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Matrix design of light weight, high strength, high ductility ECC

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Abstract: In the past decade, the research on high strength, high ductility engineered cementitious composites (HSHD-ECC) has drawn much attention worldwide. However, due to the high matrix toughness associated with HSHD-ECC, saturated multiple cracking phenomena was rarely observed, hence hindering its robustness and high strain capacity. In this paper, ECC mixtures with relatively weak matrix were designed to allow much more cracks to be initiated, meanwhile retaining features of high strength, high ductility as well as light weight. The experimental results showed that ECC mixtures with addition of air entraining agent (AEA) increases the compressive/tensile strength slightly, while adding light weight filler (LWF) materials into ECC mixtures show the opposite tendency. However, all ECC mixtures exceed 60 MPa in compressive strength that satisfy the requirement of high strength concrete. In addition, incorporating AEA and LWF materials into HSHD-ECC lowered its matrix toughness and density effectively, as a result, increased its strain capacity and extent of saturated cracking significantly. In particular, the strain capacity of HSHD-ECC with addition of fly ash cenosphere (FAC) could reach 12.5%. At micro-scale level, the fiber/matrix interfacial frictional bond was altered with the matrix design in HSHD-ECC, and the experimental findings well explained the change tendency in tensile strength of five ECC mixtures based on micromechanics theory.

Keywords: ECC; matrix design; light weight; high strength; high ductility

Introduction

Concrete is the most widely used building material in the world and it plays very important role on modern infrastructures in the past century which enables infrastructures to stand the test of time. With the rapid development of modern society, more and more mega-structures, such as super high-rise buildings, dams and long-span bridges et al, were emerging worldwide which require the concrete to possess high performance in different aspects. The characteristics of high compressive strength and high tensile ductility are extensively emphasized in high performance concrete.

High strength concrete can reduce the structural section and aid in the optimized design of size efficient members. For example, it permits size reduction of column and beam in high-rise buildings, thereby freeing up precious usable space. It can also be used in the construction of highway bridges, enabling longer spans and decreasing the number of girders needed, thus lowering the overall cost. High strength concrete is often associated with quick setting; this feature could allow concrete pavement to be swiftly ready for traffic opening. In addition, high strength concrete typically has higher elastic modulus as compared with normal concrete, which increases the stability and reduces deflection of structural members. Moreover, less liable to shrinkage cracks and smaller ultimate creep strain in high strength concrete would lead to smaller loss of pre-stress in steel; therefore it is often used in the pre-stressed structure members. In contrast of the advantages of high strength concrete, much

more brittleness is normally accompanied with the increased strength. To address this issue, short steel fiber at dosage of 1~4% by volume fraction was added into ultra-high performance concrete (UHPC) [1-5]. The addition of steel fiber allows UHPC having a slight strain-hardening phenomenon with tensile strain capacity of around 0.5% [2, 4, 6]. Nevertheless, tension-softening behavior in the post-peak-stress stage was always observed along with the spalling of matrix surrounding steel fibers [7]. To guarantee the safety of infrastructures under extreme loading, the ductility of high strength concrete needs to be enhanced to ensure the structural resiliency. This may absorb intensive energy generated during a major event like an earthquake; hence the possibility of building collapse and also the need for frequent repairs is much lessened [8].

High-ductility concretes overcome the inherent brittleness in concrete, which avoids catastrophic failure of concrete structures under extraordinary loads or even disasters such as bomb blast, thus resulting in safer buildings. Engineered cementitious composite (ECC) represents a special class of high-ductility concretes, which is the focus of this study. Designed based on micro-mechanics theory, ECC possesses an applausive tensile strain capacity of more than 3% with moderate fiber fraction less than 2% by volume [9-14]. Unlike typical brittle fracture in normal concrete or tension-soften behavior in fiber reinforced concrete (FRC) when experiencing tensile loads, ECCs exhibit metal-like strain-hardening behavior after linear elastic stage. Meanwhile, multiple micro-cracks typically below 100 μm in width develop in ECC instead of one single, localized, millimetre-sized crack often observed in normal concretes [15-18]. Such tiny crack width imparts high durability to ECC since the water permeability and chloride penetration coefficient of cracked ECC were found to be comparable to that of sound ones [12, 19-22]. Nevertheless, strength properties of PVA-ECC including compressive, tensile, and flexural strength reported in previous studies was inferior to that of high strength concrete (e.g. very-high-strength concrete [VHSC][23], UHPC, reactive powder concrete [RPC][24]), which greatly limits its wider applications. It is of great significance to combine the high strength and high ductility into one concrete material for the resilience and safety of critical structural elements.

