Bamboo Stick Diameter, Volume and Aspect Ratios Effect on the Compressive Behavior of Bamboo Sticks Reinforced Concrete Mixed with Sea Sand and Seawater

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ABSTRACT

Over the past decade, bamboo has received much attention due to its sustainability and strength. The advantages of bamboo over other natural fibres include its abundant existence, high yield, and the ability to quickly reach a maximum height and strength in 3–8 years. Bamboo can be used as an independent structural material and concrete reinforcement in the forms of bamboo culms, bamboo splints, and bamboo composite bars for low-rise and low-cost buildings. In this study, bamboo sticks were adopted as reinforcement for concrete cubes. The following influencing factors were considered: bamboo stick volume ratios of 0.6%, 1.2%, and 2.4%, bamboo stick diameters of 1 mm, 1.5 mm, and 2 mm, and bamboo stick aspect ratios of 10, 20, and 30. The test result shows that with the addition of 0.6% of sticks, the BSRC compressive strength rose by 3.24 and 17.33% for length-to-diameter ratios 20 and 30, respectively. The compressive strength of specimens was enhanced by adding 1.2% and 2.4% bamboo sticks with a length-to-diameter ratio of 10 by 21.38 and 20.94%, respectively. The obtained results were compared with the mechanical properties of conventional concrete cubes. Currently, river sand and fresh water are the most often used materials in manufacturing concrete. The widespread use of river sand and freshwater has resulted in major environmental issues. Because many places of the world lack appropriate supplies of fresh water, overuse of this resource is not advised. As a result, saltwater and sea sand were used to create both bamboo stick reinforced concrete and plain concrete specimens. Lastly, a model of strength and stress-strain was proposed.

KEYWORDS

Bamboo reinforced concrete; bamboo sticks; concrete; compression.

1 Introduction

Along with the industry and transport sectors, the Architecture, Construction, and Engineering sector turned out to be one of the significant environmental pollutants [1-3]. The building materials are responsible for 30–40% of emissions and energy consumption due to the depletion of non-renewable resources, energy-intensive production, and transportation [1, 4-6]. An active search for environmentally friendly materials with non/less-polluting manufacturing and processing methods have started, and natural fibres, industrial wastes and agricultural byproducts have gained the attention of researchers [7]. With the development of advanced materials including polymers, synthetic and carbon fibres, agricultural byproducts including bamboo residue, rice husk, coconut, and sisal have been wasted, causing permanent pollution [7]. It is obvious that full use of agricultural byproducts, which exist in abundance, would minimize the environmental burden by reducing emissions and energy consumption and saving non-renewable resources.

Over the past decade, bamboo has received much attention due to its sustainability and strength [8-10]. The advantages of bamboo over other natural fibres include its abundant existence in tropical and subtropical regions of the world, high yield, and the ability to reach a maximum height and maximum strength in 3–8 years [8, 9]. The mechanical characteristics of bamboo may vary depending on the species, moisture content and fibre direction, which is similar to wood. In general, the mechanical properties of original bamboo are comparable with that of mild steel, cast iron, aluminium alloys, and wood [11-16]. Considering the excellent mechanical properties of bamboo, many scientists have studied its use as reinforcement for concrete structures to reduce the environmental impact of steel reinforcement without reducing strength.

