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Study on Mechanical Properties and Pore Structure of Hybrid Fiber Reinforced Rubber Concrete

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Abstract: In this work, to reduce the probability of brittle failure in the support structure of deeply buried high-stress soft rock roadways, hybrid-fiber reinforced rubber concrete (HFRRC) was investigated using the orthogonal test, and the effects of various factors on the performance were studied. The mechanical properties, pore structure, and microstructure of rubber concrete reinforced by basalt fiber (BF) and polyvinyl alcohol fiber (PF) were studied from macroscale, mesoscale, and microscale perspectives. The results revealed that the content of the rubber particles has a significant impact on strength. Further, the addition of the hybrid fibers to the concrete was found to have a positive effect on the splitting tensile strength and the flexural strength. However, no significant effect was observed on the compressive strength. Furthermore, it was found that the content of BF and PF have a significant impact on the energy dissipation capacity and ductility, and the influence of the PF content is greater than that of the BF content. The concrete with 10% rubber particles of 1–3 mm, a volume fraction 0.3% basalt fiber, and a volume fraction 0.2% polyvinyl alcohol fiber was obtained as the optimal mix proportions. Moreover, it was found that the random distribution of the rubber particles and the hybrid fibers optimized the pore structure, inhibited the expansion of the cracks, and reduced the brittleness of the concrete. The findings of this study can provide a useful reference for the application of an environmentally friendly material with recycled rubber aggregate and hybrid fiber.

Keywords: rubber concrete; basalt fiber; polyvinyl alcohol fiber; pore structure



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1. Introduction

With coal mining entering the deep stage, the high ground stress, mining disturbance, and the poor stability of surroundings create great challenges for roadway support structures [1–3]. The ordinary concrete used in supporting structures exhibit brittleness [4]. Further, long-term exposure to high stresses may cause the lining spray layer to suffer due to sudden damages [5]. Moreover, in order to introduce a certain number of flexible components into the original multi-component concrete to reduce its brittleness, the addition of rubber particles into concrete was proposed [6–8]. Presently, rubber concrete is not widely used as a support material in roadway support structures. However, rubber concretes with lower density, higher energy dissipation, and toughness could be used to support high-ground stress soft rock roadways, as they could meet the demands of relieving the pressure of the surrounding rock [9–11].

The development of rubber concrete could transform waste rubber from “black pollution”, as it cannot be naturally degraded into green resources, which would have great environmental and economic significance [12–14]. Moreover, multiple studies revealed that rubber concrete is superior to ordinary concrete in many aspects [15–18]. Reda Taha et al. [17] found that rubber aggregates hinder the formation and growth of micro-cracks in the concrete and delay the appearance of macro-cracks. Issa et al. [18] indicated that rubber

concrete has a better energy absorption capacity than normal concrete because of the absorbing vibrations of the rubber particles. However, previous studies have shown that the addition of rubber particles reduces the strength of concrete due to their low elastic modulus, which restricts the application of rubber concrete [19–21].

With the development of concrete technology, fiber has been widely used in concrete structures for property and durability enhancement [22–24]. Cajka et al. [24] proved the positive influence of fiber concrete slabs on the increased load capacity and more favorable deformations compared to conventional concrete slabs. Further, some researchers have proposed that hybrid fiber-reinforced material offers better mechanical characteristics individual fibers [25–27]. Zhang et al. [26] conducted mix experiments that included steel fiber, polyvinyl alcohol fiber, and basalt fiber. The results showed that hybrid fibers can exert the best strengthening and toughening effect on concrete, achieving the best synergy with the correct fiber content. Alwesabi et al. [27] indicated the addition of hybrid fibers with enhanced ductile and post-cracking behavior compared to the addition of mono steel fibers. It has been found various types or sizes of fibers can play a different role at different scales and can be mixed into concrete to improve its performance as hybrid fiber concrete.

To mitigate the negative effects of adding rubber particles on the mechanical properties of concrete, many scholars have examined fibers with a high elastic modulus in rubber concrete [28–31]. Youssf et al. [29] indicated that the use of fiber-reinforced polymer (FRP) to confine rubberized concrete effectively negates the decrease in strength and retains the advantages of increased ductility that arise from the rubberized concrete. Karimipour et al. [30] found that the addition of rubber aggregate reduced the compressive strength, while the incorporation of steel fiber could overcome the decrease to some extent. Wang et al. [31] reported that the fracture energy and post-failure performance were largely increased by polyvinyl alcohol fiber reinforcement. They mainly focused on the mechanical properties of single-fiber reinforced rubber concrete. However, few researchers have added hybrid fibers to the system in order to form a new composite material and to analyze it from the macroscopic, mesoscale, and microscale perspectives.

In this study, an eco-friendly concrete called hybrid fiber-reinforced rubber concrete (HFRRC) was developed. Basalt fibers (BF) and polyvinyl alcohol fibers (PF) with a high elastic modulus were used as supplementary materials to improve the mechanical properties of the rubber concrete. Further, the optimal proportion of the rubber, BF, and PF were obtained through orthogonal array experiments. Moreover, the mechanical properties, pore structure, and the microstructure of the hybrid fiber-reinforced rubber concrete were thoroughly investigated, and it was determined that the developed material made the comprehensive and recycling utilization of waste possible, providing “green” materials to improve the support structures in deeply buried high-stress soft rock roadways.

2. Materials and Methods

The materials that were used, the design of the experiments, and the methods used for the preparation of the specimens and testing are briefly described below.

2.1. Materials

The cement used in this study was Chinese standard Portland cement. The chemical composition of the cement is presented in Table 1. The coarse aggregate consisted of crushed limestone with continuous grading, a particle size of 5–15 mm, and an apparent density of 2780 kg/m³. The fine aggregate was river sand with a fineness modulus of 2.6. Further, a high-performance water reducer (HPWR) obtained from the Shaanxi Qinfen Building Materials Co., Ltd., Xi'an, China, was employed to ensure fluidity and water retention. The performance indexes are shown in Table 2. The rubber particles were produced and obtained by cutting waste tires, and the main elements of the rubber are shown in Table 3. Three kinds of rubber particles with the sizes of 0.85 mm, 1–3 mm, and 3–6 mm were used to prepare the concrete. The technical indexes of the rubber particles are presented in Table 4, and the appearance of the rubber particles is shown in Figure 1.

The physical properties of BF and PF are listed in Table 5, and their appearances are shown in Figure 2.

Table 1. Chemical composition of the cement.

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Loss on Ignition
Content (%)	22.60	5.03	4.38	63.11	1.46	2.24	1.18

Table 2. Performance indexes of high-performance water reducer.

Water-Reducing Rate/%	Bleeding Rate/%	Gas Content/%	Initial Setting Time/min	Final Setting Time/min	Recommended Dosage/%
30	40	2	35	50	0.8–1.2

Table 3. Element type and relative content.

Element	C	O	S	Zn	Si
Content (%)	92.21	3.21	2.85	1.62	0.11

Table 4. Technical indexes of rubber particles.

Size/mm	Moisture Content/%	Ash Content/%	Acetone Extract/%	Metal Content/%	Fiber Content/%	Sieve Residue Content/%	Tensile Strength/MPa	Elongation at Break/%
0.85	0.62	8.75	5.12	0.02	0.00	0.014	16.8	564
1–3								
3–6								

Table 5. The physical properties of basalt fiber and polyvinyl alcohol fiber.

Properties	Length/mm	Tensile Strength/MPa	Elastic Modulus/GPa	Elongation at Break/%	Density/g·cm ^{−3}
Basalt fiber	18	3000–4800	90–110	2.5	2.63
Polyvinyl alcohol fiber	12	1600–2500	40–80	6.9	1.29

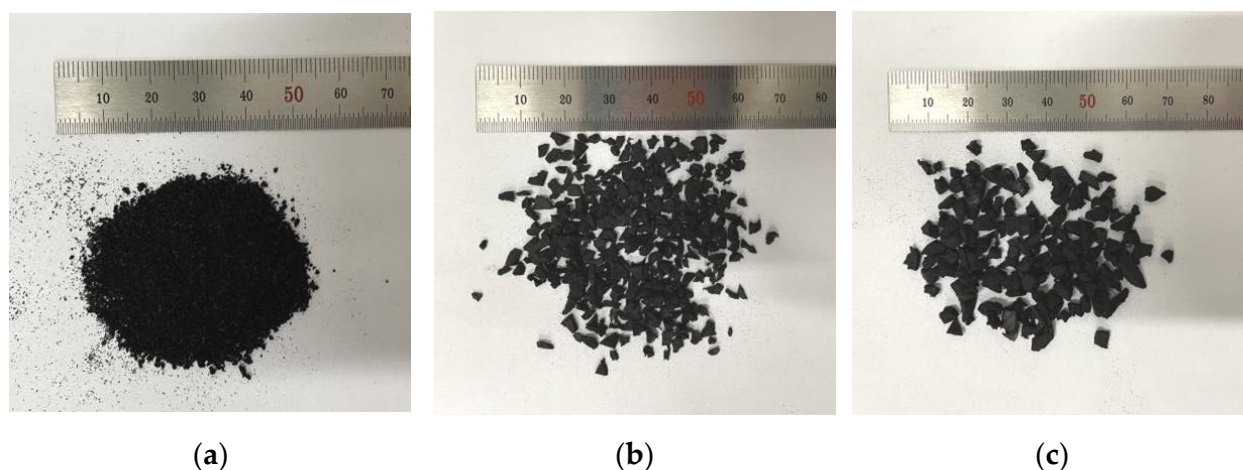


Figure 1. The appearance of rubber particle with the size of (a) 0.85 mm; (b) 1–3 mm; (c) 3–6 mm.

