Fracture Mechanics of Concrete and Concrete Structures -
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Engineered cementitious composites with low volume of cementitious materials

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ABSTRACT: Engineered cementitious composite (ECC) is an ultra ductile cement-based material reinforced with fibers. It is characterized by high tensile ductility and tight crack width control. Thanks to the excellent performance, ECC is emerging in broad applications to enhance the loading capacity and the durability of structures. However, ECC also faces a limitation on dimensional stability and on economical and sustainable issues. In general, a large amount of cementitious materials, often more than 70% by weight, is used in ECC and no coarse aggregate is allowed to be added. The high volume of cementitious materials in ECC results in a large drying shrinkage and negative effects on material cost and material greenness. In this paper, a new version of ECC is designed with low volume of cementitious materials about 25% by weight, including Portland cement, blast furnace slag and silica fume, and a large amount of filler and aggregate, including limestone powder and river sand. In this mix, only 1.2% of fibers by volume is mixed, which is 60% dosage of standard ECC. Experimental study reveals that the newly developed ECC shows tensile ductility of 2% and relatively low shrinkage. Considering the low cementitious material and fiber contents, the newly developed ECC might have a reduced cost and increased material greenness.

1 INSTRUCTION

ECC, short for Engineered Cementitious Composites, is a class of ultra ductile fiber reinforced cementitious composites originally invented at the University of Michigan in the early 1990s (Li 1993). This group of materials is characterized by high ductility in the range of 3-7% and tight crack width of around 60 µm. Figure 1 shows a typical tensile stress-strain curve of ECC and its tight crack width control (Weimann & Li 2003). Unlike plain concrete and normal fiber reinforced concrete, ECC shows a metal-like property after first cracking. The unique tensile strain-hardening behavior and high ductility results from an elaborate design using a micromechanics model taking into account the interactions among fiber, matrix and fiber-matrix interface (Li & Leung 1992). The crack width of ECC is self-controlled to around 60 µm without the presence of steel reinforcement, much smaller than the typical crack width observed in the steel reinforced concrete. ECC thus shows lower water permeability (Lepech & Li 2005) and better durability (Li 2007, Sahmaran et al. 2008, Sahmaran & Li 2008) compared with standard concrete. Therefore, the use of ECC can prolong the service life of structures and reduce the maintenance and repair cost. Nowadays ECC is emerging in broad applications, such as ECC link slab on bridge decks (Michigan DOT 2005), ECC coupling beam in high-rise buildings to enhance their seismic resistance, composite ECC/steel bridge deck and some concrete repair applications (Kunieda & Rokugo 2006).

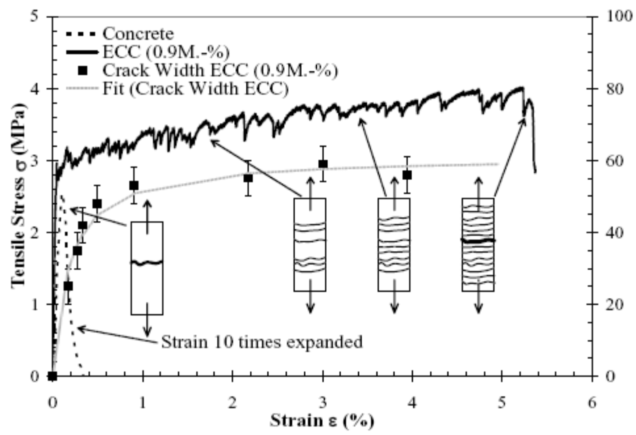


Figure 1. Tensile stress-strain curve and tight crack width control of ECC (Weimann & Li 2003).

In normal concrete, aggregates occupy a significant volume and thus play an important role in the mechanical properties and the dimensional stability of concrete (Neville 1995). However, with the presence of fibers, the addition of aggregates may cause balling at mixing and poor fiber dispersion (De Koker & van Zijl 2004). The effect becomes more pronounced when the maximum particle size increases. Fiber dispersion is one of the crucial factors affecting the unique strain-hardening properties of ECC. Poor fiber dispersion leads to a decrease in ductility and even absence of the strain-hardening behavior (Torigoe et al. 2003). Therefore, the size and amount of aggregates are limited in ECC. Fine silica sand with a maximum grain size of 250 μm and a mean size of 110 μm is typically used as fine aggregate in ECC. The sand content is usually less than 30% by the weight of solid materials. The low volume of sand and the high volume of cementitious materials results in large drying shrinkage and negative effect on material cost and material greenness (Yang et al. 2007).

