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Research Article

Effect of Rape Straw Fiber on Mechanical Properties and Microstructure of Fly Ash Concrete

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As a renewable resource, rape straw has rich fibrous tissue on the surface and woody parts, which can provide high toughness and tensile strength. However, rape straw is usually treated by on-site incineration, causing severe damage to the ecological environment and resources. Rape straw fiber (RSF) is added into fly ash concrete (FAC) to reuse rape straw effectively, protect the environment, and develop green and renewable building materials. In this test, RSF is divided into 4 volume additions of 0.1%, 0.2%, 0.3%, and 0.4% and 3 length intervals of 20–30, 30–40, and 40–50 mm to study the mechanical properties and microstructure of FAC. Results showed that RSF with a volume content of 0.1%–0.2% and a length of 30–40 mm can effectively improve the mechanical properties of FAC. Still, the excessive incorporation of large RSF can reduce the compressive strength, splitting tensile strength, and ultrasonic velocity of FAC. The compressive strength, splitting tensile strength, and sound velocity of specimens with a volume content of 0.2% and size length of 30–40 mm increased by 8.73%, 11.37%, and 7.60%, respectively, compared with those of the control group. Scanning electron microscopy results showed that RSF mixed with the appropriate amount of FAC presented the absence of agglomeration, the presence of bifurcation cracking, and other phenomena, and the ability to combine closely with FAC to fill internal pores and improve the mechanical properties of the FAC effectively.

1. Introduction

Natural plant fibers demonstrate high potential as replacements for synthetic fibers in strengthening concrete due to their characteristics of abundance and high reproducibility [1–3]. Therefore, many studies have been conducted to determine the influence of the content size and aspect ratio of natural plant fiber on the mechanical properties of concrete [4–7]. Manniello et al. [8] investigated the effect of the length-diameter ratio of asparagus fiber on the tensile properties of concrete blocks. The comparison of the tensile strength of asparagus fiber specimens with different length diameter ratios revealed that fiber concrete specimens with high length diameter ratios present better tensile properties. Bheel et al. [9] explored the mechanical properties of concrete by controlling the addition of different amounts of jute fiber and wheat straw ash and demonstrated that adding an appropriate quantity of jute fiber and wheat straw ash can improve the compressive, splitting, and bending strength values of concrete. Mukhopadhyay and Bhattacharjee [10] revealed the high surface area of banana fiber, which can be closely combined with concrete slurry, reduce internal cracks, and effectively improve the compressive strength of concrete.

Rape plant, the leading oil crop in the country, has been widely planted in south China. Its planting area and total output value account for 30% of the total worldwide. The usual treatment of rape straw by burning on the spot has caused severe damage to resources and the ecological environment [11]. The surface and wood of rape straw contain developed fiber structures; hence, rape straw fiber (RSF) can be used to improve the performance of concrete because of its high tensile strength and toughness [7, 12]. Zeng [13] revealed that adding low-content RSF to concrete can effectively improve the mechanical properties of the concrete. Mechanical properties of concrete, such as compressive and splitting tensile strengths, increase first and then decrease with the increase in RSF size and content. Liu et al. [14] observed the changes in apparent density and compressive strength of concrete by setting the content and size of RSF as test variables. The results showed that the decline of compressive strength of concrete slows down and concrete presents satisfactory plastic properties when the RSF size is more than 2.0 cm.

The concrete industry often replaces cement with auxiliary cementitious materials to reduce resource consumption on the basis of sustainable development goals [15, 16]. Fly ash, a by-product of thermal power plants, is an auxiliary cementitious material used by countries worldwide [17, 18]. Su et al. [19] investigated the influence of straw fiber mixed with fly ash and ceramsite on concrete's compressive and splitting tensile strength values. The results showed that the splitting tensile strength of fly ash concrete (FAC) is greater than its compressive strength. Geng et al. [20] explored the influence of different types and forms of straw fibers on the mechanical properties of FAC. The researchers revealed that rape straw is more advantageous than wheat and corn straws in improving the mechanical properties of FAC.

