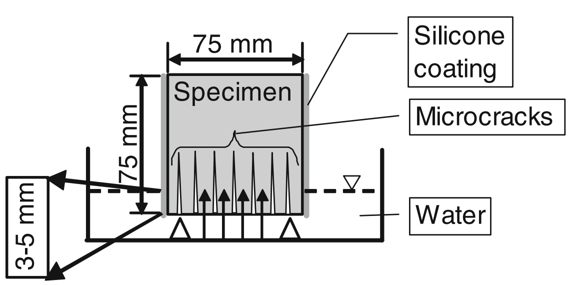

Fig. 4 Schematic diagram of sorptivity test

From this test, the absorption of the concrete is expressed as the percentage of the absorbed water divided by the dry mass of the concrete. Prism specimens were dried in an oven at 50 ± 5°C for 3 days. The specimens were then immersed in tap water and weighed every 24 h to check the increase in mass, until the increase in mass was less than 0.5% of the heavier mass which defines the saturation stage. In this test, water absorption can only take place in pores which were emptied during drying and filled with water during the immersion period. These pores can be considered as penetrable pores and therefore, the absorption of the concrete sample after immersion in water until saturation indicates its penetrability. As a result of this test, the total volume of penetrable pores was determined.

3 Results and discussions

Both absorption and sorptivity tests are based on water-flow into unsaturated concrete, through connected pores. Therefore, they both are considered as relative measures of water transport associated with capillary suction. Table 4 presents the volume of penetrable pores from water absorption test and sorptivity of the ECC mixtures determined after 28 days curing period.

3.1 Sorptivity test

Sorptivity tests were conducted to determine how load-induced microcracks of ECC affect the capillary suction (absorption) of concrete. A typical plot of the cumulative water absorption (normalized per unit surface area) as a function of the square root of time is shown in Fig. 5. It can be seen that the cumulative volume of water absorbed per unit surface area (mm^3/mm^2) in the specimens increased with the square root of time. The presence of microcracking in ECC without water repellent admixture significantly alters the transport properties measured as a function of the number of microcracks. The water absorption increase is fairly high when the number of cracks on the surface of the ECC specimens increases. In particular, for the highly damaged ECC specimen, the initial rate of water absorption was very fast thereby implying that the cracks and capillary pores were saturated in a very short time.

Table 4 Sorptivity and absorption test results of the ECC mixtures

ECC without water repellent			ECC with water repellent		
No. of cracks	Sorptivity (mm/min$^{1/2}$)	Volume of penetrable pores (%)	No. of cracks	Sorptivity (mm/min$^{1/2}$)	Volume of penetrable pores (%)
–	0.028	8.4	–	0.016	7.5
2	0.032	8.7	1	0.022	8.1
3	0.037	8.7	2	0.017	7.7
4	0.057	9.4	3	0.021	8.2
5	0.060	9.4	4	0.017	8.1
6	0.052	9.1	9	0.021	8.2
7	0.071	10.0	13	0.024	8.0
9	0.087	9.8	16	0.025	8.1
14	0.142	10.1	17	0.031	8.5

It was also observed from Fig. 5 that for the highly damaged ECC specimens (e.g. # of crack = 14), the cumulative water absorption increased non-linearly with the square root of time. The nonlinearity for the microcracked ECC specimens was likely due to the fact that the capillary absorption into the crack system is quite weak and reaches capillary rise equilibrium against gravity in the course of the test [25]. In the case of cracked specimens, therefore, the observed cumulative absorption arises from the combination of two processes: the absorption into the uncracked matrix where the capillary forces are strong compared with the opposing gravitational forces; while the absorption into the crack system reaches a limiting equilibrium value. Another reason of nonlinearity may be attributed to the fact that water may rapidly fill the microcracks due to the large capillary suction and absorption may also occur from

