Technical Note

ISSN 1997-1400 Int. J. Pavement Res. Technol. 6(3):239-242

Mechanical Properties and Impermeability of High Performance Cementitious Composite Reinforced with Polyethylene Fibers

Mingliang Xing[1+], Rui He[2], Shuanfa Chen[1], and Yongpeng Li[1]

Abstract: In view of the delicate demands of materials for engineered cementitious composites (ECC), this paper presents a simple new brand of high performance cementitious composite (HPCC) prepared with polyethylene (PE) fibers (HPCC-PE). PE and steel fibers were employed to prepare fiber reinforced cementitious composite (FRCC), respectively, in order to perform comparative analysis. The experimental results show that the addition of fibers improves flexural deformation capacity as well as impermeability. A high flexural deflection capacity, which is almost 160 times of that of conventional concrete, was achieved for HPCC-PE accompanied by multiple cracking on the bottoms of the beams at the pure bending region. Scanning electron microscope (SEM) observation reveals that the fibers in HPCC-PE can still carry loads and slip inside the fiber tunnel in spite of the abrasion damage on the periphery caused by the matrix. The low chemical bond of PE fibers with surrounding cementitious matrix increases the potential of achieving saturated multiple cracking.

DOI:10.6135/ijprt.org.tw/2013.6(3).239

***Key words**: Flexural deflection capacity; Highway engineering; High performance cementitious composite; Polyethylene fibers; Steel fibers.*

Introduction

Concrete has been widely utilized in transportation infrastructures due to its high load carrying capacity. However, conventional concrete pavements and bridge decks are prone to cracking and subsequent corrosion and spalling under environmental and mechanical loading, which is a long-standing problem facing transportation engineers [1, 2]. To combat these problems commonly observed in concrete structures, high performance cementitious composite (HPCC), which is a new class of fiber reinforced cementitious composite (FRCC), has been developed increasingly during the past few decades due to its substantially larger strain capacity and toughness compared with traditional FRCC [3, 4]. It has been shown to be effective in improving the strength, ductility, energy dissipation, and damage tolerance of structures subjected to severe loading and environmental conditions. A typical example of the HPCC is engineered cementitious composite (ECC), which was first proposed by Li [5] and then developed broadly in Japan and China [6-8]. Although ECC is outstanding for its super strain capacity and multiple cracking property, the polyvinylalcohol (PVA) fibers must be coated by a proprietary oiling agent in advance to achieve the subtle balance of the micromechanics principle on the interface. In addition, the use of fine silica sand (the maximum grain is below 300 μm) is needed for the matrix [9, 10]. Otherwise, the strong bond of PVA fibers to the surrounding cementitious matrix will tend to limit the multiple cracking effect and lead to lower strain hardening properties for the composite [9]. Thus, it will create additional demands in industrial projects, particularly in on-site construction, such as economical feasibility and constructability. To reduce the limits on the raw materials and simplify the preparation procedure of HPCC, this paper presents a simple method to prepare HPCC with polyethylene (PE) fibers and the performance study of this new HPCC. At last, the mechanism of multiple cracking was analyzed on the basis of scanning electron microscope (SEM) observation.

Experimental Program

Materials

In the experiments, ordinary Portland cement (type P.O. 42.5, China), fly ash (Grade I, China), and International Organization for Standardization (ISO) standard sand were used to prepare the matrix for the fiber-reinforced composite. In order to demonstrate the superior properties of HPCC prepared with PE fibers (HPCC-PE), a commercially available hooked-end steel fiber was employed to produce steel fiber reinforced composite (SFRCC) at the same time. Properties of the PE and steel fibers are listed in Table 1. A polycarboxylic-ether type superplasticizer admixture (SP) was adopted to adjust the characteristics of the fresh mixtures. Details of the three series of experiments performed in this study are given in Table 2. The mixing procedure of the composite materials consists of the following steps. The cementitious binders and sand were first put into the mixer and mixed for 1 minute. Then water, superplasticizer, and fibers were added in sequence, and mixing was continued for 3 minutes, which results in a uniform fluid mixture.