In summary, when studying the field of natural plant fiber-reinforced concrete, most scholars ignored the corrosive effect of the alkaline environment generated by the internal hydration of concrete on plant fibers. At the same time, most scholars only focused on the effect of a single RSF on the performance of the concrete or the effect of different types of fibers on the performance of FAC. Studies on the mechanical properties and microstructure of FAC mixed with RSF of different volume contents and length intervals are few. Therefore, this paper takes the volume content and length range of RSF as test variables and adjusts the alkaline environment inside the concrete by adding an appropriate amount of fly ash to reduce the corrosion effect of the rape straw fiber, and experimentally studies the effect of RSF on the basic mechanical properties and microstructure of FAC.

2. Materials and Methods

2.1. Raw Materials. The following test materials are used: (1) Ba gong shan brand P.O. 42.5 cement. The requirements are the strength, setting time, water consumption for standard consistency, and volume stability of the cement. Chemical properties are shown in Table 1. (2) Fly ash. Fly ash was produced by He Jin Fly Ash Development and Utilization Co., Ltd., and its performance meets the requirements of the national standard GB/50146–2014 for fly ash production and utilization [21]. Chemical properties are shown in Table 1. (3) Fine aggregate. Local river sand from Huainan with a fineness modulus of 3.1 was used as fine aggregate. (4) Coarse aggregate. Gravel with a diameter of 15–20 mm was utilized as the coarse aggregate. The apparent density is 2780 kg/m^3.

(5) Naphthalene, a water-reducing agent. FDN-C naphthalene water reducer is used, and the performance indicators are shown in Table 2. (6) RSF. RSF uses rape straw 300 mm away from the ground to wash and bake for 3 h, then divides the straw's surface fiber into 2 mm in diameter and 20–30 mm, 30–40 mm, and 40–50 mm in length, as shown in Figure 1. Modification of plant fiber by alkalization [22–24], soaking RSF in NaOH solution with a concentration of 2.0% for 24 h to remove lignin, hemicellulose, wax, and pectin on the surface of RSF, improve surface roughness, and prevent RSF from decomposing in the alkaline environment of concrete over time; decreasing the radius of the pore inside the RSF to reduce its hydrophilicity; and preventing the RSF from aggregating into clusters during concrete mixing. Wash it and dry it for standby. Performance indicators are shown in Table 3.

Table 1: Chemical properties of cement and fly ash.

Material	Mass fraction (%)				
	SiO_2	Al_2O_3	SO_3	CaO	Loss on ignition
Cement	22.60	5.03	2.24	63.11	1.18
Fly ash	45.1	24.2	1.60	1.61	2.00

The four sizes of RSF were treated into four volume contents of 0.1%, 0.2%, 0.3%, and 0.4% [25, 26]. Other raw materials are listed in Table 4. Cement and aggregate were mixed dry for 30 s, RSF and fly ash were mixed for 30 s, and then water and water reducer were placed into a mixer for 60 s in the test. Samples were then placed in the test mold, vibrated on the shaking table for 60 s, stored for 24 h, and then placed in a curing room for 28 d. As shown in Figure 2, three 100 mm × 100 mm × 100 mm test pieces are prepared for each group.

2.2. Mechanical Property Test. An ultrasonic method is a nondestructive approach for detecting the strength of concrete and testing the material, structure, and function. At the same time, the sound velocity of ultrasonic in concrete is related to the compressive strength of concrete [27–29]. An MC-6310 nonmetallic ultrasonic detector from Beijing Ming Chuang Technology Co., Ltd. was used for concrete strength measurement. Parameters, such as firing voltage and sampling period, were adjusted before testing to reduce the test error. The probe was placed on the coupling agent on both sides of the sample to maintain the same level. The test began after the sample was coupled with the probe, as shown in Figure 3. Each group of samples was set with three test areas, and each test area was charged with three test points. The ultrasonic test results are listed in Table 5.

The mechanical property test was carried out according to the Chinese standard GB/T50081-2002 (Standard for Test Methods of Mechanical Properties of Ordinary Concrete) [30]. A YAW3000 electro-hydraulic servo test press was used to test the compressive and splitting tensile strengths of specimens [31–33], as shown in Table 4.

Figure 4. Conversion coefficients of the compressive and splitting tensile strengths were 0.95 and 0.85, respectively.

2.3. Scanning Electron Microscope Observation. Samples from the central part of the FAC specimen were subjected to scanning electron microscopy. Samples with visible RSF on

Table 2: Performance index of water reducing agent.

