Fracture properties of hybrid fiber reinforced cement-based composites

Yaqing Zhang\textsuperscript{ia*}, Libo Bian\textsuperscript{ib*}, Dihong Li\textsuperscript{ic}, Haiyang Yu\textsuperscript{id}, Zixuan Li\textsuperscript{ie}, Yuchen Feng\textsuperscript{if}, Guolin Ye\textsuperscript{ig}

\textsuperscript{1}School of Civil and Traffic Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China
\textsuperscript{a}zhangyaqing123123@163.com, \textsuperscript{b}bianlibo@bucea.edu.cn, \textsuperscript{c}lidihong@bucea.edu.cn, \textsuperscript{d}1149740675@qq.com, \textsuperscript{e}zixuan_email@163.com, \textsuperscript{f}13070124996@163.com, \textsuperscript{g}yeguolinbucea@163.com

Abstract. In this paper, the effects of base material strength (4 water-binder ratios) and BF volume content on the fracture performance of composite materials were adopted, and the fracture performance parameters of PVA/BF-ECC were measured by monitoring the damage and failure process of composite materials in the stress process by acoustic emission technology. Through the test results, the mechanism of hybrid fiber restraining crack generation and restraining crack development is qualitatively analyzed. The results show that hybrid BF improves the initial fracture toughness of composites; When hybrid based on synergistic effect, although hybrid BF will greatly reduce the unstable fracture toughness, the composite can still maintain high unstable fracture toughness after replacing PVA fiber with 0.5vol%BF, the fracture toughness of the composite under four kinds of substrate strength is 13.68MPa·m\textsuperscript{1/2}, 14.38MPa·m\textsuperscript{1/2}, 12.12MPa·m\textsuperscript{1/2} and 12.20MPa·m\textsuperscript{1/2}, which is more than 20 times that of ordinary concrete.

1. Introduction

On the basis of studying polyvinyl alcohol/steel fiber-ECC and BF-ECC, a new hybrid fiber reinforced cement-based composite system, polyvinyl alcohol-basalt fiber hybrid reinforced cement-based composite (PVA/BF-ECC), is proposed, aiming at studying the synergistic effect of polyvinyl alcohol (PVA) fiber and basalt fiber (BF), and realizing the unity of strength and ductility of PVA/BF-ECC by mixing the two fibers. On the basis of fracture mechanics theory, document\textsuperscript{[1]} explains the mechanism of improving the physical and mechanical properties of cement-based materials by hybrid fibers, and points out that because there are pores and cracks with different scales in different structural layers of cement-based composites, the stress intensity values at the crack tips are also different, and the incorporation of fibers produces a reverse stress field at the crack tips. The stress intensity factor of crack tip is reduced. Fiber mixing can reduce the stress intensity factor at the crack tip as a whole, and achieve the best crack resistance and toughening effect, thus significantly improving the physical and mechanical properties and durability of fiber reinforced cement-based composites.

Sound emission occurs in the whole fracture process of concrete, and has different acoustic emission characteristics in different stages. With the help of acoustic emission technology, the cracking and propagation process of cracks can be dynamically tracked, and the critical state of concrete fracture can be determined by measuring acoustic emission characteristics in fracture process. Li Zongjin et al\textsuperscript{[2]} adopted acoustic emission characterization method, The fracture behavior of fiber reinforced...
concrete under uniaxial direct tension was studied experimentally. The acoustic emission activity and the source location of acoustic emission events were analyzed, and the initiation and propagation of damage in materials were studied. Li Dongsheng et al.[3] used acoustic emission technology to conduct three-point bending tests on corroded and non-corroded polyvinyl alcohol fiber concrete specimens. According to the correlation diagram of acoustic emission characteristic parameters, the reasons for the decrease of flexural strength and damage mechanism of PVA fiber reinforced concrete after corrosion were studied, and two acoustic emission evaluation methods were proposed to evaluate the damage degree of PVA fiber reinforced concrete specimens. Tschegg EK et al.[4] studied unreinforced and fiber reinforced concrete specimens by acoustic emission technology. The range of fracture process zone (FPZ) under uniaxial tension and compression and biaxial tension and compression shows that the FPZ of pure concrete is narrower/smaller than that of FRC specimens. Thirumalaiselvi A et al.[5] studied the damage mechanism of PVA-ECC under bending load by using acoustic emission technology and digital imaging technology, and pointed out that acoustic emission technology has great potential in studying crack bridging and damage in specimens. Therefore, acoustic emission technology has been widely used in the study of fracture properties of fiber reinforced concrete. In this test, acoustic emission technology and curve method are used to comprehensively judge the crack initiation load during PVA/BF-ECC fracture test, and at the same time, acoustic emission parameters during fracture test are monitored, so as to study the fracture properties of composite materials more accurately.