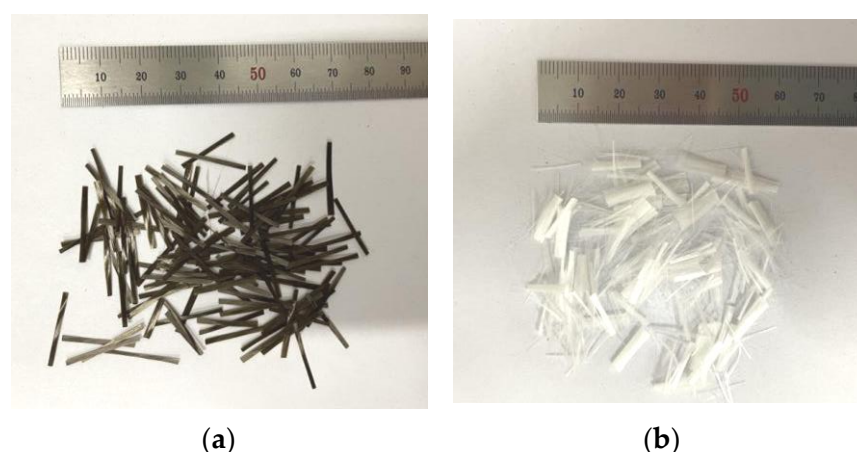


Figure 2. The appearance of the fibers: (a) basalt fibers; (b) polyvinyl alcohol fibers.

2.2. Design of Experiments Using Orthogonal Array

The optimal proportion of the hybrid fibers reinforced rubber concrete (HFRRC) was determined using the orthogonal test method [32]. In this method, four factors were designed, including the rubber particle size (factor A), rubber particle content (factor B), basalt fiber content (factor C), and the polyvinyl alcohol fiber content (factor D). Further, three levels were designed for each factor, including the rubber particle sizes of 0.85 mm, 1–3 mm, and 3–6 mm; the rubber particle content of 10%, 20%, and 30%; basalt fiber content of 0.1%, 0.2%, and 0.3%; and polyvinyl alcohol fiber content of 0.1%, 0.2%, and 0.3%.

Tests were performed according to the L_9 (3^4) Orthogonal array and consisted of four factors and three levels. The factors and the levels of the orthogonal experiment are shown in Table 6. The mixed proportions of each group of concrete are presented in Table 7.

Table 6. Factor and level of the orthogonal experiments.

Factor Level	A	B	C	D
	Rubber Particle Size	Rubber Particle Content	BF Content	PF Content
1	0.85 mm	10%	0.1%	0.1%
2	1–3 mm	20%	0.2%	0.2%
3	3–6 mm	30%	0.3%	0.3%

Note: For the rubber particles, the content replaces the corresponding percentage of fine aggregate mass with an equal volume of rubber particles.

Table 7. Mixing proportions of the experiment.

Group Number	Rubber Particle Size/mm	Rubber Particle/ $\text{kg}\cdot\text{m}^{-3}$	Basalt Fiber/ $\text{kg}\cdot\text{m}^{-3}$	Polyvinyl Alcohol Fibers/ $\text{kg}\cdot\text{m}^{-3}$	Sand/ $\text{kg}\cdot\text{m}^{-3}$	Limestone/ $\text{kg}\cdot\text{m}^{-3}$	Cement/ $\text{kg}\cdot\text{m}^{-3}$	Water Reducer/ $\text{kg}\cdot\text{m}^{-3}$	Water/ $\text{kg}\cdot\text{m}^{-3}$
OC-0	-	-	-	-	885.00	885.00	440.00	3.80	200.00
HFRRC-1	0.85	46.73	2.63	1.29	796.50	885.00	440.00	3.80	200.00
HFRRC-2	0.85	93.46	5.26	2.58	796.50	885.00	440.00	3.80	200.00
HFRRC-3	0.85	140.18	7.89	3.87	796.50	885.00	440.00	3.80	200.00
HFRRC-4	1–3	46.73	5.26	3.87	708.00	885.00	440.00	3.80	200.00
HFRRC-5	1–3	93.46	7.89	1.29	708.00	885.00	440.00	3.80	200.00
HFRRC-6	1–3	140.18	2.63	2.58	708.00	885.00	440.00	3.80	200.00
HFRRC-7	3–6	46.73	7.89	2.58	619.50	885.00	440.00	3.80	200.00
HFRRC-8	3–6	93.46	2.63	3.87	619.50	885.00	440.00	3.80	200.00
HFRRC-9	3–6	140.18	5.26	1.29	619.50	885.00	440.00	3.80	200.00

2.3. Preparation of Specimens

The materials were weighed using an electronic scale and were mixed in a double-horizontal shaft forced-type concrete mixer. Initially, the pre-weighed aggregate, rubber particles, BF, and PF were mixed for 3 min. Then, the binder material was added and was mixed for 1 min. Subsequently, the previously measured water and the water reducer were

poured into the mixed dry materials and were stirred for 3 min in order to ensure that the mixture had a uniform plastic consistency. Next, a mold was filled with three layers, and they layers were consolidated using a vibratory table. Moreover, the top surface was smoothened using a trowel. The specimens were prepared under laboratory conditions of a $(20 \pm 2)^\circ\text{C}$ temperature and 70% relative humidity. After the hardening, the specimens were released from the molds and were cured in a saturated $\text{Ca}(\text{OH})_2$ solution at $20 \pm 2^\circ\text{C}$ for 28 days.

2.4. Test Methods

The specimens were tested for their strength and porosity, and the microstructure images were observed. They are briefly described below.

2.4.1. Strength Test

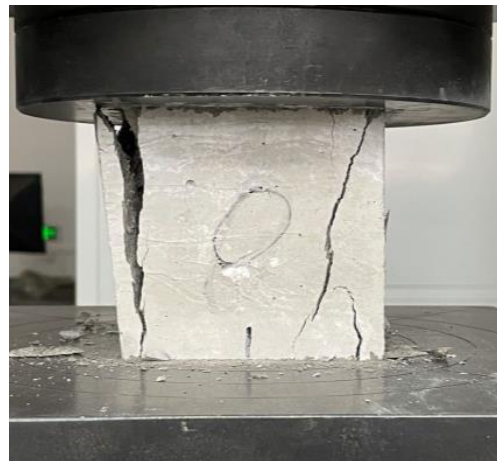
The compressive strength, splitting tensile test, and the flexural strength tests were conducted in accordance with the “Standard for Test Method of Mechanical Properties on Ordinary Concrete” (GB/T 50081-2016, Chinese standard) [33] using a WDW-1000 computer-controlled electronic universal testing machine (see Figure 3). The measuring system details are shown in Figure 4. The $100 \times 100 \times 100$ mm cubic specimens were prepared to measure the compressive and splitting tensile strengths, and specimens with sizes of the dimensions $100 \times 100 \times 400$ mm were fabricated to measure the flexural strengths (see Table 8). As per the standards, the rate of loading should be controlled for 3 mm/min in the compressive strength and splitting tensile strength tests and for 1 mm/min in the flexural strength test.

