Journal of Southeast University (English Edition) Vol. 28, No. 3, pp. 327 – 330 Sept. 2012 ISSN 1003—7985

Development of engineered cementitious composites with local ingredients

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Abstract: In order to reduce the cost of high performance polyvinyl alcohol (PVA) fiber reinforced cementitious material (called engineered cementitious composites, ECC), a ductile ECC material is developed using domestic PVA fibers along with other local ingredients, such as fly ash, cement and sand. In addition to the economic analysis of ECC, the four-point bending test and the optical microscope are employed to investigate the deflection capacity of ECC, its crack width and the occurrence of the self-healing phenomenon. The experimental results suggest that ECC made with domestic ingredients exhibits larger deformability and the average crack width is controlled around 60 μm. Furthermore, the self-healing behavior is observed in cracks of the specimens after cycles of wet and dry curing. The economic analysis shows that the cost of ECC can be greatly reduced via employing domestic PVA fibers. It is, therefore, feasible to produce low cost ECC material employing domestic PVA fibers, while simultaneously retaining high material ductility.

Key words: engineered cementitious composites (ECC); high tensile ductility; material cost; feasibility study

doi: 10.3969/j.issn.1003 – 7985.2012.03.013

Engineered cementitious composite (ECC) is a unique class of high-performance fiber-reinforced cementitious composites (HPFRCC) featuring high ductility and medium fiber content. A tensile strain capacity of 3% to 5% (300 to 500 times that of normal concrete) has been demonstrated in ECC materials adopting 2% polyethylene and PVA fibers by volume[1-2]. The large strain capacity in ECC is attributed to sequential development of multiple cracks, as opposed to continuous widening of one localized crack in concrete. Besides high strain capacity, ECC also reveals high fracture toughness and controlled crack width (typically below 100 μm), which makes ECC become an ideal material to improve the serviceability and durability of civil infrastructures.

In recent years, ECC has been increasingly applied in field applications worldwide, including dam repairs, bridge decks, coupling beams in high-rise buildings, and other infrastructures in Japan and the USA[3]. Despite increasing research activities in China, the application of ECC is very limited due to the high cost of the PVA fiber imported from Japan as well as the lack of experience with inexpensive domestic fiber (The unit cost of imported PVA fiber vs. domestic PVA fiber is 225 vs. 40 yuan/kg). Therefore, it is natural to employ local materials, especially domestic PVA fibers to develop new ECC materials suitable for applications in China. The domestic PVA fiber has significantly different physical/mechanical properties compared with commonly used PVA fibers from Japan, which suggests that extensive research is needed for the domestic PVA fibers before its wide adoption in China.

This paper presents some preliminary results of recent developments of ECC with local materials, including Portland cement, fly ash, sand and PVA fibers. First, the ECC mix design and the experimental program are presented. Furthermore, the results of the four-point bending test, optical microscope observation and simple economic analysis are reported to demonstrate the feasibility of ECC with local compositions. Finally, the conclusion is drawn based on the above discussions.

1 Experimental Program

1.1 Materials

As shown in Tab. 1, the ECC mixture includes Portland cement, fly ash, river sand, and PVA fibers. Totally there are three types of PVA fibers, including two local PVA fibers (PVA1, PVA2) produced in the Jiangsu and Sichuan provinces, respectively, along with PVA3 produced in Japan. The properties of different PVA fibers are revealed in Tab. 2. Additionally, cements with two strength grades are used, including Portland cement Ⅰ 32.5 for M1 and M2, Ⅰ 42.5 for M3 and M4. The strength grade is an indication of a cement compressive strength at 28 d. A fiber volume of 1.6% is adopted due to the difficulty of mixing with 2% domestic fibers, which have smaller diameters and tend to conglomerate during mixing (see Fig. 1).

Received 2011-12-29.

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Foundation items: The National Natural Science Foundation of China (No. 51008071, 51278097), the Natural Science Foundation of Jiangsu Province (No. BK2010413), Teaching & Research Excellence Grant for Young Faculty Member at Southeast University, the Program for Special Talents in Six Major Fields of Jiangsu Province (No. 2011-JZ-011), the Scientific Research Innovation Project for College Graduates in Jiangsu Province (No. CXLX_0136).