Concrete is one of the most widely used building materials in the world. It has a very high compression strength however is brittle by nature. The brittleness of concrete leads to a limited strain capacity under tension and, consequently, a low toughness. [17]. Many researchers have developed various ways to increase the toughness of concrete structural members by reinforcing with natural fibres including bamboo, coir, malva, sugarcane, banana, hemp, wheat straw, etc. [17-21]. Since 1950, bamboo bars made of a full culm or half-culm bamboo have been used for concrete reinforcement [22]. The studies reported that the strength of bamboo-bars reinforced concrete (BRC) members increased twice compared to plain concrete (PC) and constituted 35% of the strength of steel-reinforced concrete (SRC) [22-25]. Previous studies on BRC members showed that bamboo bars could be utilized as an alternative to steel in lightweight and low-rise buildings where access to steel is difficult and the resources of bamboo are rich [7, 26, 27]. Although bamboo bars reinforcement improves the mechanical behaviour of concrete members, its ductility is not inferior to the ductility and strength of steel reinforcement [27]. The attention of the researchers was shifted to the utilization of bamboo fibres and products based on them, such as bamboo bundle veneer lumbers and bamboo sticks, due to reported excellent mechanical properties and less-polluting production. It is known that the tensile strength and modulus of elasticity (MOE) of the bamboo single fibre can reach 309 MPa and 27 GPa, respectively [8, 28]. Although bamboo fibers are not as strong as glass or carbon, they are nevertheless a viable alternative. Since it is naturally occurring, it has obvious benefits in terms of sustainability, renewability, yield, growth rate, and cost.

Several studies tried to improve the mechanical properties of concrete by adding bamboo-based products as reinforcement. Wen et al. [29] combined bamboo fibres to enhance the flexural performance of bio-beams. The authors concluded that the bio-beams with a fibres volume ratio of 0.3% improved ductility, flexure strain, and increased peak strength by 34% compared to unreinforced bio-beams. However, the addition of more fibres (0.4% and higher) led to a decrease in flexural performance since the fibres filled the pores between the particles and reduced the bond strength. Kumarasamy et al. [30] found that the compressive, tensile and flexural strengths of bamboo fibres reinforced concrete (BFRC) specimens increased with the addition of fibres at 0.5%, 1%, 1.5%, and 2%, but it decreased at 2.5%. Terai et al. [31] reported that the flexural and compressive strength of concrete members reinforced with bamboo sticks (BSRC) were not affected by the stick volume ratio, while the tensile strength significantly increased with an increase in the volume fraction of sticks. Tan [32] reported that BSRC beams achieved 46% of the SRC beams' capacity compared to conventional PC beams. Rakesh et al. [33] studied the effect of carbonation curing on the compressive and tensile behaviour of BFRC specimens. The results showed that the compressive strength of concrete with 1% of bamboo fibres cured by carbon was 14.5% higher than that of concrete cube cured by water. The splitting tensile strength of a concrete cube with 1% of bamboo fibres cured by carbon was 18% higher than that of a concrete cube cured by water [33].

Considering the weak bonding performance of bamboo with concrete matrix, most studies developed new approaches. Ghavami [7] treated bamboo bars with Negrolin (bituminous product), wrapped with wire of 1.5 mm diameter and coated with sand. Another group of bamboo bars was coated with Sikadur 32 Gel (epoxy glue). The results of pull-out tests showed that the specimens with bamboo bars treated with Sikadur 32 Gel showed the best performance with increased bond strength by 5.29 times. Previous studies on BRC members showed that different surface modification methods, including semi-circular corrugations and binding wire, showed increased bonding strength by 80% compared to PC [7]. Similar to previous studies, Kumar et al. [36] and Mengistu [70] stated that epoxy-based adhesives increased the bonding strength of the bamboo with the concrete.