2.4.2. Porosity Test

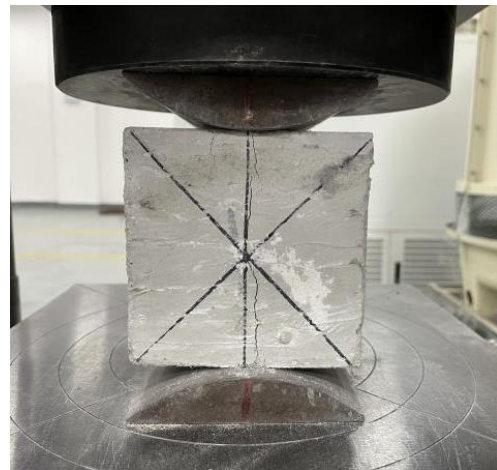
The porosity of the hardened concrete was tested using the ASTM C457 standard (Standard, ASTM C457, 2016) [34] with a TR-ASH-hardened concrete pore structure analyzer. During the sample preparation, a cube with of the dimensions of $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ was cut parallel to the concrete surface using a diamond saw, and a 20 ± 3 mm thick slice was taken. Further, rough grinding, finish grinding, and polishing were performed on the cut surface using various diamond grinding discs with different types of roughness. Thereafter, the cut surface was blackened with black ink. After the drying of the ink, the pores on the cut surface were filled with barium sulfate powder. Then, the air content, average chord length, specific surface, spacing factor, and the pore size distribution of the concrete were tested. The details of the porosity test process are illustrated in Figure 5.



Figure 3. WDW-1000 computer-controlled electronic universal testing machine.



(a)



(b)



(c)

Figure 4. Strength tests. (a) compressive strength test; (b) splitting tensile strength test; (c) flexural strength test.

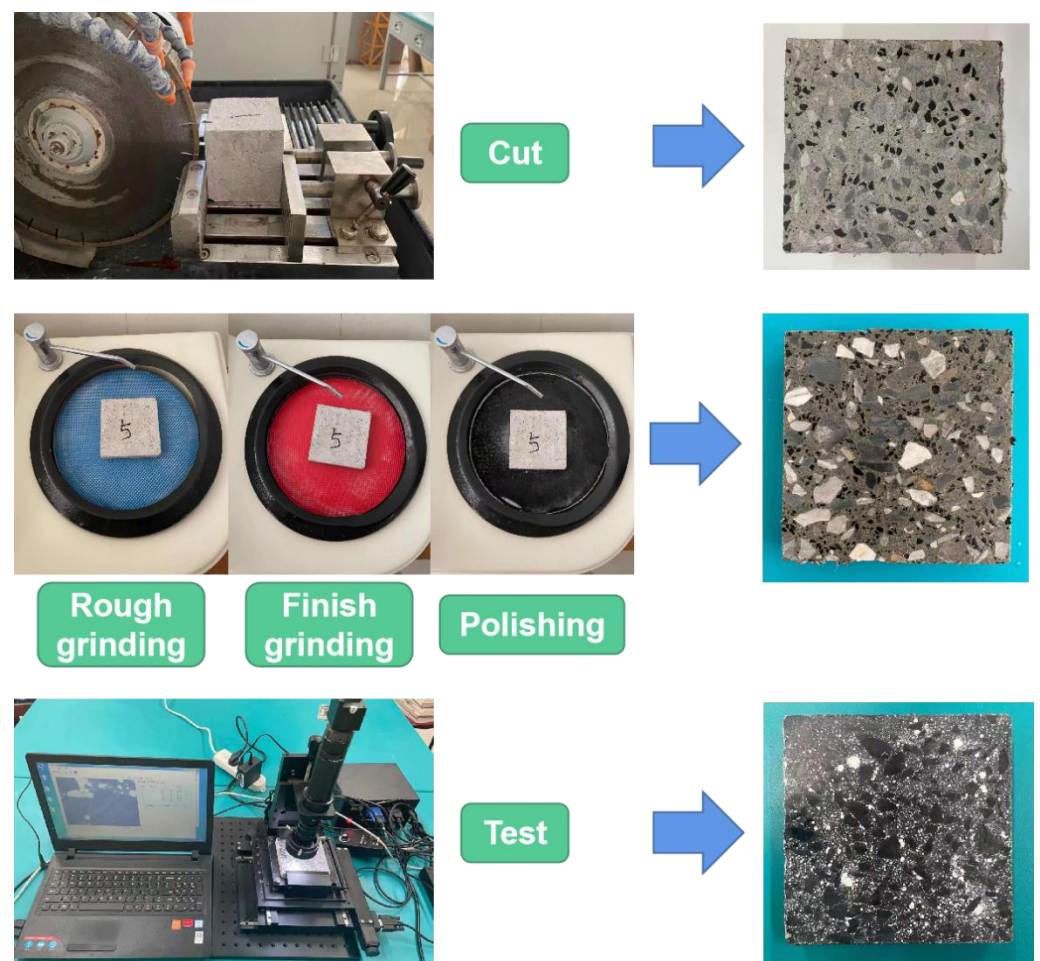


Figure 5. Details of porosity test process.

Table 8. The test parameters of strength tests.

Test Parameters	Compressive Strength Test	Splitting Tensile Strength Test	Flexural Strength Test
Specimen size			
Specimen number	30 (3 × 10)	30 (3 × 10)	30 (3 × 10)
Loading diagram			
Strength calculation	$f_C = \frac{F}{A}$	$f_T = \frac{2F}{\pi A}$	$f_F = \frac{3FL}{2bh^2}$

2.4.3. Scanning Electron Microscope Test

The microstructure of the specimen was observed using an scanning electron microscope (Zeiss Sigma 300). The samples were taken from the test cubes used in the axial compression test, which had a diameter of 5 mm and a thickness of 2 mm. To observe the

microscopic morphology of the rubber particles and the hybrid fibers in the concrete, the sample was taken without any coarse aggregate.

3. Results and Discussion

The results of the mechanical properties such as the strength, energy dissipation capacity, and ductility, visual analysis, range analysis, and the mesostructural and microstructural analysis are discussed below.

3.1. Mechanical Properties

The indexes of each group concrete are shown in Table 9.

Table 9. Results of orthogonal experiments.

Group Number	Compressive Strength/MPa	Elastic Modulus/GPa	Splitting Tensile Strength/MPa	Flexural Strength/MPa	Ductility Coefficient	Energy Dissipation Coefficient/%
OC-0	38.56	6.70	3.73	5.60	1.304	22.62
HFRRC-1	32.81	5.43	3.89	5.65	1.418	24.14
HFRRC-2	32.02	4.52	4.05	5.71	1.584	35.22
HFRRC-3	24.76	4.09	3.82	5.66	1.913	52.39
HFRRC-4	36.39	5.53	4.51	6.28	1.726	44.75
HFRRC-5	30.01	4.58	4.17	5.51	1.648	35.77
HFRRC-6	27.19	4.14	3.52	5.28	1.527	30.32
HFRRC-7	31.83	5.37	4.39	6.03	1.712	33.49
HFRRC-8	30.22	5.30	3.88	5.15	1.665	35.57
HFRRC-9	24.58	3.27	3.34	5.24	1.479	32.29

3.1.1. Strength

The compressive strength, splitting tensile strength, and flexural strength of the concrete are presented in Figure 6. The load–displacement curves are shown in Figure 7. From Figure 6, it can be observed that the compressive strength is reduced, which is as expected after introducing the rubber particles, BF, and PF. The compressive strength of group 0 (OC) was found to be 38.56 MPa. For all of groups containing concrete with rubber particles and hybrid fibers, the compressive strength was found to be lower than that of the OC. This could be attributed to the fact that the interfacial transition zone between the rubber and the cement matrix was weaker [35].

From the results, it can be observed that the compressive strength of the concrete decreases sharply as the rubber content increases, while there was a slight improvement in terms of the increase of the hybrid fiber content. By comparing the splitting tensile strength and the flexural strength of OC, which were 3.73 MPa and 5.60 MPa, respectively, it can be observed that the values of HFRRC-4, which are 4.51 MPa and 6.28 MPa, respectively, increased by 20.91% and 12.14%, respectively. This increase implies that the contribution of the hybrid fibers to the splitting tensile strength and the flexural strength is very significant. However, HFRRC-7, which has a total fiber load that is higher than HFRRC-4, exhibits lower flexural strength than HFRRC-4. This indicates that the mechanical properties of rubber concrete produced with coarse rubber particles displays a further decrease compared to rubber concrete produced with fine rubber particles and that the content of hybrid fibers has the optimal value. It is difficult to disperse hybrid fibers evenly, especially when they are present in the concrete at higher dosages; however, it is difficult for them to play effect roles in terms of improving the strength of the concrete when they are introduced to the concrete at a lower concentration, which also explains why the mechanical properties of HFRRC-1 with finer rubber particles is inferior to that of OC.

