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DEVELOPMENT OF ENGINEERED CEMENTITIOUS COMPOSITES WITH NON-OILED POLYVINYL ALCOHOL FIBERS AND NATURAL SAND

WANG Qiannan [1], BANTHIA Nemkumar [2], SUN Wei [3]

Abstract

Engineered cementitious composites (ECC) is a class of fiber reinforced cementitious composites with significant strain-hardening behavior under tension. Standard ECC mixtures are typically produced with oil-coated polyvinyl alcohol (PVA) fibers and microsilica sand (250 μm maximum grain size). In this study, ECC mixtures containing 2% non-oiled PVA fibers by volume and natural sand with maximum size of 1.19 mm were developed to reduce the cost of ECC and improve material sustainability. The mix proportion was designed experimentally by adjusting the amounts of FA, water and silica fume (SF) to obtain strain-hardening behavior and high strain capacity. Uniaxial tensile test was carried out on the mixtures at 28 days. The results show that the ECC mixtures produced with non-oiled PVA fibers and natural sand achieve strain-hardening behavior with strain capacities comparable with standard ECC. One of the mixtures (C: FA: SF = 1:2:0.2, W/CM=0.27) exhibited a high strain capacity of 3.89%. The matrix of this mixture was then studied combined with different fiber systems [2% Polyethylene terephthalate (PET) fibers, 1% PVA fibers and 1%PVA+1%PET fibers, by volume] to further reduce the cost. The tensile strain capacities of these mixtures were 0.45%, 0.57% and 1.67% respectively. Mixture with 2% PET fibers exhibited strain-softening behavior while mixtures with 1% PVA fibers or hybrid fibers achieved strain hardening.

Keywords: Engineered cementitious composites, non-oiled PVA fibers, natural sand, strain-hardening, tensile strain capacity

1. Introduction

Compared to other building materials such as metals and polymers, concrete is significantly more brittle and exhibits a poor tensile property. Based on fracture toughness

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[1] WANG Qiannan, School of Materials Science & Engineering, Southeast University, China; Currently a visiting doctoral student at the University of British Columbia, Canada, Tel: 1-6048226039, Email: wqnseu@gmail.com,

[2] BANTHIA Nemkumar, Department of Civil Engineering, University of British Columbia, Canada, Tel.: 1-6048229541, Email: banthia@civil.ubc.ca

[3] SUN Wei, School of Materials Science & Engineering, Southeast University, China, Tel.: 86-25-83795374, Email: sunwei@seu.edu.cn

values, steel is at least 100 times more resistant to crack growth than concrete. Concrete in service thus cracks easily, and this cracking creates easy access routes for deleterious agents resulting in freeze-thaw damage, scaling, discoloration and steel corrosion [1, 2]. The concerns with the inferior fracture toughness of concrete are alleviated to a large extent by reinforcing it with fibers of various materials, resulting in fiber reinforced concrete (FRC). During the last two decades, a significant effort has been made developing and researching on a new class of FRC, the so-called engineered cementitious composites (ECC). ECC exhibits strain-hardening behavior and high strain capacity in tension, despite containing low volumes of fibers[3]. This unique tensile strain-hardening behavior results from an elaborate design using a micro-mechanical model taking into account the interactions among fiber, matrix and the fiber-matrix interface [4].

The typical fiber used in ECC is the polyvinyl alcohol (PVA) fiber with a diameter of 39 μm and a length of 6–12 mm [5]. The challenge of using PVA fiber in producing ECC is that PVA fiber tends to develop very strong chemical bond with the matrix due to the presence of the hydroxyl group in its molecular chains. This high chemical bond leads to a tendency of fibers to rupture which limits the tensile strain capacity of the resulting composite[6]. In order to achieve strain-hardening behavior at the composite level, the micromechanical models suggest that the bond should be lowered to an optimal range. Following this quantitative guidance, the interface is engineered by applying oil coating to the fiber surface. It was observed that the oiling content of 1.2% gave the best result in tensile test [7,8] and this amount has been used in most PVA fiber-based ECC materials.