Water reduction rate/%	Solid content (%)	$NaSO_4$ (%)	Fluidity of cement paste (mm)	PH value	Recommended dose (%)
20	92	7–9	200	18	0.5–1.0

(a) (b) (c)

Figure 1: Rape straw fiber: (a) 20–30 mm, (b) 30–40 mm, and (c) 40–50 mm.

Table 3: Performance index of RSF.

Apparent density ($g \cdot cm^{-3}$)	Crystallinity (%)	Compressive strength (MPa)	Modulus of elasticity (MPa)
0.34	2.87	7.58	183–189

Table 4: Concrete test mix ratio (kg/m^3).

Water/cement ratio	Cement	Water	Fly ash	Sand	Stone	Water reducing agent
0.46	330	160	16.5	685	1168	3.5

(a) (b)

Figure 2: Specimen preparation. (a) Specimen pouring and (b) specimen curing for 28 days.

the surface of the fracture were selected for drying and treatment. Samples were then placed into the instrument to ensure observation under vacuum conditions after fixing [34–36].

3. Results and Discussion

The test was classified and coded according to the size and dosage of RSF in each test group. The test serial number and compressive and splitting tensile strengths of the specimen are presented in Table 5. The control group was denoted Group 0. The results in Table 5 are the average values of three test specimens from the same group.

3.1. Effect of RSF on the Compressive Strength of FAC. As shown in Figure 5(a), the compressive strength of specimens with a length range of 20–30 and 30–40 mm and a volume content of 0.1% and 0.2% significantly improved, with a maximum increase of 8.73% compared with that of the control group. However, the compressive strength of FAC gradually decreased as the volume content of RSF increased to more than 0.3%. The increase of RSF volume content from 0.1% to 0.4% compared with that of the control group. The compressive strength of specimens with a length range of 40–50 mm decreased by 2.85%, 7.75%, 11.75%, and 16.39%. This trend is observed by Song et al. [37]. When RSF is mixed with fly ash, the compressive strength of the specimen

(a) (b)

Figure 3: Ultrasonic test. (a) Measuring point map of the detection area and (b) test piece test.

Table 5: Test results.

No	RSF content (%)	RSF length (mm)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Ultrasonic velocity (km/s)
0	0	0	50.96	3.87	5.00
1–1	0.1	20–30	52.32	4.16	4.96
1–2	0.2		52.69	4.27	5.10
1–3	0.3		49.53	3.93	5.00
1–4	0.4		48.37	3.90	4.93
2–1	0.1	30–40	52.26	3.69	5.13
2–2	0.2		55.41	4.31	5.38
2–3	0.3		50.45	3.55	5.02
2–4	0.4		47.64	3.29	4.88
3–1	0.1	40–50	49.51	3.83	4.96
3–2	0.2		47.01	4.05	4.84
3–3	0.3		44.97	3.21	4.80
3–4	0.4		42.61	3.15	4.73

(a) (b)

Figure 4: Mechanical property test. (a) Compressive strength test and (b) splitting tensile strength test.

decreases with increasing RSF content. This finding indicated that RSF with a volume dosage of less than 0.3% and a length range of 20–30 or 30–40 mm can effectively improve the compressive strength of FAC, while that with a length range of 40–50 mm can reduce the compressive strength of FAC.

Figure 5(b) shows that the compressive strengths of specimens with volume contents of 0.1% and 0.2% first increase and then decrease as the length range of RSF increases from 20–30 mm to 40–50 mm, reaching the peak at 0.2%. This finding is because the RSF with a volume content less than 0.2% cannot fully react with the concrete matrix, resulting in micropores in the FAC and affecting the compressive strength. RSF with content higher than 0.2% will be aggregated and distributed in FAC, making the fiber unable to combine closely with the concrete matrix and further affecting the compressive strength of FAC. The compressive strength of specimens with a volume content of 0.3% decreased by 2.81%, 1.01%, and 11.75% compared with the control group. The compressive strength of specimens