In recent years, some researchers devoted much attention to the development of high strength, high ductility ECC materials (HSHD-ECC). Kamal et al successfully developed an ultra-high performance strain-hardening cementitious composite (UHP-SHCC) with compressive strength of 96 MPa and tensile strain capacity of 2.8%, respectively [25]. Ranade and Li further increased the strength level of high ductility concrete, making it comparable with that of UHPC. In their studies, the compressive and tensile strength of high-strength, high ductility concrete (HSHDC) reach 166 MPa and 14.5 MPa, respectively, meanwhile maintaining the tensile strain capacity of 3.4% [26, 27]. Yu et al proposed the concept of concrete structures without rebar, which requires the concrete possesses tensile strain capacity comparable to steel reinforcement, in addition to high strength [28]. They developed ultra-high ductility cementitious composites (UHDCC) with tensile strain capacity of more than 8%, and compressive strength of 120 MPa [14, 29, 30]. Above discussion on recent investigations suggests that it is feasible to combine the two characteristics of high strength and high ductility into one concrete material.

HSHD-ECC's ductility was largely achieved by much wider crack opening due to absence of interfacial chemical bond and higher ultimate tensile stress, rather than preferred saturated microcracks. In previous studies, this issue was addressed by incorporating small amount of artificial flaw or increasing the volume of inert filler in matrix. This will lead to a more homogeneous defect system or reduce matrix fracture toughness in ECC, and thereby impart saturated multiple-cracking behaviour to the ECCs [11, 31-33]. On the other hand, high strength ECC normally has relatively high compactness/density by use of very fine ingredients and low water-binder ratio when compared with normal ECC. It is reported in

previous studies [29] that the density of HS-ECC is 2380 kg/m³ which increased about 25% as compared with that of normal ECC (around 1900 kg/m³). In some practical applications such as high-rise buildings, apart from high strength and high ductility in concrete, the characteristic of lightweight is also very important. The use of lightweight concrete could reduce the dead load of concrete structures, which may subsequently reduce the size of columns, footings and other load bearing elements, and resulting in lower overall cost.

In this study, we attempt to develop HSHD-ECC with saturated multiple-cracking by controlling matrix toughness. The theoretical foundation of this approach will be discussed briefly in the following section. Furthermore, in consideration of lightweightedness for HSHD-ECC, some light weight inert filler materials or air entraining agent were incorporated into HSHD-ECC. Hence its density could be comparable or even less than that of normal ECC, thereby combining the characteristics of light weight, high strength, and high ductility into one ECC material. In this paper, compressive strength, density and tensile properties of the newly developed ECC mixtures were experimentally investigated at composite level. At microscale, the matrix toughness and fiber/matrix interface properties of ECCs were also discussed. Successful development of light weight, high strength and high ductility ECC in this paper could shed light on how to make ECC with saturated multiple-cracking behaviour, and has the potential to broaden the applications of ECC materials.

2. Material design framework

ECC was invented and designed by Li and his co-workers at 1990s based on micro-mechanics theory which involves the tailoring of matrix, fiber and matrix/fiber interface [9, 34-36]. To attain strain-hardening behaviour in ECC, there are two core criteria need to be satisfied, that is energy criteria and strength criteria as shown in following equations (1) and (2).

$$\text{Energy based criterion: } J_{tip} \leq \sigma_0 \delta_0 - \int_0^{\delta_0} \sigma(\delta) d\delta \equiv J'_b \quad (1)$$

$$\text{Strength based criterion: } \sigma_0 > \sigma_{cs} \quad (2)$$

where σ_0 is the maximum fiber-bridging stress; δ_0 is the crack opening corresponding to σ_0 ; σ_{cs} is the stress needed to trigger crack in matrix under tension; J_{tip} is the energy needed for the propagation of crack in matrix; J'_b is the complementary energy.

Equation (1) states that the crack tip toughness J_{tip} shouldn't exceed the complementary energy J'_b which could be calculated from the fiber bridge stress-crack opening (σ - δ) relationship. The successful meeting of this criterion could guarantee the steady state cracking which means the crack width keep constant as the crack tip extends. This is necessary for the appearance of multiple cracking phenomena in ECC [37]. Equation (2) expresses the cracking strength of matrix (σ_{cs}) under tension must be less than the maximum fiber bridging stress (σ_0). This criterion ensures the subsequent cracks could be initiated before achieving the peak fiber bridging stress (σ_0), hence resulting in multiple cracking phenomena. Failure of either criterion will cause the tension-softening behaviour with one localized crack, which can typically be found in normal concrete or fiber reinforced concrete (FRC).