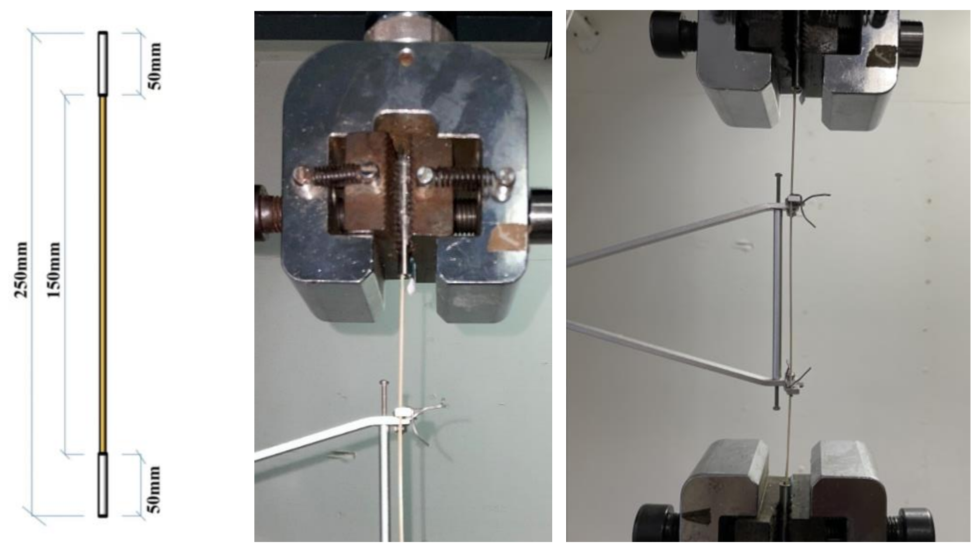
As concrete is weak in tension, the use of bamboo-based products improved the composite's mechanical properties and cracking resistance. The results of the previous studies showed great potential for the combined use of bamboo-based products as reinforcement. The main obstacle to the application of bamboo-based products as reinforcement is the lack of sufficient research on bamboo interaction with concrete and the fundamental mechanical properties of the composite. To contribute to the existing literature about the mechanical properties of concrete reinforced with bamboo-based products and address the research gaps in the corresponding field, this study presents the results of an experimental investigation of the fundamental mechanical behaviour of concrete reinforced with bamboo sticks under compression, in particular failure modes, load-deflection and stress-strain relationships. Different bamboo sticks diameters of 1 mm, 1.5 mm, 2 mm, and aspect ratios (L/D) of 10, 20, and 30, as well as bamboo sticks volume ratios (V_s) of 0.6%, 1.2%, 2.4%, were adopted for the research. The concise summary of the research gives conclusions on the potential of bamboo sticks as concrete reinforcement for structural application.

2 Materials and method

2.1 Bamboo sticks

Bamboo sticks were prepared from Moso bamboo (*Phyllostachys pubescens*), which were harvested and produced in Sichuan province, China. Similar to the production of laminated bamboo lumber, 3–4-year-old bamboo culms of brown colour are selected for harvesting [8]. After harvesting, the culms are cut into bamboo slats. Then the slats of the same thickness are crushed into slivers, from which the bamboo sticks are made. The bamboo sticks are subjected to polishing and dimensioning to the required length [34-36]. After polishing, bamboo sticks are sorted, graded and packaged for market distribution.

In this research, bamboo sticks with 1 mm, 1.5 mm, and 2 mm diameters, and a length of 250 mm were prepared and labelled as BS1, BS1.5, and BS2, respectively. The density of 1 mm, 1.5 mm, and 2 mm bamboo sticks constituted 1.2 g/cm^3, 0.89 g/cm^3, and 0.87 g/cm^3, respectively. A total of 30 specimens were prepared for the test. The aluminium tubes with a diameter of 4 mm and length of 50 mm were arranged to protect the ends of bamboo sticks from being harmed by the grip of the tensile testing machine, as shown in Fig. 1.



(a) (b) (c)

Fig. 1. Bamboo stick specimen: (a) shape and dimension; (b) aluminium tubes protection from the machine grips; (c) location of the extensometer.

The Sanyou Resin L500 series resin adhesive produced by Shanghai Sanyou Resin Co., Ltd, with a tensile strength of 30 MPa, was used to attach the aluminium tubes to the bamboo stick. The tensile tests for bamboo sticks were conducted on SANS Electromechanical universal testing machine (UTM) model CMT-4304 based on standard GB/T 1447-2005 "Fiber-reinforced plastics composites. Determination of tensile properties" [37]. The load was applied at a rate of 0.1 mm/s. The extensometer was used to measure the scale elongations from 0.1 to 25 mm. The load, elongation, and strain data were collected by the TDS data acquisition machine.

