Research Article

Mechanical and Dynamic Properties of Hybrid Fiber Reinforced Fly-Ash Concrete

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Received 4 May 2021; Revised 13 June 2021; Accepted 1 August 2021; Published 10 August 2021

Academic Editor: Suvash Paul

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In order to explore the influence of basalt-polypropylene hybrid fiber on the static mechanical properties and dynamic compression properties of fly-ash concrete, 16 groups of basalt-polypropylene hybrid fiber fly-ash concrete (HBPC) and 1 group of benchmark concrete were designed and prepared. The slump, static compressive strength, static splitting tensile strength, and dynamic compressive performance tests were tested. At the same time, the mechanism of the mechanical properties of hybrid fiber reinforced fly-ash concrete was analyzed by means of scanning electron microscopy (SEM). The results show that the failure of the benchmark concrete is mainly brittle failure. Compared with the benchmark concrete, the static compressive strength and splitting tensile strength of HBPC are significantly enhanced. Basalt-polypropylene hybrid fiber, polypropylene fiber, and basalt fiber, are extremely significant factors affecting the slump, static compressive strength, and static splitting tensile strength of HBPC, respectively. The peak stress of the benchmark concrete and HBPC increases with the increase of the loading air pressure, showing a certain strain rate effect. SEM shows that the fibers have good dispersibility in the concrete and good adhesion with the concrete matrix interface, but excessive fibers will cause fiber agglomeration, which increases the internal defects of HBPC.

1. Introduction

Since the famous British craftsman Aspdin invented Portland cement in 1824, concrete, a kind of multiphase composite material composed of sand, stone, cement, and water, has been widely used in various countries around the world. It has become one of the most widely used materials in civil engineering [1]. But the disadvantage of concrete is that it has low tensile strength and is prone to brittle failure. Once cracking occurs, it will lose its bearing capacity rapidly under the action of tensile stress, which limits the application of concrete in civil engineering to a certain extent. Therefore, how to effectively improve the mechanical properties of concrete has always been a hot topic in the engineering field all over the world [2, 3].

The splitting tensile strength of concrete is directly proportional to its compressive strength, but the tension-compression ratio is inversely proportional to its strength

grade [4–6]. Adding fiber into concrete can effectively improve the tension-compression ratio of concrete, that is, its tensile strength and toughness, and improve its brittle failure characteristics [7–9]. At present, the representative fibers are steel fiber, polypropylene fiber, basalt fiber, and synthetic fiber, and the research shows that [10–12] basalt fiber has low price, high elastic modulus, and little environmental pollution, and the splitting tensile property and durability of concrete can be improved obviously by adding it into concrete; adding polypropylene fiber into concrete can enhance the compressive strength and improve the brittle failure under compression of concrete.

Meanwhile, studies show that [13–17] when the tensile stress of concrete is less than the cracking stress, the tensile force is mainly borne by concrete, and the fiber bears less. When microcracks appear inside the component, the cracked concrete loses part of its load-bearing capacity, and the fibers that cross the microcracks begin to work, and

microfibers with low elastic modulus can significantly inhibit the early primary microcracks. With the increase of the crack width, the microfibers are continuously pulled out and broken. At this time, the macrofibers with high elastic modulus begin to play a role, effectively delaying and preventing the expansion of cracks. Therefore, the addition of a kind of fiber into concrete has great limitations for the improvement of concrete performance, and the hybrid of two types of fibers can complement each other's advantages and better play the "positive hybrid effect."

Fly ash comes from the powder collected from the flue gas of pulverized coal combustion in the boiler, which has potential hydration activity and better characteristics of reducing hydration heat. In order to improve the utilization rate of waste fly ash, it is widely used in cement mixture, steamed lime-sand brick, concrete admixture, and other building materials [18–20]. At present, domestic and foreign scholars use fly ash to replace a certain proportion of cement as the cementing material to prepare concrete. Research shows that fly ash plays a promoting role in the later stage of coagulation. Within a reasonable cement replacement rate, the compressive strength and splitting tensile strength of fly ash instead of cement concrete are improved to varying degrees [21, 22].

In 1951, Japanese statistician Genichi Taguchi proposed the orthogonal table based on the optimization rule of the experiment. The orthogonal table has become the basic tool of the orthogonal experiment design, which makes the orthogonal experiment dispersibility and neat comparability. Not only can the order of the primary and secondary effects of the factors be determined according to the orthogonal table but also the range and variance analysis can be used to analyze the test data and the degree of influence of each factor on the index, so as to find the optimal conditions or the optimal combination to achieve the purpose of the test [23–25].

At present, the research and application of hybrid fiber concrete are mostly steel-polypropylene hybrid fiber concrete [26, 27], and the research on basalt fiber and polypropylene fiber mixed into concrete is less. Therefore, in this paper, basalt fiber and polypropylene fiber are mixed into concrete and fly ash is used to replace a small amount of cement to prepare basalt-polypropylene hybrid fiber fly-ash concrete. It is expected that the two kinds of fibers will play a "positive hybrid effect." In order to further study the influence of basalt fiber, polypropylene fiber and fly ash replace part of cement on the working performance, static mechanical performance, and dynamic compression performance of concrete, and the orthogonal experiments of basalt fiber volume ratio, polypropylene fiber volume ratio, and fly-ash replacing cement ratio were designed and tested on the slump, static compressive strength, static splitting tensile strength, and dynamic compressive performance of basalt-polypropylene hybrid fiber fly-ash concrete, to provide a theoretical basis for related engineering.

