Research Article

Mechanical Properties of Polypropylene-Fiber-Reinforced High-Performance Concrete Based on the Response Surface Method

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Polypropylene fibers are added to concrete to improve the toughness of the material. Manufactured sand and fly ash with high content are used to reduce the impact on the environment and cost. The response surface method (RSM) was used to design the test and study the mechanical and bending properties of polypropylene-fiber-reinforced high-performance concrete (PPFHPC). Three process variables, including the content of polypropylene fiber (1%, 1.5%, and 2%), content of fly ash (45%, 60%, and 75%), and water-binder (W/B) ratio (0.27, 0.3, and 0.33), were considered as factors. The compressive strength, flexural strength, flexural-compressive ratio, splitting tensile strength, and first-crack strength and bending strength of thin plate were evaluated. The prediction model established by the RSM showed the correlation and predictability between the response and the factors, and the corresponding relationship equation between the factors and the response was obtained. Results of multiobjective optimization indicated that the optimal three factors (content of PPF, FA, and W/B) were 2%, 62%, and 0.27. The established model can be used to predict the basic mechanical properties and bending properties of materials. This test laid a theoretical foundation for the development of PPFHPC materials.

1. Introduction

Ordinary concrete is widely used in construction projects because of its low cost and good compressive performance. However, given the low tensile strength and toughness of concrete, the building structure cannot be effectively controlled after cracks occur under load, which leads to the failure of internal steel bars to resist external erosion media, thereby affecting the durability of the structure [1]. Therefore, finding a material with good tensile property and effective crack control is important.

Research on concrete focuses on density and durability to enhance its performance. Fiber-reinforced high-performance concrete (FRHPC) improves matrix uniformity and minimizes defects within the material by removing coarse aggregate to achieve high strength and durability. In recent years, the application of synthetic organic fibers represented by polyethylene fiber [3], polyvinyl alcohol fiber [4], and polypropylene fiber (PPF) [5, 6] in HPC has made great progress. Considering that synthetic organic fibers can significantly improve structure’s crack resistance, reduce the shrinkage crack [7], enhance the ductility [8], and affect the resistance of concrete [9], such fibers can effectively improve the wear resistance, impermeability, and tensile strength of FRHPC [10]. They can also improve the working performance of concrete and reduce the brittleness of concrete [11, 12]; thus, they are applied in bridge and pavement engineering [13].

For a long time, the fine aggregate of FRHPC is primarily natural sand, such as silica sand [14] and river sand [15]. Natural sand resources are gradually exhausted with the increase of the amount of sand used for construction, and excessive sand mining will endanger the stability of river banks and embankments and lead to the destruction of...
ecological environment [16]. Scholars began to think about finding other alternatives for production. Similarly, manufactured sand (MS) can be obtained in local after mechanical crushing and screening [17]. On the contrary, MS is more environmentally friendly than natural sand. Scholars have conducted considerable research to explore whether MS can replace silica sand and river sand as fine aggregate in concrete. Chow et al. [18] studied the influence of MS on the performance of ordinary concrete based on its particle shape, particle size distribution, stone powder content, and density. The test shows that concrete prepared by MS has better fluidity, which could increase the strength of concrete under the condition of reducing the water-binder ratio. Considering that the amount of sand used for construction has increased dramatically, domestic scholars have issued a series of technical regulations after a long time of research on the workability, mechanical properties, and durability of MS [19]. The results shows that, after scientific mixing ratio design, concrete using MS can achieve the same performance as natural sand with regard to imperturbability, frost resistance, and carbonation resistance [20]. For PPFRHPC, MS is seldom used. Thus, studying the feasibility of its application is necessary to reduce the cost and promote engineering.

PPF can be added to concrete to bridge microcracks in concrete matrix and effectively control the appearance and development of cracks, thereby controlling the crack width of concrete [21] and improving the tensile strength, flexural strength, and toughness of concrete [22, 23]. Karimipour et al. [5] studied the mechanical properties of PPF self-compacting concrete and tested the compressive strength and splitting tensile strength. In addition, the content of PPF in the experiment was 0%, 0.1%, and 0.3%. The test results showed that the fluidity of the mixture decreased with the increase of the content of PPF. When the content of PPF was 0.1%, the compressive strength was significantly improved, and the splitting tensile strength reached the highest when the content of PPF was 0.3%. Danar Daa et al. [24] reported that, with the increase of the content of PPF, the change in compressive strength was not evident; the splitting tensile strength and elastic modulus were slightly increased, and the improvement of the bending performance was evident. When the PPF content increased by 0.22%, the toughness index increased by 10.76%. When the content of PPF was 0.165%, the ductility of specimens was significantly enhanced, and the maximum toughness factor was 2.964 N/mm². We also consider the cost of fiber to promote and apply PPFRHPC in practical engineering. At present, the diameter and elastic modulus of PPF are small, and the price is high. The cheapest PPF on the market is considered to study its influence on the mechanical properties of FRHPC, reduce the cost of PPFRHPC, and explore the feasibility of its application in engineering.

