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Incorporating high volume fly ash and silica fume to improve the mechanical properties of ECC

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ABSTRACT

In order to optimize the fresh and hardened properties of engineered cementitious composites (ECC), the mineral admixtures have become key ingredients for the mix design of ECC. The emphasis of this paper is to study the mechanical properties of ECC with blending of cement and binary system of fly ash (FA) and silica fume (SF) in high volume. The combined proportion of FA and SF as cement replacement of is up to 70%. The effects of different SF contents are investigated, and the dependence of mechanical properties on testing age is examined. The results show that all ECC mixtures with FA and SF can achieve prominent strain-hardening and steady state multiple cracking by the direct tensile test and four-point bending test. In general, the incorporation of SF in ECC mixtures can enhance the mechanical properties.

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1. INTRODUCTION

Engineered cementitious composites (ECC) is known for the prominent multiple cracking capability at steady state and the tensile strain-hardening behaviour (Li et al. 2001; Li and Leung 2002). Fig. 1 illustrates the bendability of ECC (Li 2012), it is a class of fiber-reinforced cementitious composite with ultra-high ductility. The outstanding deformability accompanied by crack bridging is the outcome of design based on micro-mechanics of ECC material (Leung 1990; Li 1993). The tensile strain of ECC can be greater than 3% and even up to 5%, 300-500 times higher than that of ordinary concrete. Moreover, the average crack width can be less than 100 μm at stabilized cracking state (Li 2003). This is in contrast to a small number of widely opened cracks which would be detrimental to the structural integrity and durability (Zhang and Leng 2008; Ng et al. 2017, 2019). Benefitted from the superior ductility and crack control ability, structural elements built with ECC would in general be more durable than those built with ordinary concrete. The applications of ECC in rea llife include building components, bridge decks, road pavements, as well as patched and sprayed repair works (Lepech and Li 2006, 2009; Rokugo 2010; Zhang et al. 2013, 2017; Li 2019; Walus 2019).

In order to optimize the fresh and hardened properties of ECC, mineral admixtures such as slag (SL), fly ash (FA), and silica fume (SF), have become popular ingredients for the mix design (Yang et al. 2007; Sahmaran and Li 2009; Yang et al., 2009; Zhu et al. 2010; Li 2019). SL is economical and readily available in regions with steel-making industry. Kim et al. (2007) investigated the influence of SL on the mechanical properties of ECC, where the water/cementitious (W/C) ratio was fixed at 0.30 and the SL replacement level was 20% by mass of cement. Zhu et al. (2014) studied the effect of high volume of SL (50 to 70%) on the drying shrinkage and load-deflection curves of ECC. The results showed that SL could improve the workability and reduce the crack width in ECC. However, incorporating high volumes of SL increased the drying shrinkage and degraded the matrix strength, especially at high SL replacement level.

FA is a widely used pozzolanic concrete constituent. The beneficial effects of FA include reducing the carbon footprint, enhancing the workability, and reducing the drying shrinkage of ECC (Yang et al. 2007; Sahmaran and Li 2009; Dong et al. 2016). On the adverse side, incorporating high volumes of FA could result in lower early age strength, especially at the first 7 days. Nevertheless, the binary combination of mineral admixture could possibly improve the matrix strength of ECC at early age to fulfill the application requirements. For instance, incorporating SL in ECC with high volumes of FA could effectively increase the compressive strength at all ages, especially at early age (Zhu et al. 2012, 2014). Meanwhile, ECC blended with binary system of FA and SL manifested satisfactory tensile strain (higher than 2.5%) and steady state multiple cracking. In addition, compared to FA mixtures, incorporation of SL increased the matrix strength, the first cracking stress and the ultimate tensile stress. However, SL could slightly widen the residual crack width and slightly increase the drying shrinkage.

SF is ultrafine powder of silicon oxide and is often used in high-strength concrete production. The binary combination of FA and SF in ECC had been briefly studied (Zhu et al. 2014). Basically, the ECC mixtures with FA, FA + SL, and FA + SF showed strain-hardening and multiple cracking behaviours. However, in-depth interpretation of the phenomenal observations accounting for the effect of age was in lack. The emphasis of this paper is to investigate the mechanical properties and the age-dependent variations of ECC with binary system of FA and SF in high volume. The mechanical properties are evaluated by way of the direct tensile test, four-point bending test, and compressive strength test.