In ECC design theory, the pseudo strain-hardening (*PSH*) index, including $PSH_E = J'_b/J_{tip}$ and $PSH_S = \sigma_0/\sigma_{cs}$, are normally considered as the multiple-cracking potential indicators [16, 38-40]. A sufficient margin between J'_b and J_{tip} , σ_0 and σ_{cs} , is normally associated with better chance for achieving saturated cracking condition and thus more robust ECC behaviour. As the matrix toughness (K_m) greatly impacts on J_{tip} value ($=K_m^2/E_m$) and is decisive to σ_{cs} value, lowering matrix toughness is a very effective means to increase *PSH* value, and favors the high ductility of ECC.

3. Experimental programs

3.1 Materials and mix proportions

In this study, the ingredients for HSHD-ECC include Portland cement of CEM I-52.5, fly ash, silica fume, silica sand, water, superplasticizer (SP), and polyethylene (PE) fiber. The PE fiber has a length and diameter of 18 mm and 26 μm , respectively. The fiber nominal tensile strength is 3000 MPa, and the specific gravity of fiber is 0.97 g/cm^3 . The silica fume was added into ECC to densify the matrix due to its nano-sized particles and potential pozzolanic activity, which is normally used in high strength concrete. The silica sand with particles passing #150 sieves, which is finer than that usually used in ECCs, was adopted for more compact and higher strength matrix.

In this present study, there are five ECC mixtures as listed in Table 1. Besides the aforementioned ingredients, to lower matrix toughness and/or density of HSHD-ECC, air entraining agent (AEA) was added into the fresh paste. Alternatively, lightweight filler materials, such as crumb rubber (CR), fly ash cenosphere (FAC), and vermiculite (V) were added to replace silica sand partially/completely by equal volume. The particle size distribution of the filler materials are illustrated in Figure 1. The crumb rubber is produced by grinding scrap tyres and has the density of 1.2 g/cm^3 . FAC is a typical low density (0.8 g/cm^3) by-product of coal combustion at thermal power plants, which has hollow sphere as shown in Figure 2(a). The vermiculite is one of the most commonly used lightweight aggregate in fireproofing materials, which has a exfoliated shape and porous structure as shown in Figure 2(b). Its density used in this study is 0.5 g/cm^3 . For M-CR mixture listed in Table 1, 30% of silica sand in the control mixture (M-C) was replaced by crumb rubber by equal volume fraction. Similarly silica sand was fully replaced by fly ash cenosphere (FAC) and vermiculite (V) in M-FAC and M-V. Concrete mix M-C and M-AEA have the same mixture proportions except that M-AEA contains additional 0.2 g air entraining agent (AEA) per litre of fresh ECC paste.

Table 1 Mixture proportions of ECCs by weight (Except for fiber).

Mixtures	Cement	Fly ash	Silica fume	Silica sand	Filler materials	Water	SP	Fiber (by volume)
M-C	1	0.8	0.18	0.6	--	0.4	0.027	2%
M-AEA	1	0.8	0.18	0.6	--	0.4 +0.2g/L(AEA)	0.027	2%
M-CR	1	0.8	0.18	0.42	0.08	0.4	0.027	2%
M-FAC	1	0.8	0.18	--	0.18	0.4	0.027	2%
M-V	1	0.8	0.18	--	0.13	0.4	0.027	2%

All ECC mixtures were prepared using shear-type Hobart mixer with capacity of 10 L. All the solid ingredients including cement, fly ash, silica fume, sand and filler materials were first dry-mixed for 2 minutes. Then water, superplasticizer and/or AEA were added into the solid ingredients and mixed for 3 minutes. At last, the fibers were slowly added into the fresh mortar and mixed for another 5 minutes until no fiber cluster can be observed. After the mixing process, all the fresh ECC mixtures were cast into the moulds and covered with plastic sheets to prevent the moisture loss. All the specimens were demolded after 24 hours and then cured in air at room temperature of $25 \pm 3^\circ\text{C}$ and relative humidity (RH) of $50 \pm 5\%$ before testing at 28 curing days.