Experimental Methods

The four point bending tests give flexural stress vs. mid-span deflection performance and related mechanical parameters. Prism

[1] Engineering Research Center of Ministry of Education for Transportation Materials, Chang'an University, Xi'an, 710061, China.
[2] School of Highway, Chang'an University, Xi'an, 710064, China.
[+] Corresponding Author: E-mail mlxing@chd.edu.cn
Note: Submitted September 30, 2012; Revised December 5, 2012; Accepted December 11, 2012.

Table 1. Properties of PE and Steel Fibers.

Fiber Type	Length (mm)	Diameter (μm)	Tensile Strength (MPa)	Elastic Modulus (GPa)
PE	12	49	2500	66
Steel	28	570	2610	200

Table 2. Experimental Program and Mix Proportions.

Mix Series	Cement	Fly Ash	Sand	Water	SP	Volume Fraction (%)	
						PE	Steel
P1	1	0.2	1.2	0.38	0.008	1.7	—
P2	1	0.4	1.2	0.36	0.008	1.7	—
S1	1	0.2	1.2	0.38	0.008	—	1.7

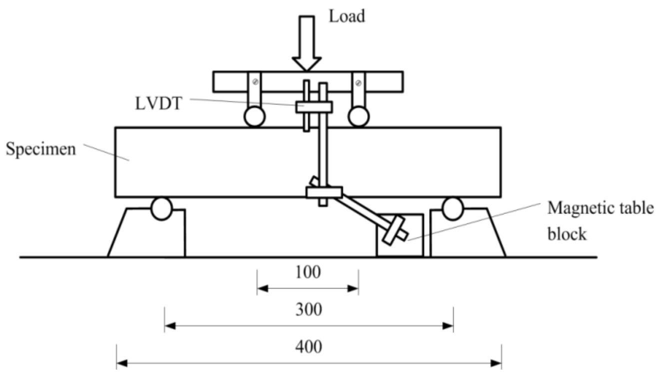


Fig. 1. Sketch of Four Point Bending Test on Beams (mm).

specimens with size of 100 ×100 × 400 mm were used to conduct bending tests. All specimens were demolded at the age of 24 hours. The load and the mid-span deflection were recorded by the computer. The test was conducted under deformation control at the speed of 0.3 mm/min, and the support span l was 300 mm. Details of the four point bending tests are shown in Fig. 1. Three measurements were done for each mixture. The portions of prisms broken in bending tests were employed for compressive test. SEM observation was conducted to detect the failure surface of the specimens after the bending tests.

Finally, impermeability tests were performed according to Chinese Standard JTG E30-2005. The cylinder specimens have a diameter of 150 mm and a height of 150 mm. The hydraulic pressure was kept constant at 1.2±0.5 MPa for 24 hours. Then the specimens were split to measure the percolating heights at 10 equal division points, the average value of which was the result of percolating height for each specimen. The impermeability result was the averages of six specimens for each mixture. It should be noted that all the tested specimens for mechanical and impermeability tests were cured to 28 days.

Results and Discussion

Mechanical Properties

Fig. 2 shows the flexural behaviors of all the mixtures. In the flexural stress vs. mid-span deflection curves, the ultimate flexural stress is defined as the flexural strength σ_{bu}, and the corresponding deflection is defined as the flexural deflection capacity δ_{bu}. These