2. Materials and Methods

2.1. Raw Materials. The binder material, used in the experiment, consists of the Chinese standard Portland cement

and fly ash. The cement adopts P·O 42.5 ordinary Portland cement, and it has 42.5 MPa compressive strength at the age of 28th day. Basalt fiber is chopped basalt fiber, and polypropylene fiber is single-tied polypropylene fiber, as shown in Figure 1. The main performance parameters of basalt fiber and polypropylene fiber are shown in Table 1. The coarse aggregate used in the experiment has the particle sizes of 5–25 mm continuous graded granite gravel with bulk density of 1465 kg/m³, apparent density of 2665 kg/m³, crushing index of 10.5%, and mud content of 0.5%. The sand selected in the experiment is natural river sand with apparent density of 2520 kg/m³ and fineness modulus of 2.7. The water-reducing agent was polycarboxylic acid superplasticizer (Type F), and the water-reducing rate was 37%. The water is ordinary tap water.

2.2. Experimental Design. Orthogonal experiment is an experimental method to arrange multifactor and multilevel experiments, which can effectively reduce the number of experiments when the number of total experiment groups is large. Its principle is to select representative and typical experimental groups from all experimental groups according to the orthogonality, so as to achieve the purpose of high efficiency, fast, and economy [28]. The factors and levels of this experiment are (1) basalt fiber volume ratio V_b (factor A); (2) polypropylene fiber volume ratio V_p (factor B); (3) fly ash replacing cement ratio R_f (factor C). The orthogonal table adopts three factors and four levels, namely, L16 (4³) orthogonal test design, as shown in Table 2. The design of reference mix proportion is shown in Table 3.

2.3. Sample Preparation. Sodium carboxymethyl cellulose can make the fiber fully disperse in the concrete in the state of monofilament and improve the reinforcement effect of the fiber, and the influence on the performance of the concrete itself can be ignored, and its dosage is generally set as 0.7% of the total mass of the cementitious material [29]. In the trial mixing process, the agglomeration phenomenon is easily formed when the fiber volume ratio is too large, so sodium carboxymethyl cellulose is added to the sample. The wet mixing and fiber sprinkling were carried out simultaneously. Firstly, sand, gravel, and cementitious materials were mixed dry; then, water and water-reducing agent were added, and at the same time, fiber was sprinkled for wet mixing. Six 100 mm × 100 mm × 100 mm cube specimens (three of them are used for the cube compressive strength test and the other three are used for the splitting tensile strength test) are prepared for each group mix proportions. In the SHPB test, there is currently no unified standard for the size of the test piece, which is generally determined based on the diameter of the SHPB equipment bar and combined with experience. It must be free from friction and inertial force during the test, and the specimen is in overall stress balance and in a uniaxial stress state. At the same time, it is necessary to control the height-diameter ratio of the specimen to be 0.5~1.0. According to the SHPB equipment in the laboratory, nine cylindrical specimens with a diameter of 74 mm and a height of 38 mm were

FIGURE 1: Appearance and microstructure of fiber: (a) appearance of basalt fiber, (b) microstructure of basalt fiber, (c) appearance of polypropylene fiber, and (d) microstructure of polypropylene fiber.

TABLE 1: Main performance parameters of basalt fiber and polypropylene fiber.

Fiber	Basalt fiber	Polypropylene fibers
Density (g/cm^3)	2.8	0.91
Tensile strength (MPa)	4000	700
Modulus of elasticity (GPa)	100	5.85
Monofilament diameter (μm)	12	8
Length (mm)	12	10
Elongation at break (%)	3.1	15

TABLE 2: Orthogonal experiment factors and levels of HBPC.

Level	Factor		
	V_b (A) (%)	V_p (B) (%)	R_f (C) (%)
1	0.1	0.1	5
2	0.2	0.2	10
3	0.3	0.3	15
4	0.4	0.4	20

Note: the percentage of basalt fiber and polypropylene fiber refers to the mass conversion relative to their respective densities, and the percentage of fly ash refers to the percentage of the quality of substitute cement.

TABLE 3: Benchmark mix proportions of concrete in kg/m^3 .

Water	Cement	Sand	Gravel	Water-reducing agent
163	330	615	1243	5.2

prepared for each group mix proportions. The static compressive strength, static splitting tensile strength, and dynamic compressive properties of the specimens were tested after 28 days of indoor standard curing under natural

conditions. The curing temperature range was $16\sim 24^\circ\text{C}$, and the humidity was more than 95%.