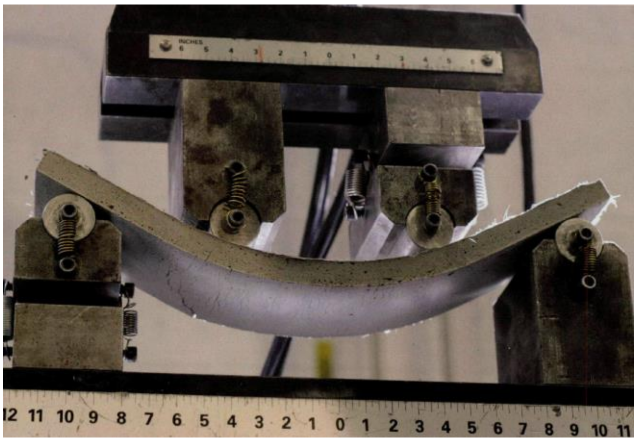


Fig. 1 ECC deformed by bending

2. EXPERIMENTAL INVESTIGATION

2.1 Raw Materials and Mix Proportions

In order to produce the ECC mixtures, ordinary Portland cement (OPC), class I FA, and SF were used as the cementitious materials. Table 1 and Table 2 respectively display the chemical compositions and physical properties of the OPC, FA and SF. Silica sand was used as the fine aggregate. It had fineness modulus of 2.01 and average grain size of 150 μm. There was no coarse aggregate in the mixtures. Polyvinyl alcohol (PVA) fiber was used as the short discrete fiber. It had length-to-diameter ratio of 200, tensile strength of higher than 1600 MPa, and density of 1300 kg/m^3.

Table 1 Chemical compositions of OPC, FA and SF

Chemical composition (%)	OPC	FA	SF
SiO_2	21.08	65.70	90.57
Al_2O_3	5.47	20.63	0.77
Fe_2O_3	3.96	4.65	1.74
CaO	62.28	2.93	0.33
MgO	1.73	2.25	1.68
R_2O	0.50	0.53	-
SO_3	2.63	0.28	-
Loss on ignition	2.35	3.03	1.70

Table 2 Physical properties of OPC, FA and SF

Physical properties	OPC	FA	SF
Relative density	3.18	2.43	2.26
Specific surface area (m^2/kg)	-	655	15000
Strength activity index at 28-day (%)	-	79.1	-
Water requirement (% of control)	-	95.0	-

Note: The strength activity index and water requirement of FA were tested in accordance with American Standard ASTM C311 - 18.

The mix proportions of ECC blended with FA and SF are summarised in Table 3. The W/C ratio by mass was fixed constant at 0.25. The amount of FA and SF in total was set as 70% replacement level of cement, whereas the SF content was varied among 0%, 5% and 10% replacement level. There were three ECC mixtures, labelled as FF70-0, FF65-05 and FF60-10. The first and second numbers behind the alphabets denote the FA and SF replacement percentages, respectively (the sum of the two percentages is 70% constant). For example, FF65-05 means that the replacement level of FA and SF is 65% and 5%, respectively.

Table 3 Mix proportions of ECC

Mixture	OPC	FA	SF	Sand	Water	HRWR	Fiber
FF70-0	381	889.0	0	462	318	15.3	26
FF65-05	381	825.5	63.5	462	318	15.3	26
FF60-10	381	762.0	127.0	462	318	15.3	26

Note: The HRWR (high-range water reducer) used was polycarboxylate-based.

2.2 Experimental Methods

From each mixture, dumbbell specimens of dimensions 150 mm length by 76 mm overall width by 20 mm thick were fabricated for direct tensile test, coupon specimens of size 320×40×12 mm were fabricated for four-point bending test, and prism specimens of size 160×40×40 mm were fabricated for compressive strength test. All specimens were demolded 1 day after casting and cured in standard curing room at 95±5% relative humidity (RH) and 20±2°C temperature for 7 days. Then the specimens were stored inside the laboratory at 50±5% RH and 20±2°C temperature until the testing age.

<u>Direct tensile test</u> The geometry of dumbbell specimen for direct tensile test is illustrated in Fig. 2. Tensile properties of ECC at age of 28 days were investigated. The tensile stress-strain curves were obtained by employing the universal mechanical testing machine. From the tensile stress-strain curves, the variations between tensile strain and tensile stress are determined, as well as the first cracking stress and ultimate stress. Additionally, the crack width after loading was measured using the crack microscope.

