# Flexural performance of a new hybrid basalt-polypropylene fiber-reinforced concrete oriented to concrete pipelines

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**Abstract:** The bending performance of a basalt-polypropylene fiber-reinforced concrete (HBPFRC) was characterized by testing 24 400×100×100 mm$^3$ prismatic specimens in a four-point bending test JSCE-SF4 configuration. The type and content of both fibers was varied in order to guarantee different target levels of post-cracking flexural performance. The results evidenced that mono-micro basalt fiber reinforced concrete (BFRC) allows the increase of the flexural strength (pre-cracking stage), while macro polypropylene fiber reinforced concrete can effectively improve both bearing capacity and ductility of the composite for a wide crack width range. Compared with the plain concrete specimens, flexural toughness and equivalent flexural strength of macro polypropylene fiber-reinforced concrete (PPFRC) and the hybrid fiber-reinforced concrete (HFRC) increased by 3.7~7.1 times and 10%~42.5%, respectively. From both technical and economic points of view, the optimal mass ratio of basalt fiber to polypropylene fiber resulted to be 1:2, with a total content of 6 kg/m$^3$. This HFRC is seen as a suitable material to be used in sewerage pipes where cracking control (crack formation and crack width control) is of paramount importance to guarantee the durability and functionality of the pipeline as well as the ductility of the system in case of local failures.

**Keywords:** basalt-polypropylene fiber-reinforced concrete, flexural performance, residual strength, optimal ratio

## 1. Introduction

It is well known that concrete is one of the most widely used civil materials for various engineering, such as hydraulic engineering, architectural engineering, road and bridge engineering. However, the concrete used in engineering usually had a large number of cracks, thus making the concrete brittle and subject to varying degrees of damage under external loads [1]. For the safety and reliability of concrete structures, higher requirements should be put forward for the energy dissipation capacity of concrete. FRC not only improves the brittleness of concrete but also significantly enhances the toughness and energy dissipation capacity of concrete [2,3]. Thus, FRC has become a widely used composite building material.

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At present, many countries in the world have successively established the standard test methods for testing the bending performance of fiber concrete, such as JSCE-SF4 [4], ASTM C1018 [5] and CECS 13:2009 [6]. These standards provide a precise calculation method for the flexural strength, flexural toughness index and energy absorption of fiber concrete materials. For now, researchers have made a lot of studies on the flexural toughness of hybrid fiber concrete, and the main fibers in these studies are mainly steel fiber[7], polyolefin fiber [8] and polypropylene fiber [9]. In addition, considering that the mechanical properties of concrete reinforced with different types of hybrid fibers, which is termed hybrid FRC (HFRC), are usually superior to that of concrete reinforced with mono-fiber [10-13], HFRC is produced to achieve overall improvement both in energy absorption capacity and tensile strength.

It's well known that coarse and long fibers control the propagation of macro-cracks and improve the toughness at the post-crack region [14,15], while micro and short fibers bridge the micro-cracks, thereby enhancing the peak-strength [16]. So the combination of different lengths of fibers, different diameters of fibers and different elastic modulus of fibers are often adopted by the researchers [17-19]. An example of HFRC is the hybrid steel-polypropylene fibers, which are commonly used and have obtained good hybrid effects [20-22]. However, steel fiber is easy to corrode, which is not conducive to the long-term stability of the structure. Moreover, the incorporation of steel fiber will not only reduce the workability of concrete but also increase the weight of concrete [23,24]. Therefore, under certain environmental conditions (such as an acidic environment), it is necessary to use corrosion-resistant material instead of steel fiber to improve the performance of concrete.

As a material with excellent physical and mechanical properties, basalt fiber is characterized by good temperature stability, high tensile strength, strong corrosion-resistance, good deformation performance, low price, safe and environmental protection, etc. [25-27], so it is more and more widely used to produce FRC. Fu et al. [28] pointed out that HBPFRC showed excellent crack propagation inhibition and fire resistance, and it showed that steel fiber could be replaced by basalt fiber in terms of fire resistance. Indeed, researchers have paid attention to the dynamic performance

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[29,30] and flexural toughness [31,32] of HBPFRC. However, in the above studies, polypropylene fibers are all fine fibers, while the previous study [33] has shown that the improvement effect of macro polypropylene fibers on the bending properties of concrete is far superior to that of fine polypropylene fibers.