2.4. Static Mechanical Property Test

2.4.1. Test Methods. Compressive strength and splitting tensile strength were tested by using the YAW-4206 pressure testing machine. According to the regulations' provisions of the National Standards of the People's Republic of China (GB/T 50081-2002) *Standard for test method of mechanical properties of ordinary concrete*, the standard size of the specimen used to measure the compressive strength and splitting tensile strength of concrete is $150\text{ mm} \times 150\text{ mm} \times 150\text{ mm}$. Because the specimen is $100\text{ mm} \times 100\text{ mm} \times 100\text{ mm}$ nonstandard specimen, the cube compressive strength and splitting tensile strength are converted into standard specimen results by multiplying the size conversion coefficient. The cube compressive strength size coefficient is 0.95, and splitting tensile strength size coefficient is 0.85.

2.4.2. Data Processing. In order to investigate the effects of basalt fiber volume ratio (A), polypropylene fiber volume ratio (B), and fly-ash replacing cement ratio (C) on the slump, static compressive strength, and static splitting tensile strength of HBPC, find out the significant factors, and calculate the range and variance results of slump, compressive strength, splitting tensile strength, and tension-compression ratio of HBPC. The calculation method is as follows:

The range calculation method is as follows:

$$R_i = \max(\overline{K_{i1}}, \overline{K_{i2}}, \dots, \overline{K_{im}}) - \min(\overline{K_{i1}}, \overline{K_{i2}}, \dots, \overline{K_{im}}) \quad (i = A, B, \text{ and } C; m = 1, 2, 3, \text{ and } 4), \quad (1)$$

where K_{im} is the sum of the test results corresponding to the level of factor m in column i , $\overline{K_{im}}$ is the average value of K_{im} , and R_i is the range of factors in column i .

R_i reflects the change range of the test index when the level of the factors in column i changes. The larger R_i is, the greater the influence of the factor on the test index is.

Therefore, the primary and secondary relationship of the factors can be judged according to R_i .

The variance is calculated as follows:

$$\text{Sum of squares of total deviations : } SST = \sum_{i=1}^n (y_i - \bar{y})^2, \quad (2)$$

$$\text{Degree of freedom : } f_t = n - 1, \quad (3)$$

where n is the number of rows (test times) of the orthogonal experiment table and $\bar{y}$ is the average value of n test indexes:

$$\text{Sum of square of deviations of factor A: } SSA = \sum_{i=1}^a n_i (\bar{y}_i - \bar{y})^2, \quad (4)$$

$$\text{Degree of freedom : } f_A = n_i - 1, \quad (5)$$

$$\text{Mean square of factor A: } MSA = \frac{SSA}{f_A}, \quad (6)$$

where A is the level number of factor A , n_i is the number of tests at level i , and $\bar{y}_i$ is the average value of index at each level of factor A . Similar to the solution of the sum of square sum of deviation, degree of freedom, and mean square of factor A , the values of SSB , SSC , f_B , f_C , MSB , and MSC can be obtained:

$$\text{Sum of the squares of deviation of error : } SSE = SST - SSA - SSB - SSC, \quad (7)$$

$$\text{Mean square of error : } MSE = \frac{SSE}{f_E}, \quad (8)$$

$$\text{Significant level of factor A: } F_A = \frac{MSA}{MSE}. \quad (9)$$

Similar to the significance level of factor A , F_B and F_C can be obtained.

2.5. Dynamic Compression Performance Test

2.5.1. Test Rig. The dynamic mechanical properties' test used a variable cross-section SHPB system with a diameter of 74 mm, as shown in Figure 2. The test rig is mainly composed of the loading drive system, compressive bar system, and data acquisition system.

2.5.2. Test Principle. The rods in the press bar system are all made of uniform steel material; the specific parameters are as follows: the striker bar is a constant cross-section cylinder steel pole, with a total length of 800 mm and a diameter of 37 mm. The incident bar is a variable cross-section steel pole, the total length is 3200 mm, the variable cross-section area is 450 mm long, the diameter of the incident end is 37 mm, and the diameter of the straight section is 74 mm. The transmission bar is a constant cross-section cylinder steel pole, with a total length of 1600 mm and a diameter of 74 mm.

As shown in Figure 3, driven by the high-pressure gas, the striker bar hits the incident bar at a certain initial velocity v_0 . At the moment of impact, a forward propagating stress pulse, namely, the incident wave ε_i , is generated in the incident bar. When the incident wave propagates along the incident bar to the contact surface between the specimen and the incident bar, the specimen begins to deform or even break, and a reverse stress pulse is generated in the incident

bar, that is, reflection wave ε_r . There is also a part of the stress pulse that penetrates the specimen into the transmission bar, continues to propagate forward, and generates a transmission stress pulse in the transmission bar, that is, a transmission wave ε_t .