Citation: Qian Shunzhi, Zhang Zhigang. Development of engineered cementitious composites with local ingredients[J]. Journal of Southeast University (English Edition), 2012, 28(3): 327 – 330. [doi: 10.3969/j.issn.1003 – 7985.2012.03.013]

Tab. 1 Mix proportion of ECC mixture kg/m^3

Mix number	ρ(cement)	ρ(fly ash)	ρ(sand)	ρ(water)	ρ(super-plasticizer)	ρ(PVA)	PVA type	Unit price/(yuan · m^{-3})
M1	419	922	335	332	5	21	PVA1	1 223
M2	419	922	335	332	5	21	PVA2	953
M3	396	872	460	314	5	21	PVA1	1 247
M4	396	872	460	314	5	21	PVA3	4 991

Tab. 2 Properties of different PVA fibers

Fiber	Diameter/μm	Length/mm	Tensile strength/MPa	Modulus/GPa	Density/(g · cm^{-3})	Price/(yuan · kg^{-1})
PVA1	27	12	1 000	8	1.3	45
PVA2	26	12	1 600	35	1.3	32
PVA3	39	12	1 620	42.8	1.2	225

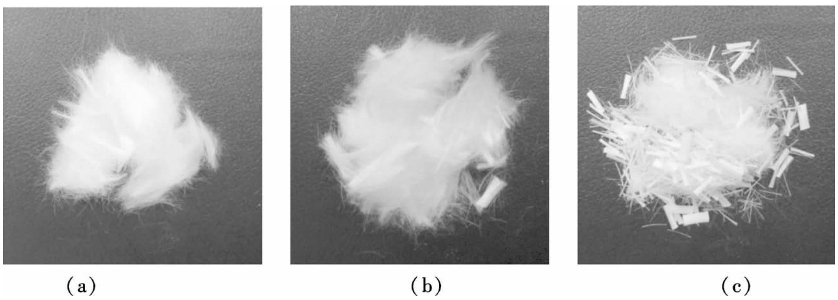

Fig. 1 Image of different PVA fibers. (a) PVA1; (b) PVA2; (c) PVA3

1.2 Mixing and testing

The matrix materials are first mixed with a high-shear mortar mixer for 1 min at low speed, followed by the addition of water and super-plasticizer. Mixing continues at low speed for 1 min and then at high speed for 2 min. Once fibers are added, the composite material is mixed at high speed for another 8 min. The fresh ECC is then cast into steel form and then demolded after 1 d of curing. The specimens are then air cured at room temperature until testing. M1 and M2 are cured for 60 d while M3 and M4 are cured for 28 d. The bending specimens have dimensions of 400 mm × 100 mm × 16 mm.

After curing, three specimens are used in the four-point bending test for each mixture. The full span of the four-point bending test is 360 mm with a middle span of 150 mm. The test is conducted under deformation control of 0.75 mm/min. Typically, it takes about 20 to 30 min before the sample exhausts its deflection capacity and fails.

2 Results and Discussion

2.1 Flexural performance

Under the four-point bending load, the mixtures M1, M2, M3 and M4 all exhibit deflection hardening behavior (see Fig. 2), revealing typical multiple-cracking behavior for all mixtures. In the flexural stress-deflection curves, the maximum flexural stress is defined as the flexural strength, and the corresponding deflection is defined as the flexural deflection capacity. Three specimens reveal some differences in terms of flexural strength and flexural deflection capacity, which is typical in ECC and reflects the inhomogeneity of the material. The flexural specimen is first manually pre-loaded to make sure that four loading points are in full contact with the specimen, which explains that the flexural stress is not zero at the beginning of the curve.

From Fig. 2 and Tab. 3, it can be seen that M1 and M3 show higher deflection capacity and flexural strength in comparison with those of M2 and M4, respectively. According to Ref. [4], the tensile strain capacity for ECCs can be derived from the deflection capacity by a simplified inverse method, which shows a linear relationship between the tensile strain capacity and the deflection capacity for ECC. While the widely used PVA3 typically shows good ductility in Ref. [2], in this particular mixture, PVA1 seems to be a better candidate fiber over PVA3 presumably due to more proper synergistic action between the fiber and the cementitious matrix.

