S3-1-4

PROCESSING SEQUENCE IN THE PRODUCTION OF ENGINEERED CEMENTITIOUS COMPOSITES

Jian ZHOU
PhD student, Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands

Shunzhi QIAN
Postdoc researcher, Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands

Guang YE
Assistant Professor, Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands
Guest Professor, Department of Structural Engineering, Ghent University, Belgium

Klaas VAN BREUGEL
Professor, Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands

Victor C. LI
Professor, Department of Civil and Environmental Engineering and Department of Materials Science and Engineering, University of Michigan, USA

ABSTRACT:
Engineered Cementitious Composites (ECC) is a class of ultra ductile fiber reinforced cementitious composites, characterized by a high ductility and a tight crack width control. In the production of ECC, beside mix design, processing is another crucial factor for both fresh and hardened properties of ECC. The processing influences the fresh properties of ECC, and the fresh properties of ECC mortar have a significant effect on the hardened properties. Therefore, in order to obtain good hardened properties, fresh properties have to be properly controlled, for example, by means of water or chemical admixture adjustments. This paper explores a complementary approach, focusing on ECC processing sequence aimed at producing ECC of both good fresh and hardened properties. For the new processing sequence, a part of liquid materials, normally water and superplasticizer, are first mixed with matrix materials and fibers are then added. After fibers disperse in mortar homogenously, the rest of the liquid materials are added to modify the workability of fresh ECC and the material properties of hardened ECC. In this paper, the influence of different mixing sequences of water was investigated by comparing the experimental results of uniaxial tensile test. The new mixing sequence was found to increase the tensile strain capacity and the ultimate tensile strength of ECC. This increase is more prominent in the mixtures with a higher water/powder ratio.

Keywords: Engineered Cementitious Composites, processing sequence, tensile strain capacity, tensile strength

1. INTRODUCTION

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 [1]. This group of materials is characterized by a high ductility in the range of 3-7% and a tight crack width of around 60 μm. Fig. 1 shows a typical tensile stress-strain curve of ECC and its tight crack width control [2]. Unlike plain concrete and fiber reinforced concrete, ECC shows a metal-like property after the first cracking. This unique tensile strain-hardening behavior results from an elaborate design using a micromechanics model taking into account the interactions among fiber, matrix and fiber-matrix interface [3]. 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 shows lower water permeability [4] and better durability [5] compared with conventional 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 [6], ECC coupling beam in high-rise buildings to enhance their seismic resistance, composite ECC/steel bridge deck and some concrete repair applications [7].

In the production of ECC, beside mix design, processing is another crucial factor for both fresh and hardened properties of ECC [8]. The processing influences the fresh properties of ECC, while the fresh properties of ECC mortar have a significant effect on the hardened properties. For instance, as the plastic viscosity of ECC mortar increases, the tensile strain capacity and ultimate tensile strength of hardened ECC increase. This might be because of the modification of fiber distribution by high plastic viscosity [9]. Therefore, in order to obtain good hardened properties, fresh properties have to be controlled. However, the fresh property control influences the mix design and might have negative effect on workability of ECC. For instance, the high plastic viscosity requires a low water/powder (W/P) ratio and results in a poor workability.

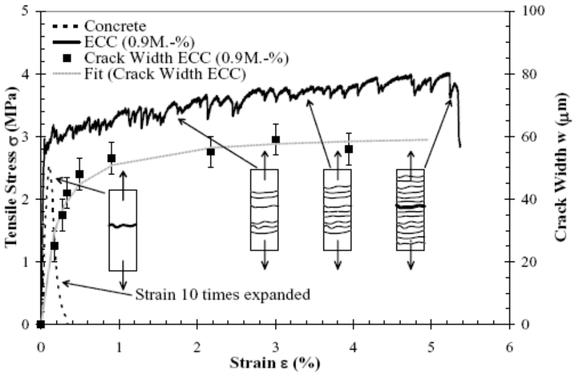

Fig. 1 Tensile stress-strain curve and tight crack width control of ECC [2]

This paper presents a new ECC processing sequence aimed at producing ECC with good fresh and hardened properties. For the conventional processing sequence, the mortar is first produced and the fibers are then added. Aforementioned, the plastic viscosity of ECC mortar determines the fiber distribution in matrix. Therefore, if the plastic viscosity is not sufficient for the good fiber distribution, although the mix design is appropriate, ECC will not show good hardened properties. Instead, for new processing sequence, a part of liquid materials, normally water and superplasticizer, are first mixed with matrix materials aiming at the fresh properties for a good fiber distribution. Then, fibers are added. After fibers disperse homogenously, the rest of the liquid materials are added to modify the workability of fresh ECC and the material properties of hardened ECC. As a result, by changing processing sequence, ECC can show more robust fresh and hardened properties and emerge in more applications.

