Finite Element Analysis of the Effect of Basalt-Polypropylene Hybrid Fiber on the Performance of RPC Beam

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Abstract. In order to improve the mechanical properties and bending resistance of RPC concrete beams, the influence of RPC beams were analyzed by finite element analysis by adding basalt-polypropylene hybrid fibers and changing their fibers blending ratios. The results show that compared with the conventional RPC beam, the cracking load, mid-span deflection and maximum compressive stress of the hybrid fiber RPC beams are greatly improved in the initial cracking state; the cracking load and cross of the hybrid fiber RPC beams in the yield state medium deflection and maximum compressive stress of concrete do not change much. Through the finite element analysis and theoretical calculation, the calculation formula of the normal section flexural capacity of basalt-polypropylene hybrid fiber RPC beams is derived.

1. Introduction
Reactive Powder Concrete (RPC) has excellent properties such as high strength, high toughness and high durability[1], and is widely used in practical engineering. Generally, RPC is blended with an appropriate amount of steel fibers to improve its strength and toughness, thereby reducing the cross-sectional size of the member and improving the mechanical properties. However, according to the research data[2-4], steel fibers are easy to corrode in coastal areas and other corrosive environments, resulting in the reduction of mechanical properties and durability of RPC components, which limits its application. In order to improve the performance of concrete in corrosive environment, many scholars at home and abroad have done a lot of research using non-metallic fibers to replace steel fibers. For example, Wang Dengke[5] studied the effects of different kinds of non-metallic fibers on the mechanical properties of marine concrete, and found that the ultimate tensile strain of concrete mixed with carbon fibers, basalt fibers and polypropylene fibers were significantly increased; Jin Shengji[6] tested the freeze-thaw resistance of basalt fiber reinforced concrete under corrosive conditions. The results show that the basalt fibers can enhance the freeze-thaw resistance of concrete significantly under corrosive conditions, and effectively prolong the service life of concrete under corrosive conditions. Lei Weili[7] made an experimental study on the corrosion resistance of polypropylene fibers self-compacting concrete. The results show that polypropylene fibers can improve the corrosion resistance and compressive resistance of concrete to a certain extent. Zhang Fan[8] studied the alkali corrosion of glass fibers and its influence on the safety of concrete structure. The results showed that the use of glass fibers in concrete would reduce the compressive strength of concrete in later period. It should be strictly prohibited to mix glass fibers in Portland cement concrete. Based on the analysis of the above literature, it can be concluded that carbon fibers are expensive and difficult to be popularized; basalt fibers and polypropylene fibers are inexpensive, while effectively improving the mechanical properties and corrosion resistance of concrete, which can be further studied. However, at present, the research on
basalt fibers and polypropylene fibers concrete mostly focuses on the properties of concrete materials with single or mixed fibers, while the research on the properties of structural components is less. Therefore, in order to improve the structural performance of RPC components and expand their application scope, this paper simulates and analyses the effects of different blending ratios of basalt fibers and polypropylene fibers on the stress-strain, mid-span bending moment and deflection of RPC beams under initial cracking and yielding conditions, providing technical reference for practical engineering applications.

2. Design of Research Program

2.1. Research Program

In this study, the concrete water-to-binder ratio was 0.22. The reactive powder concrete without fibers was used as the reference concrete (Plain) to design the mix proportion. Ten groups of RPC beams were designed for benchmark concrete by changing the mixing ratio of basalt fibers and polypropylene fibers as shown in Table 1. In this study, the beam length is set to 1500mm, the net span is 1200mm, the section size is 150mm×250mm, the longitudinal tensile reinforcement is 4C16 (HRB400 grade steel), the reinforcement ratio is 2.82%; the the erection reinforcement is 2C12 (HRB400 grade steel); the stirrup is A10@100 (HRB335 grade steel), the specific beam structure diagram is shown in Figure 1.