Zhou et al. (2009a) have developed a complementary approach to improve the fiber dispersion in ECC by properly adjusting material mixing sequence. This approach advances the development of ECC with high volume of sand. With this concept, a new version of ECC is designed with low volume of cementitious materials of 25% by weight and high volume of filler and aggregate. In this mix, only 1.2% of fibers by volume is mixed, which is 60% dosage of standard ECC. Experimental study reveals that the newly developed ECC shows tensile ductility of 2% and relatively low shrinkage.

2 IMPROVED FIBER DISPERSION BY ADJUSTING THE MIXING SEQUENCE

Figure 2 illustrates the standard ECC mixing sequences (Zhou et al. 2009a). The standard mixing sequence is carried out as follows: all powder and liquid materials are first mixed for several minutes and fibers are then added. The rheological properties of ECC mortar (without fibers) determine fiber distribution in matrix. Consequently, if the fresh properties do not reach the condition for good fiber distribution, although the mix design is appropriate, ECC will not show good tensile properties (Yang et al. 2009).

Figure 3 illustrates the new ECC mixing sequences (Zhou et al. 2009a). Proper amounts of powder and liquid materials are first mixed, aiming at the proper rheological properties for a good fiber distribution. Then, fibers are added. After fibers are mixed homogenously, the rest powder and/or liquid materials are added to tailor the workability and the mechanical properties of ECC. As a result, by adjusting the processing sequence, ECC can show more robust fresh and hardened properties.

In their study, Zhou et al. (2009a) took the water mixing sequence as an example and investigated the influence of different mixing sequences by comparing the results of the uniaxial tensile test and fiber distribution analysis. The new mixing sequence with two water addition steps resulted in more than 50 times increase of the tensile strain capacity and 5-14% increase of the ultimate tensile strength. The increased tensile strain capacity and ultimate tensile strength were attributed to the improved fiber dispersion supported by the strong correlation between the tensile strain capacity and the fiber distribution coefficient.

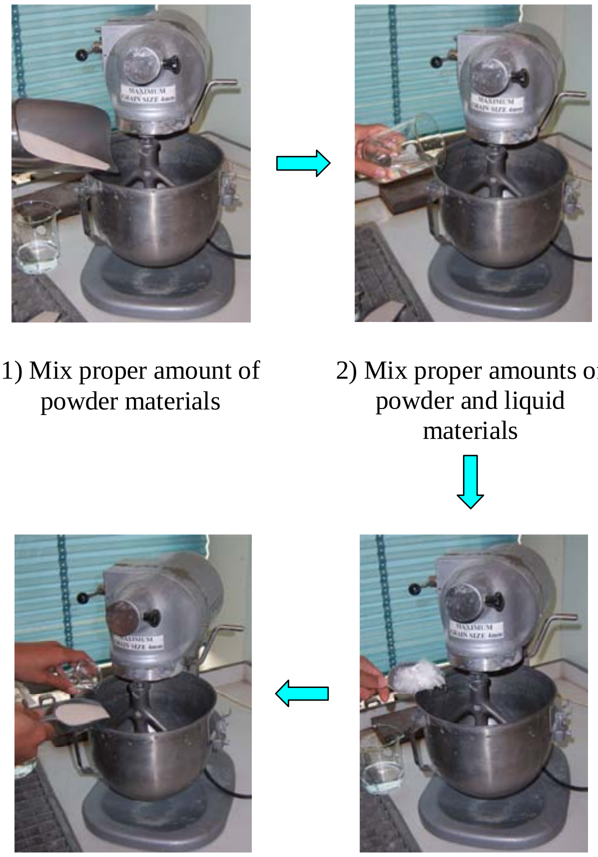
3 EXPERIMENTS

3.1 *Materials*

Three factors were investigated in the experimental program as given in Table 1: 1) addition of silica fume, 2) addition of sand and 3) different mixing sequences. River sand with the size ranging from 0.25 to 0.5 mm was mixed in ECC. The addition of sand might cause poor particle packing on the surface of fibers and thus a poor fiber-matrix interface. Silica fume was therefore added in order to improve the fiber-matrix interface. Table 2 gives the mix proportions of ECCs. The newly developed ECC with Portland cement, limestone powder and blast furnace slag (BFS) (Zhou et al. 2009b) was used as a reference (Mixture S1) in this study.

