Experimental Study on Flexural Toughness of Steel-Polyvinyl Alcohol Hybrid Fiber Reinforced Concrete

Ningyue Su* and Xiaochun Fan
School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China
Email: 1254755644@qq.com

Abstract: In order to study the flexural toughness of Steel(S)-Polyvinyl Alcohol (PVA) Hybrid Fiber reinforced Concrete, 10 specimens of hybrid fiber reinforced concrete with dimensions of 100 mm × 100 mm× 400 mm were studied by four point bending test. The load-deflection curve of hybrid fiber reinforced concrete beam was obtained, and its toughness was evaluated by flexural toughness index method. The results showed that the simultaneous incorporation of steel fiber and PVA fiber greatly improves the ultimate load and toughness index of concrete during bending failure, and fiber concrete has obvious strain hardening phenomenon. When PVA fiber volume content is 0.75% and steel fiber volume content is 1.25%, hybrid fiber concrete shows good positive hybrid effect, which is the most ideal to improve the bending performance of concrete matrix. And the research conclusion provides reference for the design and engineering application of hybrid fiber concrete.

Keywords. Hybrid fiber, concrete, flexural toughness, hybrid effect.

1. Introduction
As the most widely used construction material in engineering, concrete has the biggest disadvantages of low tensile strength, poor tenacity, and apparent brittleness. Incorporating fiber into concrete is an effective way to improve its toughness. The incorporation of fiber can not only improve the tensile strength of concrete and reduce its brittleness and it can also greatly inhibit the expansion of early microscopic cracks in the concrete [1-3]. Steel-Polyvinyl alcohol (PVA) hybrid fiber concrete usually refers to a new type of high-performance composite material obtained by mixing PVA fiber and steel fiber of different sizes and properties into regular concrete at the same time. The two kinds of fiber play their own functional characteristics in concrete. PVA fiber can evidently inhibit the generation and expansion of early micro cracks in the concrete. Larger steel fiber with high elastic modulus can inhibit the expansion and extension of cracks in concrete under greater load. Incorporation of the two types of fiber can effectively control the propagation and expansion of cracks in concrete structures at multiple stages and levels, thereby improve the mechanical properties and durability of the concrete. Scholars all over the world have carried out a large number of experimental studies on the mechanical properties of hybrid fiber concrete [4-6]. Existing results focus mainly on the hybrid effect and mechanical properties of different types or sizes of fiber. Very limited research has studied on the hybrid ratio and combination optimization of different types of fiber. In this paper, a four-point bending performance test of steel-PVA hybrid fiber concrete specimens with different volume content was used to obtain the load-deflection curve. The flexural toughness index method was used to evaluate the flexural toughness of steel-PVA hybrid fiber concrete beams with different hybrid ratios, to study the flexural toughness performance of hybrid fiber concrete with different fiber mixing.
content, and to explore the mechanism of flexural toughness of steel-PVA hybrid fiber concrete, hence give the optimal volume of hybrid fiber content of steel-PVA hybrid fiber concrete, and provide a reference for the engineering design and application of steel-PVA hybrid fiber concrete.

2. Experimental Design

2.1. Experimental Materials

The cement selected was the Huaxin brand P. 042.5 regular grade Portland cement, the steel fiber was copper-plated micro-wire steel fiber manufactured by Fangda Metal Wire Mesh Products Co, and the PVA fiber was Kuraray K-II fiber produced by the Japanese Kuraray Company. The physical properties of the steel fiber and PVA fiber are shown in tables 1-2.

| Name   | Density g/cm³ | Diameter/mm | Length/mm | Elastic Modulus/GPa | Tensile strength/MPa | Ultimate elongation/% |
|--------|---------------|-------------|-----------|---------------------|-----------------------|-----------------------|
| Steel fiber | 7.8           | 0.22        | 13        | 210                 | ≥2850                 | 25                    |

| Name   | Density g/cm³ | Diameter/mm | Length/mm | Elastic Modulus/GPa | Tensile strength/MPa | Elongation/% |
|--------|---------------|-------------|-----------|---------------------|-----------------------|--------------|
| REC15×12 | 1.3           | 0.04        | 12        | 41                  | 1650                  | 6            |