FA is an important industrial waste residue, and it is the main binding material of FRHPC. If FA can be fully used after scientific design, then it can not only save cost, but also reduce cement consumption; thus, reducing the environmental pollution caused by CO₂ emissions during the production of cement to study the influence of FA on the performance of fiber-reinforced concrete has positive significance. Rao [25] studied the influence of different contents of FA on the bending properties of materials at different ages. The results showed that, with the increase of age, the cracking strength of concrete increases; the crack spacing increases, and the ultimate deflection and ultimate strength initially increase and then decrease. FA with good particle gradation can improve concrete crack refinement and enhance concrete crack resistance. Qi et al. [26] used PPF-prepared stray-hardened cement-based composite materials. The results showed that, with the increase of FA content from 40% to 60%, the flexural strength decreases from 12.27 MPa to 9.49 MPa, and the stiffness of concrete in the hardening stage decreases with the increase of FA content. Given the fine FA particles, the reaction products fill the pores of cement hydrate, which is conducive to reducing the internal pores of concrete, enhancing the bond between the matrix and fiber [27, 28], and improving the bending performance of concrete. However, the addition of excessive FA will reduce the strength of concrete. Thus, at present, few studies are focused on fiber concrete with high content of FA. Piroti et al. [29] studied the influence of the water-binder ratio (W/B) on the mechanical properties of PPFRHPC. As the W/B decreased from 0.5 to 0.3, the mechanical properties of the material were improved, and the 28 d tensile strength and flexural strength were increased by 22% and 40%, respectively. Zhu et al. [6] found through experiments that when the W/B increased from 0.16 to 0.3, the tensile strain capacity increased from 0.6% to 3.7%, indicating that the W/B also played a positive role in improving the ductility of materials.

The Box–Behnken Design (BBD) is a response surface method (RSM) that can evaluate the nonlinear relationship between indicators and factors. It does not require repeated testing. Under the same experimental factors, it is more economical and efficient because it requires fewer experiments [30]. Adamu et al. [31] studied the water permeability and water absorption of the pervious concrete. The RSM models showed a high degree of correlation between variables and responses. The optimal durability variables were 0% RHA and 5% CCW, water permeability was 0.96 cm/s, and water absorption was 4.338%. The model can be used to predict the permeability and water absorption capacity of pervious concrete. Mohammed and Adambu [32] developed a RCR (RCR) and prepared 16 mixtures of 4 kinds of crumb rubber (CR) (0%, 10%, 20%, and 30%) and 4 kinds of nano silica (NS) (0%, 1%, 2%, and 3%) by volume replacement of fine aggregate. The physicochemical effect of adding NS on RCR was verified by microstructural analysis. RCR of high strength, high durability, and high toughness can be obtained when the volume replacement amount of fine aggregate is 10%, and NS addition amount of cementing material is 1.13% by mass.

Therefore, MS and PPF were used to prepare high-performance concrete, to study the possibility of using MS and PPF to prepare environmentally friendly and economical RHPC. RSM was used to simulate the influence of PPF content, FA content, and W/B on the mechanical properties of fiber-reinforced concrete. In addition, the thin
plate bending test combined with the digital image technique (DIC) was performed to study the bending performance and load deflection curve fitting and assess its toughness. This technique can accelerate the application of PPF-reinforced high-performance concrete (PPFRHPC) in practical construction.

2. Materials and Methods

2.1. Materials. FRHPC was primarily composed of cement, FA, fine aggregate, fiber, admixture, and water. Using ordinary Portland cement, the strength grade of grade was P.II 42.5, and the related parameters are shown in Table 1; fine aggregate was MS with particle size of 1.18–0.075 mm, and fineness modulus of 1.88. Sieve pass rate, and morphology are shown in Table 2 and Figure 1. FA was first-class grade. The synthetic fiber was PPF produced by Langfang Langzhe Insulation Material Co., LTD. The related parameters and morphology of PPF are shown in Table 3 and Figure 1. Polycarboxylic acid was used as admixture. Polycarboxylic acid water-reducing agent with water reduction rate of 23% was used, and tap water was used in the test.

2.2. Fabrication of Specimens. In order to facilitate construction in the future large-scale engineering application, according to the ratio of 17 groups in Table 4, the specific preparation process of PPFRHPC was as follows: (1) cement, FA, and MS sand were mixed and dried for 2 min. (2) PPF was added and dry mixed for 2 min. (3) Water and superplasticizer were added to the mixture and stirred for 4 min. After pouring the mold (as shown in Figure 2), the specimen was placed in the laboratory (23°C ± 2°C, 50% ± 5% RH) for 2 days. Then, the specimen was demolded and placed in the laboratory with spraying water. All specimens were wrapped with a plastic cloth until the corresponding test age.

2.3. Experimental Method. Flexural strength was determined by using the central loading method described in GB/T 17671-1999 [33]. Three specimens with a size of 40 mm × 40 mm × 160 mm in each group were tested. The specimen was placed in the testing machine with side up after it was formed. The loading speed was set at 50 N/s, and loading continued until the specimen was crushed. The average of the three measurements was determined as the flexural strength.