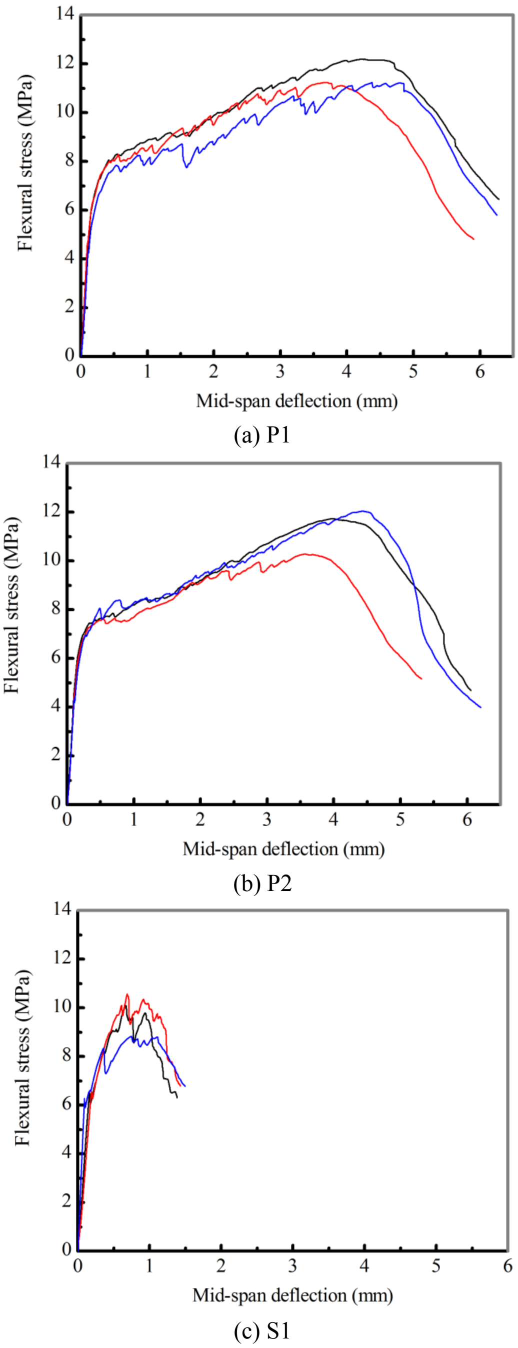


Fig. 2. Experimental Curves of Four Point Bending Tests.

experimental results show that all the mixtures show improvement in deformation ability. Although the flexural deflection capacity of S1 is much smaller when compared with P1 and P2, it remains much higher than that of conventional concrete. As for P1 and P2, their curves can be divided into three separate sections: (1) elastic stage before first cracking occurs: the stress increases linearly with deflection; (2) deflection hardening stage: the load carrying capacity still increases after first cracking occurs, but the increasing rate is much lower than that of elastic stage; (3) softening stage: the load decreases slowly with increased deformation. In addition, all the specimens of P1 and P2 exhibit multiple cracking patterns on the bottom of the pure bending region during the loading process. The cracking patterns of P1 at the peak load are shown in Fig. 3, which

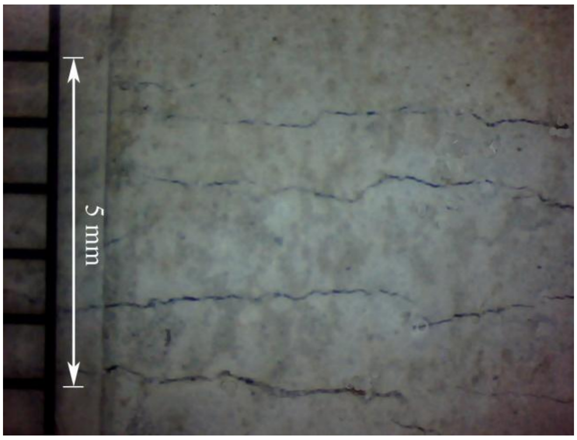


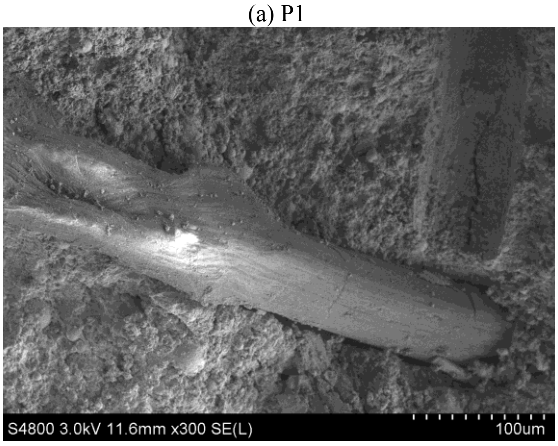
Fig. 3. Multiple Cracking at the Bottom of P1 Specimen.

Table 3. Results of the flexural and compressive tests.

Mix series	σ_{bu} (MPa)	δ_{bu} (mm)	δ_{bu}/l	σ_{cu} (MPa)
P1	11.56	4.11	1/73	46.4
P2	11.32	4.03	1/74	44.8
S1	9.83	0.70	1/428	48.9
P1 Matrix	6.38	0.029	1/10344	48.8
C*	5.73	0.025	1/12000	—

*Note: Data from Ref. [11].

(a) P1



(b) P2

Fig. 4. Micro-morphology of the Fibers on the Fracture Surface.

demonstrates that the average crack spacing is about 1.5 mm.

