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ORIGINAL ARTICLE

Study on splitting tensile toughness of seawater sea sand concrete reinforced with bamboo sticks

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Abstract: Concrete is a typical material with high compressive strength but weak tensile strength. But the tensile strength affects the formation and development of cracks in concrete, so it is an essential factor in the practical application of concrete. Concrete can be enhanced its tensile strength by incorporating sticks with good tensile resistance, and bamboo stick is a good choice. This paper conducted a series of comparative tests (64 specimens) on splitting tensile strength of bamboo stick reinforced seawater sea-sand concrete (BFRSSC). The effects of volume fraction, length-diameter ratio, and diameter of bamboo stick were studied, and the specimen's load-displacement and load-strain curves under different variables were analyzed. The result shows that the impact of stick volume fraction on splitting tensile behavior is the most obvious, while the bamboo stick diameter has the least impact on it. In addition, this paper also analyzes the toughening mechanism of bamboo stick and gives the regression model of splitting tensile strength of bamboo stick-reinforced seawater sea sand concrete, in order to lay a theoretical foundation for the promotion of bamboo stick in marine materials.

Keywords: Bamboo stick, Fiber concrete, Splitting tensile strength

1 Introduction

Compared with concrete's compression strength, plain concrete's tensile strength is usually much lower. But it is still an essential factor in studying the failure mechanism of concrete. The tensile strength of concrete is usually used to measure the cracking performance of concrete, and sometimes it is also used to analyze the adhesion strength between concrete and steel bars indirectly [1]. The splitting tensile test of the concrete is often used to measure the splitting tensile strength of the concrete, and it can be converted to axial tensile strength by the existing empirical formula. In order to improve the tensile strength of concrete, fiber is often used as an enhanced material for concrete. Although adding reinforcing fibers to concrete has little effect on improving concrete's compressive strength and elastic modulus, it can effectively enhance its toughness and tensile strength [2]. The research on fiber-reinforced concrete has been relatively mature. As early as 1963, Romualdi [3] proposed the mechanism of fiber hindering the development of concrete cracks. Then Swamy [4] further explained the mechanism of fiber-reinforced concrete through the composite material mechanism. Fiber-reinforced

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concrete can be classified into three distinct types based on fiber variations: concrete reinforced with metal fibers, that with inorganic mineral fibers, and that with organic fibers. Among metal fiber-reinforced concretes, steel fiber-reinforced concrete stands out as the most widespread. For inorganic mineral fiber-reinforced counterparts, glass fiber-reinforced concrete and asbestos fiber-reinforced concrete are commonly encountered. Organic fiber-reinforced concrete comprises two main subsets: one utilizing plant-derived fibers (such as wood fiber, bamboo stick) and the other incorporating synthetic organic fibers (like polypropylene fiber). Owing to benefits like cost-efficiency and environmental sustainability, plant fiber-reinforced concrete has consistently remained a focal point in the research on fiber-reinforced concrete. Fibers frequently employed in plant fiber-reinforced concrete include jute [5], straw [6], pine needles [7], and bamboo.

Bamboo stick has the characteristics of low density, high specific strength, large specific area, and large slenderness ratio, it is a good material for making plant fiber reinforced concrete. Bamboo sticks are extracted from the area of the vascular bundle in the original bamboo, as shown in **Fig. 1**. bamboo sticks at the knots of the original bamboo still have a high utilization rate, and the bamboo sticks at different kinds of knots still maintain a high integrity and excellent mechanical properties [8], as shown in **Fig. 2**.

Fig.1. Vascular bundle indicated by bamboo.

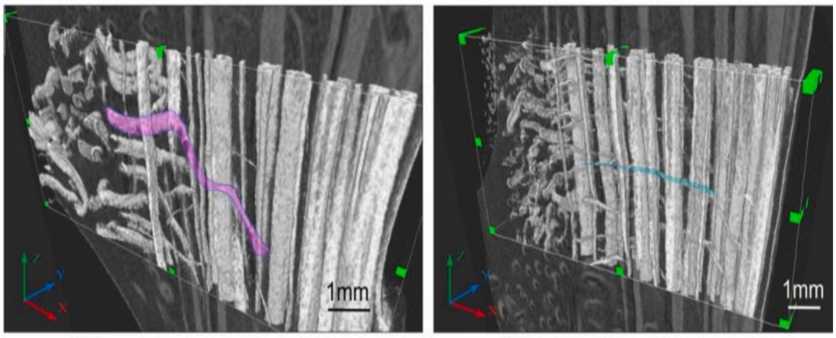


Fig.2. bamboo stick at knots [8].

As yet, there are a few experiments on the splitting tensile strength of bamboo stick reinforced concrete. The experimental study of Zhang et al. [9] shows that the splitting tensile strength of concrete will be improved after adding an appropriate amount of bamboo stick to the fine aggregate of concrete. When the volume fraction of bamboo stick is 1%, the splitting tensile strength of bamboo stick reinforced concrete at 28 days is 40% higher than that of plain concrete. Terai et al. [10] studied the splitting tensile strength of bamboo stick reinforced concrete with volume fractions of 1%, 2%, and 3%, respectively, and concluded that the splitting tensile strength increased significantly with the volume fraction. Ede et al. [11] experimented with the influence of bamboo stick and limestone flour content on the mechanical properties of self-compacting concrete (SCC). The results show that the splitting tensile strength of self-compacting concrete is 32% higher than that of ordinary self-compacting concrete when the weight ratio of stick and limestone flour is 0.5% and 10%, respectively, after 28 days of curing. Based on the above research, it can be found that bamboo stick can help improve the splitting tensile strength of concrete.

In recent years, as global engineering construction has boomed, the demand for freshwater and river sand has surged. To ease the strain on freshwater and river sand resources, researchers have put forward the idea of using seawater and sea sand to make seawater sea - sand concrete. This approach can not only cut down on the consumption of freshwater and river sand but also make it easier to utilize local materials in coastal projects. Moreover, it can attain the goals of reducing transportation costs and shortening the project timeline [12]. Yin et al. [13] found that the grain composition, compressive strength, and flexural strength of sea sand were similar to those of river sand by cement mortar test, but it was found that the chloride ion content was high and could not be directly used for the sand of prestressed concrete. Limeira et al. [14] studied the mechanical properties of sea-sand concrete with a 15% - 50% sea-sand replacement rate. The result showed that sea sand concrete's compressive strength and tensile strength were similar to those of river sand concrete. At the same time, its density, permeability, and water absorption were reduced. Xiao et al. [15] found that the compressive strength of seawater sea-sand concrete was about 13% - 60% higher than river sand concrete when the curing period was seven days, but the compressive strength was similar at 28 days. From the above research, it can be found that the mechanical properties of seawater sea-sand concrete are identical to those of concrete with freshwater and river sand, and it can replace ordinary concrete in many cases. Therefore, seawater sea-sand concrete has broad development prospects. Although there is some research about the splitting tensile strength of bamboo stick reinforced concrete, experimental study on bamboo stick reinforced seawater sea-sand concrete (BFRSSC) is very rare. So it is necessary to study its related properties.