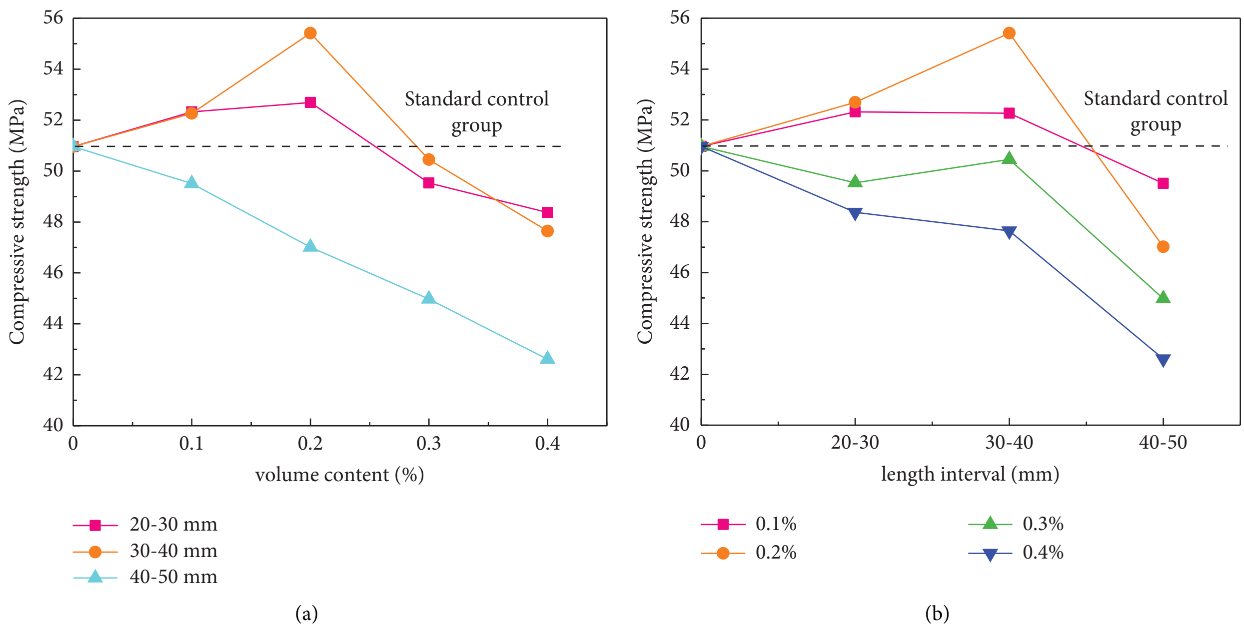

Figure 5: Effect of RSF on the compressive strength of FAC: (a) volume dosage and (b) length interval.