Therefore, basalt fiber and macro polypropylene fiber are selected to be mixed into the concrete matrix to produce HBPFRC specimens. Furthermore, according to the Code CECS 13：2009 [6], the flexural performance of HBPFRC specimens were investigated by the four-point bending tests. This paper studies the flexural properties of HBPFRC, which indicates that this hybrid fiber reinforced concrete composite is a suitable material to be used in structures, such as sewerage pipes, where cracking control is of vital importance to guarantee the durability and functionality of the pipeline as well as the ductility of the system in case of local failures.

### *1.1 Test material*

The cement adopted in this test is portland cement P.O.52.5. The coarse aggregate used were stones with grain sizes of 10-20 mm and 5-10 mm, while the fine aggregates were sands of dimensions less than 5 mm. A commercially available polycarboxylic acid superplasticizer was adopted to improve concrete workability, and the water reducing rate of it is 28%. The concrete mix proportion is shown in Table 1.

The fibers used in this test are macro polypropylene fiber with a wavy surface and micro basalt fiber with a smooth surface, as shown in Fig. 1.

In addition, the properties of the selected fibers are shown in Table 2.

### *1.2 Test material preparation*

There are eight groups of HBPFRC with different fiber content, including two groups of mono-fiber, five groups of hybrid basalt-polypropylene fiber as well as one control group (no fiber). Details of each group specimen for the flexural bending test are shown in Table 3.

The mixability of fiber is very important to improve the performance of fiber concrete. In order to make properly distribute the fiber into the concrete, referring to relevant specification and literature [6,34], the mixing process adopted in this experiment is as follows:

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(1) Pour the pre-weighted coarse and fine aggregates into the forced mixer and mix the materials for 1 minute.

(2) Evenly scatter the macro polypropylene fiber and basalt fiber into the mixer, and the mixing process still lasted for 2 minutes after the fibers are all put into the mixer.

(3) Pour the cement into the mixer and start mixing for 1 minute.

(4) Pour the water and water reducer slowly and evenly into the mixer and keep mixing for minutes.

(5) Pour out the mixture and then pour them into the mold to produce HBPFRC specimens.

Part of the production and curing procedures of HBPFRC specimens are shown in Fig. 2.

In this test, each group contained three replicate specimens. According to CECS 2009 [6], a total of 24 concrete specimens with a length × width × height of 400mm×100mm×100mm were produced, and the four-point bending test was conducted after 28 days of curing.

### *1.3 Experimental test method*

The four-point bending test was conducted to measure the flexural bending performance of concrete. The test device was the INSTRON−1346 hydraulic servo testing machine system. YOKE method is used to measure the deflection of beams [4]. Displacement control was adopted for continuous loading in the test, and the loading rate was 0.1 mm /min. After the deflection of the specimen reached 4 mm, the test was stopped. The test process was shown in Fig. 3.

## 2. Test result

### *2.1 Load-deflection curve*

The load-deflection curves of each group of HBPFRC specimens are shown in Fig. 4 (a) ~ (g).

According to Fig. 4 (a) ~ (g), it can be seen that for the control group specimen B0P0 and the mono-basalt FRC specimen B6P0, the load of which immediately decreased to zero after it reached the peak value. B0P0 and B6P0 showed obvious brittleness, and they fractured into two parts in the middle. However, compared with

B0P0, the descending stage of B6P0 was relatively slow, indicating the brittleness of concrete is somewhat improved due to the addition of mono-basalt fiber.

As for the specimens with macro polypropylene fiber, although the bearing capacity of these specimens will drop instantly after reaching the peak load, they still maintain a certain residual strength and will not break during the whole test process. It was found that the macro polypropylene fiber was continuously pulled out and broken during the loading process, which reflected the noticeable bridging effect of the fiber. The descending stage of the load-deflection curves fluctuated to some extent locally due to the pulled out and broken of fibers, but the curves were generally gentle, and even the phenomenon of secondary peak appeared in different degrees. Among them, the secondary peak value of B0P6 and B2P4 was particularly apparent. It can be seen that the addition of macro propylene fiber significantly improves the bending performance of concrete specimens.

***2.2 Flexural strength***

The peak load of each group specimen is extracted, and then the flexural strength of concrete is calculated by Eq. 1:

$$f_b = \frac{P.L}{b.h^2} \qquad (1)$$

Where $f_b$ is the flexural, MPa; $P$ is peak load, N; $L$ is the span of the specimen, mm; $b$ is the section width of the specimen, mm; $H$ is the height of the specimen section, mm.