| Test number | Test piece number | Basalt fiber (%) | Polypropylene fiber (%) | prismatic compressive strength (MPa) | tensile strength (MPa) | Modulus of elasticity (GPa) |
|-------------|-------------------|------------------|-------------------------|-------------------------------------|-----------------------|--------------------------|
| 1           | Plain             | 0                | 0                       | 86.5                                | 4.21                  | 39.2                     |
| 2           | X10P25            | 0.10             | 0.025                   | 81.8                                | 5.20                  | 43.1                     |
| 3           | X10P33            | 0.10             | 0.033                   | 80.2                                | 5.34                  | 32.8                     |
| 4           | X10P42            | 0.10             | 0.042                   | 79.8                                | 5.12                  | 41.3                     |
| 5           | X15P25            | 0.15             | 0.025                   | 83.3                                | 6.38                  | 35.7                     |
| 6           | X15P33            | 0.15             | 0.033                   | 96.5                                | 6.23                  | 40.7                     |
| 7           | X15P42            | 0.15             | 0.042                   | 88.8                                | 5.58                  | 41.2                     |
| 8           | X20P25            | 0.20             | 0.025                   | 84.4                                | 5.61                  | 40.1                     |
| 9           | X20P33            | 0.20             | 0.033                   | 89.5                                | 5.48                  | 42.3                     |
| 10          | X20P42            | 0.20             | 0.042                   | 75.3                                | 5.46                  | 40.8                     |

Note: In the table, X represents basalt fiber, the subscript value is the fiber blending ratio of 10,000; P represents polypropylene fiber, the subscript value is the fiber blending ratio of 100,000.

Figure 1 The structure diagram of the specimen(unit: mm)

2.2. Modeling process

Separate models and integral models can be used for reinforced concrete structures. Because the mechanical properties of Reinforced and concrete are quite different, this paper uses a separate model (simulated steel and concrete as two different units for simulation) for finite element simulation. That is, the longitudinal tension steel bars, the standing ribs and the stirrups are all selected by the link 8 unit; the concrete is selected by the solid65 unit for analysis. In order to prevent stress concentration, this
paper simulates a 100mm × 150mm rigid pad at the top of the beam, and simulates a 100mm × 150mm rigid pad at the beam bottom support. The finite element model of the RPC beam is shown in Figure 2, and the steel element model is shown in Figure 3.

The Poisson's ratio of the reactive powder concrete was taken to be 0.20, and the Poisson's ratio of the steel bar was taken as 0.30. The reinforced concrete beam is subjected to finite element simulation analysis using the bilinear follower model (BKN) and the Von Mises yield criterion[9]. In the parameter design, the shear transfer coefficient of the open crack of concrete is 0.5, the shear transfer coefficient of the closed crack is 0.95, and the uniaxial compressive strength is -1, that is, the crushing function is turned off. The number of iterations of each load substep in the solution control is 60. The resulting output frequency is written every substep, and the maximum number of loops is set to 20 in the Nolinear option. The solution process adopts the displacement convergence criterion, and the convergence precision is 1.5%, which can accelerate convergence and reduce calculation time.

3. Finite element simulation results and analysis

3.1. Load analysis

Figure 4 is the initial cracking load of basalt-polypropylene hybrid fiber RPC beams and ordinary RPC beam. From the chart, the initial cracking load of the plain group is 25.67 kN. The cracking load of RPC beams increases obviously after adding fibers. The initial cracking load of X15P33 group reached the maximum value of 51.68 kN, 101.3% higher than that of plain group. This is because the fibers distribute along the three-dimensional random direction in the concrete matrix, which limits the development of cracks[10], it can significantly improve the crack resistance of the matrix concrete, thereby improving the initial cracking load of the beams. It can be seen from the figure that the initial cracking load of X10P33 group, X15P33 group and X20P33 group is 65.8%, 101.3%, 34.4% higher than that of Plain group when the blending ratio of polypropylene fibers is 0.033%, which is larger than that of other blending ratio groups of polypropylene fibers. This is because in a certain range of fibers content, with the increase of fibers content, the effect of concrete reinforcement is more obvious, but when the fibers content is large, it is easy to cake, resulting in the reduction of fibers reinforcement. The analysis shows that the crack resistance of RPC beams is remarkable when 0.033% polypropylene fibers were added, but the change of basalt fibers content is not obvious.