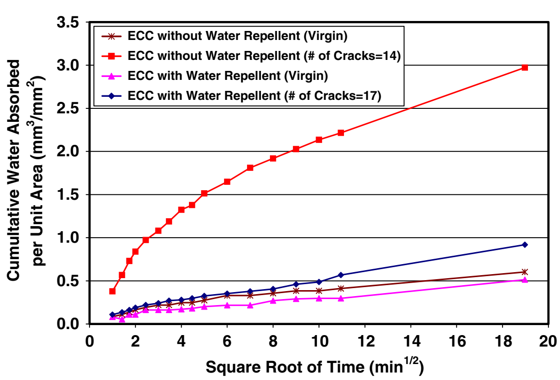

Fig. 5 Typical result of water absorption as a function of square root of time

the crack plane, and thus the cross sectional area of the specimen used for the calculation of water front is incorrect. This indicates that microcracks induced by mechanical loading facilitated the water ingress in ECC without water repellent admixture. On the other hand the use of water repellent admixture significantly increases the water absorption resistance of ECC especially for the cracked ECC specimens.

The cumulative water absorption per unit area of the specimen up to 6 h (Fig. 5) was fitted using linear regression and the equation obtained was used to describe capillary actions in the first 6 h. Figure 6 shows the relationship between the sorptivity (mm/min$^{1/2}$) over 6 h and the number of cracks, for ECC specimens with and without water repellent admixture. Corresponding values for virgin ECC specimens (data points with zero number of crack) are also included in this plot. The sorptivity test shows that ECC mixtures without water repellent admixture would be significantly more vulnerable to attack than ECC specimens with water repellent admixture, especially for the cracked specimens. As the number of cracks along the specimen grows, the sorptivity of ECC without water repellent admixture increased exponentially. On the other hand, despite the higher crack density, the ECC specimens with water repellent admixture reveal a sorptivity considerably lower than that of ECC specimens without water repellent admixture. As seen from Fig. 6, the sorptivity of ECC with water repellent admixture are almost constant for the different crack densities. Since the water repellent admixture was added during the mixing process, not only the capillary pore system but also the crack faces are hydrophobic.

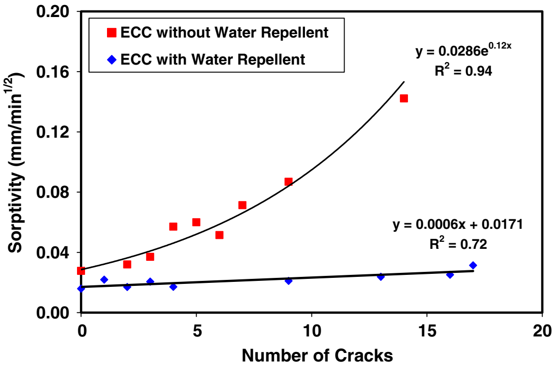

Fig. 6 Sorptivity versus number of crack for ECC mixtures

The relationship between microcrack density and sorptivity has also been examined by other researchers [26, 27]. Because of the brittle nature of conventional concrete, to produce microcracking damage, concrete specimens were loaded to different levels of compressive stress or exposed to freezing and thawing cycles. In those studies, the authors also concluded that the presence of microcracks lead to increase sorptivity. However, because of difficulty of calculating the crack frequency in conventional concrete, no information exists about the correlation between the crack frequency and sorptivity.

Figure 7 shows an irregular demarcation boundary between the wet and dry zones revealed on the surface of the specimen after 6 h of water exposure. Therefore, in addition to crack width, crack length and tortuosity may also influence the sorptivity values of ECC. Because of the presence of micro-cracks, appropriate methods are needed to gain accurate measurements of crack length of ECC specimens. Further research will be useful to study the effect of crack depth and tortuousity on water absorption and sorptivity of ECC.