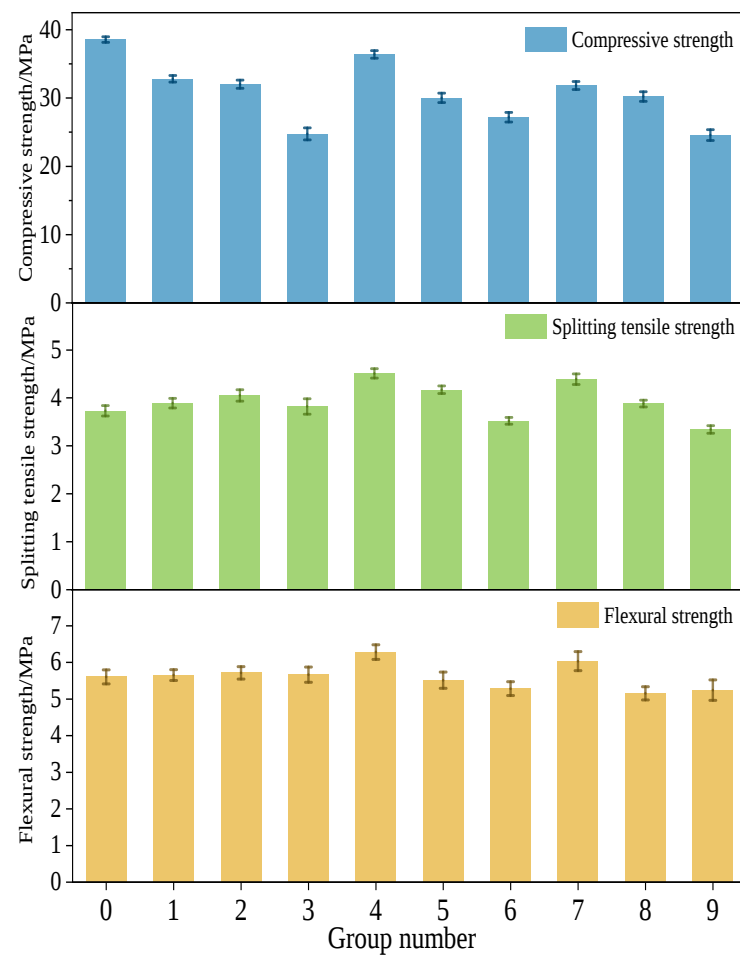


Figure 6. Strength.

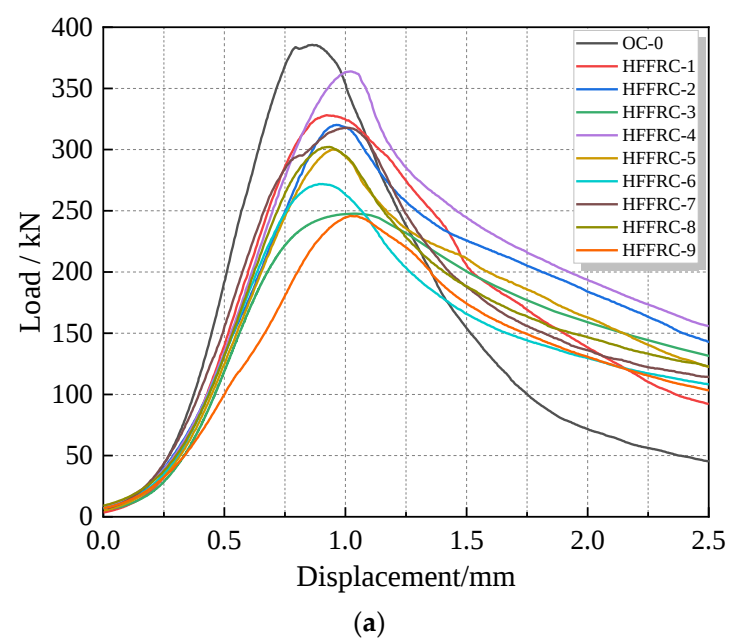


Figure 7. Cont.

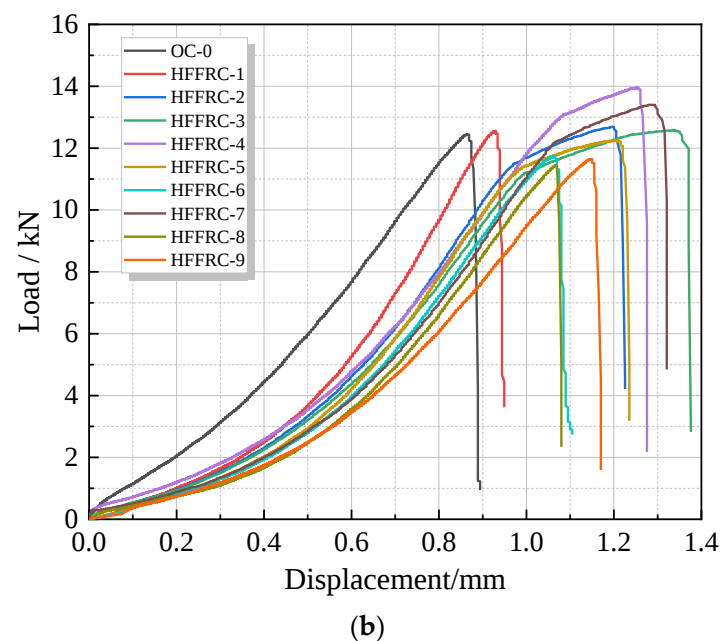


Figure 7. Load–displacement curves. (a) load–displacement curves in compression test; (b) load–displacement curves in flexural strength test.

3.1.2. Energy Dissipation Capacity

When a load is applied to the concrete, the compression process is a combination of energy absorption, dissipation, and release processes [36]. As shown in Figure 8, DE is parallel to BC , the area enclosed by ODE represents the dissipated energy W_d , and the area enclosed by DEF represents the elastic potential energy W_e .

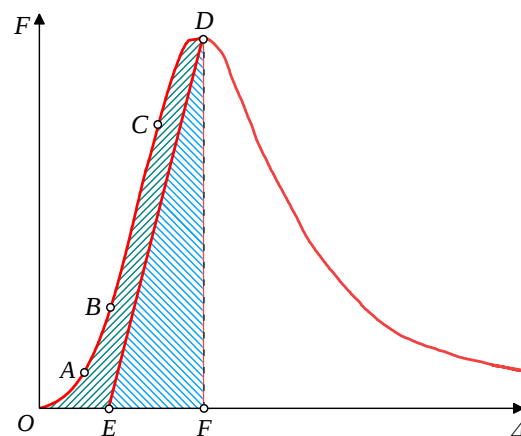


Figure 8. Schematic diagram of calculated energy dissipation.

The energy conversion of the concrete during uniaxial compression can be expressed by Equation (1):

$$W = W_d + W_e \quad (1)$$

In Equation (1), W refers to the work completed by the external force on the concrete, which is the energy input from the outside, J; W_d refers to the elastic deformation energy stored in the concrete during deformation, J; and W_e refers to the energy dissipated by the concrete during loading, which is what is the primarily cause of the internal damage and the plastic deformation of the concrete, J.

According to the second law of thermodynamics, energy dissipation is irreversible and unidirectional, while the stored elastic potential energy is bidirectional and reversible.

Therefore, the energy dissipation coefficient E_e can be represented by the percentage of dissipated energy in the total input energy, which can be expressed as shown in Equation (2):

$$E_e = \frac{W_d}{W} \quad (2)$$

From Table 9, it can be observed that the E_e of HFRRC is higher than that of OC. The group HFRRC-3 was found to have the largest energy dissipation coefficient, which was 131.61% higher than OC. Moreover, the rubber content of HFRRC-4 and HFRRC-7 were the same, and it can also be observed that the E_e of HFRRC-4, which has less hybrid fiber content, was 33.62% higher than that of HFRRC-7. This implies that when the rubber particles are smaller, the promotion effect on the energy dissipation capacity of the concrete is greater.

Generally, the rubber particles are equivalent to small elastomers, which can consume some energy through their deformation when the HFRRC is subjected to load [6]. The failure pattern diagrams are shown in Figure 9. It can be seen that the addition of the hybrid fibers creates cracks that are smaller and denser and that are accompanied by a large amount of energy consumption [12,37]. Compared to OC, it can be observed that there was less elastic potential energy left, reducing the probability of sudden failures.