The incident wave and the reflection wave are measured by the strain gauge on the incident bar, and the transmission wave is measured by the strain gauge voltage signal on the transmission bar. The voltage signal on the strain gauge is relatively weak and needs to be processed by a strain amplifier. The wiring method is a half-bridge type. The strain gauges are arranged in a symmetrical position for series connection, and the same type of strain gauge with the same resistance value is connected as temperature compensation. According to the one-dimensional elastic stress wave theory, the average strain ε , mean stress σ , and average strain rate ε' of the specimen were deduced by using the "three-wave method:"

$$\varepsilon = \frac{c_0}{l_0} \int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t) dt, \quad (10)$$

$$\sigma = \frac{AE}{2A_0} (\varepsilon_i + \varepsilon_r + \varepsilon_t), \quad (11)$$

$$\varepsilon' = \frac{c_0}{l_0} (\varepsilon_i - \varepsilon_r - \varepsilon_t). \quad (12)$$

In formulae (10)–(12), A is the cross-sectional area of the pressure rod, E is the elastic modulus of the rod, A_0 is the cross-sectional area of the test piece, l_0 is the original length

FIGURE 2: SHPB device. (a) SHPB equipment diagram. (b) Overall diagram. (c) Control and data acquisition system. (d) Specimen arrangement.

FIGURE 3: Schematic diagram of stress wave propagation.

of the test piece, c_0 is the elastic wave velocity in the rod, and t is the action time of the stress pulse.

2.5.3. Test Plan. In this test, the loading air pressure is set to 0.4 MPa, 0.5 MPa, and 0.6 MPa, which represent three strain rates of low, medium, and high, respectively. Each group of specimens is subjected to three shock tests under the same loading air pressure in order to obtain a more ideal test result. In order to keep the specimen surface in close contact with the transmission bar and the incident bar, before the test, adjust the axis position of the incident bar and the transmission bar, keep the two bars aligned with the support line and radial line, and fine-tune the height of the rod end support to ensure the two rods are aligned. Before the start of the test, in order to eliminate the influence of friction on the end face of the specimen, both ends of the specimen were evenly smeared with vaseline, and then, place the specimen in the center between the incident bar and the transmission bar.

3. Static Mechanical Performance Test Results and Analysis

3.1. Test Result. The slump, static compressive strength (f_{cu}), static splitting tensile strength (f_{ts}), and tension-compression ratio (f_{ts}/f_{cu}) of a group of benchmark concrete and 16 groups of HBPC obtained from the test are listed in Table 4.

It can be seen from Table 4 that the compressive strength and splitting tensile strength of 16 groups of HBPC are higher than the benchmark concrete, and the maximum compressive strength appears in group 11#, which is 20.87% higher than the benchmark concrete, and the maximum splitting tensile strength appears in group 15#, which is 37.65% higher than the benchmark concrete.

3.2. Range Analysis. The range of slump, compressive strength, splitting tensile strength, and tension-compression ratio of HBPC is shown in Figure 4.

It can be seen from Figure 4(a) that the influence degree of three factors on the slump of HBPC is as follows: basalt fiber volume ratio (V_b) > polypropylene fiber volume ratio (V_p) > fly-ash cement replacement ratio (R_f). With the increase of V_b , V_p , and R_f , the slump of HBPC all shows a downward trend. V_b increased from 0.1% to 0.4%, slump decreased by 65.84%, V_p increased from 0.1% to 0.4%, slump decreased by 44.53%, R_f increased from 0.1% to 0.4%, and slump decreased by 11.59%. From the slump point of view, the best combination is $A_1B_1C_1$, that is, V_b is 0.1%, V_p is 0.1%, and R_f is 5%.

It can be seen from Figure 4(b) that the order of the influence of the three factors on the compressive strength of HBPC is as follows: V_p (range: 2.7 MPa) > V_b (range: 2.07 MPa) > R_f (range: 1.77 MPa). V_b increased from 0.1% to 0.4%, the compressive strength increased by 3.68%, V_p

TABLE 4: Slump and strength test results of HBPC.

Sample	Concrete slump (mm)	f_{cu} (MPa)	f_{ts} (MPa)	f_{ts}/f_{cu}
0 [#]	179	20.3	1.58	0.07798
1 [#]	170	24.2	1.99	0.08211
2 [#]	146	24.6	2.0	0.08121
3 [#]	127	26.6	2.36	0.08866
4 [#]	84	25.3	2.27	0.08992
5 [#]	140	25.5	2.25	0.08832
6 [#]	123	25.9	2.2	0.08476
7 [#]	80	25.6	2.32	0.0908
8 [#]	96	27.2	2.37	0.08713
9 [#]	109	24.8	2.32	0.09356
10 [#]	94	25.3	2.33	0.09218
11 [#]	78	29.4	2.48	0.08425
12 [#]	68	29	2.54	0.08757
13 [#]	75	24.6	2.37	0.09624
14 [#]	44	25.7	2.43	0.09469
15 [#]	35	28.8	2.59	0.08983
16 [#]	26	28.2	2.48	0.08796

FIGURE 4: Range analysis results of three factors on mechanical properties of HBPC. (a) Slump. (b) Compressive strength. (c) Splitting tensile strength. (d) Tension-compression ratio.

increased from 0.1% to 0.4%, and the compressive strength increased by 5.49%; R_f increased from 0.1% to 0.4%, and the compressive strength decreased by 3.44%. The influence of

R_f on compressive strength is not obvious, and the overall change is within 4%. The compressive strength of HBPC increases first and then decreases with addition of fibers,

indicating that a reasonable fiber volume ratio is conducive to the improvement of compressive strength, but too high fiber volume ratio will have a negative effect on compressive strength. From the perspective of compressive strength, the best combination is $A_3B_3C_1$, that is, V_b is 0.3%, V_p is 0.3%, and R_f is 5%.