Figure 5 shows the yield load of basalt-polypropylene hybrid fiber RPC beams and ordinary RPC beam. It can be seen from the figure that the yield load of the Plain group is 177.95 kN, and the yield
load of RPC beams increased slightly after incorporation of fibers, and is basically stable between 190 kN and 200 kN. The maximum yield load of the X10P25 group was 200.60kN, which was 12.7% higher than that of the Plain group. With the change of fiber blending ratio, the flexural performance of RPC beam is obviously improved when the basalt fibers blending ratio is 0.10%, and there is no obvious law with the change of polypropylene fibers blending rate.

3.2. Deflection analysis
Figure 6 shows the mid-span deflection of the basalt-polypropylene hybrid fiber RPC beams and the ordinary RPC beam in the initial cracking state. As can be seen from the figure, the initial cracking mid-span deflection of the Plain group is 0.103 mm. When the fibers were blended, the initial cracking mid-span deflection increased to different degrees. Among them, the initial cracking mid-deflection occurred in the X15P25 group, which was 0.212 mm, which was 105.8% higher than that of the Plain group, followed by the X10P33 group and the X15P33 group. The initial cracking deflection both were 0.199 mm, both increased by 93.2%.

Figure 7 shows the yield deflection of basalt-polypropylene hybrid fiber RPC beams and ordinary RPC beam. The yield deflection of the Plain group is 2.656 mm. After the fibers were blended, the yield deflection varied with different degrees, with a small increase or a small decrease. Among them, X10P25 group, X10P33 group, X10P42 group, X15P25 group and X20P33 group increased by 12.8%, 9.34%, 2.6%, 10.1%, 1.1%.

3.3. Stress Cloud Diagram
Under initial cracking conditions, the maximum stress of RPC beams are shown in Figure 8. From the diagram, the maximum compressive stress produced by RPC beams appears in the compression zone of the upper part of the beams. The maximum compressive stress in Plain group is 2.943MPa, X10P33 group, X15P25 group and X15P33 group increased by 62.8%, 87.7% and 102.2%. Other groups increased slightly, ranging from 13.9% to 35%.

At the yield stage, the maximum stress of RPC beams is shown in Figure 9. From the diagram, the maximum compressive stress produced by RPC beams appears in the compression zone of the upper part of the beam, and the maximum compressive stress of Plain group is 41.279 MPa under yield state. Among them, the maximum compressive stress of X10P25 group increased greatly, which was 18.7% higher than that of Plain group. After adding fibers, the maximum compressive stress of RPC beams
under yield state did not increase significantly, and some experimental groups even decreased slightly. This is because the beams had already cracked, the longitudinal tension reinforcement played a major role, and the effect of fibers was not obvious.

3.4. Load-deflection curve analysis

Figure 10 shows the load-deflection curves of basalt-polypropylene hybrid fiber RPC beams and ordinary RPC beam. It can be seen from the figure that the load-deflection curves of the 10 groups of RPC beams have basically the same trend; when the load is small, the deflection increases linearly with the increase of the load, and the deflection curve turns after cracking. It can be seen that the initial cracking of the beams after the fibers is incorporated, the load increased significantly, and the anti-crack effect of the X15P33 group was more obvious.