Figure 1 Particle size distribution of inert filler materials.

(a)

(b)

Figure 2 Morphology images of (a) FAC particles and (b) vermiculite flakes.

3.2 Testing procedures

In this paper, mechanical properties of the lightweight HSHD-ECC, including compressive strength and tensile performance, were investigated via uniaxial compressive

and tensile test. The underlying mechanism of the composite performance variations induced by the addition of lightweight filler material or AEA was discussed via matrix toughness measurement and single fiber pull-out test.

The compressive test was conducted in accordance with ASTM C 109 [41]. Three cubic specimens of each ECC mixture with dimensions of $50.8 \times 50.8 \times 50.8$ mm were prepared for this test. Before the compressive test, the weight of each cube specimen was measured and the density was calculated according to ACI Committee 213 report [42]. The compressive strength and density of each ECC mixture was obtained by averaging on three specimens.

The uniaxial tensile test was carried out to characterize the tensile behaviour of ECC mixtures. The dog-bone shaped specimen was adopted to lure cracks forming in the gauge length zone which have a smaller cross section area along specimen. The dimensions of specimen in the gauge length zone are 120 mm (length) $\times$ 35 mm (width) $\times$ 15 mm (thickness). The detailed test set-up could be found in the references [43, 44]. The test was conducted under displacement control at loading rate of 0.5 mm/min which approaches quasi-static loading status. The deformation of specimen during testing was recorded by two external linear variable displacement transducers (LVDT) attached on the specimen surface, which was used to calculate the tensile strain.

Three-point bending test compliant to ASTM E399 was used to measure ECC matrix toughness by using notched beam specimen with dimensions of $305 \times 38 \times 76$ mm [11]. The full loading support span is 254 mm and the notch depth to beam height ratio is 0.4.

The matrix/fiber interaction parameters which include frictional bonding strength (τ_0) and slip-hardening coefficient (β) were measured by single fiber pull-out test. During the test, a single long PE fiber with embedment length of around 2 mm was pulled out from a block of cementitious matrix and the load-displacement relationship was recorded. The details about the sample preparation and test set-up could be found in the references [35, 45].

4. Results and discussions

4.1 Density and Compressive strength

Figure 3 presents the density and compressive strength of ECC mixtures at 28 curing days. It could be clearly seen from Figure 3 that, due to the addition of lightweight filler materials or AEA, the density of M-AEA, M-CR, M-FAC, and M-V have an evident decrease as compared with that of M-C. With partial sand replacement by crumb rubber, the density of M-CR reduced slightly from 2053 kg/m^3 for M-C to 1960 kg/m^3 . On the other hand, the AEA is expected to entrain small air bubbles into ECC, and subsequently result in 6% reduction in density. For the rest mixtures, complete replacement of silica sand by FAC and vermiculite show the most effective density reduction effect. The density of M-FAC and M-V decreased 12% and 15%, respectively, and both of which could be classified as lightweight concrete that requires density less than 1850 kg/m^3 [42].

As shown in Figure 3, the compressive strength of all five ECC mixtures, ranges from 65 MPa to 87 MPa, is greater than 60 MPa which is usually considered as the threshold value of high strength concrete [46]. Therefore all the ECC mixtures developed in this study could be classified as high strength concrete. When compared with M-C, partial or complete replacement of sand by lightweight filler materials result in a decrease of compressive strength for M-CR, M-FAC and M-V, among which, the M-FAC shows the lowest compressive strength of 65 MPa. The relatively low compressive strength in M-CR, M-FAC, and M-V can be attributed to that lightweight filler materials in ECC act as small flaws and disturb the continuity of the matrix. The detailed explanations are listed as follows:

- The crumb rubber in ECC is likely to increase porosity and separate from surrounding hydration products, which has been proved in authors' previous studies [31, 33];

- The hollow structure of FAC make it easy to break and generate small voids, as shown in Figure 2(a);
- The vermiculite has a porous structure as shown in Figure 2(b), and consequently less stress withstanding capacity than that of silica sand.

Figure 3 Density and compressive strength of ECC mixtures.

Very interestingly, the entrainment of small air voids in AEA ECC did not seem to compromise the strength gain as the compressive strength of M-AEA is slightly higher than that of M-C. The possible explanation is that the addition of AEA improves the pore microstructures in ECC by generating a large number of small air voids but not large-sized pores which are more detrimental to compressive strength of ECC. Figure 4 illustrates the image of cross section cut from dog-bone specimen for uniaxial tensile test. It could be clearly seen from Figure 4 that millimetres-sized pore was found in M-C specimen, while micrometer-sized pores were dispersed evenly in M-AEA specimen.