Compressive strength was defined on the basis of the standard GB/T 17671-1999 [33]. The blocks obtained after the bending test (six in each group) were used for the compression test. Debris was removed from the surface of the sample before placing the sample in the fixture. The two sides of the sample were used as the compression surface, and the loading speed was set at 2.5 KN/s. The average of the six test results was considered as the compressive strength.

Splitting tensile strength was defined on the basis of GB/T 50081-2002 [34]. Three specimens with a size of 100 mm × 100 mm × 100 mm in each group were tested. Circular arc pad block and pad strip were placed between the upper and lower pressing plates and test pieces of the press and loaded to failure at the speed of 0.08 MPa/s. The average of the three test results was considered as the splitting tensile strength.

Four-point bending test was defined on the basis of ASTM C1080 [35] and (GB/T 15231-2008) [36] for bending toughness test. Three specimens with a size of 400 mm × 100 mm × 15 mm in each group were used for testing. The test device is shown in the figure. The lower support span was 300 mm, and the two upper fulcrum points were applied at the middle three-minute point, namely, the pure bending section with length of 100 mm. Load sensor and digital image technology (DIC) (as shown in Figure 3) were used to collect load and deflection.

2.4. Box–Behnken Design (BBD). BBD was established by using Design-Expert 12® software. Three factors were considered as variables: PPF content (A), FA content (B), and W/B (C). The 7 d compressive strength (R1), 7d flexural strength (R2), 7d flexural ratio (R3), 28d compressive strength (R4), 28d flexural strength (R5), 28d flexural ratio (R6), 28d splitting tensile strength (R7), 28d initial cracking strength of thin plate (R8), and 28d bending strength of thin plate (R9) were set as response variables. The response surface model with 17 experimental points, 12 factorial factors, and 5 central points was established.

Table 5 shows the levels of experimental factors and the corresponding code values. The low and high levels of each factor were, respectively, coded as -1 and +1, whereas the central points were encoded as 0. The mixing ratio and corresponding response results of the 17 experimental groups in this paper are shown in Tables 4 and 6.

3. Results and Discussion

3.1. Analysis of the Mechanical Properties of PPFRHPC

3.1.1. Compressive Strength. As shown in Table 6, the 7 d compressive strength of PPFRHPC prepared by the test is 21.1–55.85 MPa, and the 28 d compressive strength is 31.65–65.65 MPa. The test results are compared by generating histograms (Figure 4). When the W/B is the same, the specimen with higher FA content has lower compressive strength in the early stage, and the compressive strength increases with the increase of test age. In general, the lower the FA content, the higher the compressive strength.

During the test, we found that when the specimen reaches the compressive strength, its appearance is complete without brittle failure (Figure 5). The specimen was kept under pressure until it was destroyed, and few cracks were observed on the side of the specimen. This result is different from the sudden bursting of concrete without fiber, indicating that fiber plays a role in cracking resistance, ensuring the integrity of the specimen, and preventing the occurrence of brittle failure of the structure.

3.1.2. Flexural Strength. As shown in Table 6, the 7 d flexural strength of PPFRHPC prepared by the test is 3.4–6.4 MPa, and the 28 d flexural strength is 4.7–7.95 MPa. The test results are compared by generating histograms (Figure 6).
Table 1: Physical properties and chemical composition of cement and fly ash.

<table>
<thead>
<tr>
<th>Name</th>
<th>Fineness</th>
<th>Strength activity index (%)</th>
<th>Specific surface area (m²/kg)</th>
<th>Ignition loss (%)</th>
<th>MgO (%)</th>
<th>SO₃ (%)</th>
<th>Cl- (%)</th>
<th>Insolubles (%)</th>
<th>Grinding aid (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>362</td>
<td>1.72</td>
<td>0.99</td>
<td>2.56</td>
<td>0.008</td>
<td>0.9</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fly ash</td>
<td>14.2</td>
<td>74</td>
<td>0.77</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Sieve pass rate of manufactured sand.

<table>
<thead>
<tr>
<th>Maximum particle size of sand (mm)</th>
<th>Sieve size (mm)</th>
<th>Passing rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.18</td>
<td>0.6</td>
<td>100</td>
</tr>
<tr>
<td>0.3</td>
<td>0.15</td>
<td>40.5</td>
</tr>
<tr>
<td>0.15</td>
<td>0.075</td>
<td>27.14</td>
</tr>
<tr>
<td>0.075</td>
<td></td>
<td>12.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.02</td>
</tr>
</tbody>
</table>

Figure 1: Polypropylene fiber (a) and machine-made sand (b).

Table 3: The properties of PPF.

<table>
<thead>
<tr>
<th>Diameter (μm)</th>
<th>Length (mm)</th>
<th>Density (g/mm³)</th>
<th>Breaking strength (MPa)</th>
<th>Breaking elongation (%)</th>
<th>Melting point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>12</td>
<td>0.92</td>
<td>579</td>
<td>27.6</td>
<td>161</td>
</tr>
</tbody>
</table>

Table 4: The mixing ratio of the 17 experimental groups.