2.2. Concrete Mix Ratio and Specimen Production

Regular concrete with a strength grade of C30 was configured in accordance with the “General Concrete Mixture Design Regulations” (JGJ55-2011) [7]. The mixture ratio is shown in table 3, and the fiber volume content of each specimen is shown in table 4. According to the “Fiber Concrete Test Method Standard” (CECS13: 2009) [8], since short fiber with a length less than 40 mm were used, the beam specimen size used in this test was 100×100×400 mm.

| Name   | Density g/cm³ | Diameter/mm | Length/mm | Elastic Modulus/GPa | Tensile strength/MPa | Elongation/% |
|--------|---------------|-------------|-----------|---------------------|-----------------------|--------------|
| Cement | 310           | 820         | 1007.5    | 41                  | 55                    | 3.62         |

| Specimen number | PVA volume content % | Steel fiber volume content % | Fiber total volume content % |
|-----------------|----------------------|------------------------------|-----------------------------|
| PS0             | 0                    | 0                            | 0                           |
| PS1             | 2.0                  | 0                            | 2.0                         |
| PS2             | 1.75                 | 0.25                         | 2.0                         |
| PS3             | 1.50                 | 0.50                         | 2.0                         |
| PS4             | 1.25                 | 0.75                         | 2.0                         |
| PS5             | 1.0                  | 1.0                          | 2.0                         |
| PS6             | 0.75                 | 1.25                         | 2.0                         |
| PS7             | 0.50                 | 1.50                         | 2.0                         |
| PS8             | 0.25                 | 1.75                         | 2.0                         |
| PS9             | 0                    | 2.0                          | 2.0                         |

Table 3. Concrete mix ratio (kg/m³).

Table 4. Specimen fiber content.
2.3. Experimental Method
The test used the American MTS electro-hydraulic servo material testing machine for loading, the loading distribution beam used a custom sliding steel support, the load collection used a load sensor, and the mid-span deflection was measured with an LVDT displacement meter. The test data were collected using the German IMC data acquisition system, and the load-deflection curve was obtained with a sampling frequency of 10 Hz. To ensure the homogeneity of the concrete matrix, the molded side of the specimen was placed on the support as the loading surface. According to figure 1(a), the specimen was continuously and uniformly loaded. The loading speed before the initial cracking was 0.05 MPa/s. To ensure a consistent deflection growth rate, the beam was loaded with displacement control after the concrete cracks, and the speed was 0.1 mm/min. The field loading test is shown in figure 1(b).

3. Analysis of Specimen Failure Form and Load-Deflection Curve
The regular concrete beam (PS0) showed apparent brittle failure patterns. When the load reached 14.92 KN, cracks began to occur in the tensile zone of the specimen. After cracks appeared in the specimen, they quickly developed to the top of the beam, and the test beam was destroyed instantly, exhibiting a phenomenon of rapid fracture of concrete as soon as it cracks, and the tenacity was poor. After the concrete was mixed with fiber or hybrid fiber, different types of fiber started to play a role at different stages and different levels when the concrete was under load. Under a small load, the fiber bore less before the concrete tension zone cracked, and the tension was mainly carried by the concrete. When micro cracks appeared inside the specimen, PVA fiber began to play a bridging role, which significantly inhibited the extension and expansion of micro cracks and effectively prevented the decrease in bearing capacity. Compared with regular concrete, hybrid fiber concrete had finer cracks and smaller spacing at the same time. As the load continues to increase, the PVA fiber started to be partially pulled out or even broken at the cracked section. At this time, the larger-sized steel fiber began to bear the tensile force. The bonding force of the hybrid fiber and the concrete matrix jointly assumed the external load. Steel fiber effectively delayed and prevented the further extension and expansion of cracks. When the failure load was reached, the specimen could still withstand a certain load, and most of the steel fibers at the failure section were pulled out or broken. As the volume of PVA fibers increased, the tensile stress distribution at the bottom of the beam became more uniform, and the effect of the hybrid fiber on crack resistance of the concrete matrix was more apparent. The failure form of hybrid fiber concrete was a typical ductile failure, and the form of failure is shown in figure 2.
Figure 2. Failure forms of hybrid fiber concrete.