The flexural strengths of FRC specimens in this test are shown in Fig. 5.

As shown in Fig. 5, the flexural strength of the control group specimen B0P0 is 4.0 MPa, while the flexural strength of the mono-basalt FRC specimen B6P0 is 4.4 MPa, increased by 10%. As for the flexural strength of the mono-macro polypropylene FRC specimen B0P6, it increases to 5.2 MPa with a growth rate of 30%. It can be seen that the improvement effect of macro polypropylene fiber on the flexural strength of concrete specimens is more significant than that of basalt fiber. Among the HBPFRC specimens, when the mass ratio of basalt fiber to macro polypropylene fiber is 1:2, the flexural strength of the specimen B2P4 reached 5.7 MPa, and the flexural strength

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increased the most, reaching 42.5%. This may be due to the good hybrid effect of basalt fiber and macro polypropylene with this hybrid ratio.

***2.3 Flexural toughness***

Flexural toughness ($T_b$) is used to describe the energy absorption capacity of concrete quantitatively. The flexural toughness evaluation method suggested by JSCE -SF4 [4] is adopted in this paper, which does not need to determine the deflection of the initial crack point, and the unstable section of the curve has little influence on it. Flexural toughness is defined as the envelope area of the load-deflection curve under deflection from 0 mm to 1/150 L (2 mm in this paper). Because control group specimens and mono-basalt FRC specimens showed brittle failure during the loading process, the flexural toughness of which are calculated by the envelope area of all load-deflection curves according to the literature [35]. Fig. 6 shows the flexural toughness of different concrete specimens.

It can be seen from Fig. 6 that the flexural toughness of the control group specimen B0P0 is only 2.0 J, while the flexural toughness of the mono-basalt FRC specimen B6P0 is 3.0 J, increasing by 50%. The flexural strength mono-macro polypropylene fiber is 13.3 J, which is 5.65 times higher than that of the control group. It can be seen that compared with basalt fiber, the macro polypropylene fiber has a more significant effect on improving the flexural strength of concrete. Among the HBPFRC specimens, the flexural toughness of B4.8P1.2 is the lowest, but it is still 4.25 times higher than that of the control group specimen B0P0. When the mass ratio of basalt fiber to polypropylene fiber is 1:2, the flexural toughness of the specimen B2P4 reached 22.4 J, and it increased by 10.2 times.

Furthermore, the equivalent flexural strength and the percentage of equivalent flexural strength of each group were calculated according to the following Eq.s (2) and (3), respectively.

$$f_e = \frac{T_b}{\delta_{tb}} \cdot \frac{L}{b.h^2} \qquad (2)$$

$$\lambda_e = f_e / f_b \qquad (3)$$

where $f_e$ is equivalent flexural strength, MPa; $\delta_{tb}$ is mid-span deflection, mm; $\lambda_e$

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is the percentage of equivalent flexural strength. The equivalent flexural strength and Equivalent flexural strength ratio of each group are shown in Fig. 7 and Fig. 8, respectively.

As shown in Fig. 6 and Fig. 7, the equivalent flexural strength and flexural toughness of each group of specimens show a consistent variation trend. This is due to that the equivalent flexural strength is just the flexural toughness multiplied by $\frac{1}{\delta_{tb}}.\frac{L}{b.h^2}$, and for the specimen of the same size, the value is constant [35]. As shown in Fig. 8, there is a certain difference between the variation trend of equivalent flexural strength and that of equivalent flexural strength ratio. For instance, the equivalent flexural strength of B6P0 is 10.2 %, which is only 36 % higher than that of the control group B0P0. However, the equivalent flexural strength ratios of specimens containing macro polypropylene were all above 30%, which were at least 3.3 times higher than that of the control group. Among the HBPFRC specimens, when the mass ratio of basalt fiber to polypropylene fiber is 1:2, the equivalent flexural strength ratio of the specimen B2P4 is the largest, which is 7.1 times higher than that of the control group.

## 3. Discussion

### *3.1 Analysis of the mechanism of hybrid fibers*

This study shows that the hybrid of fibers in concrete can effectively improve the brittleness of concrete, and the HBPFRC specimens show good bending performance, which can be attributed to that the fiber can improve various original defects in the concrete matrix and the inhibit the development of cracks in loading stage [33]. The role of fiber on improving the bending performance of concrete specimens is played throughout the whole process, from the pouring of concrete and the failure of it.