<u>Four-point bending test</u> In order to study the flexural properties of ECC, four-point bending test were conducted at the age of 3, 28 and 90 days. The test set-up is depicted in Fig. 3, and the experimental details had been described by Zhu et al. (2009). The load-deflection curves were obtained from the readings of load cell and displacement

transducers. From the load-deflection curves, the peak load and flexural strength could be determined, also the fracture energy and hence the toughness index could be computed. In addition, high-resolution photographs were taken using a digital camera to record the crack patterns and crack widths.

Compressive strength test The matrix strength of ECC was measured by way of the compressive strength test. From the test results, the relationship between strength and age could be established to study the influences of ages (3, 28 and 90 days in this study) and mix proportions (FF70-0, FF65-5 and FF60-10) on the compressive strength.

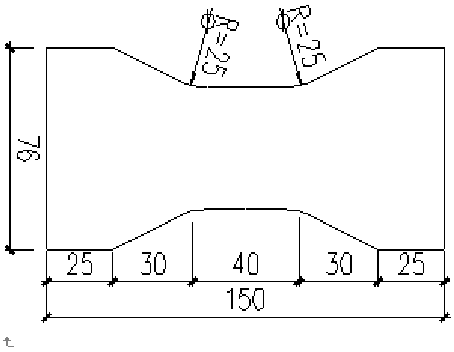


Fig. 2 Geometry of ECC specimen for direct tensile test (dimensions in mm)

Fig. 3 Four-point bending test of ECC

3. RESULTS AND DISCUSSIONS

3.1 Tensile Properties

The tensile stress-strain curves and the related parameters of tensile properties are displayed in Fig. 4 and Table 4. It can be seen from Fig. 4 that the ECC mixtures incorporating FA and SF exhibited excellent tensile strain capacity and prominent strain-hardening property. As listed in Table 4, the tensile strain fell within the range from 2.5

to 3.5%. When the SF content increased from 5% to 10%, the tensile strain slightly decreased. Compared with ECC mixture FF70-0, the tensile strain of ECC with 5% and 10% SF reduced by 13% and 16%, respectively.

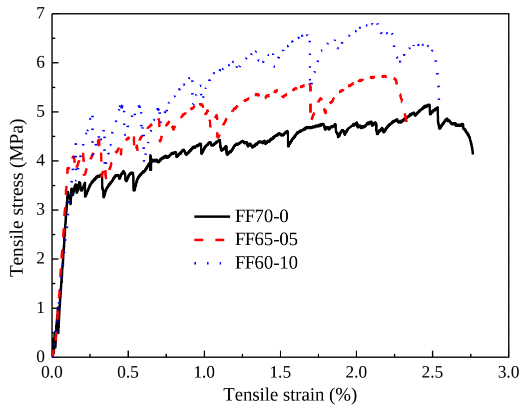


Fig. 4 Tensile stress-strain curves of ECC specimens

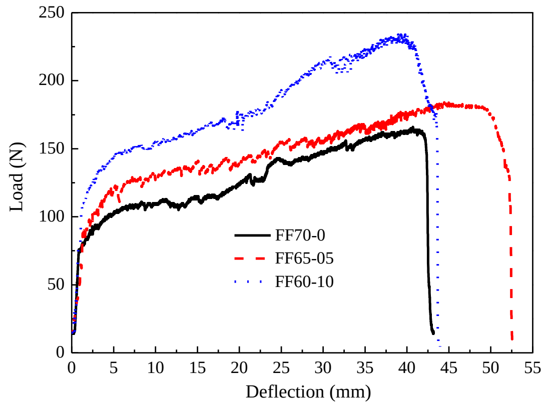
Table 4 Tensile properties of ECC specimens

Mixture	Tensile strain (%)	Ultimate tensile stress (MPa)	Range of crack width (μm)	Average crack width (μm)
FF70-0	3.20±0.42	4.66±0.41	15 to 72	34
FF65-05	3.04±0.50	5.23±0.53	22 to 68	32
FF60-10	2.93±0.46	6.05±0.36	24 to 55	29