It should be noted that M1 reveals a higher deflection capacity compared with that of M3, in spite of longer curing time. Similar to the tensile strain capacity, the deflection capacity in the four-point bending test also decreases with longer curing time[5]. In this paper, M1 is mixed with lower strength grade cement I32.5 and a smaller sand/cementitious material ratio compared with that of M3, therefore, the matrix fracture toughness for M1 is lower than that for M3. The combined effect of the lower grade cement and sand ratio may cause lower first cracking strength, resulting in higher tensile and flexural ductility for M1.

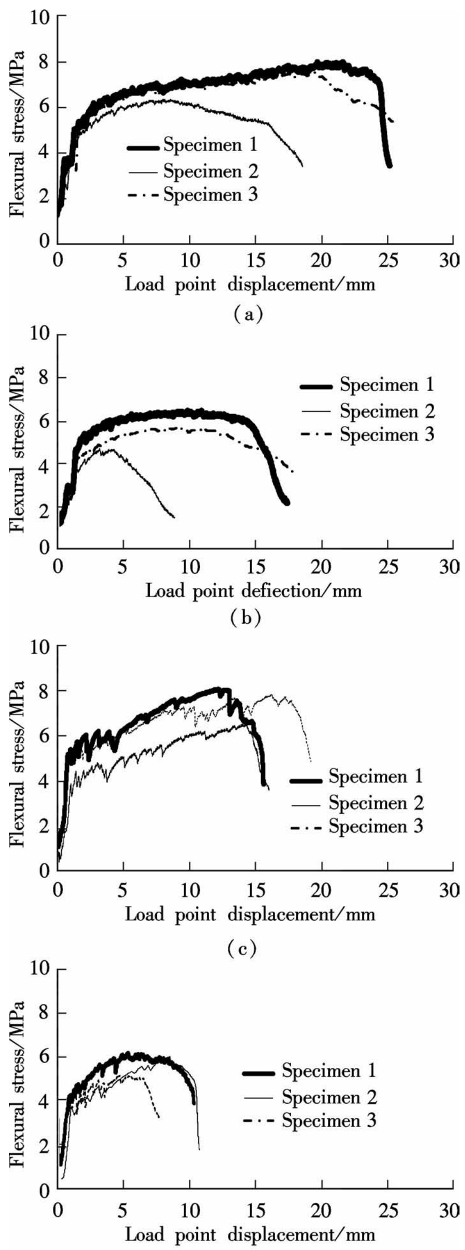

Fig. 2 Flexural stress-deflection curves. (a) M1; (b) M2; (c) M3; (d) M4

Tab. 3 Flexural properties of different mixtures

Mixture	Deflection capacity/mm	Standard deviation/mm	Flexural strength/MPa	Standard deviation/MPa
M1	16.9	7.0	7.1	0.8
M2	9.9	4.8	5.3	0.9
M3	14.7	2.3	7.5	0.9
M4	6.3		5.5	

Similar to the tiny cracks of ECC under tensile loading, tight crack width control is also an intrinsic material property of ECC, which helps to enhance the durability of ECC structures in almost all aspects. Tight crack width has been demonstrated in many recent studies as the source for the high durability of ECC[6]. As shown in Fig. 3, crack width is measured by the optical microscope with several measurements in a single crack. The average crack width is about 60 μm, which is very close to what has been documented in the literature. The ECC specimen also shows typical multiple cracking behavior, as shown in Fig. 4. Therefore, the experimental results demonstrate the feasibility to manufacture ECC using local ingredients, especially local PVA fiber.