2.2 BSRC cubes

The requirements of the standard GB/T 50081-2019 "Standard for test methods of concrete physical and mechanical properties" [38] were followed to prepare the mix design of BSRC and PC specimens. The main components of the specimens were cement, seawater, sea sand, bamboo sticks, and gravel. The use of sea sand and seawater was explained by the abundant existence of resources and lower prices of the materials [39-41]. Seawater solution was prepared using $NaCl+MgCl_2+Na_2SO_4+CaCl_2+KCl$ with water. The quantity of the chemicals is mentioned in Table 1. Normal ordinary water was used in the curing period of test specimens.

Tab. 1. Seawater solution ratio

Chemicals	NaCl	$MgCl_2$	Na_2SO_4	$CaCl_2$	KCl
Quantity (g/L)	24.53	5.2	4.09	1.16	0.695

Ordinary Portland cement PO 42.5 from Anhui Conch Cement Co., Ltd. was used for the concrete mixture. The proportions of the materials were taken by weight [38]. A slump of approximately 40 cm long with a weight of 2 kg and a tamping section of 25 × 25 mm was selected. The compression grade of the concrete was selected as 30 MPa with 28 days of curing. Therefore, the cement mass constituted 342 kg/m^3, and the water to cement ratio constituted 0.6. Sea sand constituted 704 kg/m^3. A 20 mm gravel was chosen as coarse aggregate with a mass of 1149 kg/m^3. The following groups of specimens with bamboo sticks V_s of 0.6%, 1.2%, and 2.4% were prepared. The mass of bamboo sticks constituted 0.6 g/cm^3 according to GB/T 50081-2019 "Standard for test methods of concrete physical and mechanical properties" [38]. Table 2 shows the mass of bamboo sticks for each V_s type.

Tab. 2. Materials proportions for BSRC mix design

Specimens size, mm	Volume, m^3	V_s, %	Bamboo sticks mass, g
150 × 150 × 150	0.003375	0.60	12.25
		1.20	24.375
		2.40	48.625

Each group of specimens had subgroups with different L/D ratios of bamboo sticks 10, 20, and 30. The 0.6% and 2.4% groups contained bamboo sticks with a diameter of 1.5 mm and lengths of 15 mm, 30 mm, and 45 mm. The 1.2% contained bamboo sticks with diameters of 1 mm, 1.5 mm, and 2 mm, and lengths of 15 mm, 20 mm, 30 mm, 40 mm, 45 mm, and 60 mm. Table 3 shows the details of the BSRC cubes for compression.

Tab. 3. BSRC specimens for compression test

Sample	Size, mm	V_s ratio, %	L/D ratio	Diameter, mm	Length, mm	Number
C	150×150×150	0	—	—	—	4
C0.6-1.5-15	150×150×150	0.6	10	1.5	15	4
C0.6-1.5-30			20	1.5	30	4
C0.6-1.5-45			30	1.5	45	4
C1.2-1.0-10	150×150×150	1.2	10	1	10	4

C1.2-1.5-1.5				1.5	15	4
C1.2-2.0-20				2	20	4
C1.2-1.0-20				1	20	4
C1.2-1.5-30			20	1.5	30	4
C1.2-2.0-40				2	40	4
C1.2-1.0-30				1	30	4
C1.2-1.5-45			30	1.5	45	4
C1.2-2.0-60				2	60	4
C2.4-1.5-15			10	1.5	15	4
C2.4-1.5-30	150×150×150	2.4	20	1.5	30	4
C2.4-1.5-45			30	1.5	45	4
Total	–	–	–	–	–	64