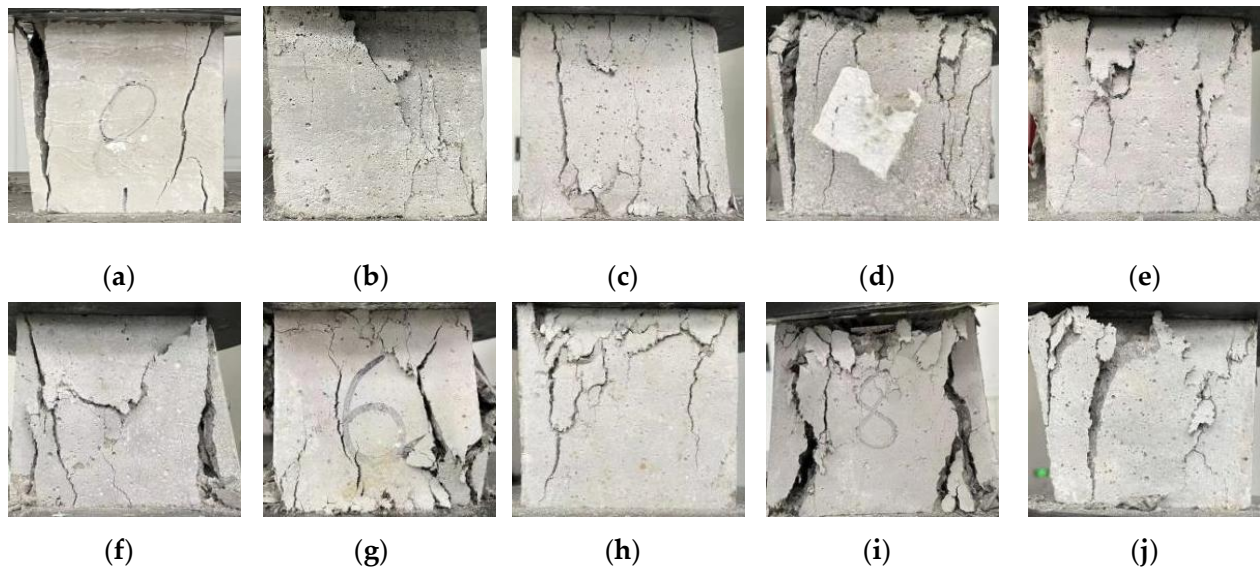


Figure 9. Failure pattern diagram. (a) OC-0, (b) HFRRC-1, (c) HFRRC-2, (d) HFRRC-3, (e) HFRRC-4, (f) HFRRC-5, (g) HFRRC-6, (h) HFRRC-7, (i) HFRRC-8, and (j) HFRRC-9.

3.1.3. Ductility

Ductility performance is expressed by the ductility coefficient μ [36], which is expressed as shown in Equation (3):

$$\mu = \frac{\Delta_u}{\Delta_y} \quad (3)$$

Δ_u and Δ_y are shown in Figure 10. Δ_u represents the ultimate displacement, which is the displacement corresponding to 0.85 times the maximum load after peak stress, and Δ_y represents the yield displacement, which is the displacement corresponding to 0.8 times the maximum load before peak stress.

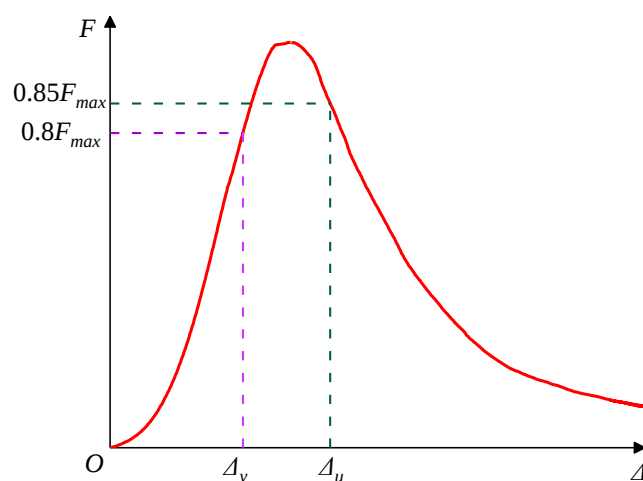


Figure 10. Schematic diagram of the calculated ductility coefficient.

From Table 9, it can be observed that the variation trend of the ductility coefficient is similar to that of the energy dissipation coefficient, which increases with the increasing rubber content and the hybrid fiber content. Further, it can also be observed that the μ of HFRRC-3 reaches the maximum value possible and is increased by 46.70% compared to OC. Furthermore, the failure pattern of HFRRC was relatively ductile, and its cracks were relatively tortuous and fine. This shows that the rubber particles and the hybrid fibers have a positive effect in terms of reducing the brittleness of the concrete.

3.1.4. Range Analysis

Range analysis intuitively shows the order of influence of each factor on the evaluation index. The range analysis results are presented in Table 10.

Table 10. Range analysis of the test results.

Index	Factor	k_1	k_2	k_3	R	Influence Order	Optimal Proportion
Compressive strength	A	29.26	31.2	28.54	2.66	$B > A > C > D$	$A_2B_1C_2D_3$
	B	32.75	30.74	25.51	7.24		
	C	29.47	30.99	28.53	2.46		
	D	28.54	30.01	30.46	1.92		
Splitting tensile strength	A	3.92	4.07	3.87	0.20	$B > C > D > A$	$A_2B_1C_3D_3$
	B	4.26	4.03	3.56	0.70		
	C	3.76	3.97	4.13	0.36		
	D	3.80	3.99	4.07	0.27		
Flexural strength	A	5.67	5.69	5.47	0.22	$B > C > D > A$	$A_2B_1C_2D_3$
	B	5.99	5.46	5.39	0.59		
	C	5.36	5.74	5.73	0.38		
	D	5.47	5.67	5.7	0.23		
Energy dissipation coefficient	A	37.25	36.95	33.78	3.47	$D > C > B > A$	$A_1B_3C_3D_3$
	B	34.13	35.52	38.33	4.20		
	C	30.01	37.42	40.55	10.54		
	D	30.73	33.01	44.24	13.50		
Ductility coefficient	A	1.64	1.63	1.62	0.020	$D > C > B > A$	$A_1B_3C_3D_3$
	B	1.62	1.63	1.64	0.021		
	C	1.54	1.60	1.76	0.221		
	D	1.52	1.61	1.77	0.253		

Note: The number after the letter represents the corresponding level of each factor. k_i represents the arithmetic mean of the experimental results corresponding to the level value of i in any column of factors. $R = \max\{k_1, k_2, k_3\} - \min\{k_1, k_2, k_3\}$.

From Table 10, it can be observed that when the compressive strength is taken as the index, the influence degree of each factor was as follows: $B > A > C > D$, in which the influence of the rubber content is the largest, and the influence of PF content is the smallest.

Further, it was found that when the splitting tensile strength is used as the index, the influence of each factor from strong to weak was $B > C > D > A$, in which the influence of the rubber content is the largest, the influence of the BF content is the second largest, and the influence of the PF content is the weakest. It was also found that when the flexural strength is taken as the inspection index, the influence of each factor from strong to weak was $B > C > D > A$, in which the influence of the BF content is the largest, followed by the PF content.

Furthermore, when the energy dissipation capacity is taken as the index, the influence of each factor from strong to weak was found to be $D > C > B > A$, in which the influence of the PF content is the largest, followed by the BF content, and the influence of rubber particle size is the weakest.

Finally, when the ductility performance is taken as the inspection index, the influence of each factor from strong to weak was found to be $D > C > B > A$, in which the PF content has the largest influence, the BF content is the second largest, and the influence of the rubber particle size is the smallest, which is similar to what was observed in the energy dissipation performance.

Further analysis showed that the content of rubber particles had a significant influence on the compressive strength and splitting tensile strength, followed by the size of the rubber particles, whereas for the ductility coefficient and the energy dissipation coefficient of the concrete, the presence of the hybrid fibers played a positive role in terms of improving the anti-cracking ability and energy dissipation capacity of the concrete.

3.1.5. Factor Index Analysis

Factor index analysis was conducted based on the test data, and the results are shown in Figure 11.