(a) PS1–3
(b) PS4–6
(c) PS7–9

Figure 3. Concrete load-deflection curve

It can be seen from figure 3 that the load-deflection curve of the steel-PVA hybrid fiber concrete has obvious concrete working phases, softening phase, fiber reinforcement phase, and slow unloading phase. At the initial stage of loading, the load-deflection curve of steel-PVA hybrid fiber concrete was basically the same as that of regular concrete, and the concrete matrix and fiber jointly bore the external force. When the initial micro cracks appeared at the bottom of the beam, the load-bearing capacity of the SPFRC decreased, and the bridging effect of the fiber apparently prevented the further reduction of its load-bearing capacity. It can be seen from the curve that when the load started to rise slowly, the increase in deflection became faster than the increase in load. The specimens had undergone plastic deformation. Under the condition of 2% total fiber volume mix, the peak load of the hybrid fiber concrete specimens had an apparent increase compared with the single-doped PVA or steel fiber specimens, and the curve became smoother. This reveals that different types of fibers play
their bridging roles at different stages of stress. When the volume contents of the steel fiber and PVA fiber were similar (PS6), the load-deflection curve was the most full, the concrete tenacity was the best, and the energy absorbed reached the maximum. The mixing of PVA fiber and steel fiber has caused obvious strain hardening of the specimen, and the incorporation of fiber significantly improved the mechanical properties and bending tenacity of the concrete.

4. Calculation and Analysis of Bending Toughness

Toughness indicates the ability of a material to absorb energy during plastic deformation and fracture. The better the toughness, the lower is the possibility of brittle fracture. According to the method of calculating flexural toughness of China’s “Fiber Concrete Test Method Standard” (CECS13: 2009), the flexural toughness index was used to evaluate the flexural toughness of the concrete. As shown in figure 4, with O as the origin, the initial crack deflection multiple was selected as 1.0, 3.0, 5.5, and 10.5 of the deflection point, denoted as A, B, C, and D respectively. The areas of OAE, OBFE, OCGE, and ODHE enclosed by the load-deflection curve and the horizontal axis were calculated by the method of quadrature, which were denoted as \( \Omega_{\delta} \), \( \Omega_{3\delta} \), \( \Omega_{5.5\delta} \) and \( \Omega_{10.5\delta} \) respectively. The bending toughness index of the specimen was calculated using the following equations:

\[
I_5 = \frac{\Omega_{3\delta}}{\Omega_{\delta}}, \quad I_{10} = \frac{\Omega_{5.5\delta}}{\Omega_{\delta}}, \quad I_{20} = \frac{\Omega_{10.5\delta}}{\Omega_{\delta}}
\]

(1)

![Figure 4. Schematic diagram of bending toughness calculation.](image)

