The influence of fly ash on the bending characteristics of cost-effective cementitious composites

Zhanfeng Qi1, Wenhua Chen1, Lei Zhang1 and Zhiyi Huang1*

1College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, Zhejiang Province, 310058, China,

*Corresponding author’s e-mail: hzy@zju.edu.cn

Abstract. In order to popularize the cost-effective strain hardening cementitious composites (SHCCs) in the tunnel reinforcement, SHCCs were prepared with domestic fibers in this paper. the crack propagation, load-deflection curve, and bending stiffness of SHCCs were studied by using the four points bending test, digital image correlation technology (DIC) and scanning electron microscopy (SEM). The results indicate that all the samples exhibit the characteristics of multi-cracking, and accordingly, the load-deflection curves present the strain hardening behavior. With the content of fly ash ranging from 40% to 60%, the number of cracks, captured by DIC technology, increased from 6 to 12. Meanwhile, the hardening phase of the bending stress-deflection curve became steady along with the flexural strengths dropping from 12.27 MPa to 9.49 MPa. In addition, through fitting the load-deflection curve, there is a good linear rule of stiffness in all the samples during hardening stages, and the stiffness also degenerates linearly with the increase of the fly ash. It is expected that the experimental outcomes are useful to design the target stiffness of cost-effective SHCCs in practical applications.

1. Introduction

With the increasing demand for transportation, a large number of mountain tunnels in China have been built and put into operation. At present, it is often the case that different degrees of the diseases, such as the cracking and seepage, are observed in the most tunnels, which pose a great threat to the structural safety of the tunnel [1, 2]. Consequently, it is urgent to take reasonable reinforcement measures to deal with the cracking and seepage of the lining.

As a new type of composite material, SHCCs provide a new idea for structural reinforcement[3]. Unlike traditional concrete materials, the SHCCs exhibit multi-cracking behavior under axial tensile load and high tensile capacity, which makes SHCCs materials can avoid brittle failure under severe loading[4]. Nowadays, SHCCs have been successfully employed to maintain tunnel lining in Japan[5]. Whereas, the price has been limiting its application on a large scale. It is well known that the REC-15 PVA is the most common fibers for SHCCs since its surface is treated by oil immersion, which could make the fibers pull out easily rather than fracture in the process of debonding[6]. The fact is that the price of the REC-15 PVA in China market is 225 yuan/kg and the cost of SHCCs is about 6000 yuan/m³, which is more than 20 times the price of ordinary C50 commercial concrete[7]. For the purpose of lowering the production cost of this kind of composites and ensure they still own the feature of strain hardening behavior. Some scholars adopt two ways to control the cost generally: 1) employing the mixed fiber, such as REC-15 PVA and low-cost fibers[8-10]; 2) employing industrial by-products as much as possible, such as fly ash [11, 12]. On the one hand, the fly ash promotes the reuse of industrial waste products and reduces environmental pollution, making SHCCs became a new green building material[7,
On the other hand, fly ash can act on the internal structure of the matrix, especially the interface between fibers and matrix [13, 14]. In order to characterize the low-cost SHCCs, the current studies mainly focus on the uniaxial stress state and pursue ultra-high tensile capacity [15, 16]. Nevertheless, it is unnecessary for SHCCs to be capable of extremely high tensile strain in practical applications. When it is utilized to strengthen the flexural tunnel lining, it is noteworthy that the bending stiffness of cost-effective SHCCs is rarely revealed.

In this paper, cementitious composites were prepared with cost-effective fibers (40 yuan/kg) and other local raw materials. Firstly, the characteristics of multi-cracking and strain hardening behavior were investigated by using the thin plate bending test and DIC technology [17]. In addition, the change rule of samples’ bending stiffness was revealed through fitting the load-deflection curve. According to the results, it may offer guidance for engineers to apply SHCCs in the tunnel with local materials.