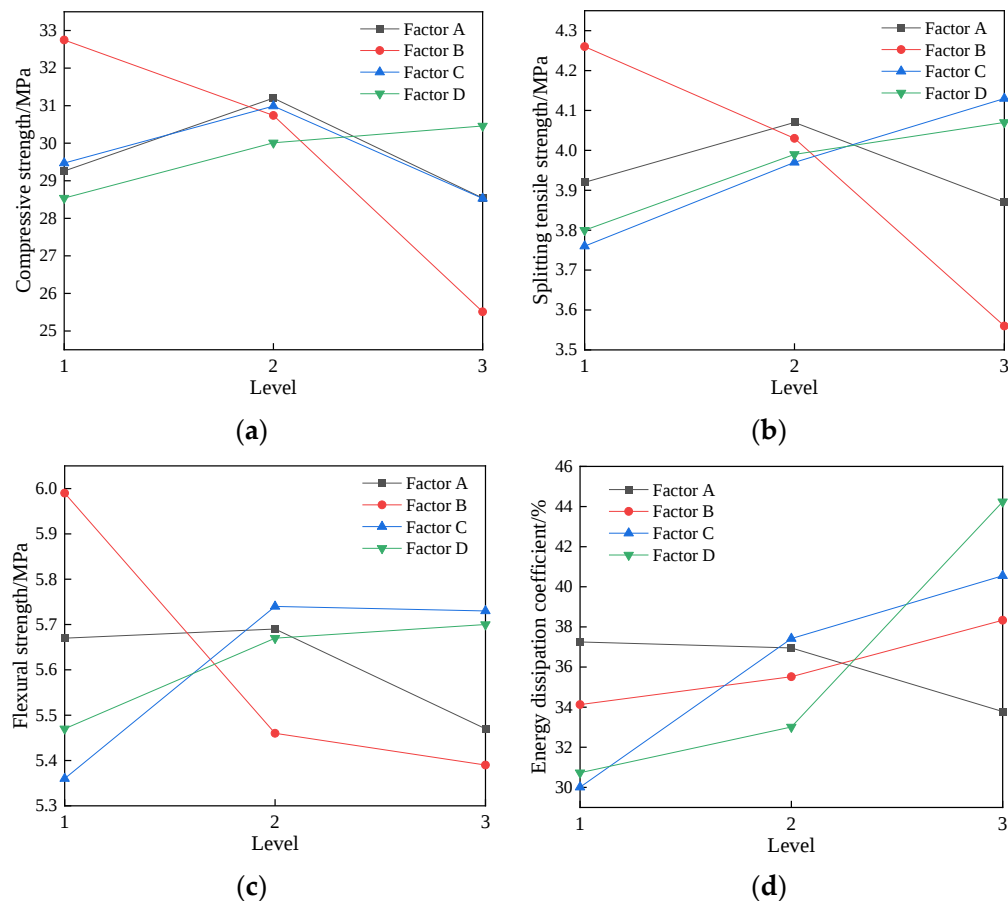


Figure 11. Cont.

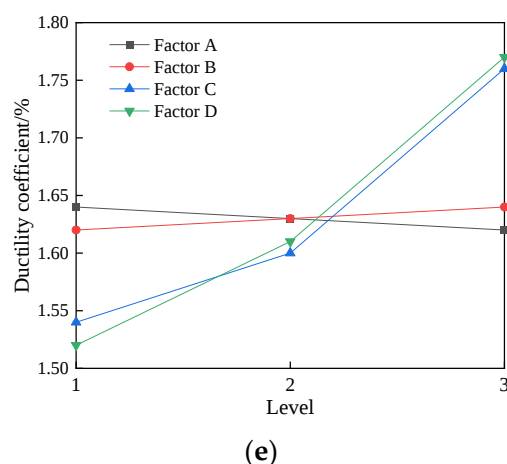


Figure 11. Results of factor index analysis. (a) compressive strength; (b) splitting tensile strength; (c) flexural strength; (d) energy dissipation coefficient; (e) ductility.

From Figure 11, it can be observed that the mechanical property index decreases rapidly with the increase of the rubber content, indicating that the rubber content is the main cause of strength reduction. Furthermore, the rubber particles were found to have an optimal particle size of 1–3 mm, showing superior performance in all indexes. However, large size rubber particles were found to lead to an increase in the weak bonding area of the concrete [38]. Moreover, it was difficult for the very smaller rubber particles to be evenly dispersed in the concrete, and the clusters of rubber particles were prone to appear in the concrete [39]. In terms of the optimal proportion of the hybrid fibers, the optimal value of PF was found to be 0.3%. Further, the 0.20% BF had the highest compressive strength and flexural strength, while the 0.3% BF was found to have the highest splitting tensile strength.

According to the compressive strength, splitting tensile strength, and flexural strength, the optimal proportions of HFRRC were determined to be $A_2B_1C_2D_3$, $A_2B_1C_3D_3$, and $A_2B_1C_2D_3$. According to the ductility coefficient and the energy dissipation coefficient, the optimal proportion of HFRRC was determined to be $A_1B_3C_3D_3$.

3.1.6. Analysis of Efficiency Coefficient Method

From this analysis, it was observed that for different evaluation indicators, the influence of each factor and the optimal proportion are also different. Moreover, it is necessary to consider the influence of each factor on different indicators while investigating the influence of each factor level. Thus, the efficiency coefficient method was used to obtain the optimal proportion, and an excellent comprehensive effect was achieved by investigating various indexes.

Initially, each indicator was defined with an efficacy coefficient according to the efficacy coefficient method. Then, the efficacy coefficient index of the group with the best result was defined as $\theta_{ij} = 1$, and the efficacy coefficient index of the group with the worst result was defined as $\theta_{ij} = 0$, where i represents the group number, and j represents the indicator number. The efficacy coefficients of the other groups were defined as the ratios of the index values to the best index values. Thereafter, the different indicators d_j of the concrete were assigned to different subjective weights based on the importance of each of the indicators.

The subjective weight coefficient of the compressive strength d_1 was taken as 0.3, and the subjective weight coefficient of the splitting tensile strength d_2 and the flexural strength d_3 was taken as 0.1. Further, the subjective weight coefficient of the energy dissipation coefficient d_4 and the ductility coefficient d_5 were taken as 0.2.

The total efficacy coefficient θ_i of group i was obtained as shown in Equation (4):

$$\theta_i = \sum_{j=1}^4 \theta_{ij} d_j \quad (4)$$

The total efficiency coefficient can comprehensively evaluate the performance of concrete. From the results, it can be observed that the total efficiency coefficient θ_4 of composition $A_2B_1C_2D_3$ was the highest, and its comprehensive performance was more balanced and superior to the other mix proportions.

3.2. Mesostucture Analysis

The pore structure parameters of each group of concretes are shown in Figure 12.

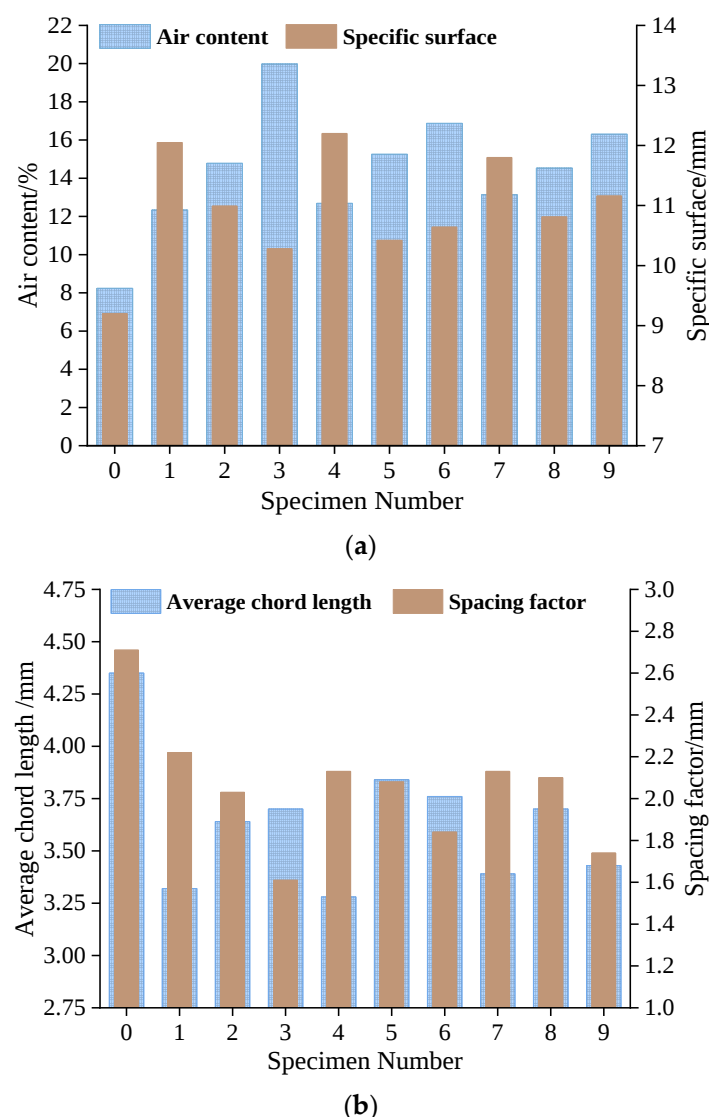


Figure 12. The pore structure parameters. (a) air content and specific surface; (b) average chord length and spacing factor.

From Figure 12, it can be observed that there are significant differences in the pore structure of OC and HFRRC. The air content and the specific surface of HFRRC were found to be larger than that of OC, while the average chord length and the spacing factor were found to be less than that of OC. It was also found that when the rubber content increased, the air content increased while the spacing factor decreased. Further, as seen from HFRRC-1, HFRRC-2, and HFRRC-3, the average chord length increased while the specific surface decreased when the rubber content increased. However, HFRRC-6, which had a higher rubber content exhibited larger average chord length and less specific surface compared to that of HFRRC-5. The hybrid fiber content of HFRRC-6 is higher than HFRRC-5, which might explain this phenomenon, which can be seen from the data for

HFRRC-8 and HFRRC-9. These pore structural characteristics suggest that the hybrid fiber alters the pore distribution of rubber concrete to some extent.