The fibers in cement-based composites can strengthen and toughen by bridging cracks, and inhibit the generation and propagation of cracks, thus changing the fracture characteristics of composites. Therefore, studying the fracture properties of hybrid fiber reinforced cement-based composites can analyze the material failure process from another angle, such as Wang Zhenbo et al.[6] based on the pre-cut beam bending test, the bridge stress-crack width relationship between cracks in hybrid fiber composites was solved by inverse calculation, and the stress-crack width relationship based on fiber, substrate and interface parameters was established by using the existing fiber bridge stress theoretical model for reference. Therefore, in this paper, the effects of base material strength (4 water-binder ratios) and BF volume content on the fracture properties of composite materials are adopted. The damage process of composite materials under stress was monitored by acoustic emission technology, and the fracture performance parameters of PVA/BF-ECC were measured. The mechanism of hybrid fiber restraining crack generation and restraining crack development was qualitatively analyzed through the test results, which laid a foundation for further study on the relationship between hybrid fiber bridging cracks.

2. Experimental design of PVA/BF-ECC fracture

2.1. materials and mixture ratio

P.O.42.5 ordinary Portland cement was used in the test. The fly ash is superfine fly ash; Sand is 100-200 mesh quartz sand; The additive is polycarboxylic acid water reducing agent with solid content of 40%. Water is tap water in Beijing; The fibers are Kuraray CES 15 polyvinyl alcohol (PVA) fiber produced by Japan kolili company and basalt fiber (BF) produced by Zhejiang shijin basalt fiber, see table 1 for related performance parameters of PVA fiber and BF.

| Fiber    | Density (g/cm³) | Diameter (mm) | Length (mm) | tensile strength (MPa) | Elastic modulus (MPa) | Elongation at break (%) |
|----------|-----------------|---------------|-------------|------------------------|-----------------------|-------------------------|
| PVA fiber| 1.3             | 0.039         | 12          | 1620                   | 42.8                  | 7                       |
| BF       | 2.8             | 0.020         | 17          | 3800                   | 93.1                  | 3                       |
In this study, the composition of cementitious materials used in the design of matrix mix ratio and fiber hybrid system are shown in Table 2 and Table 3. Among them, two kinds of fiber mixing methods were used in the experiment. The first method was to control the total fiber volume at 2.5%, study the synergistic effect between PVA fiber and BF, and design four different fiber mixing ratios.

| Numbering | PVA fiber content (%) | BF content (%) |
|-----------|-----------------------|----------------|
| P25B00    | 2.5                   | 0.0            |
| P20B05    | 2.0                   | 0.5            |
| P15B10    | 1.5                   | 1.0            |
| P00B25    | 0.0                   | 2.5            |

Table 3 Base Material Mix Ratio under Different Water-binder Ratio

| Numbering | Water-binder ratio | Cement | Fly ash | Sand | Water | water reducing agent | Thickener |
|-----------|-------------------|--------|---------|------|-------|----------------------|-----------|
| M0.25     | 0.25              | 1.0    | 1.2     | 0.8  | 0.55  | 0.0070               | 0.0002    |
| M0.30     | 0.30              | 1.0    | 1.2     | 0.8  | 0.66  | 0.0025               | 0.0002    |
| M0.35     | 0.35              | 1.0    | 1.2     | 0.8  | 0.77  | 0.0018               | 0.0004    |
| M0.40     | 0.40              | 1.0    | 1.2     | 0.8  | 0.88  | 0.0015               | 0.0004    |

2.2. specimen preparation
In this test, the bending beam specimen size is 100mm×100mm×400mm, which is cured for 28 days after forming. The mid-span notch of the beam is formed by cutting, which is cut by a cutting machine one day before the three-point bending test. The pre-notch in the span is 2mm wide and 28mm deep, and a hacksaw strip is used to manufacture the tip at the top of the notch, as shown in Fig.1.