In the casting stage, during the hardening process of the concrete matrix, the existence of fiber can restrain the micro-cracks caused by plastic shrinkage and temperature deformation, which not only reduces the number of cracks but also reduces the size of cracks. So it is beneficial to reduce the stress intensity factor at the crack tip. At the loading stage of the specimens, the fiber dissipates the stress concentration at the crack tip, thus limiting the crack propagation. Micro basalt fiber and macro polypropylene fiber play a different role in different stages.

Basalt fibers are randomly distributed in the concrete matrix, and they play a favorable role in connecting and separating pores. Thus the pores in the concrete matrix are refined, which reduces the tip stress concentration degree of the primary crack and makes the distribution of the stress field more uniform and continuous. At the same time, due to the extremely high elastic modulus of basalt fiber, it can withstand greater tensile stress under smaller strain conditions. Before the appearance of macro-cracks, it requires a large amount of energy to break itself during the expansion process of micro-crack, so that the micro basalt fiber can improve the bending performance of concrete. However, due to the low fracture elongation rate of basalt fiber, the basalt fiber will be immediately broken or pulled out once the macro-crack is formed. So the mono addition of basalt fibers cannot effectively improve the brittleness of concrete. As for the macro polypropylene fiber, it plays a bridging role and shares the load borne by the concrete matrix in the process of crack evolution from micro-crack to the macro-crack. Fig. 9 is a schematic diagram of the bridging action of macro polypropylene fiber.

As shown in Fig. 9, in the process of the crack extending upward from the bottom of the specimen, the fibers across the crack will continuously participate in sharing the stress of the concrete matrix. The lower polypropylene fibers were continuously pulled out or broken as the crack width increases. At the same time, the upper fiber will successively participate in bearing the load. With the increase of crack width, the load shared by the macro polypropylene fibers gradually increases until it is pulled out or broken, which is the reason why the concrete containing the coarse polypropylene fibers still has the residual strength for a long time after the peak load. Besides, due to the high tensile strength and elongation of the macro polypropylene fiber, the number of polypropylene fibers across the cracks will increase with the increase of the crack height in a certain deflection range. Therefore, the cumulative effect of effective fiber bridging will lead to the second peak value of HBPFRC specimens.

From the above analysis, it can be seen that basalt fiber and coarse polypropylene fiber cannot be substituted for each other in improving the bending performance of concrete. These two fibers play a role in different loading periods of concrete. The bending performance of concrete can be improved by adding two kinds of fibers into concrete collectivity in a certain proportion. Due to the positive hybrid effect of fiber, the B2P4 specimen obtained the optimal bending performance.

### *3.2 Technology and economic analysis*

Compared with steel fiber, macro polypropylene fiber has a lower price, less labor cost, strong corrosion resistance and less carbon dioxide emission in the production process [36-38]. Therefore, macro polypropylene fiber has been used to replace steel fiber in recent years. What's more, as the basalt fiber is a more environmentally friendly material compared with traditional reinforced concrete materials, it is more environmentally friendly to mix with polypropylene to produce FRC.

In terms of price, the basalt fiber used is 25 China Yuan (CNY)/kg, while the macro polypropylene fiber is 35 CNY /kg (2019 price). The cost per cubic meter of fiber for each group is shown in Table 4, where the cost-effectiveness is defined as the ratio between the improvement value of the test bending performance of each group compared with the control group and the corresponding fiber cost [39].

As shown in Table 4, since the price of basalt fiber is relatively low, it is obvious that the total price is low when the amount of basalt fiber is larger. Although the price of mono-basalt FRC specimen B6.0P0.0 is low, it shows the characteristics of brittle failure when subjected to bending and the increase in flexural strength and toughness is relatively small compared with the control group specimen B0.0. Thus, the addition of basalt fiber alone cannot effectively improve the bending performance of concrete. Among the HBPFRC specimens, the price of B2P4 is not the lowest, but it is only increased by 17.2% compared with that of the HBPFRC specimens B4.8P1.2 with the lowest price. However, when compared with B4.8P1.2 specimen, the flexural strength and flexural toughness of B2P4 increased by 16.3% and 113%, separately. Thus, the selection of B2P4 specimen will significantly improve the energy dissipation capacity of concrete material with a small increase in cost. As for the mono-polypropylene FRC specimen, although it shows high flexural strength and high flexural toughness, it has no advantages compared with the B2P4 group in terms of technology and economy. Therefore, based on comprehensive technical and economic analysis, it can be seen that B2P4 group is the test group with the optimal ratio.