The pore size distributions of the concrete are shown in Figure 13. The proportion of the big pores (pore diameter of >1 mm) in HFRRC was found to be lower than that of OC. When compared with OC, the proportion of the big pores in HFRRC-4 was found to decrease by 73.12%. Further, the proportion of the small pores (pore diameter < 0.05 mm) to all of the pores in HFRRC was found to be larger than that of OC, and the proportion of the small pores in HFRRC-3 was found to increase by 59.69% more than that of OC.

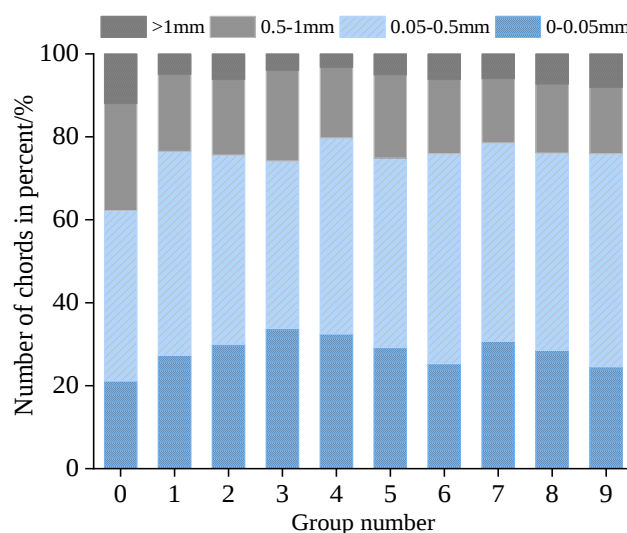


Figure 13. The pore size distribution of the concrete.

Furthermore, the bubbles in OC were mostly independent large pores, and the pores in HFRRC were smaller and finer, as shown in Figure 14. Moreover, as the particle size of the rubber decreases, finer pores can be obtained in the cement matrix. During the concrete stirring process, the large irregular bubbles introduced by the rubber particles are evenly dispersed into stable and closed micro-bubbles [40], which contribute to optimizing the pore structure of the concrete.

Figure 15 shows the distribution of the chord length frequency and the air content fraction of OC, HFRRC-1, HFRRC-4, and HFRRC-9. From the figure, it can be observed that the pore chord length has peaks at 0–0.01 mm, 0.30–0.35 mm, and 0.50–1.00 mm, respectively, and the air content fraction distribution has only one peak at 0.50–1.00 mm. The peak at 0.5–1.00 mm of the OC was found to be sharper and narrower than that of the HFRRC, indicating that the addition of the rubber particles and the fiber reduces the frequency of big pores.

Further, the water in the air–water film attached to the rubber particles was found to participate in the hydration reaction with the cementitious materials, thereby contributing towards the optimization of the pore structure of the concrete [41]. Moreover, the random distribution of the hybrid fibers in the cement matrix effectively reduces the penetrating cracks before they harden, preventing the formation of communication pores.

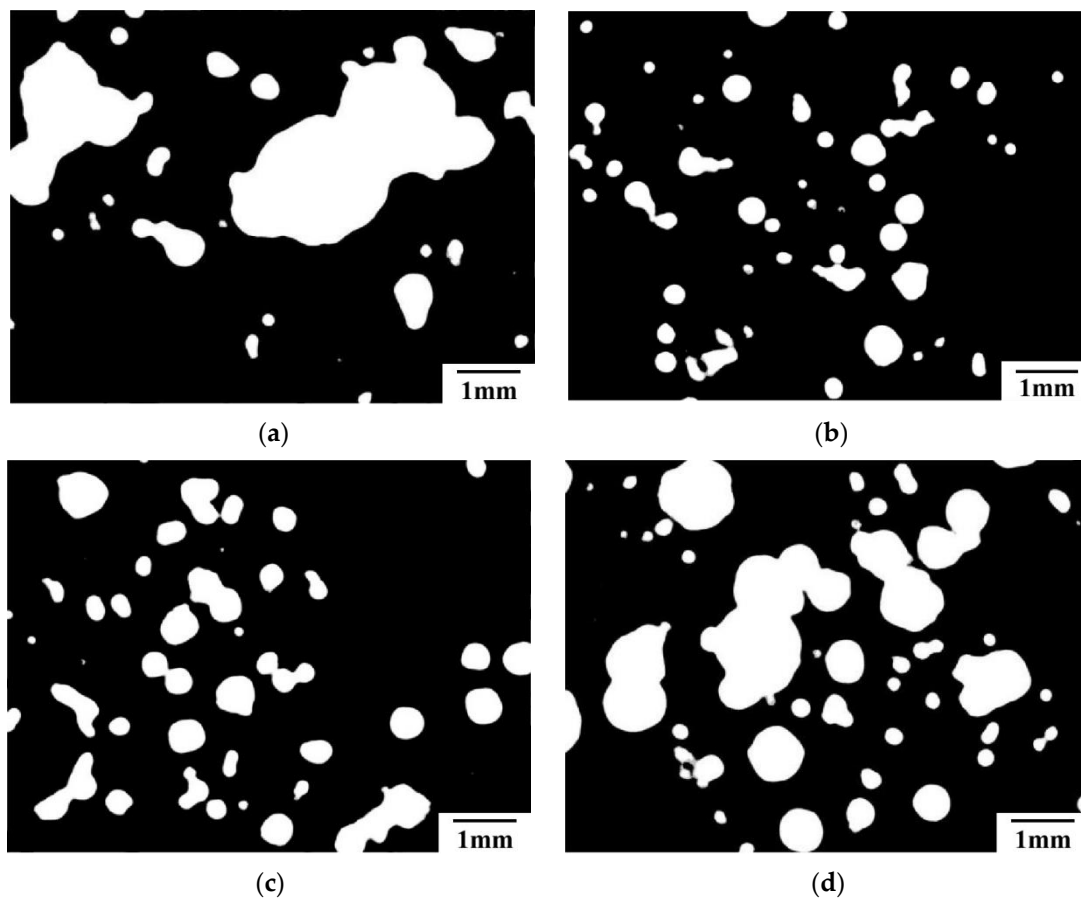


Figure 14. The surface scan image of (a) OC; (b) HFRRC-1; (c) HFRRC-4; (d) HFRRC-9. Note: In the figure, the black part is the mortar and coarse aggregate, and the white part is pores.

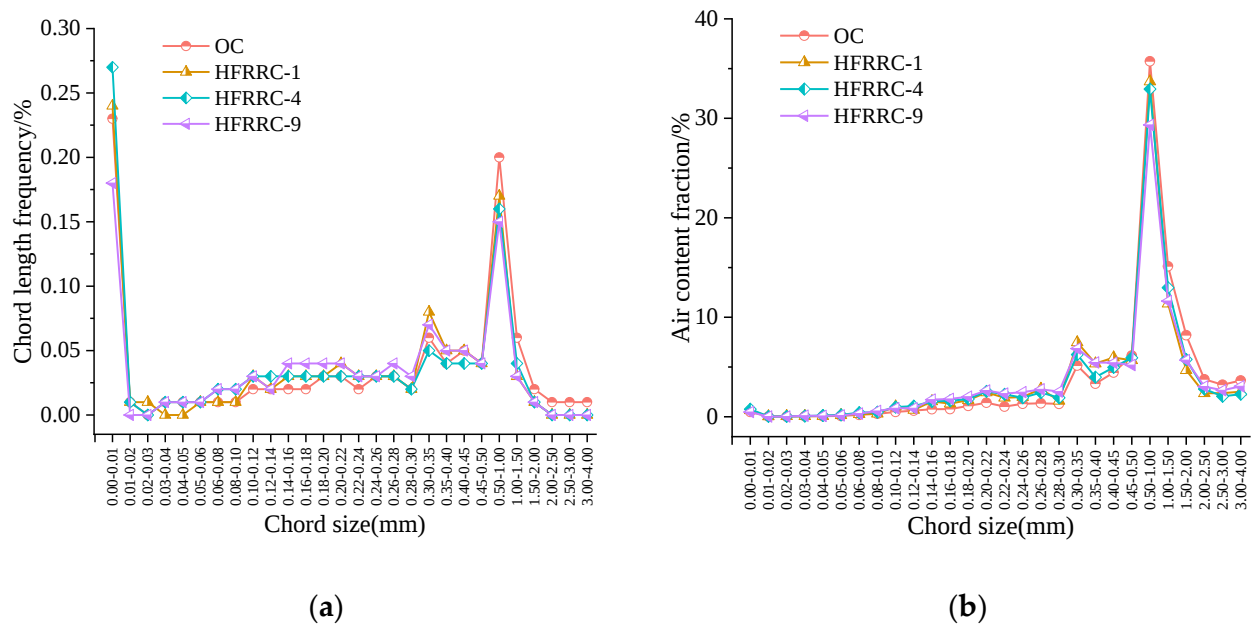


Figure 15. The distribution of (a) chord length frequency; (b) air content fraction.