2.3. test equipment and equipment
The test loading device is MTS SHT4106 universal testing machine, which adopts hierarchical loading control, and the loading speed is force control. First, it is loaded to 3kN at a speed of 15N/s, and then it is loaded at a speed of 10N/s until the specimen is completely destroyed. The extensometer is used to measure the crack opening displacement during loading, and the mid-span displacement data uses the loading point displacement of the testing machine. See fig.1 for the schematic diagram. During the test, DS5-8B all-information acoustic emission system was used to monitor the internal damage and fracture of the test piece. As shown in Fig.1, the sensor was adhered to the top points 1, 2, 3 and 4 of the test piece with high vacuum silicone grease. Before the start of each test, a 0.5mm 2B pencil was used for lead breakage test calibration. See fig.2 for placement and loading mode of pre-cut three-point bending beam, acquisition mode of crack opening displacement and acoustic emission monitoring.

2.4. acoustic emission monitoring during fracture
In this experiment, Ringing Count is taken as the special parameter of acoustic emission. By coupling CMOD-Time data measured by universal testing machine and Ringing Count-Time data measured by acoustic emission through time variables, a group of data points corresponding to ringing count and opening displacement of crack can be obtained. The relationship between P-CMOD and Ringing Count-CMOD as shown in the figure can be obtained by plotting it with the data points of load and crack opening displacement. By analyzing the ringing count caused by acoustic emission, the comprehensive curve method can qualitatively judge the turning point from linear segment to nonlinear segment on the P-CMOD curve more accurately.
3. Fracture properties of PVA/BF-ECC

3.1. Determination of Double K Fracture Parameters

3.1.1. Crack initiation load

The appearance of fracture process zone at the crack tip of concrete leads to the nonlinearity of the rising section of P-CMOD curve. Many scholars believe that the load corresponding to the turning point from linear to nonlinear of P-CMOD curve is the crack initiation load $P_{ini}$. Generally, $P_{ini}$ can be determined by curve method (P-CMOD curve or load-displacement curve). When the crack initiation load is determined by curve method, mainly by finding out the turning point from linear section to nonlinear section on the curve, this point is defined as the crack initiation point, and the corresponding load is the crack initiation load $P_{ini}$.

3.1.2. Fracture toughness

When the external load of concrete specimen reaches the crack initiation load $P_{ini}$, the structural performance is still in the linear elastic range. Therefore, by substituting the initial crack length $a_0$ and the crack initiation load $P_{ini}$ measured in the test into the linear elastic fracture mechanics formula, the crack initiation fracture toughness $K_{ini}$ of concrete can be obtained. Adopting the stress intensity factor calculation formula recommended by Tada\cite{7} in its stress intensity factor manual, For standard three-point bending beams:
In which $s$ is the span between two supports of the specimen, $b$ is the thickness of the specimen, and $d$ is the height of the specimen. When the structure is unstable, although the concrete material has entered the viscoelastic stress stage, according to the linear elastic progressive assumption, the unstable fracture toughness $K_{Ic}$ can still be calculated by the formula in linear elastic fracture mechanics, and the unstable load $P_{\text{max}}$ and the critical effective crack length $a_c$ are used for calculation. For standard three-point bending beams:

$$
K_{Ic} = \frac{3P_{\text{max}}\sqrt{a_0}}{2bd^2} f(\alpha) \\
f(\alpha) = \frac{1.99-\alpha(1-\alpha)(2.15-3.93\alpha+2.7\alpha^2)}{(1+2\alpha)(1-\alpha)^{3/2}}, \quad \alpha = \frac{a_0}{d}
$$

(1)

3.1.3. Critical equivalent length

According to the concept of elastic equivalence, the fracture process zone can be equivalent to an elastic crack, so the equivalent crack length can be determined by P-CMOD curve according to elastic theory. For the standard three-point bending notched beam, Tada[7] gives the relationship between load and crack opening displacement in its stress intensity factor book, specifically as follows:

$$
CMOD = \frac{6PSaV(\alpha)}{d^2bE} \\
V(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1-\alpha)}^{1/2}, \quad \alpha = \frac{a}{d}
$$

(2)