2. Experiments

2.1. Raw materials

P II 52.5 R cement (Ningguo Cement Factory, Anhui Province), class F fly ash (Jiaxing Power Plant, Zhejiang Province) and silica fume (Elkem Company, Shanghai) were used to prepare the composite, and the chemical composition of which is shown in Table 1. The mechanical parameters of PVA are exhibited in Table 2 and the particle size of sand ranges from 19.953 μm to 724.436 μm. The water reducing agent with reducing the rate of 24-30% was adopted. To reduce the shrinkage of the material and enhance the water retention of the slurry, the calcium sulfoaluminate expansion agent (HCSA) and the dispersible latex powder were used, respectively.

| Compositions          | Mass/% |
|-----------------------|--------|
| SiO$_2$               | 9.68   |
| Al$_2$O$_3$           | 3.63   |
| Fe$_2$O$_3$           | 3.91   |
| CaO                   | 50.59  |
| MgO                   | 1.55   |
| SO$_3$                | 1.45   |
| NaO                   | 0.12   |
| K$_2$O                | 0.39   |

2.2. Mix ratio

The amount of fly ash is taken as the variation parameter, and the dosage of fly ash replacing cement is 40%, 50%, and 60% respectively. The dosage of silica fume replacing cement is fixed at 20%. The water-to-binder ratio is fixed at 0.27 and the sand to rubber ratio is fixed at 0.36. There are three samples of each group tested. The specific proportion is shown in Table 3.

| Mix no. | Cement (%) | Fly ash (%) | Silica fume (%) | Sand (%) | Water (%) | Water reducer (%) | Expansive (%) | Plasticity (%) | Fiber (%) |
|---------|------------|-------------|-----------------|----------|-----------|-------------------|---------------|---------------|-----------|
| M1      | 0.4        | 0.4         | 0.2             | 0.36     | 0.27      | 0.2               | 10            | 0.25          | 2         |
| M2      | 0.3        | 0.5         | 0.2             | 0.36     | 0.27      | 0.2               | 10            | 0.25          | 2         |
| M3      | 0.2        | 0.6         | 0.2             | 0.36     | 0.27      | 0.2               | 10            | 0.15          | 2         |

The amount of water reducer, expansive and plasticity is the mass fraction of the cementitious material. The fiber is added by volume fraction.

2.3. Test process

The size of the sample in the bending test is 350×50×15 mm, and the loading setup is shown in figure 1. The distance between the bearings is 300 mm, and the spacing between the indenters is 100 mm with
displacement control at a rate of 0.5 mm/min. The machine's data acquisition system was applied to collect the load and displacement data. The sides of each prism painted black and white speckle is to capture the path of the crack by a high-speed camera. The measuring device is shown in figure 2.

3. Results and discussion

3.1. Crack propagation

Figure 3 displays the crack propagation on the surface of the samples, captured by DIC technology. It is observed that the crack evolution goes through three phases: (i) crack initiation stage; (ii) crack saturation stage; (iii) crack penetration stage. When the external load reaches the cracking strength of the matrix, the first crack appears at the bottom of the specimens. With the load raising, the initial crack appears slow expansion, and other cracks arise along the bottom of the specimen. Finally, the crack gradually reaches a saturated state until one of the cracks penetrates through the prism.

From figure 3 (a) and (c), obviously, the number of cracks appeared on the M3 specimen is significantly more than that on the M1 specimen in the gradually-saturating stage, and the distribution of the crack on the M3 specimen is much more uniform, which means the increase of fly ash content makes the matrix more easy to perform multi-cracking behavior. The reason is that the fly ash particles are mostly smooth spherical glass beads, and their micro-morphology is shown in figure 4 (a).
The “ball lubrication” can lower the adhesion between the fiber and the interface. Once the fly ash is added, the interface between the fiber and the interface is tailored and the fibers are pulled out easily from the substrate rather than fracture. In figure 4(b), it is apparent that there is a large number of fly ash particles in the interfacial zone. Kanda and Li gave a convincing explanation of the fly ash effect from the perspective of micromechanics[18]. Based on the energy balance equation proposed by Marshall and Cox[19], Kanda and Li gave the quasi-strain hardening criterion of PVA fiber, as expressed in Eq. (1):

$$\frac{J_b}{J_{np}} > 3, \quad \frac{\sigma_0}{\sigma_{fc}} > 1.45$$  \hspace{1cm} (1)

where $J_{np}$ is the crack tip toughness, which can be considered as the cementitious matrix toughness if fiber volume fraction is less than 5%; $J_b$ is the complementary energy calculated from the $\sigma-\delta$ curve, as schematically illustrated in the figure. 5. The $\sigma_0$ represents the maximum fiber bridging stress, and $\sigma_{fc}$ is the first cracking stress. When the amount of fly ash increases, the $J_{np}$ value decreases, enlarging the value of $J_b/J_{np}$ close to 3 or even greater, which explains that the increase of fly ash content makes the matrix crack more stable.