In order to explore the influence of different volume fractions and sizes of bamboo stick on the splitting tensile strength of seawater sea-sand concrete, a series of experiments were carried out by changing the three influencing factors of volume fraction, length, and diameter of bamboo stick. By comparing the test results, the optimum volume fraction and size of bamboo stick for improving the splitting tensile strength of BFRSSC were obtained, and the mechanism of bamboo stick reinforced concrete was analyzed. Finally, the fitting formula of splitting tensile strength of BFRSSC is obtained by regression analysis.

2 Materials and test methods

2.1 Materials

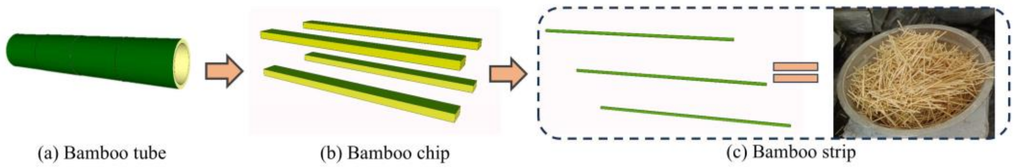


Fig. 3. Preparation process of bamboo stick.

For the test, the cement employed is Portland cement manufactured by the Nanjing Cement Plant. The fine aggregate consists of medium - grained sea sand, while the coarse aggregate is crushed stone with a particle size ranging from 5 to 20 mm. The seawater utilized in the experiment is artificially formulated. **Fig. 3** presents the flow diagram for bamboo stick preparation, and the characteristics of bamboo sticks with varying diameters are tabulated in **Table 1**.

Table 1. Bamboo stick properties

Diameter (mm)	Strength of extension (MPa)	Elasticity modulus (GPa)	Density (g/cm^3)
1	463	17	1.2
1.5	256	11	0.89
2	317	11	0.87

2.2 Mix proportions and preparation of specimens

The preparation and maintenance of concrete in this test are in strict accordance with the specification Standard for test methods of concrete physical and mechanical properties (GB / T50081-2019) [16]. And the desired grade of seawater sea-sand concrete is C30. Before preparing concrete, artificial seawater should be prepared first. The method is to mix the quantitative KCl, $CaCl_2$, Na_2SO_4, $MgCl_2$, NaCl, and tap water together.The mixed proportion of artificial seawater is KCl (0.695 g/L), $CaCl_2$ (1.16 g/L), Na_2SO_4 (4.09 g/L), $MgCl_2$ (5.2 g/L), NaCl (24.53 g/L), which is determined according to ASTM D1141-98 [17]. After that, BFRSSC can be prepared according to the mix ratio and the formulated bamboo stick content. The mix proportion of concrete used in the test is 0.6 (seawater): 1 (cement): 2.06 (sea-sand): 3.36 (stone), and it is based on JGJ 55-2011 [18].

Because it is necessary to ensure that the bamboo stick can be mixed evenly in the BFRSSC, the following method is adopted in this experiment. First, the coarse and fine aggregates were dry-mixed for one minute, and then the weighted bamboo stick was added to the mixer to be dry-mixed for 1.5 minutes to make it evenly distributed. After that, 20% of the prepared artificial seawater was added to the mixer, and then the mixture was mixed for one minute. Finally, the remaining seawater was added to the mixer, and the mixture continued to be stirred until it was mixed evenly. After mixing, the mixture was poured into a 150 mm × 150 mm × 150 mm mold and moderately vibrated immediately. Excessive vibration should be avoided during the vibration process to reduce the occurrence of the floating of bamboo sticks and concrete segregation. After 24 hours of casting, the specimens were removed and placed in a cool indoor place to sprinkle and cured for 28 days. The primary production process of the specimens is shown in **Fig. 4**.

Fig. 4. The main process of preparing BFRSSC.

2.3 Experimental Plan

Table 2. BFRSSC specimens for splitting tensile test.

Test groups	Number	V_f (%)	D (mm)	L (mm)	L/D
0-0-0	4	0%	—	—	—
0.6-1.5-15	4	0.6%	1.5	15	10
0.6-1.5-30	4	0.6%	1.5	30	20
0.6-1.5-45	4	0.6%	1.5	45	30
1.2-1.0-10	4	1.2%	1.0	10	10
1.2-1.5-15	4	1.2%	1.5	15	10
1.2-2.0-20	4	1.2%	2.0	20	10
1.2-1.0-20	4	1.2%	1.0	20	20
1.2-1.5-30	4	1.2%	1.5	30	20
1.2-2.0-40	4	1.2%	2.0	40	20
1.2-1.0-30	4	1.2%	1.0	30	30
1.2-1.5-45	4	1.2%	1.5	45	30
1.2-2.0-60	4	1.2%	2.0	60	30
2.4-1.5-15	4	2.4%	1.5	15	10
2.4-1.5-30	4	2.4%	1.5	30	20
2.4-1.5-45	4	2.4%	1.5	45	30

In this experiment, the control variable method was used to study the influence of volume fraction, length-diameter ratio, and diameter of bamboo stick on the splitting tensile strength of BFRSSC. The size of specimens in the test is 150 mm × 150 mm × 150 mm, and the curing age is 28 days. The diameters and lengths of bamboo stick are 1-2 mm and 10-60 mm, respectively, and the contents of bamboo stick are 0%, 0.6%, 1.2%, and 2.4%, respectively, according to the volume ratio. Each factor was repeated four times, and the specific test groups are shown in **Table 2** (V_f: volume fraction of bamboo stick; D: diameter of bamboo stick; L: length of bamboo stick; L/D: length-diameter ratio of bamboo stick). The numbering rule of each group is summarized in the following: the first number represents the V_f; the second number represents the diameter of bamboo stick; the third number represents the length of bamboo stick.