1) Mix all powder materials   2) Mix all liquid materials   3) Mix the fibers

Figure 2. Standard mixing sequence.



1) Mix proper amount of powder materials

2) Mix proper amounts of powder and liquid materials

3) Mix the fibers homogenously

4) Mix the rest powder and/or liquid materials to tailor the fresh and hardened properties

Figure 3. New mixing sequence.

Table 1. Factors investigated in the experimental program.

Mixture	Silica fume	Sand	Mixing sequence
S1	Non	Non	Standard
S2	Yes	Non	Standard
S3	Yes	Yes	Standard
S4	Non	Yes	New
S5	Yes	Yes	New

3.2 *Mixing and curing*

Mixtures S1-3 were mixed following the standard mixing sequence, while mixtures S4 and S5 were mixed following the new mixing sequence. Following the standard mixing sequence, all solid materials were first mixed with water and superplasticizer at low speed for 1 minute and then at high speed for 2 minutes. After fibers were added, the sample was mixed at high speed for another 4 minutes. Following the new mixing sequence, all solid materials except sand were first mixed with water and superplasticizer at low speed for 1 minute and at high speed for 2 minutes. Then fibers were added and mixed at high speed for another 2 minutes. After fibers were mixed homogenously, sand was mixed at high speed for 2 more minutes. In order to eliminate the effect of mixing time, two mixing sequences were conducted in the same total mixing time of 7 minutes.

The fresh ECC was cast into coupon specimens with the dimension of 240 × 60 × 10 mm3 and covered with plastic sheet. After 24 hours curing, the specimens were demoulded and cured at room temperature of 20°C and RH of 50% for another 27 days.

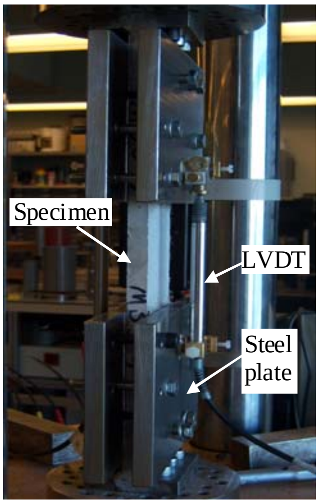
3.3 *Uniaxial tensile test*

The coupon specimens at the age of 28 days were used in the uniaxial tensile test. Four measurements were carried out for each mixture.

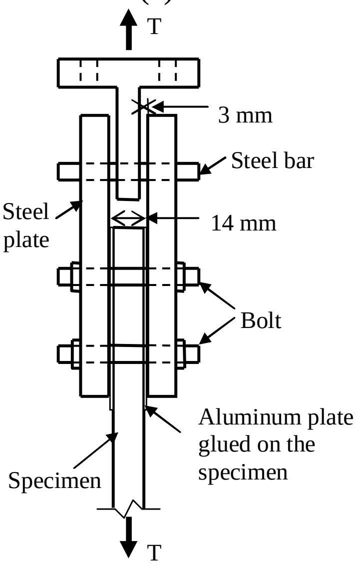
Figure 4 shows the test set-up. Before testing, coupon specimens were sanded for a flat surface and four aluminum plates were glued on two ends of each specimen. The specimen was fixed on the test set-up by clamping the aluminum plate-glued ends with two pairs of steel plates, which were connected to the loading device. Then, two LVDTs were attached on both sides of the specimen to measure the specimen deformation. The tests were conducted under displacement control with a loading rate of 0.005 mm/s. The testing gauge length was 70 mm.

Table 2. Mix proportion (weight %).