<table>
<thead>
<tr>
<th>Mix number</th>
<th>The code value of the variable</th>
<th>The actual value of a variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std</td>
<td>A (%)</td>
<td>B (%)</td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>
Figure 6 shows that the higher the dosage of FA, the lower the flexural strength. In general, the strength of concrete with high FA content is lower in the early stage, but the slow pozzolanic reaction in the later stage strengthens the interface adhesion between fiber and concrete matrix and promotes the strengthening and toughening role of fiber.

During the test, the specimen did not completely fracture when it reached the flexural strength (Figure 7). Therefore,
the fiber can protect the structure from brittle fracture and can avoid the brittle failure caused by one-time crack expansion after the ultimate failure.

Experimental studies have shown that [33] after the specimens that used PPF dedicated for ultra-high toughness cement-based composite materials reach the flexural strength, the machine will automatically unload after only a slight crack appears at the bottom of the specimen, and it can still reach 80% to 90% of the initial flexural strength without brittle fracture when being reloaded. After three times of flexural test damage, the machine can still reach more than 75% of the initial flexural strength, with high toughness and safety.

3.1.3. Flexural-Compressive Ratio. Flexural-compressive ratio is regarded as a preliminary indicator of concrete toughness index. In general, the greater the bending ratio, the better the toughness of the material.

\[ \eta = \frac{R_f}{R_c} \times 100\% \]

where \( \eta \) is the flexural-compressive ratio, %; \( R_f \) is the flexural strength, MPa; and \( R_c \) is the compressive strength, MPa.

The test results of flexural-compressive ratio are shown in Figure 8. The maximum value of 7d and 28 d flexural-
compressive ratio of PPFRHPC is 19% and 15%, respectively. With the increase of the test age, the growth rate of the compressive strength of the specimen is faster than that of the flexural strength. Thus, the flexural-compressive ratio shows a downward trend. The higher the content of FA, the more evident the increase of flexural-compressive ratio.

3.1.4. Splitting Tensile Strength. The 28 d splitting tensile strength of PPFRHPC prepared by the test is between 6.25 and 8.95 MPa (as shown in Figure 9). The higher the FA content, the higher the W/B. In addition, the lower the PPF content, the lower the splitting tensile strength. When the W/B is 0.3, and the FA content is 45%, the PPF content increases from 1% to 2%, and the split tensile strength increases by 10%. When the PPF content is 1%, and the W/B is 0.3, the FA content increases from 45% to 75%, and the splitting tensile strength decreases by 11%. When the PPF content is 1%, and the FA content is 60%, the W/B increases from 0.27 to 0.33, and the split tensile strength decreases by 14%. Therefore, the W/B and FA content have a greater influence on the splitting strength compared with the PPF content.
As shown in Figure 10, when the concrete cracks, the fiber can pull both ends of the specimen to inhibit the crack and avoid the occurrence of brittle failure. This result is consistent with previous studies [5]; that is, PPF can be regarded as a “crack nail” in the matrix to prevent the propagation and expansion of cracks.

3.1.5. Bending Properties of Thin Plates. Previous studies have shown that [35] load-deflection curve can reflect the toughness of the material under bending load. Most of the thin plate specimens did not show the strain-softening behavior of traditional concrete after cracking. The bending deformation increases gradually with the increase of load, and the specimen shows an evident strain-hardening property.

During the test, the initial load increases linearly with deflection. During this time, no cracks appear in the concrete matrix, and most of the bending load is borne by the cement matrix. With the increase of load, the stress in the specimen reaches the initial crack strength of the concrete matrix. Then, the first crack appears in the weak area of the pure bending section of the specimen, and the load-deflection curve changes suddenly. Given that PPF has a large deformation capacity, it can bear more stress to suppress the development of cracks. Therefore, PPF plays a bridging role during crack opening, and then the deflection continues to increase. Moreover, the load shows a fluctuation growth. When the load increases to the fracture stress of the fiber, the fiber will be pulled or pulled out from the concrete matrix until the penetration crack appears, at which point the specimen is destroyed.

Based on analysis shown in Table 7, when the FA content increases from 45% to 75%, the initial crack load and peak load increase. Thus, the initial crack strength and peak strength show an increasing trend, and the load-deflection curve is longer. The internal structure of the matrix becomes dense with the increase of FA, which strengthens the bond between the fiber and concrete matrix [8], delays the appearance of the first crack, enhances the crack resistance of the specimen, and promotes the strengthening and toughening effect of the fiber [4, 5]. When the PPF content increases from 1% to 2%, and the FA content is 45%, the initial cracking strength and bending strength increase. However, when the FA content is 60% and 75%, the two factors begin to decline, indicating the optimal content to achieve the maximum strengths within the test range. In general, the PPF content increases. The load-deflection curve (Figure 11(a)) shows that the strain-hardening process is longer, and the curve is longer because of the bridging action of fibers, indicating that the toughness has improved. Therefore, when the W/B increases from 0.27 to 0.33, the initial cracking strength and flexural strength decrease, which may be due to excessive water, thereby reducing the specimen strength. Figures 11(b) and 11(c) are images obtained by DIC, and the deformation of thin plate and the distribution of strain can be clearly seen. This is consistent with previous research [37].