## 4. Conclusions

(1) The addition of hybrid basalt fiber and polypropylene fiber can effectively

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improve the flexural strength of concrete. Also, the addition of macro polypropylene fiber proved to increase the post-cracking flexural toughness of concrete. Compared with the control group, when the mass ratio of basalt fiber to polypropylene fiber is 1:2, the flexural toughness and equivalent flexural strength of the HBPFRC specimen were increased by 10.2 times, and the percentage of equivalent flexural strength of it was increased by 7.1 times.

(2) The basalt fiber mainly improves the flexural performance of concrete before the occurrence of macro-cracks, while the macro polypropylene fiber plays the bridging role and improve the flexural performance of concrete in the process of crack evolution from micro-crack to the macro-crack.

(3) B2P4 specimen significantly improve the energy dissipation capacity of concrete material with just a small increase in cost. From the perspective of both technology and economy, when the mass ratio of polypropylene fiber to basalt fiber is 1:2, the bending performance and economic benefits of FRC reach the optimal level, and this mix ratio is the optimal fiber mixing ratio in this test.

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**List of table captions**

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**Table 1 Concrete mix proportion**

| Materials | Mass(kg/m$^3$) |
|---|---|
| Cement | 375 |
| Coarse aggregate 10~20mm | 545 |
| Coarse aggregate 5~10mm | 545 |
| Sand | 850 |
| Water | 135 |
| Water reducer | 3.75 |

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**Table 2 Properties of the selected fibers**

| Fiber type | BF | PF |
|---|---|---|
| Diameter (mm) | 0.013 | 0.8 |
| Length (mm) | 19 | 50 |
| Elastic modulus (GPa) | 95-115 | 7.4 |
| Shape | straight | corrugated |
| Tensile strength (MPa) | 3300-4500 | 706 |
| Aspect ratio | 1460 | 63 |
| Density (g/cm3) | 2.75 | 0.95 |
| Elongation (%) | 2.4-3.0 | 10 |

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**Table 3 Details of each group specimen**

| Specimen | The fiber content in kg/m$^3$(% in volume) | |
|---|---|---|
| | BF | PF |
| B0.0P0.0 | 0.0 (0%) | 0.0 (0%) |
| B0.0P6.0 | 0.0 (0%) | 6.0 (0.63%) |
| B6.0P0.0 | 6.0 (0.22%) | 0.0 (0%) |
| B1.2P4.8 | 1.2 (0.04%) | 4.8 (0.51%) |
| B2P4 | 2.0 (0.07%) | 4.0 (0.42%) |
| B3.0P3.0 | 3.0 (0.11%) | 3.0 (0.32%) |
| B4.0P2.0 | 4.0 (0.15%) | 2.0 (0.21%) |
| B4.8P1.2 | 4.8 (0.17%) | 1.2 (0.13%) |

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**Table 4 Price of fibers and cost-effectiveness for per cubic meter FRC**

| Specimen | Total price (CNY) | Cost-effectiveness | |
|---|---|---|---|
| | | Flexural strength (kPa/CNY) | Flexural toughness ($10^{-3}$ J/CNY) |
| B0.0P0.0 | 0 | / | / |
| B0.0P6.0 | 210 | 5.7 | 53.8 |
| B6.0P0.0 | 150 | 2.7 | 6.7 |
| B1.2P4.8 | 198 | 6.1 | 50.0 |
| B2P4 | 190 | 8.9 | 107.4 |
| B3.0P3.0 | 180 | 6.1 | 70.0 |
| B4.0P2.0 | 170 | 3.5 | 58.2 |
| B4.8P1.2 | 162 | 5.6 | 52.5 |

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## List of figure captions

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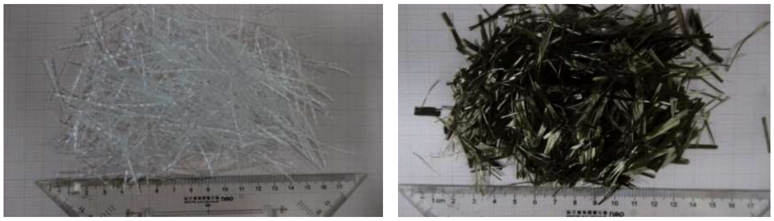