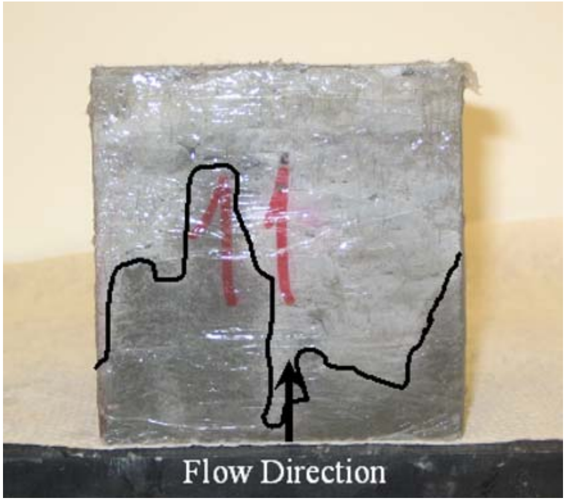

Fig. 7 Typical cracked ECC prism (75 × 75 × 50 mm) after 6 h water exposure

According to Neville [28], typical sorptivity is 0.09 mm/min$^{1/2}$ for normal concrete with a W/C ratio of 0.4. Other research suggested that ordinary Portland cement concrete with W/C ratio of 0.4–0.5 would have sorptivity of about 0.23 mm/min$^{1/2}$ [29–31]. Therefore, the measured sorptivity (<0.04 mm/min$^{1/2}$) for these cracked and virgin ECC specimens with water repellent admixture at W/CM ratio of 0.27 was significantly lower than that of conventional concrete, and the measured sorptivity (<0.15 mm/min$^{1/2}$) for the cracked ECC specimens without water repellent admixture was not particularly high when compared to that of conventional concrete.

The reason for the lower sorptivity of ECC mixtures may be attributed to a significantly lower W/CM ratio, high FA content and absence of coarse aggregate. The use of fly ash probably resulted in a denser matrix, by reducing the pore size and thickness of transition zone between fiber and surrounding cementitious matrix [32]. According to the Mehta and Monteiro [33], the existence of microcracks in the interfacial transition zone at the interface with coarse aggregate is the primary reason that concrete is more permeable than the corresponding hydrated cement paste and mortar. Also in general, everything else being the same, the larger the aggregate size the higher the local water–cement ratio in the interfacial transition zone and, consequently, the weaker and more permeable would be the concrete.

Moreover, the sorptivity values of cracked ECC specimens given in Table 4 likely represent upper limits of sorptivity in actual structures. This is because the effect of self-healing of micro-cracked ECC has not been accounted for in these specimens due to the short experimental duration. In this experimental study, the sorptivity of ECC specimens was determined following exposure to water for 6 h. Under wet and dry cycles, micro-cracks in ECC were found to close due to self-healing [34], thus slowing further water intake and reducing the rate of water absorption. This healing can be due to continued hydration of unhydrated cement particles, creating C–S–H bridges between crack lips.

3.2 Absorption test

The volume of penetrable pores of ECC mixtures determined from the absorption test is summarized in Table 4. Figure 8 shows the relationship between the volume of penetrable pores and the number of cracks. As expected, this table clearly demonstrates the increase in volume of penetrable pores with mechanical loading in the ECC specimens with and without water repellent admixture. The microcracks formed in the ECC specimens due to the mechanical loading may bridge the larger capillaries in the matrix, thus increase the volume of penetrable pores. These microcracks may also hold water between the crack surfaces after the test, effectively serving to increase the penetrable pores. The volume of penetrable pores of ECC without water repellent admixture appears approximately linearly proportional to the damage levels (measured as the number of cracks). It was also found that results obtained from ECC with water repellent admixture do not appear to indicate any particular trend. Therefore, the volume of penetrable pores obtained from absorption test in accordance with ASTM C642 is independent of the number of microcracks induced by mechanical loading for ECC with water repellent admixture. Moreover, the ECC specimens with water repellent admixture reveal about 2% lower volume of penetrable pores compared to the ECC specimens without water repellent admixture.