A total of 64 BSRC cubic samples were prepared for the compression test. The samples were divided into 15 groups, considering the V_s ratio and L/D ratio. For example, the specimen labelled as C0.6-1.5-15 can be explained as follows: C – compression sample, 0.6 – the volume ratio of bamboo sticks, 1.5 – the diameter of the bamboo stick in mm, and 15 – the length of bamboo stick in mm. In addition, 4 control PC specimens were prepared for the tests labelled as C. The BSRC mixing procedure is summarized in the following steps:

1. Coarse aggregates were placed in the mixer first, followed by cement and fine aggregates; the materials were subjected to dry mixing for 1 minute to ensure an even distribution of bamboo sticks throughout the concrete;
2. The bamboo sticks were added to the mixture, and the mixture was mixed for 1.5 minutes; 20% of the water was added and mixed for another 1 minute;
3. The remaining water was added to the mixture, and the mixer was run for approximately 2–3 minutes before being stopped, and the test specimens were prepared.

After the mixing procedure, the concrete was poured into moulds and tamped in 3 equal layers with a tamping rod with a diameter of 16 mm and length of 508 mm. Each layer consolidated 25 tamping rod strokes. A vibrating machine was utilized to fill the concrete into empty spots where the rod could not sufficiently fill it. Each specimen was vibrated for 10 seconds. After the casting was completed, the specimens were de-moulded using an air compressor machine. The concrete was cured for continuous 28 days to achieve its maximum strength.

Compression tests were conducted according to the standard GB/T 50081-2019 “Standard for test methods of concrete physical and mechanical properties” [38]. The WANCE electro-hydraulic servo compression testing machine model HTC-206B, 2000 kN, was adopted for the tests. The load was applied at a rate of 0.5 MPa/s. To determine compressive strain and Poisson's ratio, four Foil resistance strain gauges with the size of 20 mm × 3 mm and resistance of 120Ω were pasted on the surface of the specimens. Strain gauges were attached in the center of the left and right sides of the specimen, in both horizontal and vertical directions.The load, displacement, and strain data were collected with the manual displacement equipment and strain gauges connected to the data acquisition machine. The compression strength was calculated according to standard GB/T 50081-2019 [38]. The values of MOE and Poisson’s ratio were obtained from the analysis of stress-strain curves.

3 Results

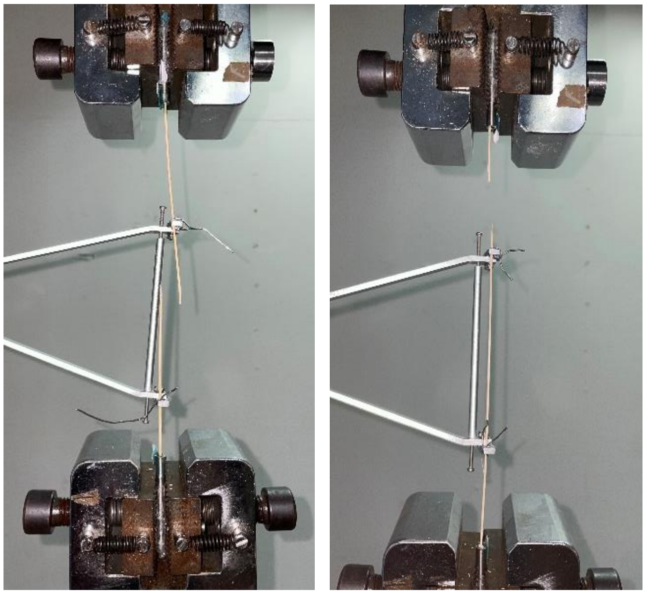
3.1 Tensile behaviour of bamboo sticks

Most of the specimens failed in the middle part (Fig. 2 a), and some of the specimens broke near the edges (top or bottom) where the bamboo stick was glued into aluminium tubes to prevent local damage from the machine grips (Fig. 2 b). All failures happened due to the tearing of bamboo fibres. The general tensile test results are summarized in Table 4. The following equation was used to calculate the tensile strength of bamboo sticks.

$$f_t = \frac{F_t \times 4}{\pi d^2} \quad (1)$$

Where, f_t – the tensile strength, MPa; F_t – the ultimate tensile failure load, N; d – is the diameter of the stick, mm.