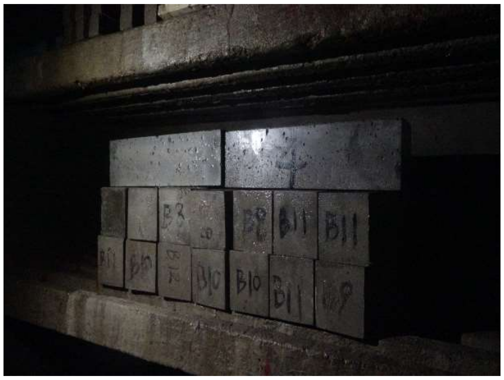
(a)Polypropylene fibers (PF) (b) Basalt fibers (BF)

**Fig. 1** External shapes of fibers.

(a) Inclusion of PF

(b) Inclusion of BF

(c) Specimen casting



(d) Specimen maintenance

**Fig. 2** Partial production procedures of specimens.

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**Fig. 3** Test process diagram.

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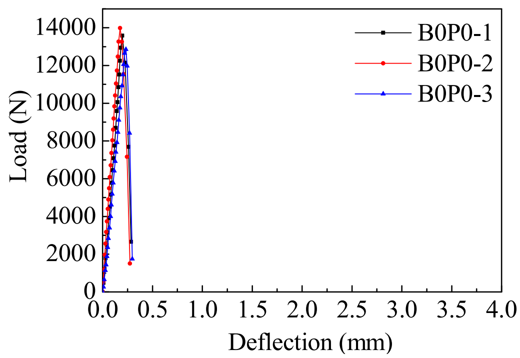
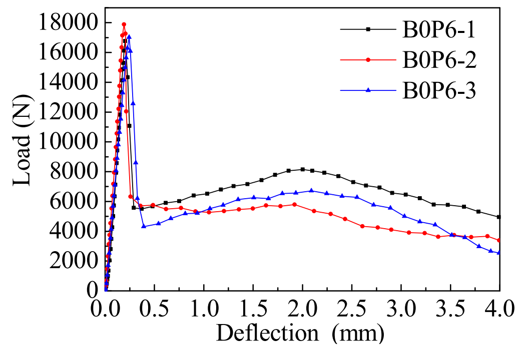
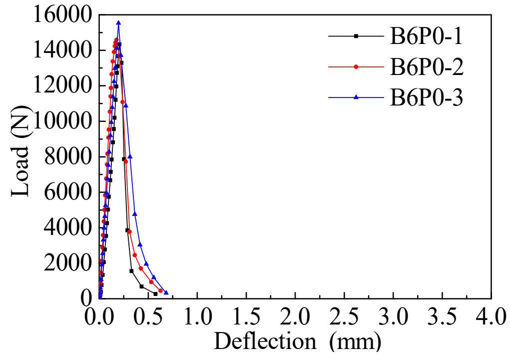
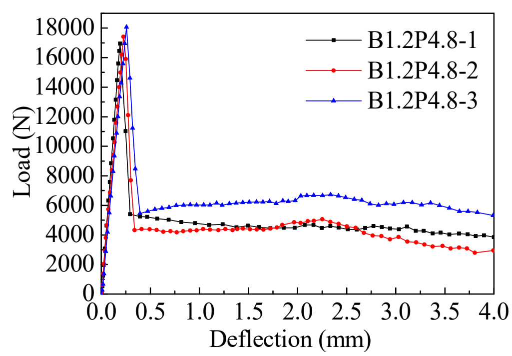