It can be seen from Figure 4(c) that the factors influence the splitting tensile strength of HBPC are V_b (range: 0.48 MPa) $> R_f$ (range: 0.22 MPa) $> V_p$ (range: 0.19 MPa). V_b increased from 0.1% to 0.4%, splitting tensile strength increased by 11.61%, V_p increased from 0.1% to 0.4%, splitting tensile strength increased by 3.23%, R_f increased from 0.1% to 0.4%, and splitting tensile strength increased by 5.05%. The influence of V_b on the splitting tensile strength of HBPC is greater than that of V_p and R_f and the latter two have similar influences on the splitting tensile strength of HBPC. The addition of basalt fiber and polypropylene fiber is conducive to the improvement of HBPC splitting tensile strength, but the effect of polypropylene fiber on the splitting tensile strength of HBPC is less obvious than that of basalt fiber. This is mainly due to the high elastic modulus of basalt fiber, which bears more load than polypropylene fiber in the later stage of concrete cracking, which effectively prevents the expansion of concrete cracks [30, 31]. It shows that fiber hybrids can exhibit good synergy, and the splitting tensile strength of the benchmark concrete can be improved. From the perspective of splitting tensile strength, and the best combination is $A_4B_3C_2$, that is, V_b is 0.4%, V_p is 0.3%, and R_f is 10%.

It can be seen from Figure 4(d) that the influence degree of three factors on the tension-compression ratio of HBPC is as follows: $R_f > V_b > V_p$. V_b and R_f have an increasing trend in the influence of HBPC tension-compression ratio, V_b increased from 0.1% to 0.4%, tension-compression ratio

increased by 7.84%, V_b increased from 5% to 20%, and tension-compression ratio increased by 8.86%. With the increase of V_p , the tension-compression ratio first decreases, then increases, and then decreases, but the overall variation range is within 3%, and the influence is not obvious. If only considering the improvement of the concrete tension-compression ratio, the optimal combination is $A_4B_1C_4$, that is, V_b is 0.4%, V_p is 0.1%, and R_f is 20%.

3.3. Variance Analysis. The variance calculation results are listed in Table 5. V_b and V_p are extremely significant factors for HBPC slump, R_f is a nonsignificant factor, V_p is an extremely significant factor for HBPC compressive strength, V_b and R_f are significant factors, V_b is an extremely significant factor for HBPC splitting tensile strength, V_p and R_f are significant factors, and fly ash is more significant than polypropylene fiber; R_f is an extremely significant factor for the HBPC tension-compression ratio, V_b is a significant factor, and V_p is a nonsignificant factor that affects the tension-compression ratio of HBPC.

3.4. Analysis of HBPC Efficacy Coefficient Method. The efficacy coefficient method is a comprehensive evaluation method for multiple objectives. According to the results of slump, compressive strength, and splitting tensile strength of HBPC in Table 5, the maximum and minimum values are selected as the satisfactory and unallowable values of the efficacy coefficient method index evaluation system. The specific values are shown in Table 6.

Calculate the efficiency coefficient values of each index of 16 groups of HBPC according to the satisfactory value and the unallowable value of each index. The calculation formula is as follows:

$$d_i = \frac{\text{Actual value} - \text{Unallowable value}}{\text{Satisfactory value} - \text{Unallowable value}} \times 40 + 60 \quad (i = 1, 2, \text{ and } 3), \quad (13)$$

where d_1 is the efficacy coefficient value of each group of HBPC slump, d_2 is the efficacy coefficient value of each group of HBPC compressive strength, and d_3 is the efficacy

coefficient value of each group of HBPC splitting tensile strength:

$$\text{Total efficacy coefficient value of each group of HBPC: } d = \sqrt[3]{d_1 \times d_2 \times d_3}. \quad (14)$$

The calculation results are shown in Table 7.

According to the comparison of the total efficacy coefficient values of the data in Table 7, the total efficacy coefficient of the specimens in 12[#] group is the largest, which is 87.84. Therefore, combining the three indexes of slump, compressive strength, and splitting tensile strength, the best mix ratio combination is $A_3B_4C_2$.

3.5. Failure Mode Analysis. Figure 5 shows the failure mode of part of specimens under the static compressive strength test, and Figure 6 shows the failure mode of the part of specimens' static splitting tensile strength. In the static compressive strength test, the 0[#] group, the benchmark concrete specimen, shows obvious damage and large flaking, while the surface of the concrete specimen mixed with basalt

TABLE 5: HBPC slump and strength variance analysis results.

Index	Sources of variation	Sum of square	Mean square	Freedom	F value	Significance
Concrete slump (mm)	A	16473.7	5491.2	3	43.37	**
	B	7101.2	2367.1	3	18.7	**
	C	609.7	203.2	3	1.61	—
	E	759.4	126.6	6		
f_{cu} (MPa)	A	10.303	3.434	3	14.77	*
	B	23.288	7.763	3	33.39	**
	C	8.692	2.898	3	12.46	*
	E	1.395	0.233	6		
f_{ts} (MPa)	A	0.525	0.175	3	19.74	**
	B	0.112	0.037	3	4.2	*
	C	0.131	0.044	3	4.92	*
	E	0.053	0.009	6		
f_{ts}/f_{cu}	A	0.000096	0.000032	3	9.84	*
	B	0.00001	0.000003	3	1.03	—
	C	0.00015	0.00005	3	15.46	**
	E	0.000019	0.000003	6		

Note: ** represents extremely significant, * represents significant, and — represents nonsignificant.