2.4 Test method

This study was carried out by the Standard for test methods of concrete physical and mechanical properties (GB/T50081-2019) [16]. The loading equipment adopts the WANCE servo press machine with a maximum load of 200 tons, and the loading speed is controlled at 0.05 MPa/s. The test fixture is shown in **Fig. 5 (a)**. Before the splitting tensile test, the center lines of the bottom and top of the specimens were drawn, and the specimens were placed in the center of the pressing plate of the press after the fixture and spacers were installed to ensure that the center line of the specimens and the center line of the pressing plate were consistent. In addition, the vertical and horizontal strain gauges were pasted in advance at each specimen's front and rear centers (the size of a single strain gauge is 20 mm × 3 mm), as shown in **Fig. 5 (b)**, and TDS540 collected the vertical and horizontal strain data. The splitting tensile strength of specimens can be obtained by Eq. 1.

$$f_{\mathrm{ts}} = \frac{2f}{\pi A} = \frac{0.637f}{A} \tag{1}$$

In the formula: f_{ts} is the splitting tensile strength of concrete (MPa); f is the failure load of the specimen (N); A is the splitting surface area of the specimen (mm^2). In addition, the calculated splitting tensile strength is accurate to 0.01 MPa.

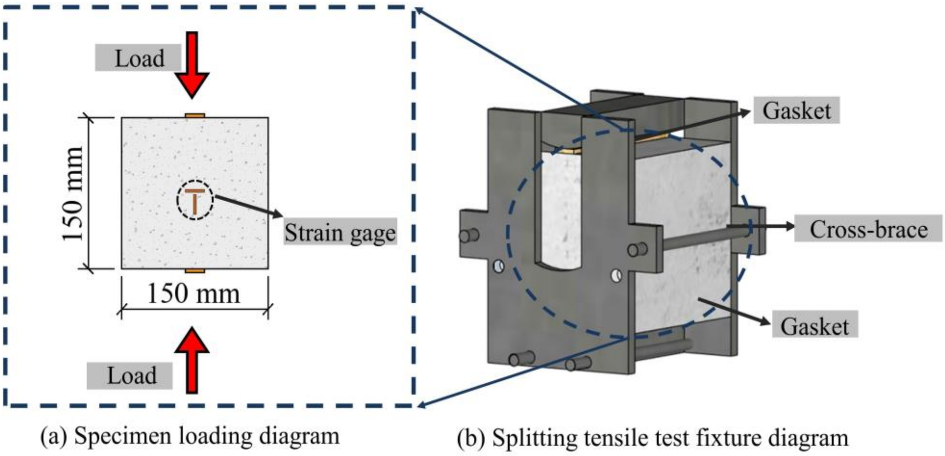


Fig. 5. Test fixture and free-body diagram of the specimen.

3 Result and discussion

3 .1 Analysis of failure modes

Fig. 6 (a) shows the failure characteristics of control specimens (when the V_f in seawater sea-sand concrete is 0%) and BFRSSC specimens (D=1.5mm) in the splitting tensile test. During the experiment, as the load gradually increased, the control specimen made a crisp sound without warning. Then it immediately reached its ultimate strength and was split in two. The cracks produced by control specimens are straight and have few bifurcations. Overall, each control specimen appears to have a penetrating main crack, and this failure mode belongs to apparent brittle failure. The damage patterns of the BFRSSC specimens were different from those of the control specimens, as shown in **Fig. 6 (b)-Fig. 6 (c)**. When the V_f was small (0.6%), the splitting tensile failure mode of the specimen was similar to that of the control specimen. With the increase in load, penetrating cracks appeared rapidly on the surface of the specimen, and the specimen was also suddenly broken into two halves without warning. However, compared with the control specimen, their sounds were smaller when they broke, and the main cracks were more torturous. When the V_f was large (1.2% and 2.4%), the failure of the specimen showed a prominent plastic characteristic. They showed a more muffled fracture sound when cracking, accompanied by bamboo sticks being pulled off; the specimens were destroyed and produced several apparent cracks. In addition, after reaching the ultimate strength failure, the cracks of quite a few specimens failed to penetrate the specimens quickly, and the integrity of the specimen was well guaranteed. After comparison, it can be found that the development speed of cracks of the latter was slower than that of the control specimen and the specimens with low bamboo stick content, and their crack widths were much smaller than that of the control specimen.

It can be found that the larger the *L*/*D* ratio of the bamboo sticks, the larger the crack width and the lower the complexity of the crack path for the same stick content and stick diameter, as shown in **Fig. 6 (e)-Fig. 6 (g)**. When V_f and *L*/*D* ratio are the same, by observing **Fig. 6 (e)** and **Fig. 6 (h)**, the crack width increases with the increase of diameter and the crack progression is towards the main crack. It can be seen from **Fig. 6 (i)** that the fiber bridging effect is enhanced by the increase of bamboo stick doping, and when the length is larger, the stick pull-out is dominant.

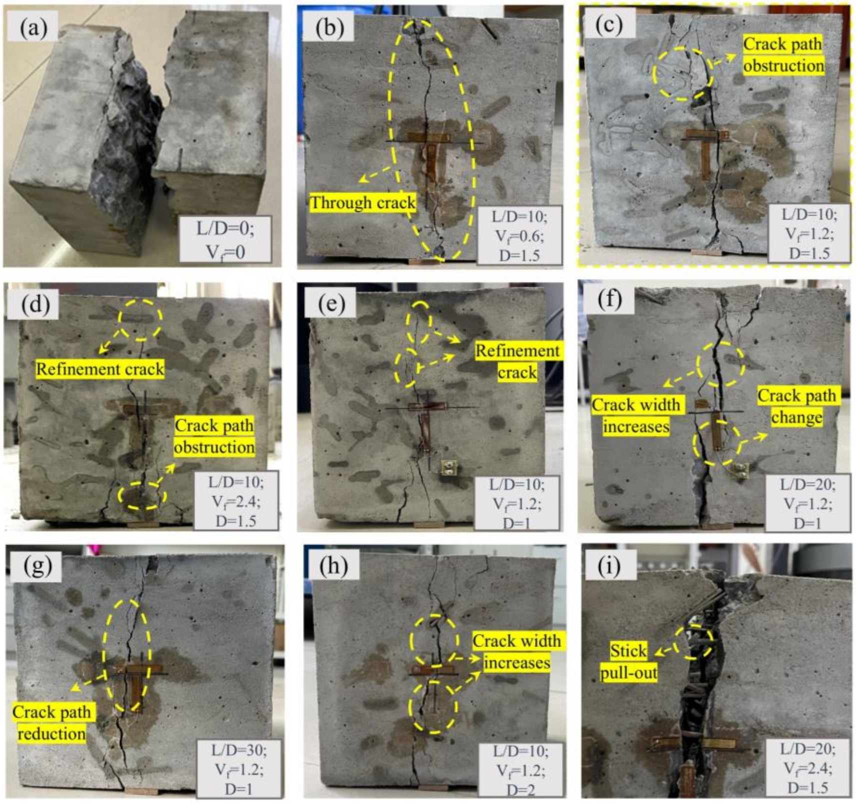


Fig. 6. The failure modes of the specimens.