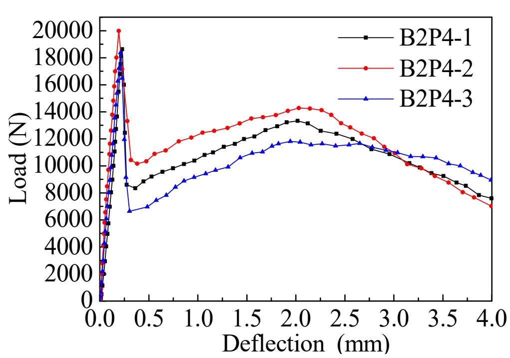



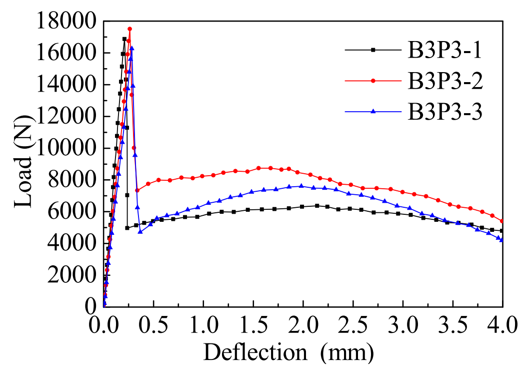

(a) B0.0P0.0 (b) B0.0P6.0



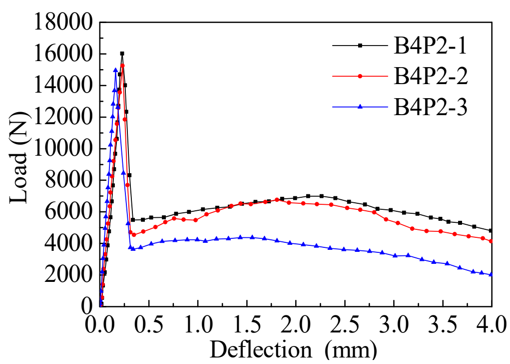



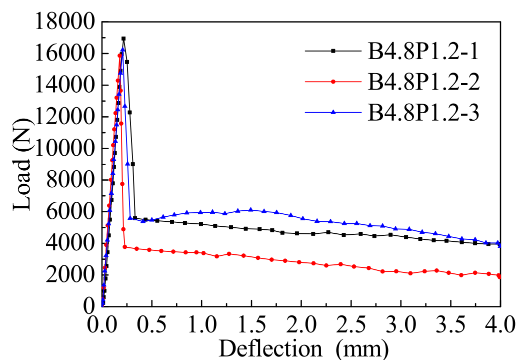

(c) B6.0P0. (d) B1.2P4.8




(e) B2P4 (f) B3.0P3.0




(g) B4.0P2.0 (h) B4.8P1.2

**Fig. 4** Load-deflection curve of HBPFRC specimens.

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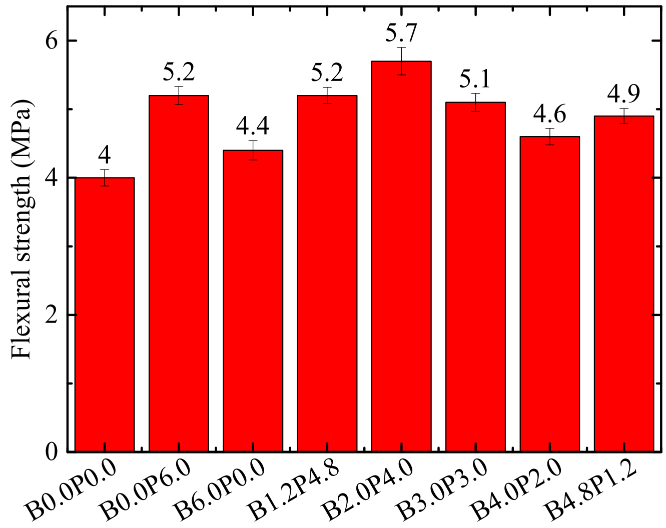


**Fig. 5** Flexural strength of FRC specimens.

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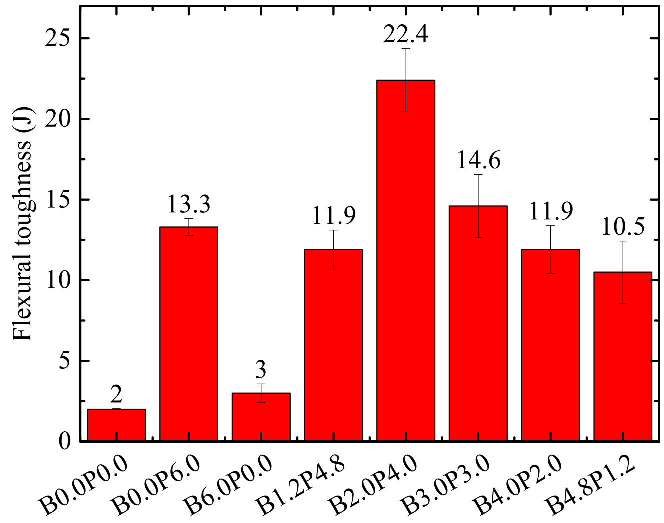