According to the micromechanical design principles of ECC, to achieve strain-hardening, matrix fracture toughness has to be limited such that steady-state crack initiation could occur before the tensile load reaches the maximum fiber bridging stress. Large aggregate particles are hence eliminated in the standard ECC mixture as a result of micromechanical-based design calculations. For these reasons, the production of standard ECC mixtures has been restricted to the use of a fine aggregate such as microsilica sand with a maximum grain size of 250 μm [9].

Compared with conventional concrete, ECC materials contain considerably higher cement content, typically two to three times higher. The high cement content in ECC is a consequence of rheology control for easy fiber dispersion and, more essentially, matrix toughness control for strain-hardening behavior[10, 11]. High cement usage apparently compromises sustainability performance of the material, as cement production is responsible for 5%~7% of global greenhouse gas emissions generated by human activities. In addition, such matrix and the surface-treated PVA fibers result in undesired high material cost and processing complications. Accordingly, the main objective of the current research is to design a new class of ECC to reduce the cost and improve material greenness, while retaining the tensile properties of standard ECC mixtures.

This paper presents the development of ECC mixtures produced with non-oiled PVA fibers and natural sand (1.19 mm maximum grain size) under the guidance of micromechanical principles. The properties of matrix and fiber-matrix interface were modified by adjusting the fly ash (FA) content, water/cementitious materials (W/CM) ratio and adding silica fume (SF). Compressive and uniaxial tensile tests were performed and one of the mixtures exhibited comparable tensile property with typical ECC mixtures. The matrix of this mixture was chosen to do further research to study the possibility of producing ECC with lower-cost fiber systems. Mixtures with 2% polyethylene terephthalate (PET) fibers, 1%

PVA fibers and 1%PVA+1%PET fibers (by volume), were produced and their tensile properties were discussed.

2. Experimental program

2.1 Materials and mix proportions

The materials used in this study were Type I Portland cement (C), Class C fly ash (FA) , silica fume (SF), natural sand (S) with a maximum grain size of 1.19mm, water (W), superplasticizer (SP), non-oiled PVA fibers and PET fibers. The properties of fibers are given in Tab. 1.

Tab.1: The proporties of fibers

Type of fiber	Length, mm	Diameter, µm	Tensile strength, MPa	Elastic modulus, GPa
PVA	8	40	1560	40
PET	6	33~36	400~600	9~10

Two groups of materials were produced in this study. The first group was ECC materials containing non-oiled PVA fibers and natural sand. The volume fraction of PVA fibers was 2%. The matrix was modified to get better strain-hardening behavior and higher tensile capacity. The mix proportion can be found in Tab.2. The mix proportion of a standard ECC mixture, known as ECC M45 [12], was used as a start. However, the fiber and sand in this mixture were replaced with non-oiled PVA fibers and natural sand, respectively, and the mixture was numbered as M1. The contents of fly ash, silica fume and water were adjusted for better tensile behavior. The experimental study revealed that among the first group of ECC mixtures, M4 showed the best tensile property. The matrix of M4 was then chosen for producing the second group of materials, in which different fiber systems (Tab.3) were used to assess the possibility of producing ECC with lower-cost fibers.

Tab.2: Mix proportion of the ECC mixtures with 2% PVA fibers

Mixture ID	C	FA	SF	S/CM ratio[a]	W/CM ratio[b]	SP[c]	PVA fiber (by volume)
M1	1	1.2	-	0.36	0.27	0.0033	2%
M2	1	2	-	0.36	0.27	0.0024	2%
M3	1	2	-	0.36	0.32	-	2%
M4	1	2	0.2	0.36	0.27	0.0067	2%

[a] S/CM: sand/cementitious materials
[b] W/CM: water/cementitious materials
[c] SP: superplasticizer

Tab.3: Mix proportion of the ECC mixtures with other fiber systems

Mixture ID	C	FA	SF	S/CM ratio	W/CM ratio	SP	PVA fiber (by volume)	PET fiber (by volume)
M5	1	2	0.2	0.36	0.27	0.0067	-	2%
M6	1	2	0.2	0.36	0.27	0.0067	1%	-
M7	1	2	0.2	0.36	0.27	0.0067	1%	1%

2.2 Mixing and curing

The matrix materials were first mixed with a HOBART mixer for 1 min at a low speed. Then water and superplasticizer were added at low speed. Mixing continued at low speed for 1 min and then at high speed for 2 min. After fibers were added, the mixture was mixed at high speed for another 2 min.