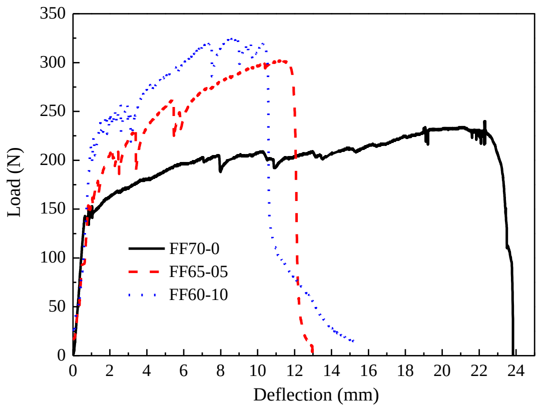
The binary system of FA and SF improved the tensile properties of ECC. The first cracking stress increased from 3.1 MPa without SF to 4.2 MPa with 5% or 10% SF. The ultimate tensile stress increased with the SF content. From the results, the ultimate tensile stress of mixtures FF65-05 and FF60-10 was 10% and 30% higher than that of FF70-0, respectively. Multiple cracking behaviour was apparent among all mixtures, the average crack width was smaller than 35 μm. Particularly, addition of SF further decreased the average crack width.

3.2 Flexural Properties

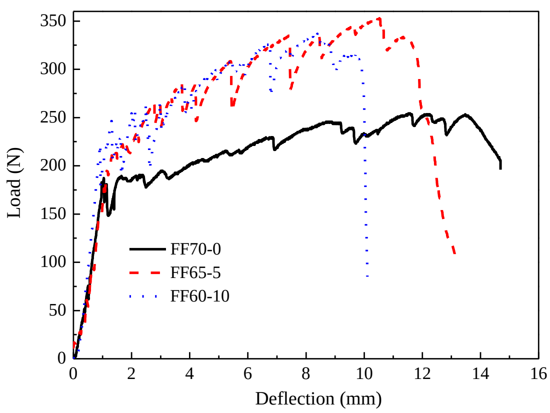
From the four-point bending test results, Fig. 5 displays the load-deflection curves of the ECC specimens at 3, 28 and 90 days. The characteristic parameters obtained from the load-deflection response are listed in Table 5 and Table 6. From Fig. 5, the load-deflection curves of ECC specimens have similar slopes at the beginning, indicating that the matrix of ECC mixtures had similar initial flexural stiffness. It is observed that the 3 ECC mixtures had excellent ductility at 3 days with the mid-span deflection at peak load being greater than 40 mm. However, the deflection at peak load decreased as the age increased from 3 days to 90 days. Besides, the binary system of FA and SF incorporated into ECC decreased the long-term deformability. For example, at the age of 28 days, compared with mixture FF70-0, the deflection at peak load of mixtures FF65-05 and FF60-10 decreased by 48% and 54% respectively. Meanwhile, it is noted that the deflection at peak load of mixtures FF65-05 and FF60-10 changed only slightly when the age at testing was prolonged from 28 days to 90 days.



(a) 3-day



(b) 28-day



(c) 90-day

Fig. 5 Load-deflection curves of ECC specimens

Table 5 Flexural parameters of load-deflection response of ECC specimens

Mixture	Age	First cracking load (N)	Peak load (N)	Flexural strength (MPa)	Mid-span deflection (mm)
FF70-0	3-day	77	162	3.8	41.2
	28-day	141	230	5.4	22.5
	90-day	170	250	5.8	13.8
FF65-05	3-day	89	182	4.4	49.2
	28-day	150	300	7.1	11.7
	90-day	195	324	7.6	10.6
FF60-10	3-day	106	235	5.1	40.2
	28-day	215	322	7.4	10.4
	90-day	225	350	7.8	8.7

The load-deflection curves demonstrated prominent strain-hardening among all ECC mixtures at all ages. As seen from the flexural parameters in Table 5, the binary system of FA and SF enhanced the first cracking load, peak load, and flexural strength. The enhancement could be attributed to the suitable bond strength between fiber and matrix relative to the matrix strength of ECC (Li et al. 1995; Zhu et al. 2012). There was diminishing return upon increasing the SF content from 5% to 10%. For instance, at age of 28 days, the flexural strength of mixture FF65-05 was 31% higher than that of mixture FF70-0, while the flexural strength of mixture FF60-10 was merely 4% higher than that of mixture FF65-05.

For all the ECC mixtures, when the testing age was prolonged, the first cracking load, peak load, and flexural strength increased at different degrees. Taking mixture FF65-05 with 5% SF content as an example, the 28-day flexural strength was 61% higher than the 3-day flexural strength, whereas the 90-day flexural strength was 73% higher than the 3-day counterpart. Similar trend was observed for mixture FF60-10 with 10% SF content, the 28-day flexural strength was 45% higher than the 3-day flexural strength, whereas the 90-day flexural strength was 55% higher than the 3-day counterpart. Among all ECC specimens, multiple cracking was clearly observed at steady state.