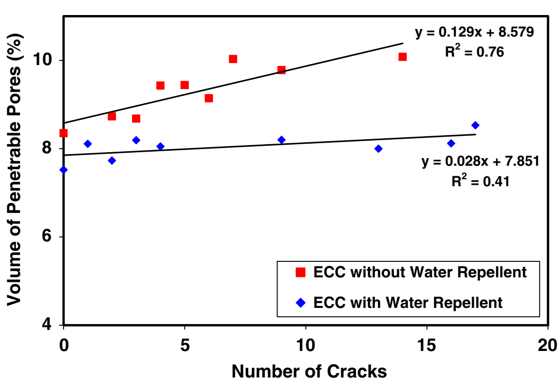

Fig. 8 Volume of penetrable pores versus number of crack for ECC mixtures

4 Conclusion

Cracks, irrespective of their nature, have a considerable influence on the transport properties of cementitious materials. As a consequence, the transport properties could be strongly impacted, and material and structural degradation processes could be accelerated. From the test results and analysis of cracked ECC specimens with/without water repellent admixture, the following conclusions can be drawn:

1. Cracking increases the sorptivity of ECC mixtures without water repellent admixture. The extent of such increase is dependent on the microcrack density produced due to mechanical loading. The sorptivity of ECC without water repellent admixture was found to increase exponentially with crack density. 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.
2. For the ECC mixture with water repellent admixture, the presence and number of microcracks had little or no effect on the sorptivity. The water repellent based on water soluble silicone was very effective in reducing the sorptivity of cracked ECC.
3. ECC mixtures with water repellent admixture showed lower percentages of penetrable pores compared to the ECC mixture without water repellent admixture.
4. For the ECC mixture without water repellent admixture, the influence of crack density is stronger on sorptivity than on the volume of penetrable pores.

From the results of this study, it is concluded that capillary suction as a transport property of ECC is not necessarily a concern when compared with normal concrete, even when the ECC is loaded into the microcracked strain-hardening stage, at least up to 1.5% tensile strain in this set of experiments. The use of water repellent admixture further reduces the water sorptivity and absorption properties of cracked ECC to a level significantly lower than that of normal *uncracked* concrete.