The initial crack load and peak load in the four-point bending test were recorded, and the initial crack strength $\sigma_c$ and bending strength $\sigma_m$ were calculated, respectively.
The adhesion between the concrete matrix and fiber is small, which has a more significant effect on strength. The excessive content of FA shows a downward trend, indicating that the content of FA has a more significant effect on strength. The initial cracking strength and bending strength of FA was 75%, the content of PPF increased from 1% to 2%. The initial cracking strength and bending strength increased by 76.29% and 57.67%, respectively. Under the same W/B, when the content of PPF is 1.5%, and the content of FA is 45%, the presence of fiber increases the bending strength of concrete. When the content of PPF is 1.5%, and the content of FA is 45%, the W/B changes from 0.27 to 0.33, and the initial cracking strength and bending strength decrease by 32.38% and 35.20%, respectively. When the content of fiber is 1.5%, and the content of FA is 75%, the W/B changes from 0.27 to 0.33, and the initial cracking strength and bending strength decrease by 47.21% and 23.53%, respectively, indicating that the decrease of the initial cracking strength and bending strength is primarily caused by the increase of the W/B [5].

Flexural toughness is used as the main index to measure the toughness of fiber-reinforced concrete. The flexural toughness of specimens is evaluated by referring to the toughness index method of ASTM C1080. On the load-deflection curve, the area under the curve corresponding to the initial crack deflection \( \delta_c \) is the toughness index of specimens. The area of multiples of \( \delta_c \) such as \( 3 \delta_c, 5.5 \delta_c, \) and \( 15.5 \delta_c \) to \( S \delta_c \) is used as the corresponding bending toughness indices \( I_{5}, I_{10}, \) and \( I_{30} \), which are calculated by Equations (6)–(8). Based on this result, the residual strength index \( R \) among the deflections of adjacent end points is calculated by

\[
I_5 = \frac{S_{5\delta_c}}{S_{\delta_c}},
\]

\[
I_{10} = \frac{S_{10\delta_c}}{S_{\delta_c}},
\]

and

\[
I_{30} = \frac{S_{30\delta_c}}{S_{\delta_c}},
\]

where \( \sigma_c \) is the initial cracking strength, MPa; \( P_c \) is the initial crack load, N; \( l \) is the span of specimen, mm; \( b \) is the width of specimen mm; \( h \) is the height of specimen, mm; \( \sigma_m \) is the bending strength, MPa; and \( P_m \) is the peak load, N.

As shown in Table 7, the bending strength of the specimen increased by 18%–55% during the loading process from the initial cracking strength to the ultimate strength. The ultimate elastic deformation of the material was characterized by the initial crack deflection of the specimen; the plastic ultimate deformation was characterized by the ratio of the peak deflection to the initial crack deflection. Through calculation, the ratio is approximately 5.66–30.85, indicating that the material prepared by the test has good ductility.

The large initial crack deflection indicates that the first crack appears relatively late. The larger the peak deflection is, the longer the strain-hardening stage on the load-deflection curve is, and the better the toughness of the specimen is. The better the bond between the fiber and concrete matrix is, the better the bridging effect between them is.

The 28 d initial cracking strength and bending strength of PPFHRPC were 1.94–7.3 MPa and 3.01–8.60 MPa, respectively. The W/B was 0.3, and the content of FA was 45%. The content of PPF increased from 1% to 2%. The initial cracking strength and bending strength increased by 76.29% and 57.67%, respectively. Under the same W/B, when the content of FA was 75%, the content of PPF increased from 1% to 2%. Therefore, the initial cracking strength and bending strength show a downward trend, indicating that the content of FA has a more significant effect on strength. The excessive content of FA may lead to the presence unhydrated FA. Consequently, the adhesion between the concrete matrix and fiber is small, forming the weak link of the matrix and then reducing the strength. Before the first crack appeared, the fiber does not bear any force, and all the force is borne by the matrix; thus, the initial cracking strength reflects the strength change of the matrix. The higher the FA content is, the lower the cracking strength is. After the first crack appears in the matrix, the fiber begins to bear the load, which is similar to the role of “microreinforcement” in the concrete, forming a disorderly support system in the internal. The higher the content of fiber is, the greater the support effect is. During the stress process, the presence of fiber increases the bending strength of concrete.

Table 7: Calculated results of mechanical properties of thin plates with different mix proportions and ages.