3.2 Splitting tensile strength and ultimate displacement

The test results are shown in **Table 3**. In **Table 3,** f_{ts} is the splitting tensile strength of specimens (MPa); C_{V1} is the coefficient of variation of f_{ts}; *u* is the ultimate displacement of specimens (mm); C_{V2} is the coefficient of variation of *u*. It can be seen that the coefficient of variation of most test results is low. The test results are compared and discussed below.

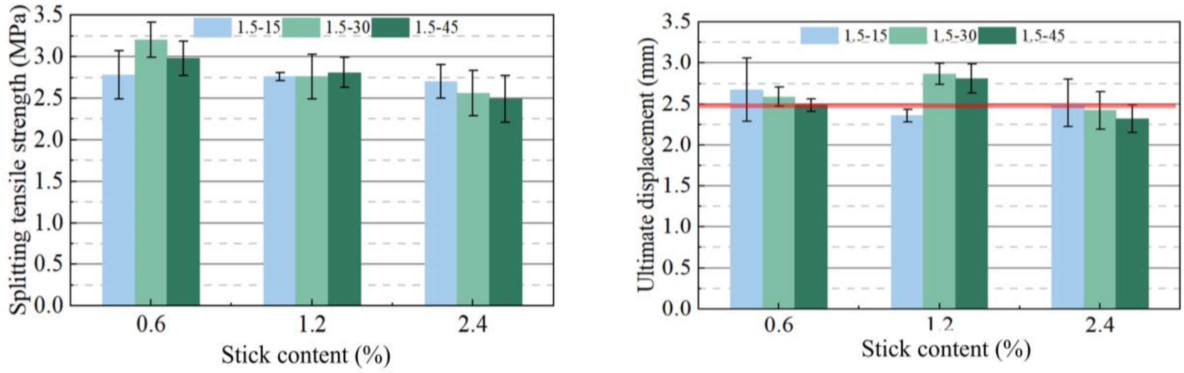
In order to evaluate the effect of bamboo stick content and length-diameter ratio on the splitting tensile properties of BFRSSC, specimens with V_f of 0.6%, 1.2%, 2.4%, *L/D* of 10, 20, 30, and *D* is 1.5 mm were analyzed. **Fig. 7** shows the changing trends of splitting tensile strength and ultimate displacement (the displacement at the maximum load of each specimen) compared to control specimens. The red lines in **Fig. 7** represent the strength and displacement of the control group, respectively.

The following conclusions can be drawn from **Fig. 7** and **Table 3**. When comparing different bamboo stick content, the test groups with V_f of 0.6% have the highest splitting tensile strength at each *L*/*D*, and the test groups with V_f of 1.2% have the highest ultimate displacement except for the groups with *L* of 1.5 mm. When V_f is 0.6%, the splitting tensile strength of the group of 0.6-1.5-3.0 and 0.6-

1.5-4.5 is 14% and 6% higher than the control group, respectively. And their ultimate displacement of the test group of 1.2-1.5-3.0 and 1.2-1.5-4.5 is 16% and 14% higher than that of the control group. It is because incorporating bamboo stick plays a crack bridging mechanism when concrete cracks [19], and bamboo stick increases the splitting tensile strength and plastic deformation capacity of seawater sea-sand concrete. Both splitting tensile strength and ultimate displacement increase with the increase of V_f because of this effect of bamboo stick at first.

Table 3. Test results

Test groups	f_{ts} (MPa)	C_{V1}	Relative strength	u (mm)	C_{V2}	Relative displacement
0-0-0	2.81	0.03	1.00	2.47	0.01	1.00
0.6-1.5-15	2.78	0.10	0.99	2.67	0.14	1.08
0.6-1.5-30	3.20	0.07	1.14	2.59	0.05	1.05
0.6-1.5-45	2.98	0.07	1.06	2.49	0.03	1.01
1.2-1.0-10	2.98	0.07	1.06	2.65	0.06	1.07
1.2-1.5-15	2.76	0.02	0.98	2.36	0.03	0.96
1.2-2.0-20	2.98	0.07	1.06	2.54	0.08	1.03
1.2-1.0-20	2.90	0.04	1.03	2.33	0.08	0.94
1.2-1.5-30	2.76	0.10	0.91	2.87	0.05	1.16
1.2-2.0-40	2.80	0.04	1.00	2.80	0.08	1.13
1.2-1.0-30	2.96	0.01	1.05	2.58	0.11	1.05
1.2-1.5-45	2.81	0.06	1.00	2.81	0.06	1.14
1.2-2.0-60	2.89	0.06	1.03	2.83	0.06	1.15
2.4-1.5-15	2.70	0.07	0.96	2.51	0.11	1.02
2.4-1.5-30	2.56	0.11	0.91	2.42	0.10	0.98
2.4-1.5-45	2.49	0.11	0.89	2.32	0.07	0.94

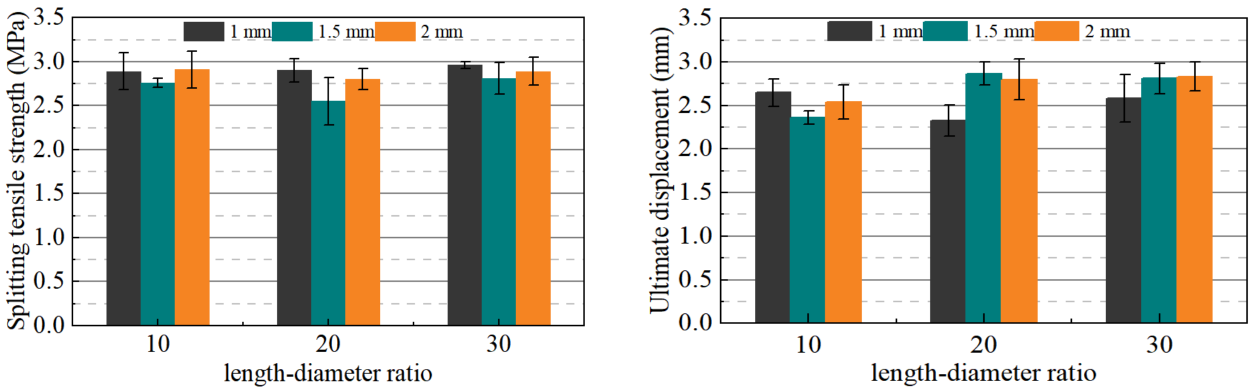


(a) Splitting tensile strength. (b) Ultimate displacement.