The fresh mixture was cast into six contoured specimens with a length of 195 mm and critical section of 7 mm x 15mm (Fig. 1) for uniaxial tensile tests and cylindrical specimens with a diameter of 75 mm and height of 150mm for compressive test. After 1 day curing in moulds covered with plastic sheet, the specimens were demoulded and cured in lime-saturated solution at a temperature of 20 °C until specific testing ages.

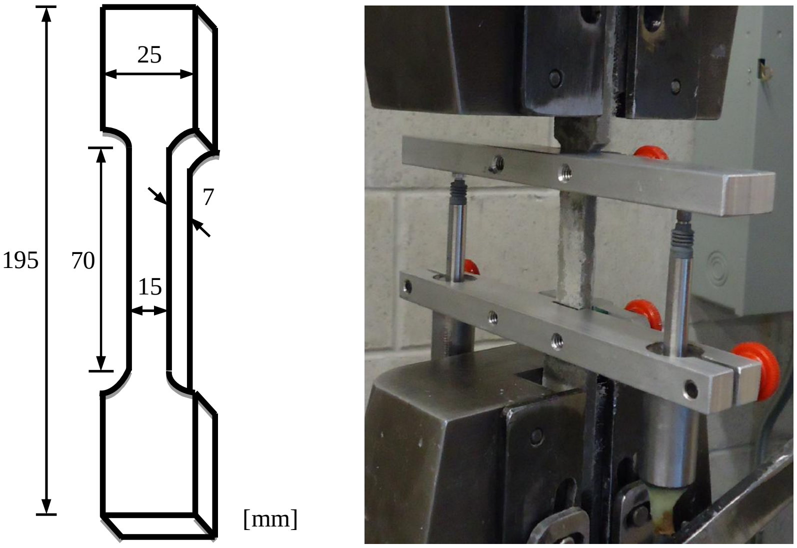

Fig. 1: Uniaxial tensile test set-up

2.3 Testing

The compressive tests were carried out on cylindrical specimens at the age of 7-day and 28-day. The ends of cylinders were ground before testing to ensure a flat and parallel surface and a better contact with the loading device.

The uniaxial tensile test was performed for each mixture at the age of 28-day (Fig. 1). A closed-loop controlled Instron testing system was used in displacement controlled mode to conduct the tensile test. The testing gauge length was 60mm. The loading rate of tensile test for ECC materials are usually set at 0.005mm/s by most researchers regardless of the size or gauge length of the specimens [12, 13]. However, it makes more sense to load the specimen at a specific rate in terms of strain instead of deformation. The strain rate of the tests can be calculated by dividing the loading rate in terms of deformation by the gauge length of the test. Although the gauge length increases during a tensile test, the error of using the initial gauge length is acceptable. The most often used gauge lengths of the tests performed by Li and co-workers were 180 mm and 101.6 mm. As a result, the strain rate would be either 0.0027%/s or 0.0049%/s. Considering that the specimen size and the gauge length used in this study were smaller, the loading rate was determined to be 0.002mm/s which was equivalent to a strain rate of 0.0033%/s.

3. Results and discussion

3.1 Compressive test

The compressive strengths of mixtures at 7-day and 28-day are shown in Tab. 4. The mixture M1 exhibited the highest strength at both ages due to its relatively high cement content. The compressive strength of M3 was the lowest as a result of higher W/CM ratio. The difference between M2 and M4 was that M4 contained silica fume while M2 did not. And, consequently, the compressive strength of M4 was slightly higher than M2. The compressive strength of M4, M5, M6 and M7 at 7-day were close but their strengths at 28-day showed some differences. These mixtures shared the same matrix while with different fiber systems. The interface between matrix and fibers at 7-day was not strong enough due to the low cement content (cement: FA= 1:2). The fibers act as defects instead of reinforcing agents at early age. Therefore, the different fiber systems did not appear to affect the strength much. However, the interface improved with time due to the hydration of cement and the pozzolanic reaction of fly ash. Fibers started to play the role of reinforcing elements and the 2% PVA fiber system had the best effect on compressive strength at 28-day, followed by hybrid fibers (1% PVA fibers and 1% PET fibers)and 1% PVA fibers. M5 containing 2% PET fibers exhibited the lowest compressive strength at 28-day.