TABLE 6: Satisfactory and unallowable values of each index.

Value type	Slump (mm)	Compressive strength (MPa)	Splitting tensile strength (MPa)
Satisfactory value	170	52.7	4.68
Unallowable value	26	47.5	3.89

TABLE 7: HBPC efficacy coefficient analysis results.

Sample	Concrete slump (mm)	Index		Concrete slump (mm)	Efficiency coefficient		Total efficacy coefficient
		Compressive strength (MPa)	Splitting tensile strength (MPa)		Compressive strength (MPa)	Splitting tensile strength (MPa)	
1 [#]	170	24.2	1.99	100	60	60.51	71.34
2 [#]	146	24.6	2.0	93.33	63.08	60	70.69
3 [#]	127	26.6	2.36	88.06	74.62	84.81	82.29
4 [#]	84	25.3	2.27	76.11	68.46	84.3	76.02
5 [#]	140	25.5	2.25	91.67	70	81.27	80.49
6 [#]	123	25.9	2.2	86.94	73.08	74.18	77.82
7 [#]	80	25.6	2.32	75	70.77	87.85	77.54
8 [#]	96	27.2	2.37	79.44	83.08	85.82	82.74
9 [#]	109	24.8	2.32	83.06	64.62	90.89	78.72
10 [#]	94	25.3	2.33	78.89	68.46	89.87	78.59
11 [#]	78	29.4	2.48	74.44	100	87.85	86.80
12 [#]	68	29	2.54	71.67	96.92	94.94	87.04
13 [#]	75	24.6	2.37	73.61	63.08	96.46	76.51
14 [#]	44	25.7	2.43	65	71.54	97.97	76.95
15 [#]	35	28.8	2.59	62.5	95.38	100	84.16
16 [#]	26	28.2	2.48	60	90.77	92.41	79.54

FIGURE 5: Failure modes of specimens in the static compressive strength test. (a) 0[#] group. (b) 11[#] group. (c) 12[#] group. (d) 15[#] group.

FIGURE 6: Failure modes of specimens in the static splitting tensile strength test. (a) 0[#] group. (b) 11[#] group. (c) 12[#] group. (e) 15[#] group.

fiber, polypropylene fiber, and fly ash is relatively complete, with only small cracks on the surface and small peeling off at the corners; in the static splitting tensile strength, the benchmark concrete showed obvious brittle failure, the specimen fractured into two halves, accompanied by a larger sound when it is destroyed, while the specimens of the 11[#], 12[#], and 15[#] groups were not split into two parts after being destroyed, and the main crack appeared on the surface of the specimen. The integrity of the specimen was better, showing a phenomenon of cracking but not scattering, and the sound was dull when it was destroyed.

3.6. HBPC Strength Prediction Model. According to the theory of mechanics composite materials, it can be assumed that the strength of HBPC is composed of concrete original strength, basalt fiber reinforcement, polypropylene fiber reinforcement, and fly ash instead of cement reinforcement.

Assume that the strength regression model is as follows:

$$f = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \phi, \quad (15)$$

where f is the concrete compressive strength or split tensile strength (MPa), α_0 is the concrete matrix compressive strength or split tensile strength (MPa), α_1 , α_2 , and α_3 is the regression coefficient, ϕ is the test parameter, x_1 is the basalt fiber volume ratio (%), x_2 is the polypropylene fiber volume ratio (%), and x_3 is the fly-ash replacing cement ratio (%).

Substituting the data in Table 4 into regression model (15), the least squares method is used to estimate α_0 to obtain the regression equation of HBPC compressive strength and splitting tensile strength:

$$f_{cu} = 47 + 640x_1 + 1005x_2 - 12.4x_3 \quad (R^2 = 0.83), \quad (16)$$

$$f_{ts} = 3.65 + 161x_1 + 61x_2 + 152x_3 \quad (R^2 = 0.86). \quad (17)$$

In formulae (16) and (17), f_{cu} is the compressive strength of HBPC (MPa), f_{ts} is the splitting tensile strength of HBPC (MPa), and R^2 is the coefficient of determination.

Figure 7 shows the relative error comparison between the predicted and measured values of HBPC compressive strength and splitting tensile strength. It can be seen that the maximum error occurs in 0[#] group, with an error of 7.8%, indicating that the model has high accuracy and can provide certain reference value for engineering construction.

4. Dynamic Compression Performance Test Results and Analysis

4.1. Stress Balance Verification. During the shock test, whether the stress at both ends of the specimen can be balanced before failure determines the reliability of the test results [32]. Therefore, the data balance needs to be verified before the start of the experiment, and the verification basis is $\varepsilon_i(t) + \varepsilon_r(t) = \varepsilon_t(t)$. Figure 8 is the stress balance at both ends of the assembly. It can be seen that the sum of the incident stress and the reflection stress is basically equal to the transmission stress, the stresses at both ends of the specimen are balanced, and the test results are reliable.