Figure 4 Cross section of dog-bone specimen from (a) M-C and (b) M-AEA

4.2 Tensile performance of ECC mixtures

The relationship between tensile stress and strain of all ECC mixtures obtained from the tensile test are displayed in Figure 5 (a)~(e). From these curves, all tensile properties can be

derived such as elastic modulus, first cracking strength, tensile strength and strain capacity. They are defined as the slope between tensile stress of 1.5 MPa and 3.0MPa in initial linear elastic stage, stress value corresponding to the appearance of first stress-drop in curve, the maximum tensile stress and its corresponding strain, respectively. All the results are averaged from three curves and illustrated in Table 2.

As observed in Figure 5 and Table 2, the strain capacity of control mix M-C is 4.16%, which is around 400 times that of normal concrete and can be regarded as high ductility ECC. Nevertheless, it is still far from saturated multiple cracking state when compared with the other four ECC mixtures and the crack pattern which will be discussed in later section could also demonstrate this conclusion. Unsaturated cracking in M-C may be due to its high matrix toughness associated with high compressive strength, as a result, the initiation of new crack needs relatively high external load/energy as manifested by its high first cracking strength of 6.36 MPa, and subsequently causing lower *PSH* index. On the other hand, due to the fiber bridging effect, the ultimate tensile strength of M-C is 9.73 MPa which is about three times that of C80 concrete according to Chinese concrete structure design code [47]. It is also higher than that of PVA-ECC (usually below 7 MPa) due to relatively low tensile strength and hydrophilic property of PVA fiber [10, 35].

Figure 5 Tensile stress versus strain curves of ECC mixtures.

Table 2 Tensile properties of ECC mixtures

Mixtures	M-C	M-AEA	M-CR	M-FAC	M-V
First cracking strength (MPa)	6.36±0.41	3.95±0.40	4.43±0.26	4.53±0.15	4.05±0.26
Tensile strength (MPa)	9.73±0.31	10.88±0.14	8.37±0.40	8.80±0.38	8.05±0.15
Strain capacity (%)	4.16±0.23	6.95±0.35	6.66±0.20	12.50±0.84	11.20±0.39
Modulus E_m (GPa)	20.4±0.3	20.1±0.2	18.2±1.1	19.6±0.8	19.4±0.6

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In comparison with M-C, the first cracking strength of M-AEA, M-CR, M-FAC, and M-V are notably lower which is reduced from 6.36 MPa to 3.95~4.53 MPa. The first cracking strength is closely related to matrix fracture toughness (K_m), which is measured by three-point test and listed in Table 3. As expected, the addition of AEA and lightweight filler materials in ECC lowered its matrix fracture toughness and crack tip energy effectively ($J_{tip} (=K_m^2/E_m)$). Hence new crack is likely to be triggered easier under tension, which favours the potential saturated multiple cracking. The reduction in matrix toughness due to the addition of AEA, crumb rubber, FAC and vermiculite could be explained as follows:

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- The addition of AEA entrains small air voids, thus disrupt the continuity of matrix.
- The crumb rubber was separated from the matrix therefore acted as small flaw in ECC matrix [31, 48]. Additionally, the crumb rubber entrains notable amount of air bubble during mixing due to its non-polar properties, consequently leading to increased porosity [31].
- The FAC particles have a loose bond with matrix, which promote the propagation of micro-crack around the FAC shell [11, 32].
- The vermiculite has flake shape and a porous structure as shown in Figure 2(b), which weakens the matrix.

Table 3 Measured matrix toughness of ECC mixtures.

Mix.	M-C	M-AEA	M-CR	M-FAC	M-V
K_m (MPa* $\sqrt{m}$)	0.51	0.42	0.45	0.34	0.32
J_{tip} (J/m ²)	13.76	8.77	11.12	5.89	5.27

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On the other hand, tensile strength of M-CR, M-FAC, and M-V reduced modestly as compared with that of M-C, among which the M-C shows the lowest tensile strength of 8.05 MPa. This nevertheless is still much higher than that of C80 concrete. Overall, the strength change causes larger margin between tensile strength (σ_0) and first cracking strength (σ_{cs}) and therefore a higher PSH_s index, which is a good sign for saturated cracking state. Conversely, similar to the tendency in compressive strength, tensile strength of M-AEA increases from 9.73 MPa to 10.88 MPa despite entrained small air voids. The addition of AEA was probably to improve the pore structure and prevent the appearance of large flaw in ECC, thus increase the tensile strength of the ECC.