Tab.4: Compressive strength of mixtures at 7-day and 28-day

Mixture ID		M1	M2	M3	M4	M5	M6	M7
Compressive Strength/MPa	7-day	41.31	25.34	20.42	26.03	25.15	25.21	25.32
	28-day	65.27	49.51	38.36	50.76	42.76	44.73	45.10

3.2 Uniaxial tensile performance

The uniaxial tensile test results in terms of first-crack strength, ultimate tensile strength, and tensile strain at the peak stress of the mixtures at 28-day, are displayed in Tab. 5. The typical stress-strain curves are presented in Fig. 2 and Fig. 3.

Tab.5: Tensile properties of mixtures at 28-day

Mixture ID	First-crack strength, MPa	Ultimate tensile strength, MPa	Tensile strain capacity, %
M1	4.02	4.97	1.67
M2	3.21	4.01	2.99
M3	2.76	3.57	3.63
M4	3.22	4.43	3.89
M5	1.42	1.57	0.45
M6	2.54	3.32	0.57
M7	3.12	3.78	1.67

The first phase of the test was to design a matrix to achieve good tensile performance with 2% of non-oiled PVA fibers and natural sand. According to the micromechanical design principles of ECC, to achieve strain-hardening and higher strain capacity, the chemical bond of the fiber-matrix interface and toughness of matrix have to be limited. Three attampts have been tried in this study on the basis of M1 which had the same mix proportion as the standard ECC: (1) increasing the fly ash content to a FA/C ratio of 2; (2) increasing the W/CM ratio of M2 from 0.27 to 0.32; (3) adding silica fume to M2 (C:FA:SF=1:2:0.2).

As seen from Tab. 5 and Fig. 2, all of the mixtures exhibited strain-hardening behivour, that was, a sustained increase in load capacity beyond the first matrix crack, with strain capacities ranging from 1.67% to 3.89%. After the first cracking, the load continued to increase accompanied by multiple cracking, which contributed to the inelastic strain as stress increases. As the fly ash content increased, the tensile strength droppd while the tensile strain increased. According to the research of Wang and Li [11], increasing the fly ash content in ECC mixtures tends to reduce the fiber-matrix interface chemical bond and matrix toughness, while increasing the interface frictional bond, in favor of attaining high tensile strain capacity. A higher W/CM ratio could also result in a lower fiber/matrix interface bond strenth and lower matrix toughness as well. As a result, M3 attained a tensile capacity of 3.63%. However, higher W/CM ratio has nagative effects on the fiber dispersibility and the strength of mixture. The tensile performance of M4 suggested that the addition of silica fume lead to a high strain capacity of 3.89% while retaining a relatively high tensile strength compared with M3. This was atrributed to the improved fiber dispersion and a higher fiber-matrix interface frictional bond [14]. The experimental results revealed that M4 had the optimum matrix in terms of tensile performance in production of ECC with non-olied PVA fibers and natural sand with a maximum size of 1.19mm.