<table>
<thead>
<tr>
<th>Mix number</th>
<th>( P_c ) (N)</th>
<th>( \delta_c ) (mm)</th>
<th>( \sigma_c ) (MPa)</th>
<th>( P_m ) (N)</th>
<th>( \delta_m ) (mm)</th>
<th>( \sigma_m ) (MPa)</th>
<th>( I_5 )</th>
<th>( I_{10} )</th>
<th>( I_{30} )</th>
<th>( R_{I_{5},3} )</th>
<th>( R_{I_{10},10} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>145.81</td>
<td>0.17</td>
<td>1.94</td>
<td>225.81</td>
<td>2.84</td>
<td>3.01</td>
<td>6.35</td>
<td>11.98</td>
<td>43.36</td>
<td>94.67</td>
<td>156.92</td>
</tr>
<tr>
<td>2</td>
<td>256.84</td>
<td>0.32</td>
<td>3.42</td>
<td>354.84</td>
<td>7.25</td>
<td>4.73</td>
<td>6.19</td>
<td>10.79</td>
<td>32.36</td>
<td>94.24</td>
<td>107.87</td>
</tr>
<tr>
<td>3</td>
<td>410.13</td>
<td>0.33</td>
<td>5.47</td>
<td>499.13</td>
<td>1.92</td>
<td>6.66</td>
<td>5.02</td>
<td>10.84</td>
<td>38.67</td>
<td>83.09</td>
<td>139.16</td>
</tr>
<tr>
<td>4</td>
<td>240.58</td>
<td>0.32</td>
<td>3.21</td>
<td>332.59</td>
<td>1.99</td>
<td>4.43</td>
<td>5.40</td>
<td>11.75</td>
<td>45.80</td>
<td>90.75</td>
<td>170.24</td>
</tr>
<tr>
<td>5</td>
<td>363.61</td>
<td>0.36</td>
<td>4.85</td>
<td>451.61</td>
<td>8.07</td>
<td>6.02</td>
<td>6.56</td>
<td>10.32</td>
<td>33.21</td>
<td>82.22</td>
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<td>11.10</td>
<td>33.03</td>
<td>74.16</td>
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The calculation results of bending toughness index and residual strength index are shown in Table 7. According to ASTM C1018, when \( I_5 > 5, I_{10} > 10, I_{30} > 30 \), the toughness of the material is good. As shown in Table 7, the bending toughness index increases with the increase of deflection, indicating that the toughness of PPFRHPC gradually increases with the increase of deformation. Except for groups 7, 9, and 12, the bending toughness indices shown in Table 7 meet the requirements, indicating that the load imposed on the thin plate specimen gradually increases with the increase of bending deflection within a certain deformation range, which indicates bending deformation hardening. The residual strength index \( R \) shows the trend of the bending strength of concrete material with deflection. Based on the calculation results shown in Table 7, the value of \( R \) increases gradually with the increase of deflection, indicating that load increases with the increase of deflection within the corresponding deformation range.
3.2. Establishment and Analysis of the Response Surface Model. The response surface model was established by multiple regression analysis in Design Expert 12® software. The accuracy of the regression model and significance of the influencing factors were tested by ANOVA. In addition, the lack of fitting can measure the degree of fitting between the model and data. When the p-value is smaller than 0.05, the fitting was seriously insufficient, indicating that the model was not well fitted to the data. When p > 0.1, no significant mismatches are found.

The p-values for lack of fitting in all nine models are greater than 0.1, which means that the lack of fitting is not significantly related to pure error. Therefore, the established model can well reflect the relationship between experimental variables and response values.

The final equation is based on nine practical factors of response:

\[
\sqrt{R_1} = 25.47141 - 8.58148A - 0.022237B - 48.83435C - 0.000184AB + 27.11409AC - 0.141420BC,
\]

\[
\frac{1}{R_2} = 3.988 + 0.2249A - 0.048B - 17.739C + 0.000608AB + 0.0844BC + 0.084463AC - 0.053A^2 + 0.00018958B^2 + 23.068C^2,
\]

\[
\frac{1}{\sqrt{R_3}} = 3.30116 - 0.207387A - 0.031447B - 11.94665C + 0.000496AB + 0.817973AC + 0.043523BC - 0.030457A^2 + 0.0001266B^2 + 12.85075C^2,
\]

\[
\frac{1}{R_4} = 0.2622 - 0.0041A - 0.0024B - 1.282C - 0.00028AB + 0.0077AC + 0.0046BC + 0.0014A^2 + 0.000012B^2 + 1.814C^2,
\]

\[
\frac{1}{R_5} = 2.310 + 0.2296A - 0.025201B - 11.1196C + 0.000151AB - 0.262044AC + 0.0316BC - 0.055A^2 + 0.000131B^2 + 16.901C^2,
\]

\[
\ln(R_6) = -1.918 - 1.32004A + 0.075B + 17.5414C - 0.003119AB + 2.02834AC - 0.022707BC + 0.321A^2 - 0.000416B^2 - 30.41540C^2,
\]

\[
\log_{10} R_7 = -0.32286 - 0.1073A + 0.022768B + 5.99482C - 0.000979AB + 0.218335AC - 0.006050BC + 0.038220A^2 - 0.000175B^2 - 12.37572C^2,
\]

\[
\frac{1}{\sqrt{R_8}} = -0.955229 - 1.24881A - 0.066712B + 29.24174C + 0.010250AB + 0.212157A^2 + 0.000403B^2 - 48.61759C^2 ,
\]

\[
\frac{1}{\sqrt{R_9}} = -0.441918 - 0.821076A - 0.044680B + 18.88730C + 0.006794AB + 0.139063A^2 + 0.000271B^2 - 31.48246C^2 .
\]

3.3. Influence of Different Factors on the Mechanical Properties of PPFRHPC

3.3.1. Compressive Strength. The compressive strength at 7 d and 28 d is given by Equations (9) and (12), respectively. Based on p-value analysis, the most significant factor is the content of FA, followed by the W/B. The compressive strength is always inversely proportional to the content of FA and W/B. The content of FA affects the content of PPF and W/B, indicating that FA has a great influence on the compressive strength of specimens.