The results of the flexural and compressive tests are summarized in Table 3, where the ultimate compressive strength is denoted by σ_{cu}. The flexural strength of S1 is lower than P1 and P2 in spite of the higher strength of steel fiber, which can be traced back to the smaller number of fibers that was caused by the greater diameter of steel fibers at the same fiber fraction. In addition, the stiffness of steel fibers is much higher than that of PE fibers and matrix. Thus, the interfacial structure between steel fibers and matrix is prone to be damaged under bending load because of the lack of compatibility of deformation, leading to defects in the composites and sudden breaks. When comparing the P1 and P1 Matrix, it's obvious that the addition of PE fibers greatly increases the compressive strength and deformation capacity. P1 and P2 can still carry the load when the deflection is below 1/75 of the support span, which is almost 160 times of the deflection capacity of conventional concrete and 140 times of P1 Matrix, as shown in Table 3. The flexural and compressive strengths of P1, P2, and S1 all can reach the demand of common structures. Based on the discussion above, it appears that both P1 and P2 can be termed as HPCC.

SEM Observation

Inspection on the fracture surface of P1 and P2 specimens revealed obvious pull-out failure type fibers in both the mixtures, and the length of protruded fibers is about 4 mm. The micro-morphology of the fibers will give more evidence to the failure type of fibers, as shown in Fig. 4. Obvious fiber pull-out traces can be found in Fig. 4. It indicates that the abrasion damage affects only the fibers' periphery, leaving their core intact and allowing further fiber sliding at the loading process. The chemical bond of PE fibers with rounding cementitious matrix is lower when compared with PVA fibers as a result of its hydrophobic nature. According to Kanda and Li [9, 12], reducing the chemical debonding energy enhances the complementary energy by minimizing premature fiber breakage during the fiber/matrix interface debonding process. Thus, the low chemical bond of PE fibers can increase the potential of achieving saturated multiple cracking in fiber reinforced cementitious composites. Before the failure of fiber-bridging action, most of the fibers on the crack surface have suffered pull-out process, which can absorb a large amount of energy and enhance the deformation behavior of the composites greatly. As a result, P1 and P2 show significant improvement in the flexural deflection capacity. Also, the flexural stress has been increased after the first cracking.

Impermeability

It is well known that the durability of concrete structures in harsh environments is highly dependent upon the transportation properties of the concrete material itself [13, 14]. Therefore the impermeability of these three composites was studied in comparison with the matrix of P1. The test results are plotted in Fig. 5. It shows that the addition of fibers can improve the impermeability of the composites to some extent. This improvement occurs because the random distributed fibers restrict the development of early age cracking induced by the shrinkage of the matrixes and ease the stress concentration, reducing the porosity of the composites. Thus, the transportation channel of water is diminished by the fibers, and the impermeability improves.

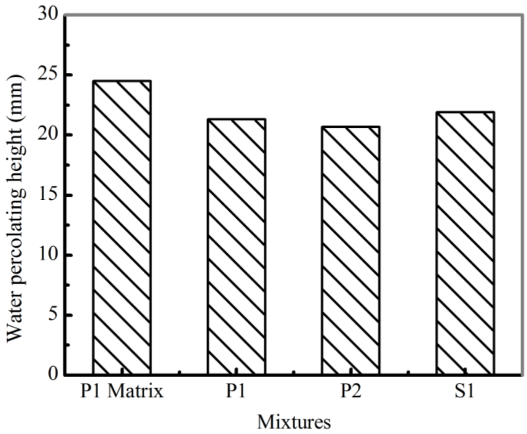


Fig. 5 Impermeability of the mixtures.

Conclusions

A set of FRCC was developed with PE or steel fibers in this paper. The unique ductile and multiple cracking performances were achieved for PE fiber reinforced composites, which can be named as a new vision of HPCC. The following conclusions can be drawn from the study.

(1) Under four point bending tests, all the composites exhibit plastic deformation performance. The flexural deflection capacity of HPCC-PE can reach up to 1/75 of the support span with the company of multiple cracking patterns, which is even larger than SFRCC and almost 160 times of the deflection capacity of conventional concrete. The flexural strength of all the produced composites is higher than 9 MPa, with the compressive strength higher than 40 MPa.