As can be seen, the average tensile strength and MOE for bamboo sticks constituted 462.94 MPa and 17 GPa, 256.36 MPa and 11.1 GPa, 316.51 MPa and 10.9 GPa for bamboo sticks of 1 mm, 1.5 mm, and 2 mm diameters, respectively. In previous studies, the tensile strength of bamboo fibres could reach up to 400 MPa and the MOE up to 36 GPa [42-45]. Chen et al. [43] reported the highest tensile strength and MOE for chemically isolated bamboo fibres, amounting to 1.77 GPa and 26.85 GPa, respectively. In the current study, the obtained tensile strength and MOE values of bamboo sticks are in line with previous studies.



(a) (b)

Fig. 2. Failure modes of the bamboo stick: (a) bamboo stick tearing in the middle part; (b) bamboo stick tearing near the edges.

Tab. 4. Tensile properties of bamboo sticks

Sample	f_t, MPa	E_t, GPa	Sample	f_t, MPa	E_t, GPa	Sample	f_t, MPa	E_t, GPa
BS1	468.74	7.75	BS1.5	177.62	7.81	BS2	237.48	8.58
BS1	410.67	17.52	BS1.5	334.88	10.54	BS2	336.00	9.32
BS1	448.01	16.54	BS1.5	185.02	11.74	BS2	222.96	11.85
BS1	535.11	21.05	BS1.5	281.23	11.34	BS2	329.78	9.34
BS1	435.57	18.43	BS1.5	310.83	13.81	BS2	471.85	14.44
BS1	443.85	18.63	BS1.5	368.19	12.68	BS2	332.89	10.54
BS1	551.7	19.42	BS1.5	220.17	10.37	BS2	311.11	12.92
BS1	497.78	18.08	BS1.5	173.17	10.29	BS2	281.04	10.83
BS1	389.93	16.11	BS1.5	214.62	11.41	BS2	280.00	13.59
BS1	448	16.55	BS1.5	297.88	11.11	BS2	361.93	8.52
Mean	462.94	17.01	Mean	256.36	11.11	Mean	316.51	10.99

STD	51.59	3.58	STD	70.90	1.59	STD	70.42	2.13
COV	0.11	0.21	COV	0.28	0.14	COV	0.22	0.19
CHV	378.07	11.13	CHV	139.73	8.50	CHV	200.66	7.49

Note: f_t – tensile strength, MPa; E_t – modulus of elasticity in tension, GPa; SDV – standard deviation; COV – coefficient of variation; CHV – characteristic value.

Most of the specimens failed in a brittle manner due to the tearing of bamboo sticks with a specific cracking sound right before the failure. According to Fig. 3, sticks with a 1 mm diameter had the strongest tensile strength and MOE values. As can be seen, the tensile strength and MOE increased with the decrease in bamboo sticks diameter, which was similar to the findings of previous studies [46, 47]. This phenomenon was explained by the fact that with a decrease in stick diameter, the number of defects and flaws in the stick also decreases leading to better tensile properties [48]. This statement is also applicable to synthetic fibres [46, 47].