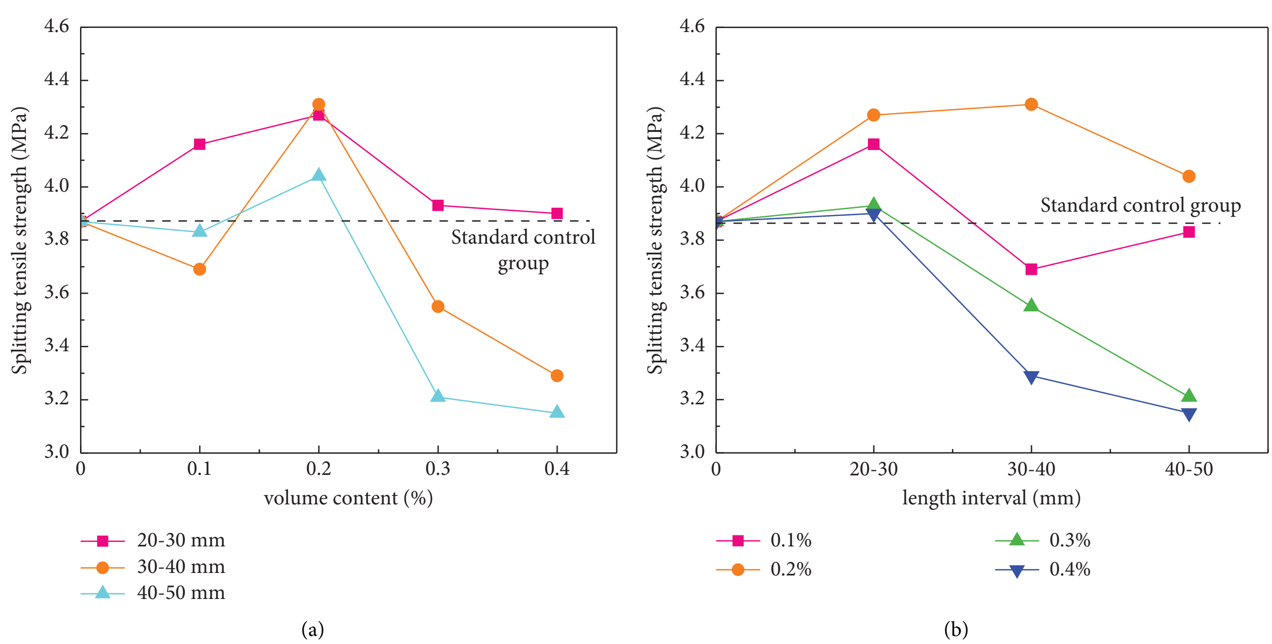

Figure 6: Effect of RSF on the splitting tensile strength of FAC: (a) volume dosage and (b) length interval.

with a volume content of 0.4% decreased by 5.08%, 6.51%, and 16.39% compared with the control group. Bheel et al. [38–40] conducted a similar investigation and showed that adding a large amount of wheat straw ash causes the dilution reaction of the concrete matrix, resulting in a limited supply of Ca $(OH)_2$ used for the formation of hydration products and leading to the reduction of compressive strength.

3.2. Effect of RSF on the Splitting Tensile Strength of FAC. According to Figure 6(a), the splitting tensile strength of specimens with a volume content of 0.1%–0.4% increased by 7.49%, 10.33%, 1.55%, and 0.78% when the length range of RSF was 20–30 mm. The splitting tensile strength of specimens with a volume content of 0.2% increased by 11.37% and 4.39% when the RSF length range was 30–40 and

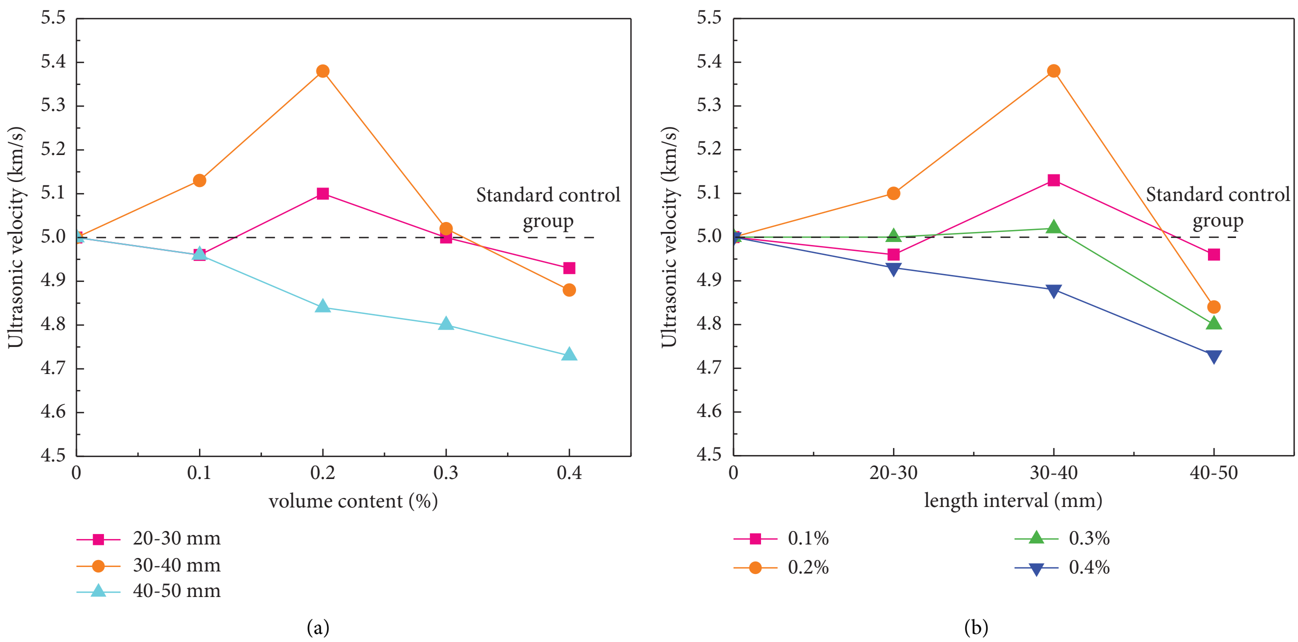

Figure 7: Effect of RSF on FAC ultrasonic velocity: (a) volume dosage and (b) length interval.