Table 6 Fracture parameters of ECC specimens

Mixture	Age	First cracking energy (J)	Fracture energy (J)	Toughness index
FF70-0	3-day	0.057	5.243	92
	28-day	0.080	4.470	56
	90-day	0.099	3.893	39
FF65-05	3-day	0.078	7.400	95
	28-day	0.062	2.829	46
	90-day	0.091	2.883	32
FF60-10	3-day	0.094	7.062	75
	28-day	0.093	2.762	30
	90-day	0.081	2.564	32

The related fracture parameters including fracture energy and toughness index of the ECC mixtures were computed, as summarised in Table 6. It is apparent that the fracture energy and toughness index decrease as the testing age extends. At a given age, the binary combination of FA and SF decreased the toughness index. For example, at age of 28 days, the toughness index values of mixtures FF65-05 and FF60-10 were 12% and 42% lower than that of mixture FF70-0, respectively. Nevertheless, the toughness index at 90 days was minimally affected by increasing the SF content from 5% to 10%. For instance, the toughness index values of ECC mixtures FF70-0, FF65-05 and FF60-10 at 90 days were 39, 32 and 32, respectively.

3.3 Compressive Strength

The compressive strength results of ECC specimens at 3-day, 28-day and 90-day are plotted in Fig. 6 and listed in Table 7. From Fig. 6, mixture FF70-0 without SF yielded the lowest compressive strength at all ages. The incorporation of 10% SF content yielded greater compressive strength enhancement than 5% SF content. At age of 3 days, the compressive strength of mixtures FF65-05 and FF60-10 was respectively 20% and 34% higher than that of mixture FF70-0. The percentages varied within narrower ranges at later ages. Comparing the 28-day compressive strength results, the above percentages were 21% and 27% respectively. It is noted that the compressive strength increased at a much lower rate from 28-day to 90-day, this is in accordance with the expectation due to the gradual process of pozzolanic reaction. Correspondingly, the above percentages became 8% and 11% at 90-day age. Judging from the 28-day compressive strength of 48 MPa to 61 MPa, the ECC mixtures in this study would suffice for structural applications.

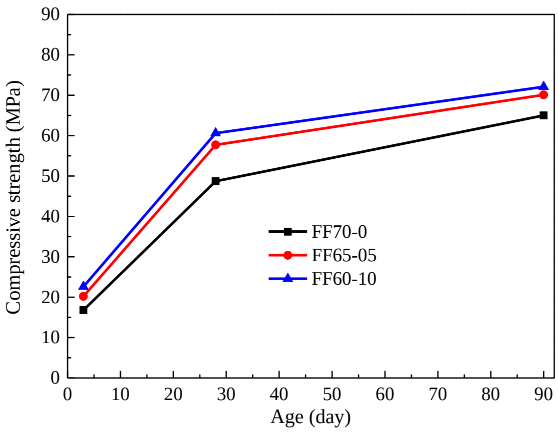


Fig. 6 Compressive strength of ECC specimens

Table 7 Compressive strength of ECC specimens

Mixture	Compressive strength (MPa)		
	3-day	28-day	90-day
FF70-0	16	48	65
FF65-05	20	58	70
FF60-10	22	61	72

4. CONCLUSIONS

The mechanical properties of ECC (engineered cementitious composites) produced by cement blended with high volume binary system of FA (fly ash) and SF (silica fume) have been investigated. Specimens of ECC were fabricated for undergoing the direct tensile test, four-point bending test, and compressive strength test. The combined amount of FA and SF was set as 70% by mass of the cementitious content, and the SF content was varied among 0%, 5% and 10% replacement level of cement. Results of direct tensile test revealed that the tensile strain is greater than 2.5% at 28 days. The incorporation of SF increased the first cracking stress, ultimate tensile stress, and decreased the average crack width. Results of four-point bending test demonstrated prominent strain-hardening behavior. The addition of SF enhanced the first cracking load, peak load and flexural strength, and decreased the deflection at peak load, fracture energy and toughness index at 28-day age and beyond. Results of compressive strength test indicated that the SF increased the compressive strength at all ages.

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