4.2. HBPC Failure Mode. The failure mode of the typical HBPC specimens after the dynamic compression mechanical properties test is selected for analysis, and the 0[#], 11[#], 12[#], and 15[#] groups are taken as examples to observe the test phenomena. It can be seen from Figure 9 that the 0[#] group, that is, the ordinary concrete specimens are broken into small pieces after being impacted, showing obvious brittle failure. With the increase of loading pressure (strain rate), the specimens are broken into small pieces accompanied by scattered powder particles, and the failure degree of the specimens increases rapidly. The 11[#] group is the specimen with the best static compressive strength; under 0.4 MPa loading air pressure impact, the surface of the specimen appeared to have microcracks, but there was no fracture, and integrity remained relatively good; under 0.5 MPa loading air pressure impact, the surface of the specimen began to appear more obvious cracks, but there was no fracture. Under the loading air pressure of 0.6 MPa, the surface cracks of the specimen showed a “trigeminal star shape” and fracture occurs. The 12[#] group is the specimen with the best static mechanical performance, none of the specimens appeared to have fracture under the impact of the three kinds of loading air pressure, the integrity of the specimens was maintained very well, and there was no brittle failure like ordinary concrete, showing a certain ductile failure characteristics. The 15[#] group is the specimen with the best static splitting tensile strength, and the failure of the specimen is more serious than that of the 11[#] and 12[#] groups; under the impact of 0.5 MPa loading air pressure, a crack through the whole specimen is formed on the surface and the specimen fractured into two halves; with the increase of the impact loading air pressure, the specimen failure degree intensified.

FIGURE 7: Comparison of predicted and measured values of HBPC compressive strength and split tensile strength.

FIGURE 8: Stress balance verification.

4.3. Dynamic Compressive Strength. Table 8 shows the peak stresses of the benchmark concrete and HBPC under different loading air pressures impacts. It can be seen that the peak stresses of 16[#] groups of HBPC under different loading air pressures are all higher than that of benchmark concrete, which shows that the mixing of basalt fiber, polypropylene fiber and fly ash into concrete is beneficial to improve its dynamic compression mechanical properties; when the loading air pressure is 0.4 MPa, the peak stress of benchmark concrete is 21.1 MPa; when the loading air pressure is 0.5 MPa, the peak stress of benchmark concrete is 23.1 MPa, 9.48% higher than that at 0.4 MPa; when the loading air

pressure continues to increase to 0.6 MPa, the peak stress of benchmark concrete is 24.4 MPa, 15.64% higher than that at 0.4 MPa. This indicates that, with the increase of the loading air pressure, the peak stress (dynamic compressive strength) of the benchmark concrete is increasing, and both are higher than the cube compressive strength (20.3 MPa) of the benchmark concrete used in this test, showing a certain strain rate strengthening effect. Similar conclusions can be obtained by analyzing the dynamic compressive strength of HBPC in other groups, and this article will not repeat the description.

4.4. Stress-Strain Curve. Taking the 0[#], 11[#], 12[#], and 15[#] groups as examples for analysis, Figure 10 shows the stress-strain curves of the above four groups. It can be seen that, with the impact air pressure increase, the dynamic compressive strength, strain value, and plasticity of benchmark concrete and HBPC specimens also increase; the 0[#] group specimens show obvious brittle failure, and the stress-strain relationship of the 11[#], 12[#], and 15[#] groups specimens can be divided into elastic stage, crack expansion stage, plastic deformation stage, and failure stage, and the stress in the plastic stage increases linearly with the increase of strain. After the elastic limit stress is reached, the internal microcracks of the specimen begin to expand and then enter the significant plastic deformation stage. With the slow increase of the dynamic strength, when the yield stress is reached, the strain of the specimen increases slightly, the stress decreases sharply, and the specimen is completely destroyed.

FIGURE 9: Failure mode of 0#, 11#, 12#, and 15# group under 0.4 MPa, 0.5 MPa, and 0.6 MPa loading air pressure.

TABLE 8: Peak stress of each group of specimens.

Sample	Peak stress (MPa)		
	0.4	0.5	0.6
0#	21.1	23.1	24.4
1#	23.1	23.6	25.3
2#	24.6	27.5	30.2
3#	25.3	27.9	30.9
4#	26.1	30.3	31.4
5#	28.5	30.6	33.5
6#	30.6	32.9	38
7#	32.7	34.8	35.3
8#	35.3	36.8	39.6
9#	35.6	37.3	39.7
10#	36.7	41.9	42.2
11#	41.5	58.7	63
12#	43.9	50.7	51.8
13#	41.5	44.5	47.6
14#	40	42.2	46.9
15#	39.8	50.2	50.9
16#	33	36.3	38.2

FIGURE 10: Stress-strain curves of HBPC under different loading air pressures. (a) 0# group. (b) 11# group. (c) 12# group. (d) 15# group.