Yang et al. [9] reported that W/P ratio has the largest effect on the plastic viscosity of ECC mortar and the hardened properties of ECC composite among the four factors they studied, including Class-C fly ash to Class-F fly ash ratio, W/P ratio, amount of superplasticizer and amount of viscosity modifying admixture. Following this concept, different mixing sequences of water were studied in this paper. Of five mixtures, two were mixed with new mixing sequence, and three were mixed with conventional mixing sequence. The influence of difference mixing sequences was investigated by comparing the experimental results of uniaxial tensile tests.

2. Experimental Program

2.1 Materials

ECC with Portland cement CEM I 42.5N, limestone powder and BFS has been developed in a previous study [10]. The newly developed ECC showed a tensile strain capacity higher than 3%. It was used as reference in this study. Table 1 gives the mix proportion of ECC investigated. All mixtures have the same proportion of matrix materials but different W/P ratios. Among the five mixtures, M1, M3 and M5 were mixed with the conventional mixing sequence. M2 and M4 were mixed with the new mixing sequence, i.e. the mixture was first mixed in the W/P ratio of 0.27 and then the rest of the water was added. The new mixing sequence will be described in detail in the following section.

Table 2 lists the chemical compositions of the matrix materials, i.e. CEM I 42.5N, limestone powder and BFS. The densities of CEM I 42.5N, limestone powder and BFS are 3150 kg/m^3, 2700 kg/m^3 and 2850 kg/m^3, respectively. Fig. 2 shows the particle size distribution curves of CEM I 42.5N, limestone powder and BFS, which were measured with laser-diffraction technique. The mean particle sizes of CEM I 42.5N, limestone powder and BFS are 16.2 µm, 13.4 µm and 10.6 µm, respectively. In all mixtures, the fiber content is 2% by volume. The fiber used in this study is PVA fiber with a length of 8 mm and a diameter of 40 µm. The tensile strength of PVA fiber is 1600 MPa and the density is 1300 kg/m^3. The surface of the fiber is coated with 1.2% oil by weight to reduce the fiber-matrix chemical bond.

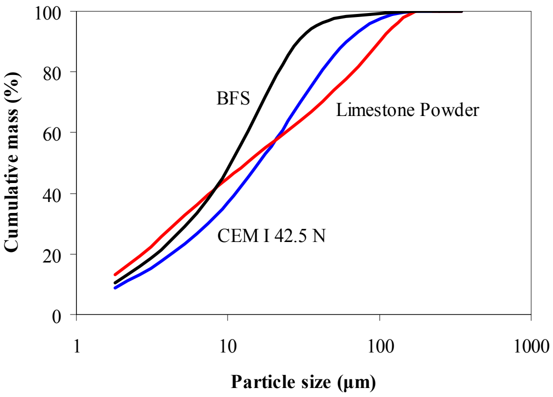

Fig. 2 Particle size distribution of CEM I 42.5N, BFS and limestone powder, measured with laser-diffraction technique.

Table 1 Mix proportion of ECC (weight percentage)

Mix Number	CEM I 42.5N	Limestone Powder	BFS	W/P ratio	Super-plasticizer	PVA fiber (by volume)
MS1	1	0.8	1.2	0.27	0.02	2%
MS2	1	0.8	1.2	0.27+0.03	0.02	2%
MS3	1	0.8	1.2	0.3	0.02	2%
MS4	1	0.8	1.2	0.27+0.08	0.02	2%
MS5	1	0.8	1.2	0.35	0.02	2%

Table 2 Chemical composition of CEM I 42.5N, limestone powder and BFS. The chemical compositions of CEM I 42.5N and limestone powder were from the producer and that of BFS was measured by energy dispersive X-ray analysis.

Compound	CEM I 42.5N (%)	Limestone powder (%)	BFS (%)
CaO	64.1	-	40.77
SiO_2	20.1	0.26	35.44
Al_2O_3	4.8	0.08	12.98
Fe_2O_3	3.2	0.06	0.53
MgO	-	0.21	7.99
K_2O	0.52	-	0.49
Na_2O	0.28	-	0.21
SO_3	2.7	-	0.1
$CaCO_3$	-	98.8	-

2.2 Mixing and Curing

In the previous study [10], ECC was mixed in the following sequence. The matrix materials were first mixed with a HOBART® mixer for 1 minute at low speed. Then water and superplasticizer were added at low speed mixing. Mixing continued 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 2 minutes. In this study, the mixture MS2 and MS4 were first mixed in the W/P ratio of 0.27 in the above sequence. Then the rest of the water were added and mixed at high speed for another 2 minutes. MS1, MS3 and MS5 were mixed in the conventional mixing sequence, except that the last step took 4 minutes instead of 2 minutes in order to maintain the same mixing time in all mixes.