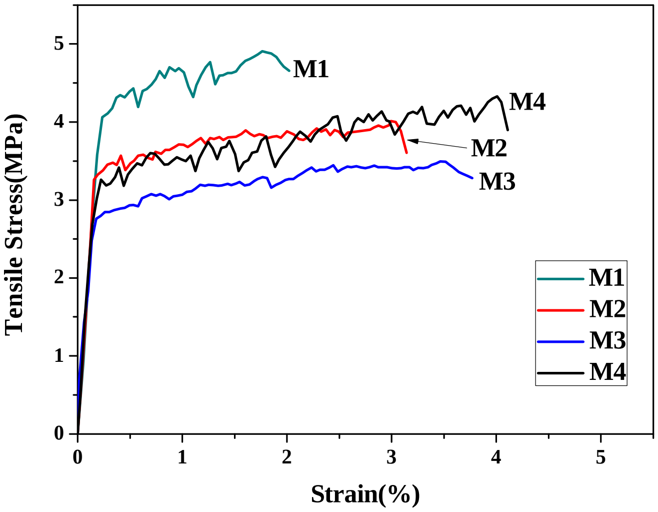

Fig. 2: Tensile behavior of ECC mixtures with 2% of PVA fibers at age of 28-day

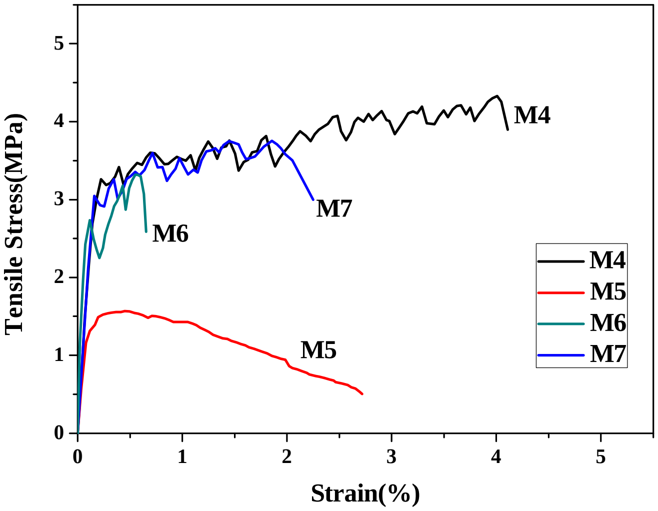

Fig. 3: Tensile behavior of mixtures with different fiber systems at age of 28-day

The second phase of the test was to study the tensile properties of mixtures with different fiber systems. The matrix of M5, M6 and M7 was the same as M4 which had the highest tensile strain capacity. Due to the low tensile strength and low elastic modulus of PET fibers, M5, which contained 2% PET fibers, only attained a tensile strain capacity of 0.45%, exhibited strain-softening behavior and no multiple-cracking occurred in the uniaxial tensile test. Except for M5, all of the mixtures exhibited strain-hardening behavior as shown in Fig. 3. M6 with 1% PET fibers exhibited a tensile strength of 3.32MPa and a tensile strain capacity of 0.57%. Interestingly, the hybrid fiber system of 1% PVA fibers and 1% PET fibers (M7) seemed to have better tensile performance than 1% PVA fibers, achieving a tensile strain capacity of 1.67%. Besides, both the first crack strength and the ultimate tensile strength were improved by using hybrid fibers. However, there was still a big gap in the tensile performance between the 2% hybrid fiber system and the 2% PVA fibers system.

4. Conclusions

In order to reduce the cost and improve the material sustainability, a set of ECC mixtures was developed with non-oiled PVA fibers and natural sand (with a maximum size of 1.19 mm). The mix proportion was designed by adjusting the amount of fly ash, water and silica fume, accompanied by compressive and uniaxial tensile tests. Furthermore, the influence of different fiber systems on the mechanical properties was revealed. The following conclusions were drawn:

1. ECC mixtures produced by non-oiled PVA fibers and natural sand can attain strain-hardening behavior with strain capacity ranging from 1.67% to 3.89%. Increasing the FA/C ratio from 1.2 to 2 lead to a lower tensile strength but a higher strain capacity. The same tendency was noted as the W/CM ratio increased from 0.27 to 0.32. The addition of silica fume improved both the tensile strength and the strain capacity.
2. The study resulted in an optimized ECC mix proportion with C:FA:SF=1:2:0.2 and W/CM of 0.27. This mixture exhibited a tensile strength of 4.43MPa and a high strain capacity of 3.89% at 28-day.
3. The compressive strengths of mixtures with different fiber systems at 7-day were close to each other, while the results at 28-day suggested that mixture with 2% PVA fibers exhibited the highest strength, followed by mixture with hybrid fibers (1% PVA fibers and 1% PET fibers)and mixture with 1% PVA fibers. Mixture containing 2% PET fibers exhibited the lowest compressive strength at 28-day.
4. Mixture produced with 2% PET fibers showed strain-softening behavior with a strain capacity of 0.45%. Mixtures with other fiber systems such as 1% PVA fibers and hybrid fibers attained strain-hardening behavior, and the strain capacity of these mixtures at 28-day were 0.57% and 1.67%, respectively.

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