Fig. 7. Comparison of splitting tensile strength and ultimate displacement between each group with D of 1.5 mm.

However, their splitting tensile strength decrease when the stick content is further increased after 0.6%, and their ultimate displacement decrease when the stick content is further increased after 1.2%. The following facts can explain this phenomenon. When the bamboo stick content is too high, the concrete's porosity will increase to form a porous structure, and there are more bamboo sticks at the splitting surface, which makes contact between the matrix insufficient and affects the strength [10-11]. With the increase of porous structure, the specimens are destroyed in advance when the bamboo sticks have not fully played the role, which decreases their ultimate displacement.

As for the groups with L of 1.5 mm (L/D = 10), their splitting tensile strength and ultimate displacement are similar to that of the control group. It is because bamboo stick is too short, and the stick is easily pulled out and cannot play a better connection to strengthen the concrete under the action of the load [20-21]. With the increase of L/D, the change trends of the splitting tensile strength and the ultimate displacement are first increased and then decreased. This phenomenon shows an optimal L/D to maximize the specimen's splitting tensile strength and deformation capacity. When L/D is too small, bamboo stick cannot play its due role, and when L/D is too big, the stick's negative effect will weaken the specimen's performance. In this paper, the most suitable L/D is 20 for the BFRSSC specimen.



(a) Splitting tensile strength.

(b) Ultimate displacement.

Fig. 8. Comparison of splitting tensile strength and ultimate displacement between each group with different *D*.

In order to evaluate the effect of the diameter of bamboo stick on the splitting tensile properties of BFRSSC, specimens with *D* of 1 mm, 1.5 mm, 2 mm, and V_f is 1.2% analyzed. **Fig. 8** shows the changing trends of splitting tensile strength and ultimate displacement (the displacement at the maximum load of each specimen) compared to control specimens. The red lines in **Fig. 8** represent the strength and displacement of the control group, respectively.

By analyzing **Fig. 8 (a)**, it can be found that the change of bamboo stick diameter in the 1-2 mm range will not significantly influence the splitting tensile strength. When the *D* increases from 1 mm to 1.5 mm, the splitting tensile strength of specimens with three kinds of *L*/*D* decreases slightly, and they decrease by 5.7 % on average; when the *D* increases from 1.5 mm to 2 mm, the splitting tensile strength of specimens with three kinds of *L*/*D* increase slightly, and they grow by 3.8% on average. This changing trend is consistent with the trend of tensile strength of bamboo sticks with different diameters used in the test (**Fig. 9**). It can be seen from the figure that the splitting tensile strength of the specimens is greatly affected by the tensile strength of bamboo stick, and the strength of the specimens does not change with the increasing trend of bamboo stick diameters.

By analyzing **Fig. 8 (b)**, it can be found that the effect of *D* on the ultimate displacement of BFRSSC specimens is also related to *L*/*D*. When *L*/*D* is 10, bamboo sticks are too short to play their role fully. Therefore, the ultimate displacement of the three groups is similar. When *L*/*D* is bigger, the bamboo sticks in concrete can play their role better. And bamboo sticks with large diameters can help concrete produce more significant deformation.

Based on the above analysis results, the following conclusions can be drawn: (1) Increasing the content of bamboo stick in a certain range can help improve concrete's splitting tensile strength and plastic deformation capacity. (2) Excessive bamboo stick content will weaken the splitting tensile strength and plastic deformation capacity of BFRSSC. (3) There is an optimal *L*/*D* to maximize the splitting tensile strength and deformation capacity of BFRSSC. (4) bamboo sticks with large diameters can improve the plastic deformation capacity of BFRSSC.

3.3 Mechanism analysis of bamboo stick reinforced concrete

Through the proof of theory and practice, the destruction process of concrete mainly includes three stages: the crack generation stage, the stable crack propagation stage, and the crack entering the unstable extension stage [22]. Due to its composition, the concrete is uneven and has some potential defects [23]. With the increase of the load on the concrete, these defects will form micro-cracks, and then the micro-cracks will gradually increase and converge. And they will develop into macroscopic cracks visible to the naked eye. Eventually, it will lead to the failure of concrete specimens. In the splitting tensile test, the failure surface of control specimens often passes through the area formed by two spacers, and the failure surface is relatively flat. The composition of the control specimen is fairly uniform. Under the action of concentrated force, the tensile stress at the midline of the specimen is large, and the cracks develop from the midline surface to the interior. Finally, the specimen is divided into two parts which are relatively uniform and neat.

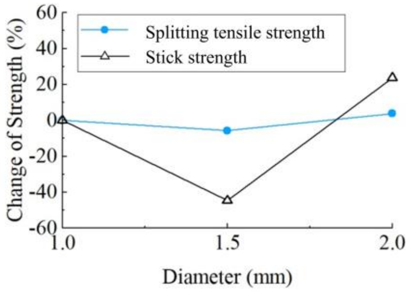


Fig. 9. Change trends of the strength of the stick and the average strength of specimens (V_f = 1.2%).

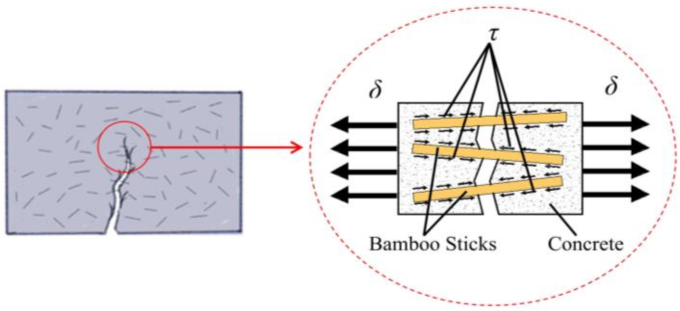


Fig. 10. Schematic diagram of bamboo stick hindering crack development.