| Specimen Number | Ultimate load /kN | Flexural Toughness Index \( I_5 \) | Flexural Toughness Index \( I_{10} \) | Flexural Toughness Index \( I_{20} \) |
|----------------|------------------|----------------|----------------|----------------|
| PS0            | 14.92            | 1.11           | 1.11           | 1.11           |
| PS1            | 19.26            | 3.98           | 9.38           | 17.26          |
| PS2            | 22.71            | 5.23           | 12.95          | 26.81          |
| PS3            | 26.68            | 6.25           | 14.20          | 26.17          |
| PS4            | 28.55            | 5.31           | 12.08          | 21.70          |
| PS5            | 31.46            | 5.67           | 13.59          | 26.01          |
| PS6            | 35.27            | 6.79           | 14.42          | 26.93          |
| PS7            | 33.18            | 5.19           | 11.84          | 22.04          |
| PS8            | 29.42            | 5.40           | 11.58          | 20.00          |
| PS9            | 28.39            | 5.39           | 11.19          | 16.40          |
It can be seen from Table 5 that the toughness index $I_4$ is 3.58–6.12 times higher than that of regular concrete; the toughness index $I_{10}$ is 8.45–12.99 times higher than that of regular concrete; $I_{20}$ is 14.77–24.26 times higher than that of regular concrete. It shows that the addition of hybrid fibers enables the concrete to absorb more energy, thereby pronouncedly improves the brittleness and toughness of the concrete. The reinforcement and toughening effect of concrete is the best when the volume content of PVA fiber is 0.75% and the content of steel fiber is 1.25%, and the flexural toughness index $I_8$, $I_{10}$ and $I_{20}$ all reach the maximum. The flexural toughness index $I_{30}$ is 24.26 times that of regular concrete. In general, the ideal flexural toughness indices of elastic materials are 5, 10, and 20 respectively, indicating that the hybrid fiber concrete absorbs more energy, has obvious crack resistance, and exhibits good toughness.

5. Conclusion
In this paper, through four-point bending performance test of steel-PVA hybrid fiber concrete test beam, the influence of different fiber mix volume contents on concrete bending performance was studied. The failure form and load-deflection curve of the specimen were analyzed, the bending toughness was evaluated, and the following conclusions were drawn:

(1) Steel-PVA hybrid fiber concrete beam is a typical form of ductile failure, showing apparent strain hardening phenomenon. The simultaneous incorporation of steel fiber and PVA fiber can significantly improve the toughness index and peak load of the concrete. PVA fiber can effectively control the development of initial cracks. Different types of fibers play their role of toughening and cracking resistance at different stress stages of the concrete matrix.

(2) After adding steel-PVA hybrid fibers, the flexural toughness of concrete can be greatly improved. The toughness index $I_5$ is 3.58–6.12 times higher than that of regular concrete; the toughness index $I_{10}$ is 8.45–12.99 times higher than that of regular concrete; $I_{20}$ is 14.77–24.26 times higher than that of regular concrete. It indicates that the hybrid fiber concrete absorbs more energy, has obvious crack resistance, and exhibits excellent toughness.

(3) The mixing effect of PVA fiber with a volume content of 0.75% and steel fiber with a volume content of 1.25% is the best, the concrete has the largest flexural toughness index, showing a good positive mixing effect, and greatly improving the ultimate bearing capacity and flexural toughness of the matrix.

References
[1] Wei J Y, Liu H W and Zhang Y 2017 Impact resistance properties research for Steel-PVA hybrid fibers concrete Concrete 12 51–62
[2] Mei G D, Li J X and Liu X F 2013 Hybrid fiber reinforced concrete flexural behaviour and hybrid effects Concrete (2) 21–24
[3] Xu A H 2014 Influence of Steel-PVA hybrid fibers for cement concrete on bending toughness Highway Engineering 39(2) 88-92
[4] Yu J, Zhai T W and Liang X W 2018 Fluidity and mechanical properties of steel-PVA fiber reinforced concrete Journal of Building Materials 21(3) 1-10
[5] Zhong G C, Zhou Y and Xiao Y 2020 Stress-strain behaviour of Steel-Polyvinyl alcohol hybrid fiber reinforced concrete under axial compression and tension Engineering Mechanics 37(S) 1-10.
[6] Hua Y, Lian J Y and Zhou T Q 2005 Relationship between the mechanical properties of hybrid fiber reinforced concrete and length/diameter aspect ratio of hybrid fiber Journal of building materials 8 (1) 71-76
[7] State Standards of the People's Republic of China 2011 Code for Design of Concrete Mix Proportion JGJ55-2011 Beijing: China Architecture & Building Press.
[8] The standard of China Engineering Construction Association 2009 Standard for Test Methods of Fiber Concrete CECS13: 2009 Beijing: China planning press.