4. Simulation formula of normal section flexural capacity of hybrid fiber RPC beam

Due to the high tensile strength of hybrid fiber RPC, the contribution of concrete in the tension zone should be considered when calculating the normal section flexural capacity. This paper uses Zheng Wenzhong [11] to calculate the normal section flexural capacity formula:

\[ αf_b x = f_y A_s + k f_t b \left( h - \frac{x}{\beta} \right) \]  

\[ M_u = αf_b x \left( h_0 - \frac{x}{\beta} \right) - k f_t b \left( h - \frac{x}{\beta} \right) \left[ 0.5 \left( h - \frac{x}{\beta} \right) - a_s \right] \]  

Where:  
- \( M_u \) is the normal section bending capacity of the RPC beam; \( f_y \) and \( f_t \) are the axial compression and tensile strength design values; \( A_s \) is the longitudinal tensile section area; \( a_s \) is the longitudinal tension of the reinforcement to the section. The distance between the edges of the tension; \( \alpha \) and \( \beta \) are the equivalent rectangular stress coefficients of the compression zone, \( \alpha = 0.9, \beta = 0.77 \); \( k \) is the equivalent rectangular stress coefficient of the tension zone, \( k = 0.25 \); \( x, b, h, h_0 \) is the height of the compression zone, the section width, the section height, and the section effective height.

Considering the influence of different blending ratios of basalt fibers and polypropylene fibers on the flexural capacity of RPC beam [12], the formula (2) was modified, and the experimental data were fitted to obtain basalt-polypropylene hybrid fiber RPC beams bending capacity formula:

\[ M_{fu} = (1 + \beta_X \lambda_X + \beta_P \lambda_P) M_u = (1 + 0.145\lambda_X + 0.109\lambda_P) M_u \]  

Where: \( M_{fu} \) is the normal section flexural capacity of hybrid fiber RPC beam; \( \beta_X \) and \( \beta_P \) are the influence coefficients of basalt fibers and polypropylene fibers on flexural capacity; \( \lambda_X \) and \( \lambda_P \) are the content of basalt fibers and polypropylene fibers respectively. Characteristic parameters (\( \lambda = \rho l/d \); \( \rho \) is the fiber volume incorporation ratio; \( l/d \) is the fiber aspect ratio; the basalt fibers length-to-diameter ratio is 1000, and the polypropylene fibers aspect ratio is 600).

Comparing the calculated value of flexural capacity of normal section of hybrid fiber RPC beams with the simulated value of \( M_{fu} \), it can be seen that the average value of \( M_{fu}/M_{fu} \) is 0.998, the standard deviation is 0.052, and the coefficient of variation is 0.052. It shows that the calculated value is in good agreement with the simulated value. The formula can be used to calculate the flexural capacity of normal section of basalt-polypropylene hybrid fiber RPC beams.
5. Conclusions
In order to improve the flexural behavior of RPC beams in corrosive environments, the effects of different blending ratios of basalt fibers and polypropylene fibers on the flexural capacity of RPC beams were analyzed. The following conclusions were obtained:

(1) Under the initial cracking state, the cracking load of the RPC beams increased significantly after the incorporation of the hybrid fibers, the mid-span deflection increased, and the maximum compressive stress of the concrete also increased. Among them, the indexes of the X10P33 group, the X15P25 group and the X15P33 group were obviously increased.

(2) Under the yielding state, the yield load, mid-span deflection and maximum stress of the RPC beams increased slightly after the incorporation of the hybrid fibers, but the individual groups have a downward trend. It can be seen that the incorporation of hybrid fibers can effectively improve the crack resistance and toughness of the RPC beams, and the effect of reinforcing the mid-span bending moment and the mid-span deflection is small.

(3) Considering the influence of the blending of hybrid fibers on the flexural capacity of normal section of RPC beam, the formula of the flexural capacity of normal RPC beam is modified. The formula is proposed: 

\[ M_{fu} = (1 + 0.145\lambda_X + 0.109\lambda_P)M_u. \]

The research on hybrid fiber RPC beam is limited to finite element simulation analysis. For practical application in construction engineering, it is still necessary to further study and improve through practical experiments.

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