3.2. Load-deflection curve

As shown in figure 6(a), the curves are the representative bending characteristic curves of three mix ratios. Apparently, all the curves demonstrate the large deformation and the largest deflection occurred in the M3 specimens, which ultimate deflection value exceeds 10 mm. Besides, all the curves go through three stages in the bending process; elastic stage, hardening stage and softening stage, and displacement
mainly occurs in the hardening stage. Compared with M1 samples, the hardening stage of M3 specimens is pretty stable, which implicates that the hardening process of the matrix can be of great stability with the increase of fly ash content addition.

Figure 6 Results of four-point bending tests: (a) relationship between flexural stress and load point deflection; (b) cracking strength and bending strength of specimens.

Figure 6(b) presents the first cracking strength and flexural strength of the three groups of specimens. It is obvious that the cracking strength and flexural strength of the matrix decrease from 9.2 MPa to 4.96 MPa and from 12.27 MPa to 9.49 MPa with the fly ash raising, respectively. Because the hydration activity of fly ash is lower than that of cement clinker, the amount of hydration product such as C-S-H is less, which could lead to strength decrease. However, the flexural strength of M3 is still higher than the ordinary concrete (5 MPa).

3.3. Bending hardening stiffness

It is different from the ordinary concrete that the SHCCs wouldn’t perform the brittle failure due to the bridging effect of fibers after the original cracking. Generally speaking, a large displacement always appears in the hardening stage for SHCCs. Thus, it is of great significance to concentrate on the bending stiffness in the hardening phase. When the SHCCs enters the hardening stage after initial cracking, the load-deflection curve approximates simple linear relationship as shown in the figure. 7. The slope of the line is defined as the hardening stiffness \( K_h \), then

\[
p = K_h \delta + b
\]

where \( p \) is the load in the hardening stage, \( \delta \) is the displacement, and \( b \) is the intercept of the load axis.

According to the principle of the least square method, the load-deflection curves of the three groups are linearly fitted in the hardening stage. Figure 8(a) exhibits the fitting results. The outcome shows that
6

Figure 8 Test result: (a) stiffness fitting results of the load-displacement curve; (b) degeneration law of flexural hardening stiffness with fly ash content. The correlation coefficients of linear fitting are above 0.90 under all conditions of different fly ash content, which indicates that the fitted stiffness values are able to represent the hardening response. Figure 8(b) demonstrates the variation law of fitting stiffness $K_h$. Obviously, the fitting stiffness degrades with the FA/C value, referring to the increase of fly ash replacement. The reason is that the elastic modulus is damaged and equivalent inertia moments reduce due to the cracks. Moreover, the trend of stiffness degrades linearly with the change of FA/C value, the correlation coefficient of which is close to 1.

Figure 9 Analysis of Zhang’s results: (a) fitting results of the load-displacement curve; (b) degeneration law of flexural hardening stiffness with fly ash content. In order to confirm the stiffness degradation rule, the bending test results of ECC sheet, made of REC-15 fibers by Zhang[20], were also analyzed in figure 9(a). The ratio of fly ash to cement is 1.2, 2.2 and 4, respectively. Similarly, the hardening stage of the load-deflection curve is fitted according to the least squares principle, and all the correlation coefficients reached above 0.9. The degradation rule is shown in figure 9(b), and its drop trend still delivers a linear correlation, which is consistent with the rule obtained by using cost-effective in this paper. It should be noted that the degeneration slope between figure 8(b) and figure 9(b) is discrepant because Zhang’s didn’t add the silica fume to the SHCC mixtures. The effect of silica fume on bending stiffness will be studied in future work by the author.

4. Conclusions

(1) The DIC technology shows that all the cementitious composite samples, consisting of cost-effective PVA fibers and local ingredients, exhibit multi-cracking behavior under bending load, and the number of visible cracks increases from 6 to 12 with the replacement of fly ash content ranging from 40% to 60%.
(2) The bending stress-deflection curves of all specimens perform strain hardening behavior. With the augment of fly ash, the hardening state becomes more stable, while the bending cracking strength and flexural strength of the matrix drop off. As the ratio of fly ash to cement equals to 3, the cracking strength and flexural strength are the lowest, 4.96 and 9.49 MPa, nevertheless, the flexural strength of which is still greater than the ordinary concrete (5 MPa).

(3) The bending stiffness of SHCCs in the hardening stage presents an awesome linear correlation, and the stiffness in the hardening stage degenerate linearly with the increasing content of fly ash. Specifically, the higher the fly ash content, the smaller the stiffness of SHCCs in hardening stage.