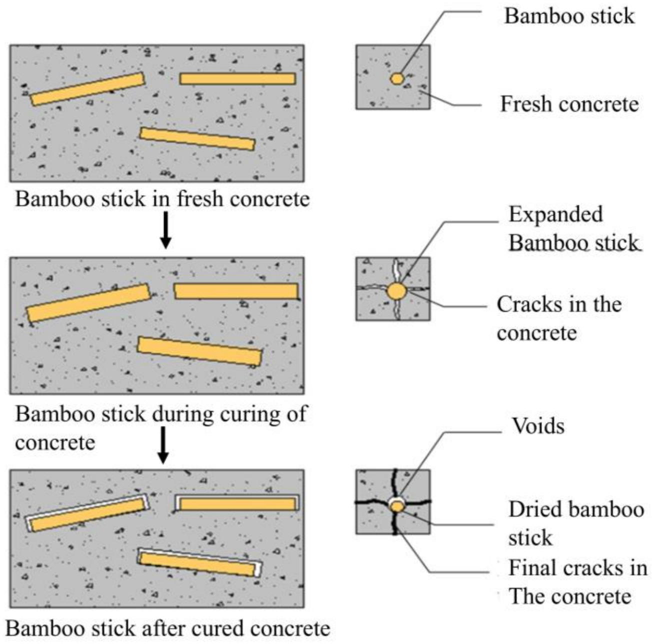
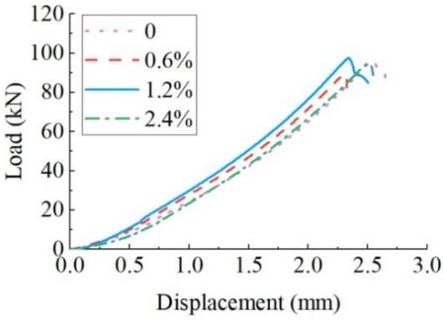
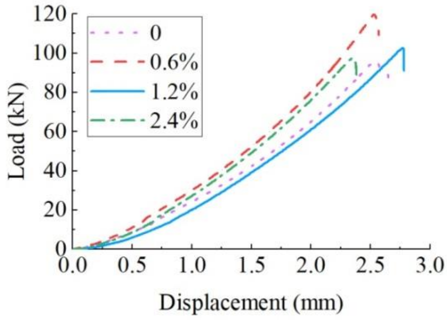


Fig. 11. The behavior of bamboo stick as reinforcement in concrete.

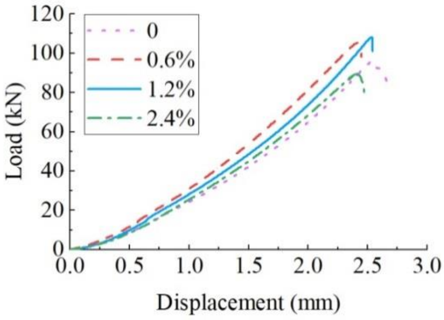
The addition of bamboo stick changes this situation. Because bamboo sticks have higher tensile strength and can form a good bonding power with the concrete, it can hinder the further development of macroscopic cracks by connecting the matrix and achieve the purpose of increasing the toughness of concrete and improving the fracture energy [24]. The bridging effect of bamboo stick in concrete is transmitted by stick deformation and friction resistance. When the crack in the concrete has progressed to intersect with the bamboo stick, the bamboo stick will bear part of the stress and slow down the crack development or make the crack bifurcate and deflect to achieve the purpose of energy absorption better [25]. Therefore, under tension, the crack development path of the BFRSSC specimen is more tortuous and has more bifurcations. And its fracture surface is more uneven than the control specimen, and many broken bamboo sticks exist on it. bamboo stick hinders the development of cracks in concrete, as shown in **Fig. 10**. In the figure, σ is the tensile stress in the concrete, and τ is the shear stress the bamboo stick provides when it hinders cracking. In addition, in the hardening stage of concrete, bamboo stick can also hinder the development of nearby cracks through the bonding force between it and the matrix. Due to the three-dimensional random distribution of bamboo stick in the matrix, it can bear part of the force when the matrix shrinks, reducing the initial cracking of concrete and increasing toughness [26]. However, incorporating bamboo stick into the mixture will also lead to more pores in the concrete. It is because bamboo stick can absorb some water. And bamboo stick will change in size during curing and drying, resulting in more pores in concrete [27], as shown in **Fig. 11**. The pores can affect the adhesion between bamboo stick and matrix. Besides, stress concentration will occur easily around the pores. So pores can weaken the strength of concrete. When the effect of stick reinforcement is greater than the weakening effect caused by the pores, the splitting tensile strength of specimens will increase; when the stick content is too high, the porosity of the specimen will be larger, and the effect of stick reinforcement is less than the weakening effect caused by the pores. The splitting tensile strength of specimens will reduce. Therefore, the splitting tensile strength of concrete can be improved by controlling the V_f.