The fresh ECC was cast into coupon specimens with the dimension of 240 mm × 60 mm × 10 mm. After 1 day curing in moulds covered with plastic paper, the specimens were demoulded and cured under sealed condition at a temperature of 20°C for another 27 days.

2.3 Uniaxial Tensile Test

A uniaxial tensile test set-up was developed to investigate ultra ductile fiber reinforced concrete as shown in Fig. 3 [10]. The specimen is clamped by four steel plates, one pair at each end. Each pair of steel plates is tightened with four bolts. Two pairs of steel plates are fixed on the loading device with two steel bars for each pair. Between the pairs of steel plates and the loading device, there is a ±3 mm allowance. It is used to minimize the eccentricity in the direction perpendicular to the plate of the specimen by moving the steel plates along the steel bar. The tensile force is transferred to the specimen by the friction force between the steel plates and the specimen. Four aluminum plates, 1 mm thick each, are glued on both sides of the ends of specimen in order to improve the friction force, to ensure the clamped area work together and to prevent the local damage on the specimen due to the high clamping force.

The experimental procedure is described in details hereafter. The coupon specimens were sanded to obtain a flat surface with a larger bond strength with the aluminum plates. After cleaning the specimen surface and the aluminum plate with Acetone, the aluminum plates were glued on the specimen. The glue was cured for 1 day before testing. Before placing the specimen in the test set-up, two pairs of steel plates were connected to the bottom and the top parts of loading device, respectively. The lower end of the specimen was first clamped with the steel plates by tightening four bolts. Then the upper end of the specimen was clamped with the other pair of steel plates. Finally, two LVDTs were mounted on both sides of the specimen. The testing gauge length was

70 mm. The tests were conducted under deformation control with a loading speed of 0.005 mm/s. Four specimens were tested for each mixture.

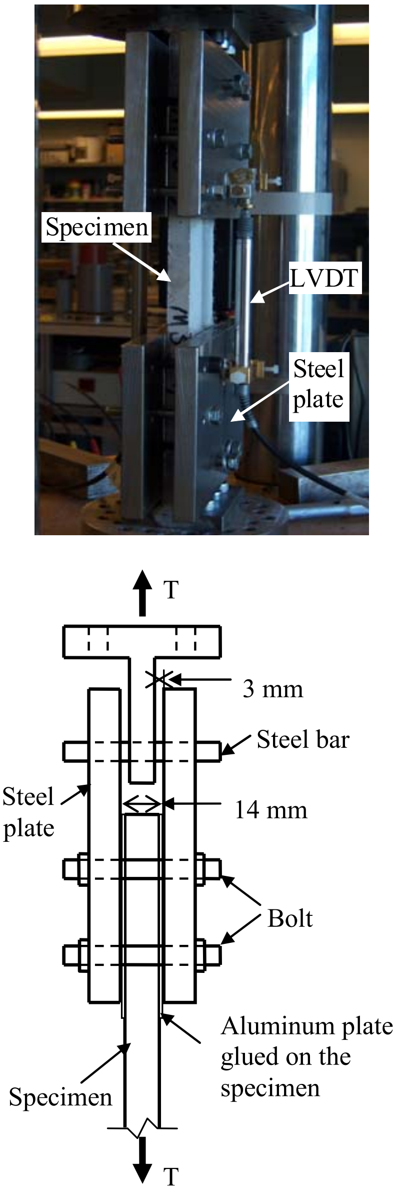

Fig. 3 Uniaxial tensile test set-up

3. Results and Discussion

Under the uniaxial tensile loading, MS1-4 all show a multiple-cracking behavior as shown in Fig. 4, while MS5 shows a single-cracking behavior. In Fig. 5 the uniaxial tensile stress-strain curves of MS1-5 at the age of 28 days are plotted. For the mixtures MS1-4, the tensile stress increases dramatically at the very beginning and drops. The first stress drop corresponds to the first cracking in the specimen, and the peak stress before this drop is called the first cracking strength related to the tensile strength of the matrix. After the first cracking, the tensile stress still increases slowly, which generates new cracks, and the strain develops a large value. The uniaxial tensile stress-strain curves of MS5 are featured by a prominent peak at very little strain corresponding to the first cracking. Although after this peak, the stress drop is followed by an increase of stress, the stress does not exceed the first cracking strength and no new crack forms.