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References

1. Oh BH, Cha SW, Jang BS, Jang SY (2002) Development of high-performance concrete having high resistance to chloride penetration. Nucl Eng Des (Switzerland) 212(1–3):221–231
2. Beeldens A, Vandewalle L (2001) Durability of high strength concrete for highway pavement restoration. In: CONSEC '01: third international conference on concrete under severe conditions, Vancouver, BC, Canada, pp 1230–1238
3. Hwang CL, Liu JJ, Lee LS, Lin FY (1996) Densified mixture design algorithm and early properties of high performance concrete. J Chin Inst Civil Hydraulic Eng 8(2):217–229
4. Chang PK, Peng YN, Hwang CL (2001) A design consideration for durability of high-performance concrete. Cement Concr Compos 23(4–5):375–380
5. Mehta PK (1986) Concrete: structure, properties, and materials. Prentice-Hall, Englewood Cliffs, NJ, pp 353–367
6. Mora J, Aguado A, Gettu R (2003) The influence of shrinkage reducing admixtures on plastic shrinkage. Mater Constr 53(271–272):71–80
7. Weiss WJ, Shah SP (2002) Restrained shrinkage cracking: the role of shrinkage reducing admixtures and specimen geometry. Mater Struct 35(246):85–91
8. Mihashi H, De Leite JPB (2004) State-of-the-art report on control of cracking in early age concrete. J Adv Concr Technol 2(2):141–154
9. Wittmann FH (2002) Crack formation and fracture energy of normal and high strength concrete. Sadhana 27(4): 413–423
10. Li VC (1998) ECC—tailored composites through micromechanical modeling. In: Banthia N et al (eds) Fiber reinforced concrete: present and the future. CSCE, Montreal, pp 64–97
11. Li VC (2003) On engineered cementitious composites (ECC)—a review of the material and its applications. J Adv Concr Technol 1(3):215–230
12. Li VC, Wang S, Wu C (2001) Tensile strain-hardening behavior of PVA-ECC. ACI Mater J 98(6):483–492
13. Lepech M, Li VC (2005) Water permeability of cracked cementitious composites. In: Proceedings of eleventh international conference on fracture, CD-Paper 4539, Turin, Italy
14. Şahmaran M, Li M, Li VC (2007) Transport properties of engineered cementitious composites under chloride exposure. ACI Mater J 104(6):604–611
15. Martys NS, Ferraris CF (1997) Capillary transport in mortars and concrete. Cement Concr Res 27(5):747–760
16. Martinola G, Baeuml MF, Wittmann FH (2004) Modified ECC by means of internal impregnation. JAdv Concr Technol 2(2):207–212
17. Wittmann FH (2001) Protection of reinforced concrete structures by surface impregnation and monitoring. In: Zhou S, Wittmann FH (eds) Transfer 2—repair and maintenance of reinforced concrete structures. Shanghai, pp 279–286
18. Gerdes A (1997) Protective coatings of concrete structures for high durability. In: Wittmann FH (ed) Proceedings of a RILEM-WTA-seminar on high performance of cement-based materials. Aedificatio Publishers, Germany, pp 157–165
19. Li VC, Wu C, Wang S, Ogawa A, Saito T (2002) Interface tailoring for strain-hardening PVA-ECC. ACI Mater J 99(5):463–472
20. Bush TD, Kamel AA, Kalluri PA (1997) Influence of field variables on laboratory performance of silane treated concrete. ACI Mater J 94(3):193–202
21. American Society for Testing and Materials, ASTM C1585 (2004) Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes. American Society for Testing and Materials, USA
22. American Society for Testing and Materials, ASTM C642 (1997) Standard test method for density, absorption, and voids in hardened concrete. American Society for Testing and Materials, USA
23. Hall C (1989) Water sorptivity of mortars and concretes: a review. Mag Concr Res 41(147):51–61
24. Gummerson RJ, Hall C, Hoff WD (1981) Water movement in porous building materials—3. A sorptivity procedure for chemical injection damp proofing. Build Environ 16(3): 193–199
25. Hall C, Hoff WD (2002) Water transport in brick, stone and concrete. Spon, London
26. Gagne R, Popic A, Pigeon M (2003) Effects of water absorption on performance of concretes subjected to accelerated freezing and thawing tests. ACI Mater J 100(4):286–293
27. Samaha HR, Hover KC (1992) Influence of microcracking on the mass transport properties of concrete. ACI Mater J 89(4):416–424
28. Neville AM (1995) Properties of concrete, 4th edn. Longman Group Limited, London
29. Tsivilis S, Tsantilas J, Kakali G, Chaniotakis E, Sakellariou A (2003) The permeability of portland limestone cement concrete. Cement Concr Res 33(9):1465–1471
30. Chindaprasirt P, Jaturapitakkul C, Sinsiri T (2005) Effect of fly ash fineness on compressive strength and pore size of blended cement paste. Cement Concr Compos 27(4): 425–428
31. Mohammed TU, Yamaji T, Hamada H (2002) Microstructures and interfaces in concrete after 15 years of exposure in tidal environment. ACI Mater J 99(4):352–360

32. Kuroda M, Watanabe T, Terashi N (2000) Increase of bond strength at interfacial transition zone by the use of fly ash. Cement Concr Res 30(2):253–258
33. Mehta PK, Monteiro PJM (2006) Concrete: structure, properties, and materials, 3rd edn. McGraw Hill, New York
34. Yang Y, Lepech MD, Li VC (2005) Self-healing of ECC under cyclic wetting and drying. In: Proceedings of international workshop on durability of reinforced concrete under combined mechanical and climatic loads, Qingdao, China, pp 231–242