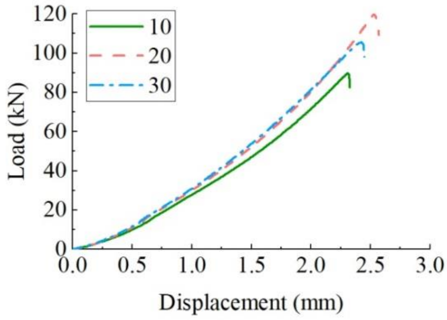
(a) D = 1.5 mm, L = 15 mm



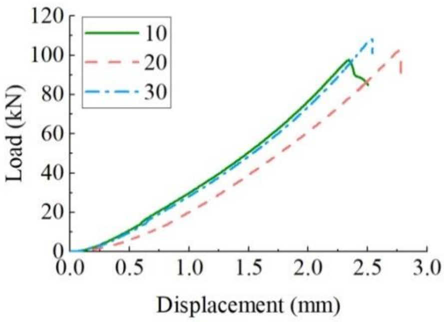
(b) D = 1.5 mm, L = 30 mm



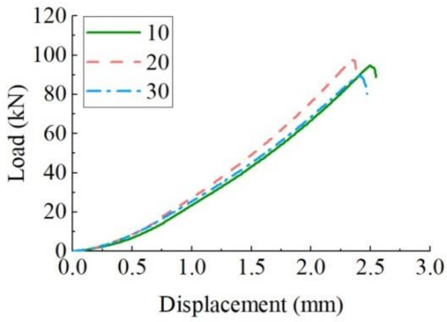
(c) D = 1.5 mm, L = 45 mm



(d) D = 1.5 mm, V_f = 0.6%



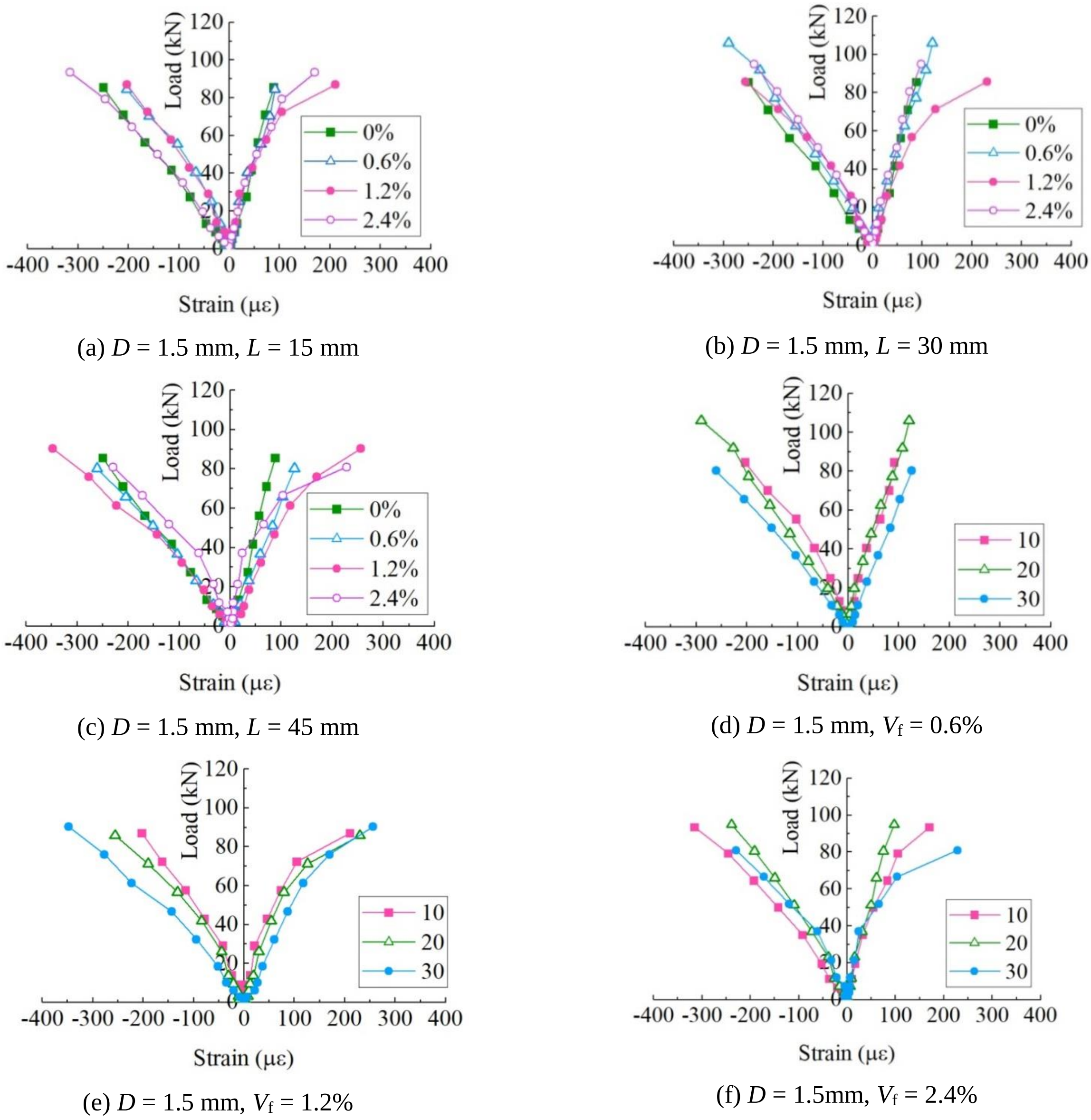
(e) D = 1.5 mm, V_f = 1.2%



(f) D = 1.5 mm, V_f = 2.4%

Fig. 12. The axial load-displacement curves of specimens with different V_f (a - c) or L/D (d - f)

The bamboo stick used in the test is a thin round rod-type bamboo stick, mainly acting through the friction and bonding force between the concrete matrixes. When the bonding fails, the slip phenomenon between the bamboo stick and matrix occurs, and the bamboo stick exits the work. In this experiment, bamboo sticks were pulled out and broken on the splitting failure section of BFRSSC specimens. Therefore, it is necessary to consider the critical role of the bond strength between bamboo stick and concrete. In theory, with the increase of the L/D, the contact surface between stick and matrix will become more significant. So the bonding force between stick and concrete should increase. In addition, when the L/D is larger, the sticks will have more chances across the macro cracks to play a better force transmission. However, the specimens' biggest splitting tensile strength does not appear in the groups with the largest L/D in this test. It is because the L/D that is too big will cause a negative weakening effect on BFRSSC caused by the phenomenon of kinked agglomeration, which appears easily during mixing.



(a) D = 1.5 mm, L = 15 mm
(b) D = 1.5 mm, L = 30 mm
(c) D = 1.5 mm, L = 45 mm
(d) D = 1.5 mm, V_f = 0.6%
(e) D = 1.5 mm, V_f = 1.2%
(f) D = 1.5mm, V_f = 2.4%

Fig. 13. The load-strain curves of specimens with different V_f (a-c) or L/D (d-f).

3.4 Analysis of load-displacement curve

The load-displacement curves are analyzed because the V_f and L/D are the main influencing factors on the splitting tensile strength of BFRSSC. **Fig. 12** shows the axial load-displacement curves of BFRSSC under different V_f or L/D. At the initial loading stage, each specimen's load-displacement curves develop linearly. When the displacement reaches about 0.5mm, the development trend of each group begins to show differently. From **Fig. 12 (a)-Fig. 12 (c)**, it can be found that the slopes of most BFRSSC specimens' curves are usually bigger than the control group. This phenomenon indicates that bamboo sticks help concrete improve its rigidity. Because there are many macro cracks in the concrete before reaching the ultimate load, bamboo sticks hinder the development of cracks. When the displacement is bigger, the rigidity difference between BFRSSC specimens and the control group is more distinct. After the load increased to the ultimate load of each group, obvious cracks appeared on the surface of the specimens. Then the bearing capacity of all groups decreases rapidly till destruction completely, no matter what the V_f is. That indicates that bamboo stick only plays an enhanced role before destruction but plays a limited role after visible cracks appear. From **Fig. 12 (d)-Fig. 12 (f)**, it can be found that when the L/D is different, the rigidity of load-displacement curves of each group of specimens is similar. And this result shows that the effect of V_f on rigidity is more significant than that of L/D.