(2) The main failure type of fibers in HPCC-PE is pull-out mode. Although abrasion damage occurs on the fibers' periphery during the pull-out process, the fibers can still carry loads and cause the improvement of flexural deflection capacity and multiple cracking.

(3) The addition of fibers restricts the development of early age cracking induced by the shrinkage of the matrixes and reduces the porosity of the composites, leading to the improvement of impermeability for the composites. All the experimental results demonstrate that HPCC-PE is a superior choice for repair and rehabilitation material of transportation infrastructures.

Acknowledgment

This research is funded by the National Key Technology R & D Program of China in the 12th Five-year Plan (No. 2011BAE27B04) and Special Fund for Basic Scientific Research of Central Colleges in Chang'an University (No. CHD2011TD003, CHD2011JC018).

References

1. Qian, S.Z., and Li, V.C. (2011). Ductile Concrete - Engineered Cementitious Composites (ECC) for Durable Bridge Deck Repair and Rehabilitation, Transportation Research Board 90th Annual Meeting, Papr No. 11-2566, Washington, DC, USA.
2. Chen, S.F., Zheng, M.L., and Wang, B.G. (2009). Study of High-Performance Concrete Subjected to Coupled Action from Sodium Sulfate Solution and Alternating Stresses, *Journal of Materials in Civil Engineering,* 21(4), pp. 148-152.
3. Naaman, A.E., and Reinhardt, H.W. (1996). Characterization of High Performance Fiber Reinforced Cement Composites—HPFRCC, High Performance Fiber Reinforced Cement Composites 2 (HPFRCC 2), *Proceedings of the Second International RILEM Workshop,* E&FN Spon. London, UK, pp. 1-24.
4. Parra-Montesinos, G.J. (2005). High-Performance Fiber-Reinforced Cement Composites: An Alternative for Seismic Design of Structures, *ACI Structural Journal,* 102(5), pp. 668-675.
5. Katz, A., and Li, V.C. (1996). A Special Technique for Determining the Bond Strength of Microfibers in Cement Matrix by Pull-out Test, *Journal of Materials Science Letters,* 15, pp. 1821–1823.
6. Kanakubo, T. (2006). Tensile Characteristics Evaluation Method for Ductile Fiber-Reinforced Cementitious Composites, *Journal of Advanced Concrete Technology,* 4(1), pp. 3-17.
7. Xu, S.L., and Cai, X.H. (2010). Mechanics Behavior of Ultra High Toughness Cementitious Composites after Freezing and Thawing, *Journal of Wuhan University of Technology (Materials Science Edition),* 25(3), pp. 509-514.
8. Zhang, J., Gong, C.X., Ju, X.C., Guo, Z.L. (2010). Bending Performance of Ductile Fiber Reinforced Cementitious Composites, *Engineering Mechanics,* 27(3), pp. 112-115 (in Chinese).
9. Redon, C., Li, V.C., Wu, C., Hoshiro, H., Saito, T., and Ogawa, A. (2001). Measuring and Modifying Interface Properties of PVA Fibers in ECC Matrix, *Journal of Materials in Civil Engineering,* 13(6), pp. 399-405.
10. Xu, S.L., and Li, H.D. (2008). A Review on the Development of Research and Application of Ultra High Toughness Cementitious Composites, *China Civil Engineering Journal,* 41(6), pp. 45-60 (in Chinese).
11. Li, H.D., and Xu, S.L. (2010). Research on Flexural Properties and Flexural Toughness Evaluation Method of Ultra High Toughness Cementitious Composites, *China Civil Engineering Journal,* 43(3), pp. 32-39 (in Chinese).
12. Kanda, T., and Li, V.C. (1999). New Micromechanics Design Theory for Pseudostrain Hardening Cementitious Composite, *Journal of Engineering Mechanics,* 125(4), pp. 373-381.
13. Buenfeld, N.R. (1995). Measuring and Modeling Transport Phenomena in Concrete for Life Prediction of Structures. In: Glanville J., Neville A. (editors). *Prediction of Concrete Durability: Proceedings of STATS 21st Anniversary Conference,*London, UK, pp. 77–90.
14. Wang, K., Jansen, D., Shah, S., and Karr, A. (1997). Permeability Study of Cracked Concrete, *Cement and Concrete Research,* 27(3), pp. 381–93.