This conclusion is conducive to adjust the mix ratio in this paper to help engineers design the SHCCs with targeted bending hardening stiffness.

Acknowledgments
This work was supported by the Zhejiang Provincial Important Research Project of China with Grant No. 2018C03029 and the Zhejiang Provincial Transportation Science and Technology Project of China with Grant No. 2018QNA4023. Authors wishing to acknowledge the director from the Electron Microscope Scanning Laboratory.

References
[1] Liu, H.J. (2007) Study on mechanical and numerical model for road tunnel defects diagnosis[D], Shanghai, Tongjing University, (In Chinese).
[2] Zeng, X.D. (2018) Treatment of tunnel lining cracks and water leakage in operation tunnels, Journal of Water Resources and Architectural Engineering, 3:201-205, (In Chinese)
[3] Li, V.C., Mishra, D.K., and Wu, H.C. (1995) Matrix design for pseudo strain-hardening fiber reinforced cementitious composites. Materials and Structures, 28: 586-595.
[4] Wang, S., Wu, C., and Li, V.C. (2001) Tensile strain-hardening behavior of polyvinyl alcohol engineered cementitious composite (PVA-ECC). ACI Materials Journal, 98: 483-492.
[5] Li, V.C. (2019) Engineered Cementitious Composites (ECC): Bendable Concrete for Sustainable and Resilient Infrastructure, Springer Berlin Heidelberg. New York, pp. 335-338.
[6] Li, V.C. (2002) Interface Tailoring for Strain-hardening PVA-ECC. ACI Materials Journal, 99: 463-472.
[7] Ma, H. (2017) Research on materials and structure of ECC overlay on airfield pavement [D]. Nanjing: Southeast University, (In Chinese).
[8] Pan, Z., Wu, C., Liu, J., Wang, W., and Liu, J. (2015). Study on mechanical properties of cost-effective polyvinyl alcohol engineered cementitious composites (PVA-ECC). Construction and Building Materials, 78: 397-404.
[9] Ma, H., Qian, S.Z., Zhang, Z.G. and Li, V.C. (2015). Tailoring engineered cementitious composites with local ingredients. Construction and Building Materials, 101: 584-595.
[10] Li, Z.H., Chen, W.K., Zhou, X., and Chen, F.Q. (2016). A feasibility study of engineered cementitious composites with local ingredients. Applied Mechanics and Materials, 858: 208-213.
[11] Alva, P., Michele, F., and Surendra, P. (2000) High Content of Fly Ash (Class F) in Extruded Cementitious Composites. ACI Materials Journal, 97: 509-517.
[12] Wang, S. and Li, V.C. (2007) Engineered Cementitious Composites with High-volume Fly Ash. ACI Materials Journal, 104: 233-241.
[13] Wongkeo, W., Thongsanitgarn, P., Ngamjarurojana, A., and Chaipanich, A. (2014) Compressive strength and chloride resistance of self-compacting concrete containing high level fly ash and silica fume. Materials & Design, 64: 261-269.
[14] Khatib, J. M. (2008) Performance of self-compacting concrete containing fly ash. Construction and Building Materials, 22: 1963-1971.
[15] Zhou, Y.W., Xin, B., Yu, K.Q., Sui, L.L., Xing, F. (2018) Mechanical Properties of Hybrid Ultra-High Performance Engineered Cementitious Composites Incorporating Steel and Polyethylene Fibers, 11: p. 1448.
[16] Yu, K., Wang, Y., Yu, J., and Xu, S. (2017). A strain-hardening cementitious composites with the tensile capacity up to 8%. Construction and Building Materials, 137: 410-419.
[17] Shih, M.H., and Sung, W.P. (2013). Application of digital image correlation method for analyzing crack variation of reinforced concrete beams. Sadhana, 38: 723-741.
[18] Kanda, T. and Li, V.C. (1998) Multiple cracking sequence and saturation in fiber reinforced cementitious composites. JCI Concrete Research and Technology, 9:19-33.
[19] Marshall, D. B., and Cox, B.N. (1988) A J-integral method for calculating steady-state matrix cracking stresses in composites. Mechanics of Materials, 7: 127-133.
[20] Zhang Z.G. Research on the Self-healing Mechanism and Fatigue Damage of ECC Applying on Steel Bridge Deck overlay [D]. Nanjing: Southeast University, 2016. (In Chinese).