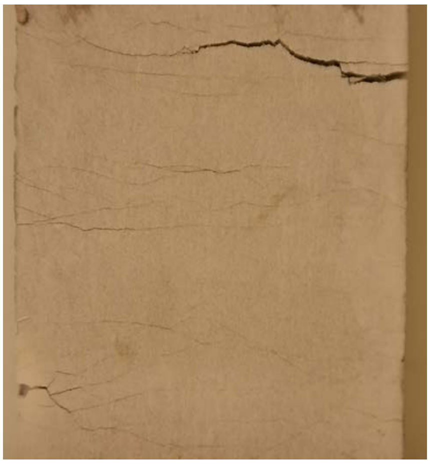

Fig. 4 Specimen crack pattern (60mm wide)

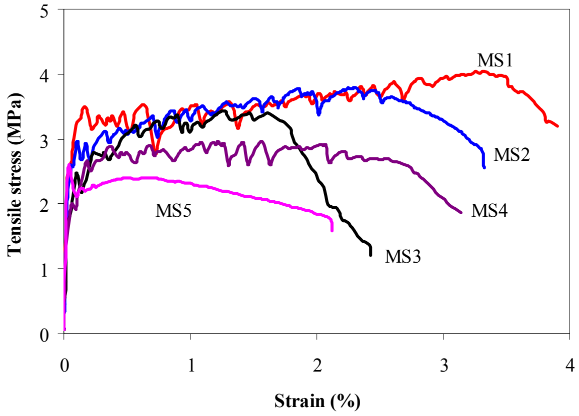

Fig. 5 Uniaxial tensile stress-strain curves of MS1-5 at the age of 28 days

Averaging the results of four measurements, the tensile strain capacity, the ultimate tensile strength and the first cracking strength can be calculated and they are given in Figs. 6-8, respectively. MS1 shows the best tensile properties, i.e. the largest tensile strain capacity, the highest ultimate tensile strength and the highest first cracking strength. As the W/P ratio increases, the tensile strain capacity, the ultimate tensile strength and the first cracking strength all decrease both for the mixture mixed with old and new mixing sequences. For the same W/P ratio, the mixtures MS2 and MS4 mixed with the new mixing sequence show a larger strain capacity and a higher ultimate tensile strength than the mixtures MS3 and MS5 mixed with the old mixing sequence, respectively. The increases of strain capacity and ultimate tensile strength appear more prominent in the mixtures with higher W/P ratio. The mixtures with the W/P ratio of 0.3 show a 66% increase of tensile strain capacity and a 5% increase of ultimate tensile strength. While for the mixtures with the W/P ratio of 0.35, although M5 does not have any multiply-cracking behavior, M4 still shows a tensile strain capacity of 2%, which is more than 50 times that of M5. Also, the ultimate tensile strength of M4 is 14% higher than that of M5. This might be because of the better fiber distribution modified by the new mixing sequence. This is confirmed by the observation of a large amount of fiber bundles in mixing with the conventional sequence but not in the mixing with the new sequence. However, the new mixing sequence does not have much effect on the first cracking strength, suggesting little change in the properties of matrix.