40–50 mm, respectively, and the splitting tensile strength of specimens in other sections was smaller than that of the control group. Yin and Bei [41] observed that when the size of PVA fiber is too long, the splitting tensile strength of concrete specimens is reduced. This finding indicated that RSF with a length range greater than 40 mm increased the occurrence of bifurcation and fracture in FAC, which ineffectively improved the splitting tensile strength of the specimen.

As shown in Figure 6(b), the splitting tensile strength of specimens with lengths ranging from 20–30 mm increases by 7.49% when the volume content of RSF is 0.1% compared with that of the control group. The compressive strength of specimens with a range of 30–40 mm and 40–50 mm decreased by 4.65% and 1.03%, respectively, compared with the control group. The increase rates of specimens from 20–30 mm to 40–50 mm are 10.33%, 11.37%, and 4.39% when the volume content of RSF is 0.2%. The tensile strength of FAC with RSF with a volume content of 0.3% and 0.4% first increases and then decreases with the long interval. Zeng et al. [42] also observed that adding a low amount of RSF can effectively improve the tensile strength of concrete and that the splitting tensile strength increases first and then decreases with increasing size and amount of RSF. Therefore, the volume dosage and length of RSF should be controlled at about 0.3% and 30–40 mm, respectively, to improve the splitting tensile strength of FAC effectively.

3.3. Effect of RSF on the Ultrasonic Sound Velocity of FAC. Figure 7(a) presents the increase in RSF volume content from 0.1% to 0.4% compared with that of the control group. Moreover, the sound velocity of specimens with a length range of 20–30 and 30–40 mm both increased first and then decreased, with a maximum increase of 7.60%. The RSF of specimens with a length range of 40–50 mm decreased by 0.8%, 3.2%, 4.0%, and 5.4%. This finding indicated that the satisfactory bonding effect of concrete slurry RSF with a length range of 20–40 mm improves the compactness of FAC and further enhances the sound velocity of ultrasonic waves in FAC. The addition of RSF with a length range of 40–50 mm will reduce the sound velocity in FAC.

According to Figure 7(b), the ultrasonic velocity value of the specimen with a length range of 20–30 and 30–40 mm at an RSF volume content of 0.2% increased by 2.0% and 7.6%, respectively, compared with that of the control group. The sound velocity of specimens with a length range of 40–50 mm decreases by 3.2% compared with that of the control group. The sound velocity of the specimen increases first and then decreases with the increase of the length range when the volume fraction of RSF is 0.1%, 0.3%, and 0.4%. Hence, the sound velocity of ultrasonic waves in FAC can reflect the compactness of the specimen, and the compactness of the specimen is related to the strength of FAC. A high sound velocity corresponds to a high FAC strength. Conversely, a low speed of sound indicates a low FAC intensity. Shang et al. [43] found that as the internal structure of concrete becomes denser, the compressive strength increases accordingly and that the interference of ultrasonic waves in the propagation of concrete becomes weak. Thus, the speed of sound becomes high.

3.4. Microstructure. The microstructure of the fracture surface was observed via SEM. Figure 8 illustrates the SEM photos of hydration maintained in experimental groups 2-2, 2-4, 3-2, and 3-4 at 500 times for 28 d.

The fracture surface of the sample was formed by the combination of RSF, fly ash, and concrete slurry. The random distribution of RSF in the FAC in three dimensions without