As shown in Figure 12, when the content of FA is certain, and when the W/B is 0.27, the compressive strength decreases with the increase of the content of fiber. When the W/B is 0.33, the compressive strength increases slowly with the increase of fiber content. However, the compressive strength at C = 0.33 is smaller than that at C = 0.27. When A = 1%, B = 45%, and C = 0.27, the best compressive strength can be obtained.

As shown in Figure 12, in models R1 and R4, the contour lines of B are denser than those of C, and the three-dimensional (3D) graph is steeper, indicating that factor B has a greater influence on response R1 than factor C, which is the
same as the previous conclusion [6]. The curvature of 3D graph can represent the significant degree of interaction among various factors, and 3D graph can make the interaction more evident. In model R1, the interaction between C and B factors is evident. Regardless of the content of PPF, the compressive strength decreases with the increase of FA content. Therefore, the addition of excessive FA greatly reduces the compressive strength of concrete.

3.3.2. Flexural Strength. The flexural strength at 7 d and 28 d is given by Equations (10) and (13), respectively. Based on $p$-value analysis, the most significant factor is the content of FA, followed by W/B and the content of PPF. When the content of FA increases, the fine powder gradually fills up the pores in the concrete matrix. Therefore, the compactness between the aggregate and cementitious material and the bond strength between the fiber and concrete are improved, thereby increasing the flexural strength.

As shown in Figure 13, the flexural strength always initially increases and then decreases with the increase of FA content and W/B, indicating the optimal content of FA and W/B to achieve the maximum flexural strength within the test range. When the content of PPF is certain, the flexural strength increases initially and then decreases at a W/B of 0.27 or 0.33. When $A = 2\%$, $B = 63\%$, and $C = 0.27$, the best flexural strength can be obtained.

As shown in Figure 13, in models R2 and R5, the contour lines of B are denser than the contour lines of C, and the 3D graph is steeper, which indicates that factor B has a greater influence on response R1 than factor C; that is, the influence of FA content on the flexural strength is greater than that of W/B. In model R2, the interaction between C and B factors is evident. Regardless of the content of PPF, the flexural strength increases initially and then decreases with the increase of FA content, indicating the optimal content of FA within the test range to achieve the maximum flexural strength.

3.3.3. Flexural-Compressive Ratio. The flexural-compressive ratio at 7 d and 28 d is given by Equations (11) and (14), respectively. Based on $p$-value analysis, the most significant factor is the content of FA, followed by the content of PPF. This result is consistent with changes in flexural strength because the flexural-compressive ratio is a response related to flexural strength. When the content of FA increases, the fine powder gradually fills up the pores in the concrete matrix, improving the compactness between the aggregate and the cementitious material and...
the bond strength between the fiber and concrete, thereby increasing the flexural strength and affecting the flexural-compressive ratio.

As shown in Figure 14, the flexural-compressive ratio always increases slowly with the increase of the content of PPF and increases initially and then decreases with the increase of FA content, indicating the optimal content of FA and W/B to achieve the maximum flexural-compressive ratio within the test range. When the content of PPF is certain, the flexural-compressive ratio increases initially and then decreases at a W/B of 0.27 or 0.33. When A = 2%, B = 75%, and C = 0.27, the optimal flexural-compressive ratio can be obtained.

As shown in Figure 14, in models R3 and R6, the contour lines of factor B are denser than the contour lines of factor C, and the 3D graph is steeper, indicating that factor B has a greater influence on response R3 and R6 than factor C. As shown in the diagram, the flexural-compressive ratio always increases with the increase of the content of FA, and it is more evident in the 28d flexural-compressive ratio (R6) because of the reaction of FA. The internal pores of the concrete matrix are filled. The PPF bridge with concrete matrix enhances the flexural strength, thereby increasing the flexural-compressive ratio.

3.3.4. Splitting Tensile Strength. The prediction model of split tensile strength is given by Equation (15). According to p-value analysis, the most significant factor is the content of FA, followed by W/B. The splitting tensile strength is always proportional to the content of PPF and inversely proportional to the W/B. With the increase of FA content, the splitting tensile strength increases initially and then decreases.

As shown in Figure 15, in model of R7, the contour lines of B are denser than those of C, indicating that the content of FA has a greater impact on the splitting tensile strength than the W/B.