4.5. Fiber Crack Resistance Effect of HBPC. Figure 11 shows the crack resistance mechanism model of HBPC [33]. It is obvious that mixing basalt fiber and polypropylene fiber into concrete has a good synergistic effect. On the one hand, polypropylene fiber has small size and large number. It exerts a good crack resistance effect in the crack generation stage of the dynamic compression performance test, delays the stress concentration at the tip of the microcrack stage, and can prevent the expansion of the microcrack. When microcracks develop into macrocracks, the stress is transferred from polypropylene fiber to basalt fiber. Because basalt fiber has the advantage of high elastic modulus, its deformation under tensile stress is small, and it can produce adhesive force and mechanical bite force with the concrete matrix, which inhibits the expansion of macrocracks, transfers the stress to the concrete on both sides of cracks, causes multiple cracks in the concrete, and delays the appearance of dynamic compression failure of the concrete. As

the cracks continue to expand, the polypropylene fibers are broken and the basalt fibers are pulled out or slip in the concrete matrix can also absorb a large amount of dynamic compression energy. It can be seen that the hybrid of basalt fiber and polypropylene fiber can work synergy in different dynamic compression loading stages, play a crack resistance and reinforcement effect, effectively improve the dynamic compression resistance of concrete, improve the concrete's antidynamic compression performance effectively, and have better antidynamic compression performance than nonfiber and one kind of fiber.

5. SEM Microanalysis

It can be seen from Figure 12 that the exposed fiber surface is covered with dense thorn-like or spherical substances, which are mainly cement hydration matrix (C-S-H gel). During the hydration reaction of HBPC, C-S-H gel and cement

FIGURE 11: Crack resistance mechanism model of HBPC.

FIGURE 12: Fiber and matrix bonding.

FIGURE 13: SEM image of HBPC fiber distribution and bonding.

secondary hydration product ettringite tightly wrap the fibers. When the fiber is under tension, it can form a certain mechanical bite force with the cement matrix, so the single fiber dispersed in the HBPC acts like a steel bar. The tight combination of fiber and concrete matrix plays the role of secondary microreinforcement. At the same time, the fiber interacts to form a three-dimensional network structure and the bridging effect of the fiber strengthens the bond between

the fiber and the matrix, which effectively improves the mechanical properties of HBPC. It can be seen from Figure 13 that excessive fiber mixing into concrete will cause fiber agglomeration, which reduces the compactness of the concrete, affects the full bonding of the fiber and the concrete matrix, increases the internal defects of the concrete, and ultimately leads to the decrease of the strength of the concrete.

6. Conclusions

- (1) The static compressive strength and static splitting tensile strength of HBPC are both higher than those of benchmark concrete. The maximum increase of static compressive strength compared with the benchmark concrete is 20.87%. The maximum increase of static splitting tensile strength compared with the benchmark concrete is 37.65%.
- (2) Basalt fiber and polypropylene fiber are extremely significant factors affecting the slump of HPBC, and the degree of influence of basalt fiber is greater than that of polypropylene fiber. Polypropylene fiber is the extremely significant factor affecting the compressive strength of HPBC, and basalt fiber is the extremely significant factor affecting the splitting tensile strength of HPBC.
- (3) Based on the efficacy coefficient method, the test results of slump, static compressive strength, and static splitting tensile strength of HBPC are comprehensively analyzed. The best combination of the three factors is $A_3B_4C_2$. According to the test results, the strength prediction model between the static compressive strength and static splitting tensile strength of HBPC was established. The prediction accuracy of the model is high, and it can provide reference for engineering practice.
- (4) The integrity of the benchmark concrete remains poor after the dynamic compression test. The addition of basalt-polypropylene hybrid fiber and fly ash can inhibit the deformation and failure of concrete and improve the failure mode after dynamic compression load. With the increase of loading air pressure, the failure degree of the benchmark concrete and HBPC specimens increased, and the peak stress increased, showing a certain strain rate strengthening effect.
- (5) At the loading air pressure of 0.4 MPa, the 12[#] group is when the basalt fiber volume ratio is 0.3%, the polypropylene fiber volume ratio is 0.4%, and the fly-ash replacing cement ratio is 10%, and the peak stress is larger, and the dynamic compression properties are better. At the loading air pressure of 0.5 MPa and 0.6 MPa, the 11[#] group is when the basalt fiber volume ratio is 0.3%, the polypropylene fiber volume ratio is 0.3%, and the fly-ash replacing cement ratio is 5%, and the peak stress is larger, and the dynamic compression properties are better, which are closer to the test results of static compressive strength.
- (6) With the help of SEM microanalysis, it can be known that the fibers can be well bonded to the concrete matrix, and the three-dimensional randomly distributed fibers form stable load-carrying structures inside the HBPC, which improves the internal stress distribution of the concrete matrix and inhibits the generation and expansion of cracks. However, excessive fiber incorporation will cause fiber agglomeration, which will affect the full bonding of the fiber

and the concrete matrix, which is not conducive to the improvement of the mechanical properties of HBPC.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The research was financially supported by the Funding Project of Anhui University of Science and Technology (no. QN2019115) and Introduced Talent Research Funding of Anhui University of Science and Technology (no. 13190022).

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