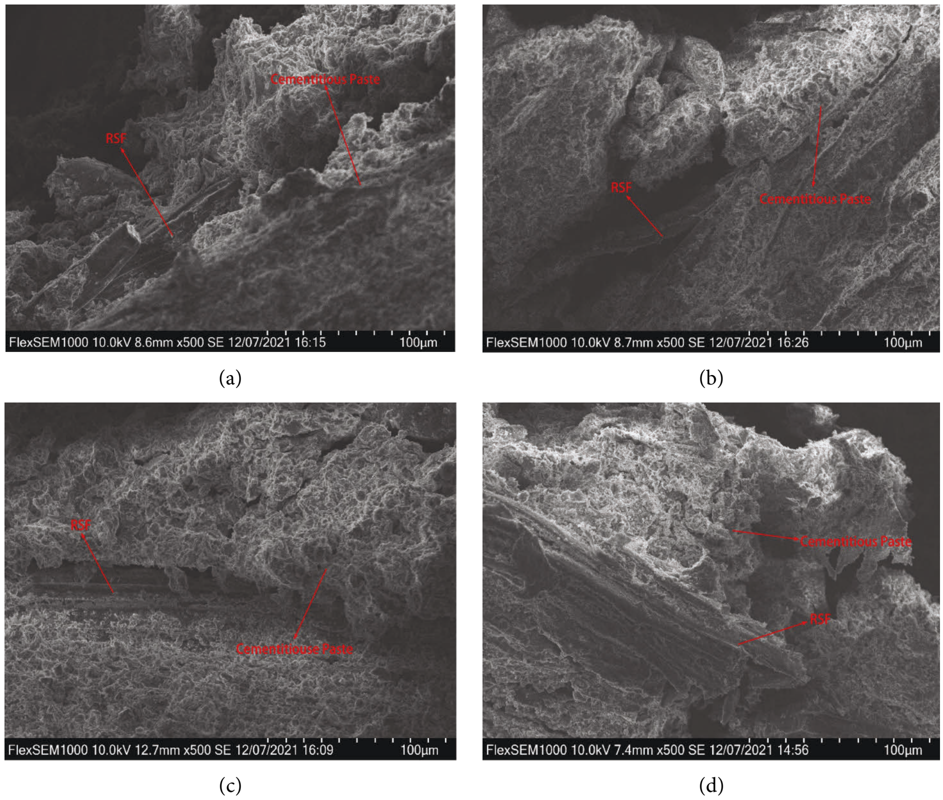

Figure 8: Specimen morphology: (a) 2-2, (b) 2–4, (c) 3-2, and (d) 3-4.

agglomeration effectively inhibited the development of FAC cracks and crack expansion caused by drying and chemical shrinkage in the hydration process. Figure 8(a) shows the sample with an RSF size of 30–40 mm and a volume content of 0.2%. The dense connection between RSF and concrete slurry and RSF-filled micropores in the FAC is conducive to the improvement of the compressive and tensile properties of the FAC. Large harmful pores exist between the RSF and concrete slurry when the RSF size is constant and the volume content decreases, and the maximum pore size of about 200 μm (Figure 8(b)) results in a significant decrease in the compressive strength of FAC. However, the compressive strength slightly decreases when tiny pores with a maximum size of about 50 μm (Figure 8(c)) are observed between the RSF and concrete slurry. The RSF content remains unchanged, and the size increases. This result agrees with that observed by Zhang et al. [44]. When excessive RSF is added, harmful and less-harmful holes in the concrete increase. As shown in Figure (d)8, fiber bifurcation and fracture will occur and result in a reduced bonding effect between RSF and FAC when the size and dosage of RSF increase simultaneously.

4. Conclusions

This study aims to investigate the effect of RSF on the basic mechanical properties and microstructure of FAC by controlling RSF with different volume contents and lengths as test variables. The following conclusions can be drawn from this study:

(1) RSF has an important research role in developing green and renewable building materials. Mechanical properties of FAC can be effectively improved with the volume admixture of 0.1%–0.2% and the length range of 30–40 mm, while the compressive strength, splitting tensile strength, and ultrasonic speed of FAC can be reduced with the volume admixture of more than 0.3% or the length range of 40–50 mm.

(2) index parameters of the specimen reached the optimum when the volume content of straw fiber was 0.2% and the size length was 30–40 mm. The compressive strength of the sample was 55.41 MPa, with a maximum increase of 8.73%. The splitting tensile strength was 4.31 MPa, with a maximum increase of 11.37%. The ultrasonic speed was 5.38 km/s, with a maximum increase of 7.60%.

(3) The microstructure of the fracture surface of the sample was observed via SEM. The appropriate incorporation of RSF can fill the internal pores of FAC, enhance the bonding effect in FAC, and improve the mechanical properties of FAC, such as compressive and splitting tensile strength.

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 no conflict of interest.

Acknowledgments

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