3.3.5. Bending Properties of Thin Plates. The prediction model of initial cracking and bending strength is given by Equations (16) and (17). Based on p-value analysis, the most significant factor is the content of FA, followed by the content of fiber. The initial cracking strength and bending strength always increase initially and then decrease with the increase of fiber and FA content, indicating the optimal content of PPF and FA to achieve the maximum initial cracking strength and bonding strength. With the increase of fiber content, many fibers disperse evenly in the concrete matrix. During cracking,
the initial cracks appear late because of the synergistic effect of concrete and fiber. After cracking, the bending strength of the matrix is improved because of the bridging effect of fiber. However, if the content of fiber is further increased, then the fiber may agglomerate. Given the excessive addition of fiber, the bubbles appear inside the concrete, which weakens the combination between the fiber and matrix and reduces the flexural capacity of the material. When the content of FA is increased because of the filling effect of fine powder, the specimen becomes dense, and the contact area between the fiber and matrix increases, which promotes the role of fiber. However, with the increase of FA content, the slow pozzolanic
reaction decreases the concrete strength, resulting in low cracking strength and bending strength. When the W/B is constant, and the content of FA is 45%, the initial cracking and bending strength increase gradually and then decrease with the increase of fiber; when the content of FA is 75%, the initial cracking and bending strength increase initially and then decrease slowly with the increase of fiber. However, when $B = 75\%$, the strength is greater than that when $B = 45\%$. Therefore, 75\% is the optimal content of FA in the test range. Therefore, when $A = 1\%$, $B = 75\%$, and $C = 0.27$, the best initial cracking strength and bending strength can be obtained.

As shown in Figure 16, in models R8 and R9, the contour lines of B are denser than those of A, and the 3D graphics are steeper, indicating that FA content has a greater impact on initial cracking strength and bending strength than PPF content. In models R8 and R9, the interaction between

![Figure 16: Contour plots. (a, b) 28d initial crack strength (R8). (c, d) 28d bending strength (R9).](image-url)

### Table 8: Definition of factors and responses in multiobjective optimization.

<table>
<thead>
<tr>
<th>Name</th>
<th>Goal</th>
<th>Lower limit</th>
<th>Upper limit</th>
<th>Importance</th>
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<td>1</td>
<td>2</td>
<td></td>
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<tr>
<td>The content of FA (%)</td>
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<td>75</td>
<td></td>
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<tr>
<td>Water-binder ratio</td>
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<td>0.33</td>
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<tr>
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factors A and B is evident, which is consistent with the above-mentioned conclusion.

4. Optimization of the Content of Three Factors

Simultaneously obtaining the maximum value of various responses is difficult. Therefore, multiobjective optimization technology is adopted to optimize multiple responses. In this study, compromise optimization was performed for nine responses. As mentioned previously, the PPF content (A), FA content (B), and W/B (C) are independent variables. 7 d compressive strength (R1), 7 d flexural strength (R2), 7 d flexural-compressive ratio (R3), 28 d compressive strength (R4), 28 d flexural strength (R5), 28 d flexural-compressive ratio (R6), 28 d splitting tensile strength (R7), 28 d initial cracking strength (R8), and bending strength (R9) of thin plates are dependent variables. RSM was used to find the optimal content of the three factors to maximize the nine response values. Process optimization features in Design-Expert 12® software were used in this study. The definition of factors and responses in the optimization process is shown in Table 8. Each factor and reaction use a different level of importance. Based on multiobjective optimization, a relatively close solution satisfying the predetermined upper and lower limits is obtained.

Desirability refers to the closeness of the response to the expected value; the closer the value is to 1, the better the result is. Figure 17 shows the change in expected value function based on multiobjective optimization. The expected value of about 0.860 indicates that response surface optimization is feasible.

5. Conclusion

Using the BBD design of the RSM, this study conducted experimental research on the compressive strength, flexural strength, and splitting tensile strength of high-performance fiber concrete mixed with PPF and investigated toughness through a four-point bending test. The following conclusions were drawn:

(1) Mechanical sand can be substituted for natural sand to prepare PPFHPC. Its mechanical properties are remarkable under standard curing conditions, and its toughness is better than ordinary high-performance concrete.

(2) The working performance of HPC decreases slightly with the addition of fiber, but the ductility is improved, which can be used in practical engineering. Compared with concrete without fiber, the mechanical properties of HPC mixed with PPF are
significantly improved. The 28d flexural strength increased by 69.65%, split tensile strength increased by 43.12%, initial crack strength increased by 276.28%, and bending strength completely increased by 86.05%.

(3) Increasing FA content has adverse effects on compressive strength. The compressive strength at 28d decreased by 52.3%, but it has also positive effects on compression ratio and toughness.

(4) The response surface models of 7d compressive strength (R1), 7d flexural strength (R2), 7d flexural ratio (R3), 28d compressive strength (R4), 28d flexural strength (R5), 28d flexural-compressive ratio (R6), 28d splitting tensile strength (R7), 28d initial cracking strength (R8), and bending strength (R9) were established. The accuracy of nine models was verified by variance analysis. In addition, the relation equation between response and factors is obtained, which can be used to select the content of the three factors based on different actual conditions, based on multivariate optimization technology of the RSM. The optimal values of nine responses were 35.6 MPa, 6.26 MPa, 17.08%, 57.16 MPa, 7.87 MPa, 13.76%, 7.85 MPa, 5.18 MPa, and 6.37 MPa, respectively.

Data Availability

The data that support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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References