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For ECC materials, tensile strain capacity is one of the most important and representative parameters. As can be seen from Figure 5 and Table 2, due to lower matrix toughness the strain capacity of M-AEA, M-CR, M-FAC and M-V was improved significantly when compared with that of M-C. This is especially true for M-FAC and M-V which exhibited quite remarkable strain capacity of 12.5% and 11.2%, respectively. This is close to the highest level that has been reported in cement-based materials in previous studies [14, 29, 30]. The M-AEA and M-CR show strain capacity of 6.95% and 6.66% that is lower than that of M-FAC and M-V. However, these values still increased by 67% and 60%, respectively, when compared with that of M-C.

In addition to strain capacity, crack pattern is also very critical for ECCs since the strain capacity is contributed by the number of cracks and average crack width. Typically, formation of more number of cracks along specimen is preferred due to saturated cracks. As the crack width play decisive role on permeability and aggressive ion penetration, tight crack width in ECC is also appalusive. Figure 6 and Table 4 summarize the crack information in ECC mixtures. The crack width of each crack within the gauge length was read and recorded using optical microscope with minimum scale of 10 μm after unloading. In order to avoid the reading error caused by different people during the measuring process, all of the reading work was completed by one person. As listed in Table 4, the number of cracks in M-AEA, M-CR, M-FAC and M-V ranges from 108 to 125, which is much more than that of M-C of 55. This is due to the lower matrix toughness as well as easier crack initiation under tension.

The crack pattern is further illustrated in Figure 7 which shows the representative portion of ECC specimens. It is revealed that the average spacing between adjacent cracks is much smaller in these four ECC mixtures compared with the control mix, making them approach more saturated cracking state and enhanced strain capacity. In term of average crack width, M-AEA and M-CR show tighter crack than that of M-C. Conversely, average crack width of M-V is 86 μm and comparable to M-C, while M-FAC exhibits the largest crack width of 110 μm . It could also be found in Figure 6 that the percentage of cracks below 100 μm in M-AEA and M-CR is more than the other three ECC mixtures, while some cracks over 200 μm were observed in M-FAC. That is why the strain capacity of M-AEA and M-CR is lower than that of M-FAC and M-V, although with comparable total number of cracks.

Overall, all HSHD-ECC mixtures presented great enhancement of strain capacity. The M-AEA and M-CR exhibited closely spaced tight crack width that is suitable for exterior applications, such as bridge, dam, pavement et al, which require low water permeability and ion penetration coefficient. On the other hand, the M-FAC and M-V show pronounced strain capacity albeit with relatively large crack width. Their comparable strain capacity with steel rebar is preferable for interior structure elements where compatible deformation of both materials is desirable when subjected to extreme load like earthquakes [49].

Table 4 Crack pattern of ECC mixtures.

Mix	M-C	M-AEA	M-CR	M-FAC	M-V
Number of cracks	55 $\pm$ 4	106 $\pm$ 11	102 $\pm$ 9	112 $\pm$ 13	119 $\pm$ 9
Average crack width (μm)	90	69	56	110	86

Figure 6 Crack distributions with respect to crack width.

Figure 7 Observed crack pattern of ECC mixtures.

4.3 Fiber/matrix interfacial properties

In accordance with micro-mechanics design theory, composite properties of ECC are closely related to the matrix toughness, fiber attributes, and fiber/matrix interfacial properties. Besides the crack tip toughness J_{tip} as shown in Table 3, complementary energy (J'_b) which could be derived from fiber/matrix interfacial parameters is also critical to the PSH_E index, subsequently impact on cracking behaviour of ECCs. Additionally, the interaction between a single fiber and matrix is decisive to the tensile strength of ECCs since a number of fibers bridge crack and bear the external load after cracking. In this section, the fiber/matrix interface properties are discussed and then linked to the tensile properties of ECC based on micro-mechanics theory.