3.5 Analysis of load-strain curve

Fig. 13 shows the load-strain curves of specimens with different V_f or L/D. **Fig. 13 (a)-Fig. 13 (c)** shows the load-strain curves of each specimen under different stick contents. The tensile strain in the diagram is positive (horizontal strain); the compressive strain is negative (vertical strain). In the initial stage of loading, both load-strain curves change linearly. Then the slope of tensile strain curves of BFRSSC decreases obviously with the increase of load. And the curves of specimens with larger V_f change more significantly. Besides, the ultimate strains of specimens with larger V_f are bigger than others, indicating that the increase of the V_f helps to increase the deformation capacity of the specimen. While vertical load-strain curves don't connect much with V_f, this result indicates that the connection between the matrix and the bamboo stick is good [28]. **Fig. 13 (d)-Fig. 13(f)** shows the load-strain curves of BFRSSC with different L/D. After the linear curves, the slope of the horizontal load-strain curves of specimens with larger L/D decreases more obviously with the increase in load. And the maximum horizontal strain of specimens with larger L/D is also bigger than others. Therefore, it can be concluded that increasing the L/D can help the specimen to increase the deformation capacity.

3.6 Comparison between this test and other research

The improvements in splitting tensile strength of this test and other research about the plant fiber concrete are compared in **Table 4** (the forms of plant fibers discussed here are all sticks). From **Table 4**, such conclusions can be obtained.

(a) Compared with untreated wheat straw fiber or untreated pine needle fiber reinforced concrete, bamboo stick reinforced concrete has greater splitting tensile strength. (b) Plant fiber that has been diluted alkali treated will gain better performance for concrete. (c) Dilute alkali-treated bamboo stick reinforced concrete should be further studied.

Table 4. Comparison of research results of bamboo stick concrete.

Reference	Types of concrete	Types of fiber	The max strength growth rate (%)	Fiber content (%)	Fiber size (mm)
This research	Seawater sea-sand concrete	Untreated bamboo stick	14	0.6	L: 30 D: 1.5
Ede et al. [11]	Self-compacting concrete	Dilute alkali-treated bamboo fiber	32	0.5*	L/D: 50 Max L: 50
Farooqi et al. [29]	Plain Concrete	Wheat Straw fiber	-7.5	1*	-
Long et al. [7]	Plain Concrete	Dilute alkali-treated pine needle fiber	10.6	2	L: 30

Note: In the calculation of fiber content, " * " indicates the use of cement weight ratio calculation, and other cases are calculated by volume fraction.

4 The fitting formula of splitting tensile strength

It can be known from the splitting tensile strength test results in 4.1 that the V_f and L/D play a major role in the splitting tensile strength of BFRSSC. Therefore, the fitting formula can be derived from the test results when the diameter of bamboo stick is 1.5 mm. By referring to the formula of splitting tensile strength of steel fiber reinforced concrete in the standard of Steel fiber reinforced concrete [30], a formula considering the influence of V_f and L/D on the splitting tensile strength of BFRSSC is proposed based on the test results. It is determined by formulas (2) and (3):

$$f_{\mathrm{bfts}} = f_{\mathrm{ts}}(1+\alpha A) \tag{2}$$

$$\alpha = 16.47806t^2 - 0.89399t + 0.007974 \tag{3}$$

In the formulas: α is the influence coefficient of the V_f on the splitting tensile strength of BFRSSC, which is obtained by fitting the experimental data with a diameter of 1.5 mm, and 0 is taken when V_f is 0; A is the length-diameter ratio of bamboo stick, A = L/D; f_{ts} is splitting tensile strength of the control specimen； f_{bfts} is the calculated splitting tensile strength of the BFRSSC specimens.

According to the derived formulas (2) and (3), the fitting calculation results in M_c and the test results in M_t are compared, as shown in **Table 5.** It can be seen from the table that the derived formula has a good prediction effect, and the error between the predicted value and the experimental value is within 7%.

Table 5. Comparison between calculation results and test results.

Test groups	M_c (MPa)	M_t (MPa)	M_c / M_t
0.6-1.5-15	2.90	2.78	1.043
0.6-1.5-30	2.99	3.20	0.934
0.6-1.5-45	3.08	2.98	1.034
1.2-1.5-15	2.80	2.76	1.014
1.2-1.5-30	2.79	2.76	1.011
1.2-1.5-45	2.78	2.81	0.989
2.4-1.5-15	2.70	2.70	1.000
2.4-1.5-30	2.59	2.56	1.012
2.4-1.5-45	2.47	2.49	0.992

5 Conclusion

In this paper, the splitting tensile property of BFRSSC was studied, and the effects of V_f, L/D, and D on the splitting tensile strength and ultimate displacement of specimens were compared. By analyzing the test results, the following main research conclusions can be drawn:

(1). There is an optimal V_f and L/D, respectively, to improve the splitting tensile strength and plastic deformation capacity of BFRSSC. Too much bamboo stick will form empty space in concrete to reduce the splitting tensile strength, and if the L/D is too large, aggregation and winding can easily occur in the concrete mixing process.

(2). bamboo stick helps to improve the splitting tensile properties mainly by hindering the formation and development of cracks in concrete.

(3). The fitting formula of the splitting tensile test results of BFRSSC is deduced from the splitting tensile strength of BFRSSC. The splitting tensile strength of BFRSSC can be approximately deduced by the V_f and L/D and the mechanical properties of the matrix, which has a certain reference value.

The above conclusions reveal that incorporating bamboo stick with a suitable volume fraction and size exerts a positive impact on the mechanical properties of seawater sea - sand concrete. This demonstrates the feasibility of blending bamboo stick into seawater sea - sand concrete. Additionally, untreated bamboo stick was utilized in this experiment.

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CRediT authorship contribution statement

Haitao Li: Conceptualization, Funding acquisition, Supervision, Investigation, Formal analysis, Writing – original draft. **Lincai Ge**: Investigation, Formal analysis, Writing – original draft. **Ziang**

Wang: Investigation, Formal analysis, Writing – original draft. **Usama Sayed**: Investigation. **Zixian Feng**: Investigation. **Xin Xue**: Investigation. **Patrick Adjei**: Investigation. **Ottavia Corbi**: Supervision, Investigation. **Ileana Corbi**: Supervision, Writing – review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest in this work.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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