3.3. Microstructure Analysis

Figure 16 displays the micro-structure of the interfacial zone in HFRRC. From Figure 16a,b, it can be observed that the bond between the rubber and the cement matrix is not as dense as that of that between the aggregate and the cement matrix.

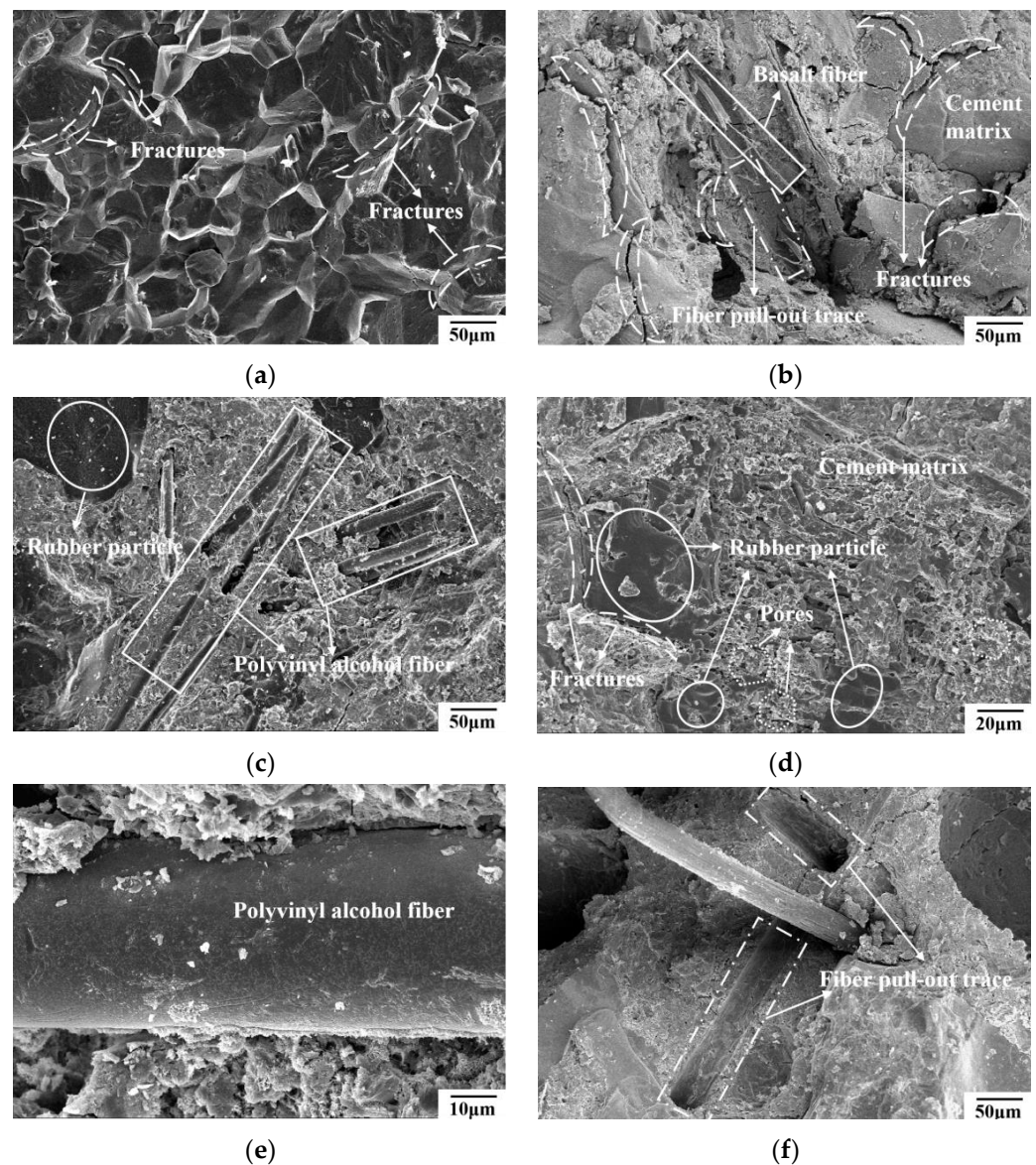


Figure 16. Micro-structures of the interfacial transition zone. (a) cement matrix; (b) basalt fiber/cement matrix; (c) polyvinyl alcohol fiber/cement matrix; (d) rubber particle/cement matrix; (e) polyvinyl alcohol fiber; (f) fiber pull-out trace.

Because rubber particles did not participate in the hydration of cement, the interfacial transition zone between rubber particles and cement matrix is mainly composed of siliceous material, which is created by a type of physical bond and does not contain any chemical products [42,43]. However, the gaps between the rubber particles and the cement matrix provide the rubber particles enough space to contract and relieve the stress concentration, which could boost the energy dissipation capacity [43]. Moreover, it was also found that the presence of randomly distributed rubber particles effectively resists the propagation of cracks in the cement matrix, thus improving the toughness of HFRRC compared to OC.

However, the excessive amount of rubber particles leads to the aggravation of the weak interface. Moreover, differential deformation and the internal stress were found to occur in the interfacial zone, and debonding behavior was observed when the load was applied. This confirms that the mechanism used to add the rubber particles weakens the strength of the concrete from the microscopic perspective.

Further, the hybrid fibers were found to form a crisscrossed and disordered distribution in the cement matrix (Figure 16c,d), which effectively provided a crack bridging effect

in the different crack propagation stages due to the size differences of BF and PF. From Figure 16e, it can be observed that the fiber removed from the matrix is attached with a large amount of hydration, indicating good bonding between the fiber and the matrix. The scratches on the cement matrix (Figure 16f) indicate that the fiber can dissipate damage energy, which, in turn, results in multiple tiny fractures instead of wide fractures.

4. Discussion

Experiments involving HFRR strength tests showed that the addition of rubber particles is beneficial to the energy dissipation and deformation ability of concrete but that it has a negative effect on the compressive strength of concrete. The influence of higher rubber content on strength cannot be ignored, so it is necessary to determine the appropriate rubber particle content. An overall comparison of the test results shows that large-sized rubber particles are prone to decreasing the strength, with increases in this type of rubber particle resulting in the bonding area of the concrete being weakened. Nevertheless, it is difficult to disperse rubber particles with a size of 0.85 mm evenly, and this uneven dispersion can introduce finer pores into the cement matrix. Therefore, the performance of rubber particle with the size of 0.85 mm is inferior to those with a size of 1–3 mm.

The positive effect of hybrid fibers on the splitting tensile strength and the flexural strength is greater than that of compressive strength. A higher amount of hybrid fibers also significantly influences the energy dissipation capacity and ductility, which is important for the failure mode of concrete. However, it is not the case that a higher content of hybrid fibers improves the performance of the concrete. This can be attributed to the fact that an excessive hybrid fiber content is prone to poor dispersion. When the hybrid fibers have the tendency to cluster, the clustered fibers will become the weak points of the concrete. The comprehensive evaluation of the test results showed that the HFRR-4 with 0.3% BF and 0.2% PF exhibited the best performance.

5. Conclusions

Based on the results obtained in this research, the following conclusions can be drawn:

- (1) The orthogonal array test results of the hybrid fiber-reinforced rubber concrete were analyzed using range analysis, factor index analysis, and the efficacy coefficient method. The results showed that the rubber particle content has the largest influence on the strength of the concrete. The hybrid fiber content has a significant influence on the ductility and the energy dissipation capacity. Further, the influence of PF was found to be greater than that of BF. After comprehensive consideration, the concrete with 10% rubber particles of 1–3 mm in size, 0.3% BF, and 0.2% PF was considered to be optimal mix proportions.
- (2) The pore structure of the concrete was optimized with the addition of rubber particles and hybrid fibers. When compared to OC, the proportion of the big pores (pore diameter > 1 mm) in HFRR-4 was found to decrease by 73.12%. Further, the air content and the specific surface of HFRR were found to be much larger than that of OC, while the average chord length and the spacing factor were less than that of OC.
- (3) The microscopic experiments showed that the weak adhesion between the rubber particles and the cement matrix reduced the mechanical strength, while the random distribution of hybrid fibers has positive effects on relieving tip stress and inhibiting crack development. Furthermore, the entire post-crack propagation process can be synergistically prevented with the presence of the rubber particles and hybrid fibers.

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