Figure 8 displays the typical PE fiber pull-out curves obtained in this study. It could be seen that there are two evident stages in the curves, which are linear elastic (pre-peak) and pull-out (post-peak) stages, respectively. The load increases during the pre-peak stage in which the embedded fiber segment stretches against the surrounding matrix. Due to

hydrophobic nature of PE fiber, no sudden load-drop was observed after the peak, which is not the case for PVA fiber. Subsequently, it enters the pull-out (post-peak) stage during which the entire embedded fiber was gradually pulled out against interfacial friction with continuous reduction of embedment length. As the contact length between fiber and matrix decrease linearly during pull-out process, the load should decrease linearly with the displacement. However, slight curvature in the curves was observed that may imply the presence of slip-hardening coefficient (β), which denotes an enhancement in frictional bond with slippage. Figure 9 presents the calculated interfacial parameters of ECC mixtures including τ_0 and β value based on the tested single fiber pull-out curves. The detailed calculation method of interfacial parameters could be found in the references [50, 51]. It is observed from Figure 9 (a) that replacing sand by lightweight filler material tends to decrease τ_0 value, which is probably caused by the much lower hardness of crumb rubber, FAC, and vermiculite as compared with silica sand. On the other hand, the addition of AEA increases τ_0 value slightly. From Figure 9 (b), it could be seen that the average β value of ECC mixtures ranges from 0.03 to 0.05, which is one order of magnitude smaller than what was found in PVA-ECC. This is because PE fiber is much more abrasion-resistant than PVA fiber as it is usually used for the production of bullet-proof vest, and therefore less fiber delamination occurred as compared to what was normally observed in PVA fiber [35].

Figure 8 Typical single PE fiber pull-out curves.

(a)

Figure 9 Interfacial parameters between PE fiber and surrounding matrix.

Figure 10 Computed fiber bridging σ - δ curves of ECC mixtures.

The theoretical relationship between fiber bridging stress and crack opening displacement (σ - δ) is shown in Figure 10, which is computed based on micro-mechanics theory [52]. After calculation based on the interfacial parameters, the maximum fiber bridging stress is proportional to the frictional bond (τ_0) that well explains the tendency of tensile strength in five ECC mixtures as listed in Table 2. Additionally, the theoretical complementary energy (J'_b) could be obtained by subtracting the area under σ - δ curve from the product of maximum fiber bridging stress (σ_0) and its corresponding crack opening (δ_0). The $PSH_E (=J'_b/J_{tip})$ index of ECC mixtures and number of cracks in different mixtures are plotted in Figure 11. The value of PSH_E of five ECC mixtures ranges from 12.7 to 36.1, which satisfy the energy criterion of equation (1). Due to the matrix re-design, the PSH_E index of ECC mixtures increases as compared with M-C, especially for M-FAC and M-V, which reach 31.6 and 36.1, respectively. This allows more stringent requirement of J'_b/J_{tip} for robust multiple cracking behaviour [39], which in turn is conducive to the development of saturated multiple cracks. As shown in Figure 11, the number of crack developed in ECC

specimens largely follow the trend of PSH_E index, which again confirmed that PSH_E index could be an indicator on how saturated the multiple cracking behaviour would be.

Figure 12 Correlation between PSH_E index and number of cracks in ECCs.

4. Conclusions

In this paper, through matrix designing, different kinds of lightweight, high strength, and high ductility ECC materials were successfully developed to widen its applications in structural elements. The density, compressive strength, and tensile properties of ECC mixtures were experimentally investigated. The addition of air entraining agent (AEA) and light weight inert filler materials decrease the density of ECCs, especially for the mixtures with fly ash cenosphere (FAC) and vermiculite. Both have density below 1850 kg/m^3 which could be classified as light weight concrete.

In term of strength properties, while the addition of AEA shows a slight enhancement of compressive/tensile strength which may be due to the improvement of pore structures, generally ECC mixtures with addition of light weight filler materials reduce the compressive/tensile strength. However their compressive strengths still exceed 60 MPa thus satisfy the lower bound of high strength concrete.

Due to effective reduction of matrix toughness, all ECC mixtures with re-designed matrix clearly showed more saturated multiple cracking behaviours. This in turn increased their strain capacity significantly, especially for the ones with addition of FAC and vermiculite, which achieved 12.5% and 11.2%, respectively. At micro-scale level, the fiber/matrix interfacial frictional bond (τ_0) of ECC mixtures exhibited the similar tendency to that of tensile strength, which well explains the underlying mechanism of alteration in tensile strength. The PSH_E index also well correlated with the number of cracks in ECC specimens which is manifested by saturated multiple cracking behaviours.

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