**Fig. 6** Flexural toughness of FRC specimens.

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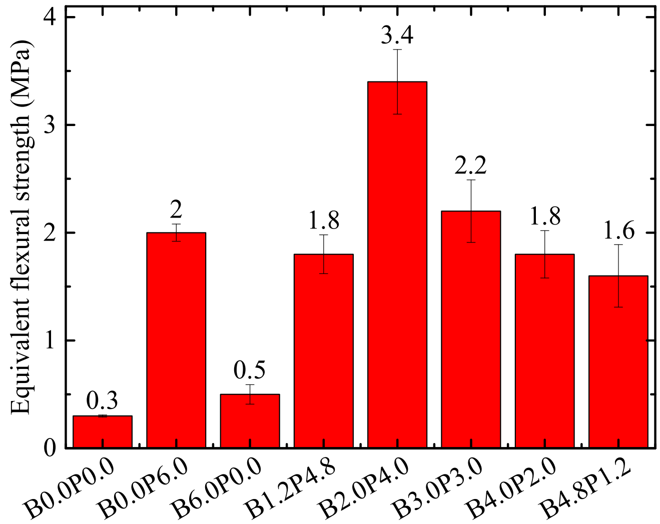


**Fig. 7** Equivalent flexural strength of FRC specimens.

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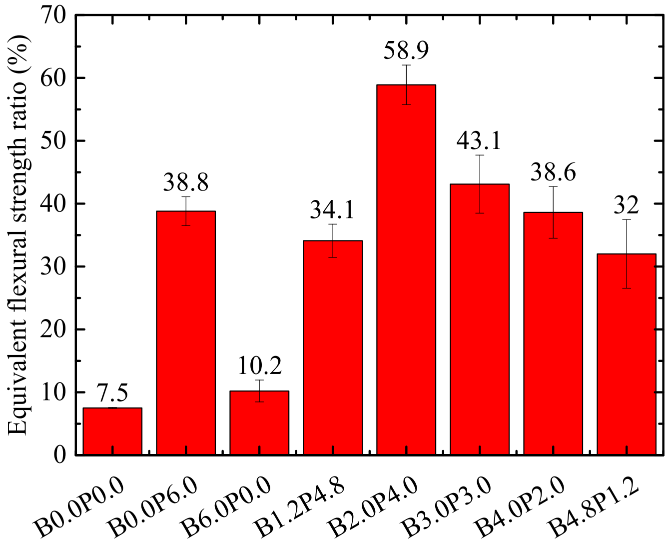


**Fig. 8** Equivalent flexural strength ratio of FRC specimens.

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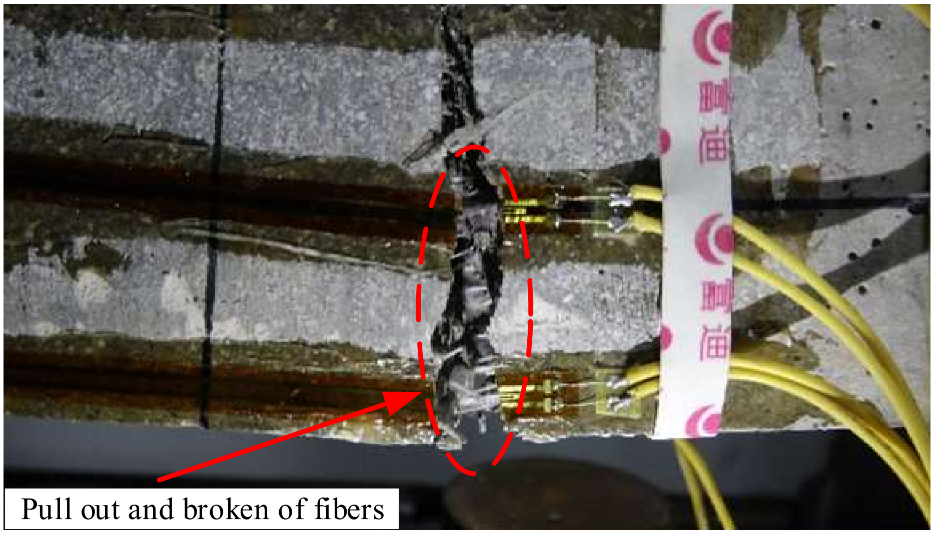


**Fig. 9** Schematic diagram of the bridging action of macro polypropylene fibers.