Mixture	CEM I 42.5 N	BFS	Limestone powder	Silica fume	Sand	PVA fiber	Water	SP
S1	0.3	0.7	1.0	0	0	0.02 (vol.%	0.5	0.015
S2	0.3	0.7	1.0	0.1	0	0.02 (vol.%)	0.525	0.02
S3&5	0.3	0.7	1.0	0.1	2.1	0.012 (vol. %)	0.525	0.01
S4	0.3	0.7	1.0	0	2.0	0.012 (vol.%)	0.5	0.008



(a)



(b)

Figure 4. Uniaxial tensile test set-up.

3.4 *Drying shrinkage measurement*

Drying shrinkage measurements were conducted for mixtures S2 and S5. The fresh ECC was cast into three prism specimens with the dimension of 160 × 40 × 40 mm^3. After 24 hours sealed curing at room temperature of 20°C, the specimens were demoulded and the initial length of the prism specimens was measured. Then, the specimens were exposed to room temperature of 20°C and RH of 50%. The drying shrinkage measurement began and lasted for around 100 days. The length change of the specimens was measured with a length gauge.

4 RESULTS AND DISCUSSION

4.1 *Uniaxial tensile test*

The typical uniaxial tensile stress-strain curves of S1-5 at the age of 28 days are plotted in
Figure 5. The tensile strain capacity and the ultimate tensile strength calculated by averaging the results of the four measurements for each mixture are given in Figure 6 and Figure 7, respectively. Under the uniaxial tensile loading, all mixtures S1-5 show multiple-cracking behavior. The mixtures S1-5 at 28 days exhibit the tensile strain capacity ranging 0.5-3.7% and the ultimate tensile strength ranging 2.6-3.8 MPa.

The effect of silica fume is investigated by comparing the results of S1 with S2 and S4 with S5. The addition of silica fume results in 22-51% increase of tensile strain capacity and 8-31% increase of ultimate tensile strength. The increases can be attributed to the improved fiber-matrix interface, which has been observed in an experimental study (Yan et al. 1999).

The mixtures S2 and S3 were both mixed following the standard mixing sequence. Besides the materials used in S2, sand was also added in S3 and the amount of sand was the same as the total amount of the other solid materials. The fiber content was therefore decreased from 2% to 1.2% by volume. As illustrated in Figures 6 and 7, when ECCs are mixed following the standard mixing sequence, the addition of sand results in bad tensile properties of ECC. The tensile strain capacity is decreased by 85%, and the ultimate tensile strength is decreased by 26%.

The new mixing sequence was adopted for mixture S5 to recover the good tensile properties. Comparing the tensile strain capacity and ultimate tensile strength of S3 and S5, which have the same mix proportion, the adjusted mixing sequence improves the mechanical properties of ECC. S5 exhibits 4.1 times tensile strain capacity and 1.2 time of ultimate tensile strength of S3. The better tensile performance might be because of the improved fiber distribution by adjusting the mixing sequence. In mixture S5, the sand content is up to 50% by weight and the fiber content is as low as 1.2% by volume, which is only 60% of the fiber content in S2. However, S5 shows a comparable tensile strain capacity of 2.2 % and ultimate tensile strength of 3.5 MPa. The lower dosages of cementitious materials and fibers reduce the cost and improve the greenness of ECC.

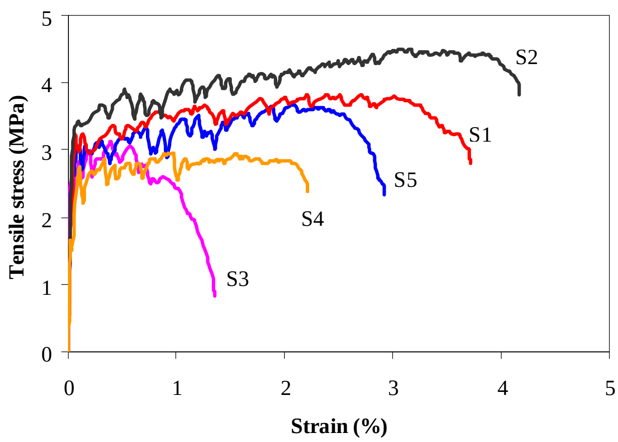


Figure 5. Typical uniaxial tensile stress-strain curves of S1-5 at the age of 28 days.