In this formula, CMOD is the crack opening displacement, $P$ is the external load, $a$ is the equivalent crack length, $S$ is the span between two supports of the specimen, $b$ is the thickness of the specimen, $d$ is the height of the specimen, and $E$ is the elastic modulus. Because equation (5-3) is a sixth power function about $\alpha$, the solution is very complicated. In order to facilitate the calculation, a simplified formula[8] is proposed:

$$
CMOD = \frac{P}{Eb}\left[3.70 + 32.60\tan^2\left(\frac{\pi}{2}\alpha\right)\right]
$$

(4)

Therefore, we can get:

$$
a_c = \frac{2d}{\pi}\arctan\sqrt{\frac{CMOD_c}{32.6P_{\text{max}}} E_c b - 0.1135}
$$

(5)

$$
E_c = \frac{1}{bc_{c,i}}\left[3.70 + 32.60\tan^2\left(\frac{\pi}{2}\alpha\right)\right]
$$

(6)

In which, $a_c$ is the critical equivalent length, $CMOD_c$ is the critical crack opening displacement, $P_{\text{max}}$ is the instability load, $E_c$ is the calculated elastic modulus, and $c_i = CMOD_i/F_i$ is calculated by (CMOD, $P_i$) at any point on the elastic section of P-CMOD curve.

3.2. Fracture properties of PVA/BF-ECC based on synergistic effect hybrid

The P-CMOD curves of PVA/BF-ECC prefabricated notched three-point bending beams under different water-binder ratios were measured. As shown in Fig.3, it was clearly observed that the fracture performance of PVA fiber composite was the best under all water-binder ratios. With the increase of BF fiber instead of PVA, the peak displacement of the curves began to retract, and the slope of softening curves also began to steep. According to the method for determining the double $K$ fracture parameters introduced in section 1, the critical equivalent length $a_c$, the fracture toughness $K_{Ic}$ at initiation and the fracture toughness $K_{Ic}$ at instability can be obtained by analyzing the P-CMOD curve. It should be noted
that the specimen size used in this test is non-standard size, which should be converted into the fracture toughness of standard specimen.

3.2.1. Influence of BF Volume Substitution Rate on Fracture Properties
Firstly, the influence of hybrid ratio of strength fibers of each substrate on crack initiation load \( P_{\text{ini}} \) and instability load \( P_{\text{max}} \). Fig. 4 reflects the change of \( P_{\text{ini}} \) and \( P_{\text{max}} \) with the change of fiber mixing ratio under the strength of each substrate. \( P_{\text{ini}} \) shows an increasing trend with the increase of the content of BF equivalent volume instead of PVA fiber when the strength of the substrate is constant.

For \( P_{\text{max}} \), when the water-binder ratio is 0.25, it decreases with the increase of BF substitution content. When the water-binder ratio is 0.30, it shows a trend of increasing at first and then decreasing, and \( P_{\text{max}} \) is the largest when P20B05 is mixed. However, when the water-binder ratio is 0.35 and 0.40, it decreases at first and then increases. In addition, as can be seen from table 4, CMOD\(_c\), the critical crack opening displacement corresponding to \( P_{\text{max}} \), decreases with the increase of BF substitution content. Considering the change rule of \( P_{\text{max}} \) comprehensively, it can be seen that BF has stronger ability in crack width control than PVA fiber.
The mixing ratio of P00B25 is consistent with the instability load, that is, the instability fracture increased at first and then decreased. The highest value is obtained when the water-binder ratio is 0.30; toughness of the composite decreases at first and then increases at the mixed ratio of P25B00 and 0.35, and the water-binder ratio is 0. On the contrary, the instability load at 35 and 0.40 is larger than for the mixed ratio of P00B25, the instability load suddenly increases when the water-binder ratio is P25B00, P20B05 and P15B10, the instability load also decreases with the increase of water-binder ratio; three-point bending beam shows a decreasing trend at various hybrid ratios; Under the mixed ratio of PVA/BF-ECC pre-notched Fig.6, with the increase of water-binder ratio, the crack initiation load of PVA fiber alone is much higher than that with BF alone. In fracture mechanics, crack initiation fracture toughness indicates the ability of a structure with cracks to resist external forces when cracks begin to propagate, and the structure is only subjected to external loads when cracks have not yet developed. Unstable fracture toughness indicates the ability of a structure to resist external forces when unstable failure occurs. According to the test results, BF has a higher ability to resist external forces when the composite works with cracks before the cracks begin to propagate, while PVA fiber has a higher ability to delay damage after the cracks begin to propagate.