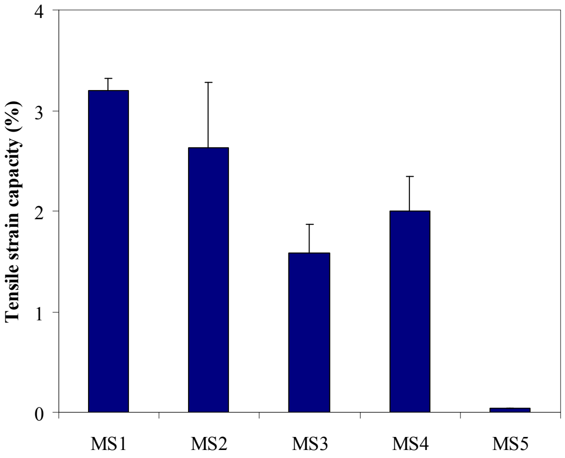

Fig. 6 Tensile strain capacity of MS1-5 at the age of 28 days

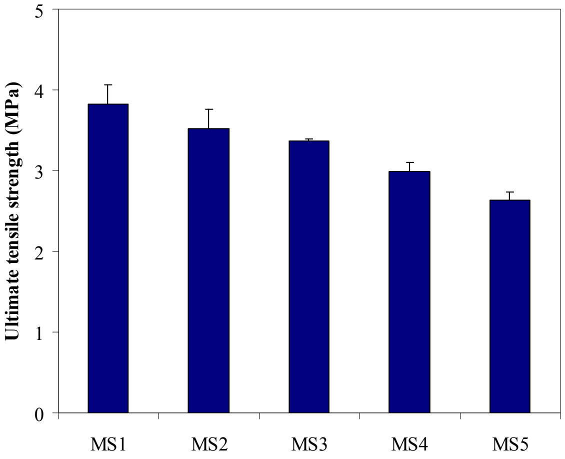

Fig. 7 Ultimate tensile strength of MS1-5 at the age of 28 days

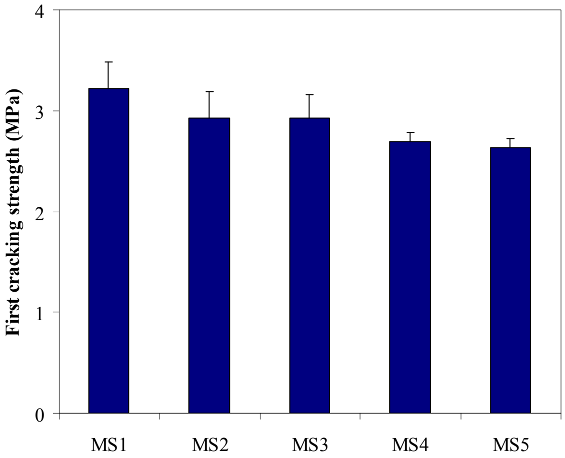

Fig. 8 First cracking strength of MS1-5 at the age of 28 days

4. Conclusions and future work

The new ECC processing sequence is proposed aiming to produce ECC of good fresh and hardened properties. As an example, the influence of different mixing sequences of water was investigated by comparing the experimental results of uniaxial tensile test. Based on the results and discussion presented in this paper, the following conclusions are drawn:

(1) The new mixing sequence increases the tensile strain capacity and the ultimate tensile strength of ECC. This increase is more prominent in the mixtures with higher W/P ratio. This might be because of better fiber distribution modified by the new mixing sequence.

(2) The new mixing sequence does not affect the properties of matrix.

In a follow-up study, the influence of mixing sequence on fiber distribution and fresh properties will be investigated to interpret the experimental observation in this study.

ACKNOWLEDGEMENTS

This research is financially supported by the Delft Clusters and Heijmans Infrastructure B.V. Their support is gratefully acknowledged. We would like to thank Kuraray Co. Ltd, Carmeuse S.E. and ORCEM B.V. for providing PVA fiber, limestone powder and BFS, respectively.

REFERENCES

1. Li, V.C., “From Micromechanics to Structural Engineering – the Design of Cementitious Composites for Civil Engineering Applications”, JSCE J. Struct. Mech. Earthquake Eng. 1993, 10 (2) 37-48.
2. Weimann, M.B. and Li, V.C., “Hygral behavior of engineered cementitious composite (ECC)”, Int. J. for Restoration of Buildings and Monuments 2003, 9 (5) 513-534.
3. Li, V.C. and Leung, C.K.Y., “Theory of Steady

State and Multiple Cracking of Random Discontinuous Fiber Reinforced Brittle Matrix Composites", J. Eng. Mech.-ASCE 1992, 118 (11) 2246-2264.

4. Lepech, M.D. and Li, V.C., "Water Permeability of Cracked Cementitious Composites", in Proc. 11th Int. Conf. on Fracture, 2005, paper 4539.
5. Li, V.C., "Engineered Cementitious Composites (ECC) – Material, Structural and Durability Performance", in Nawy, E. (ed.), Concrete Construction Engineering Handbook, Boca Raton: CRC Press, 2007, Chapter 24.
6. Michigan DOT, "Bridge Decks Going Jointless: Cementitious Composites Improve Durability of Link Slabs", Construction and Technology Research Record 2005, 100 1-4.
7. Kunieda, M. and Rokugo, K., "Recent Progress on HPFRCC in Japan", J. Adv. Concr. Tech. 2006, 4 (1) 19-33.
8. Li, V.C., "Integrated Structures and Materials Design", Mater. Struct. 2006, 40 (4) 387-396.
9. Yang, E.H., Sahmaran, M., Yang, Y. and Li, V.C., "Rheological Control in the Production of Engineered Cementitious Composites", Submitted to ACI Mater. J..
10. Zhou, J., Qian, S., Guadalupe Sierra Beltran, M.G.M., Ye, G., van Breugel, K. and Li, V.C., "Development of Engineered Cementitious Composites with Limestone Powder and Blast Furnace Slag", Submitted to Mater. Struct..