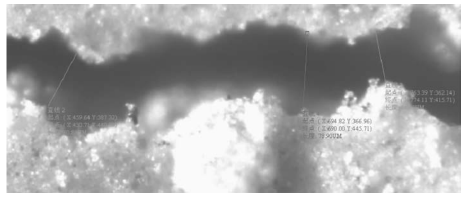

Fig. 3 Crack width measured by optical microscope (Crack widths are 60, 78 and 54 μm, respectively)

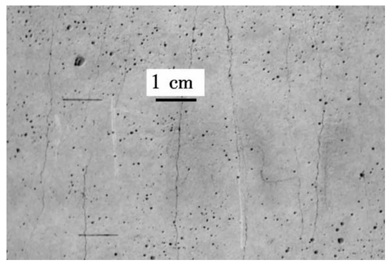

Fig. 4 Typical multiple cracking behavior of ECC under bending load

2.2 Self-healing behaviour

In previous studies[7-9], tight crack width has been found to promote self-healing behaviour, which is readily available in ECCs[10-11]. While there are many factors contributing to the self-healing behaviour, calcium carbonate deposition and continuous hydration of cementitious materials[9] are considered as the two most important ones.

The self-healing phenomena under wet-dry cycles are also observed for micro-cracked ECC produced with local ingredients. It is found that a white residue forms within cracks and within the pores on the surface of the specimens, as shown in Fig. 5. This preliminary findings suggest that self-healing behavior is very likely to be the characteristics of the ECC produced with local ingredients.

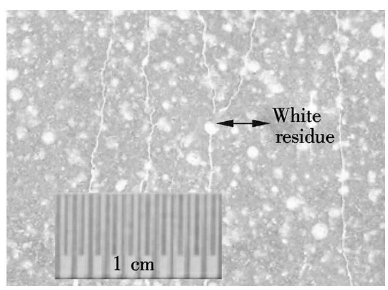

Fig. 5 White residue formed within cracks and the pores on the surface of micro-cracked ECC

Further research work about the chemical composition of the white residue formed after wet-dry cycles needs to be conducted in the future.

2.3 Cost reduction of ECC with domestic PVA fiber

As an ideal material, ECC can improve the serviceability and durability of the civil infrastructures. While the life cycle cost is a more reasonable criterion to evaluate the performance of the civil infrastructure, the initial material cost for the construction project is still very critical during the decision-making stage. Therefore, the application of ECC in China may be largely hindered due to its extreme high cost, mainly driven by the high unit cost of the PVA fiber imported from Japan.

As shown in Tab. 1, the unit cost of ECC with domestic PVA fibers (M1, M2 and M3) is about one fifth to one forth compared with that of the imported fiber PVA3 (M4). The preliminary results in this study suggest that it is feasible to produce ECC with domestic PVA fibers, while retaining good material ductility. The low cost ECC employing domestic PVA fibers may greatly promote the adoption of ECC in civil engineering fields in China.

3 Conclusion

To reduce the material cost of ECC and promote its application in civil engineering fields, the feasibility of producing ECC with domestic PVA fiber is discussed in this paper. The results presented in this preliminary study can provide a basis for the future exploration of adopting domestic PVA fiber to produce ECC for field applications. For a complete understanding of the properties of ECC produced with domestic PVA fiber, much more research work needs to be done in the future.

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基于当地材料制备高延性水泥基复合材料的研究

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摘要:为了降低高性能聚乙烯醇(polyvinyl alcohol, PVA)纤维增强水泥基复合材料 ECC(engineered cementitious composites)的成本,用国产 PVA 纤维和其他本地原材料如粉煤灰、水泥和细砂等研制了高延性 ECC 材料. 采用四点弯曲试验和光学显微镜研究了 ECC 的弯曲变形能力、裂缝宽度及裂缝自愈合现象,并对其进行了经济性分析. 实验结果表明:利用国产原料制备的 ECC 均表现出大变形能力,平均裂缝宽度能控制在 60 μm 左右;开裂的试件经过干湿循环养护之后,裂缝中出现了自愈合现象;经济性分析表明利用国产 PVA 纤维可以极大地降低 ECC 成本. 利用国产 PVA 纤维等材料制备高性价比的 ECC 是可行的.

关键词:高延性水泥基复合材料;高延性;材料成本;可行性分析

中图分类号:U444