**3.2.2. Influence of Water-binder Ratio on Fracture Properties**

The first is the influence of water-binder ratio on crack initiation load and instability load. As shown in Fig.6, with the increase of water-binder ratio, the crack initiation load of PVA/BF-ECC pre-notched three-point bending beam shows a decreasing trend at various hybrid ratios; Under the mixed ratio of P25B00, P20B05 and P15B10, the instability load also decreases with the increase of water-binder ratio; for the mixed ratio of P00B25, the instability load suddenly increases when the water-binder ratio is 0.35, and the water-binder ratio is 0.0. On the contrary, the instability load at 35 and 0.40 is larger than that at 0.25 and 0.30. Then, the influence of water-binder ratio on fracture toughness at initiation and fracture toughness at instability is discussed.

As shown in Fig.7, consistent with the law of crack initiation load, the fracture toughness decreases with the increase of water-binder ratio. With the increase of water-binder ratio, the instability fracture toughness of the composite decreases at first and then increases at the mixed ratio of P25B00 and P15B10, and the toughness at 0.40 is slightly higher than that at 0.35. The mixing ratio of P20B05 increased at first and then decreased. The highest value is obtained when the water-binder ratio is 0.30; The mixing ratio of P00B25 is consistent with the instability load, that is, the instability fracture toughness suddenly rises when the water-binder ratio is 0.35. It can be seen from the above laws that
crack initiation load and fracture toughness have high sensitivity to the strength of substrate, but the factors affecting the unstable fracture toughness may be complicated. The change of unstable fracture toughness reflects the difference of mechanism between BF and PVA fibers in strengthening and toughening cement-based composites. Then, the influence of water-binder ratio on critical fracture opening displacement CMODc is analyzed. It can be seen from Fig 8 that with the increase of water-binder ratio, the value of CMODc in each hybrid ratio shows an increasing trend, which indicates that when the strength of the substrate is low, composite materials have better bending ability, and the better the toughening effect of fiber on composite materials.

4. Conclusion

(1) When the strength of the substrate is the same, the equal volume of BF is used instead of PVA fiber, and the fracture toughness of PVA/BF-ECC increases with the increase of the relative volume content of BF; The fracture toughness of PVA/BF-ECC with the same fiber blending ratio decreases with the increase of water-binder ratio.

(2) For the unstable fracture toughness, when the strength of the substrate is constant and based on the synergistic effect, the unstable fracture toughness after mixing BF is much smaller than that when adding PVA fiber alone.

(3) When the PVA fiber is replaced by 0.5vol%BF in high strength substrate, the fracture toughness is 13.68MPa\(\cdot\)m\(^{1/2}\) and 14.38MPa\(\cdot\)m\(^{1/2}\), respectively. In the low strength substrate, when 0.5 vol% BF replaces PVA fiber, the unstable fracture toughness is 12.12MPa\(\cdot\)m\(^{1/2}\) and 12.20MPa\(\cdot\)m\(^{1/2}\), respectively, which can keep high unstable fracture toughness.
References

[1] Cheng qi, Wu keru. Hybrid fiber cement-based composites and their applications [J]. industrial architecture, 2002(09):51-53.

[2] Li F M, Li Z J. Acoustic Emission Monitoring of Fracture of Fiber-Reinforced Concrete in Tension[J]. Materials Journal, 2000,97(6).

[3] Li D S, Hai C, Ou J. Fracture behavior and damage evaluation of polyvinyl alcohol fiber concrete using acoustic emission technique[J]. Materials and Design, 2012,40.

[4] Tschegg E K. Energy dissipation capacity of fibre reinforced concrete under biaxial tension-compression load. Part II: Determination of the fracture process zone with the acoustic emission technique[J]. Cement and Concrete Composites, 2015,62:187-194.

[5] Thirumalaiselvi A, Sindu B S, Sasmal S. Crack propagation studies in strain hardened concrete using acoustic emission and digital image correlation investigations[J]. 2020.

[6] Wang Zhenbo. Study on mechanical properties of polyvinyl alcohol-steel fiber hybrid reinforced cement-based composites [D]. Tsinghua University, 2016.

[7] Tada H, Paris P C, Irwin G R. The stress analysis of cracks handbook[M]. ASME Press, 2000.

[8] Xu Shiling. Fracture Mechanics of Concrete [M]. Science Press, 2011.