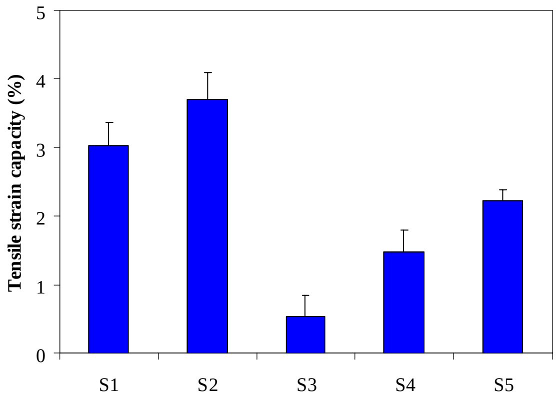


Figure 6. Tensile strain capacity of S1-5 at the age of 28 days.

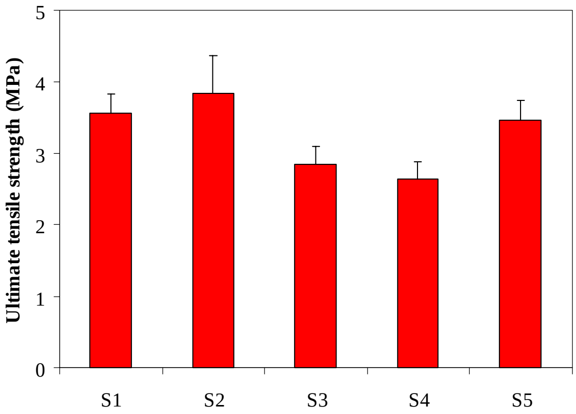


Figure 7. Ultimate tensile strength of S1-5 at the age of 28 days.

4.2 *Drying shrinkage measurement*

The mixture S5 also shows advantage on the dimensional stability. Figure 8 shows the drying shrinkage of S2 and S5 measured for 90 days. Each value represents the average drying shrinkage of three measurements. Due to the absence of coarse aggregate, the drying shrinkage of ECC is higher than normal concrete. At the age of 100 days, S2 shows a drying shrinkage of 2730 µstrain, while S5 shows a drying shrinkage of 1480 µstrain. The addition of sand results in around 45% decrease in the drying shrinkage.

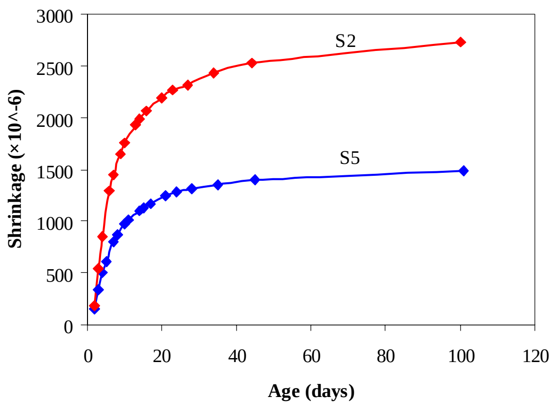


Figure 8. Drying shrinkage of S2 and S5 at room temperature of 20°C and RH of 50%.

5 CONCLUSIONS

Properly adjusting ECC processing sequence improves the fiber distribution and thus the tensile properties of ECC. Following this concept, a version of ECC with low volume of cementitious materials was developed. Besides, silica fume was also added into ECC in order to improve the fiber-matrix interface properties and the tensile properties of ECC. Based on the experimental results and the above discussion, the following conclusions can be drawn:

- The addition of silica fume results in the increase of tensile strain capacity and ultimate tensile strength. The increase can be attributed to the improved fiber-matrix interface.
- Properly adjusting mixing sequence improves the tensile properties of ECC with high volume of sand. The ECC mixture with 50% (by weight) sand and 1.2% (by volume) fiber shows a comparable tensile strain capacity of 2.2 % and ultimate tensile strength of 3.5 MPa.
- The addition of sand results in a great amount of decrease in the drying shrinkage.
- Considering the low cementitious material and fiber contents, the newly developed ECC is expected to have a reduced cost and increased material greenness.

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