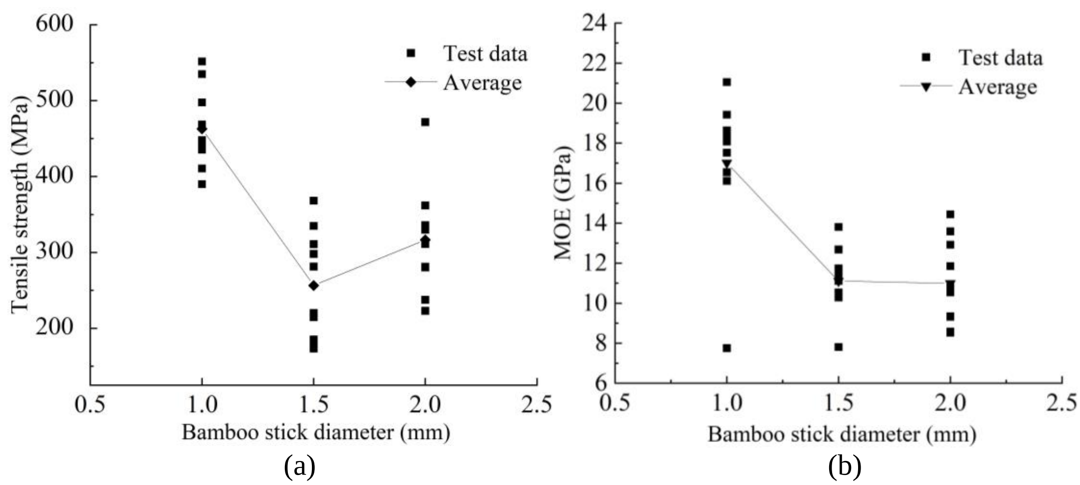


Fig. 3. Tensile strength and MOE of bamboo sticks: (a) tensile strength; (b) MOE

Obviously, the specimen of 2 mm diameter should have the lowest tensile strength. However, the tensile strength of a bamboo stick with a 1.5 mm diameter was the lowest compared to other diameters. This phenomenon can be explained by the presence of factors that could affect the tensile performance of bamboo sticks. It is known, that the mechanical properties of bamboo vary depending on species, moisture content, presence of nodes, and location along and across the culm. The authors assume, that the presence of nodes could lead to lower values for specimens with a 1.5 mm diameter (Fig. 4).

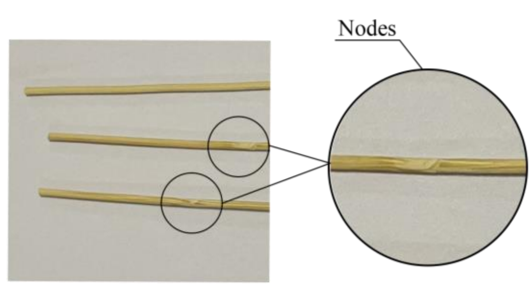
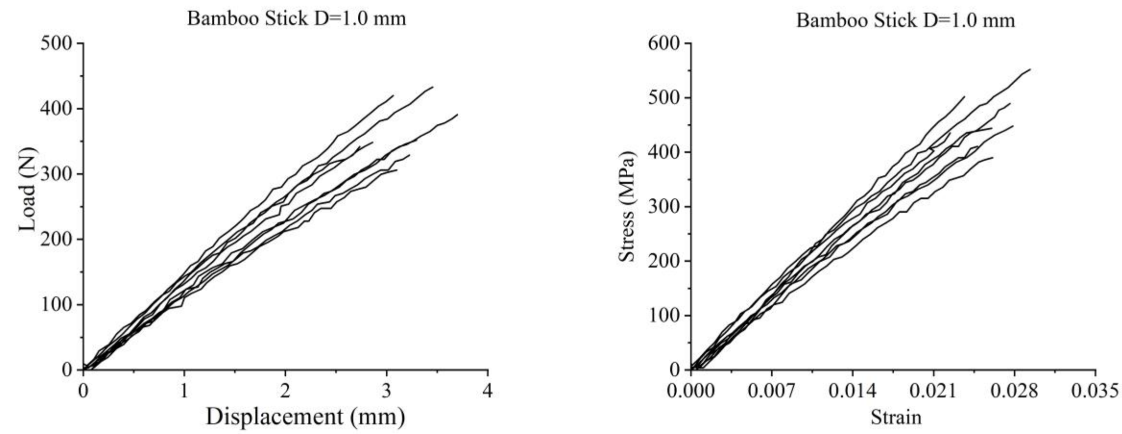
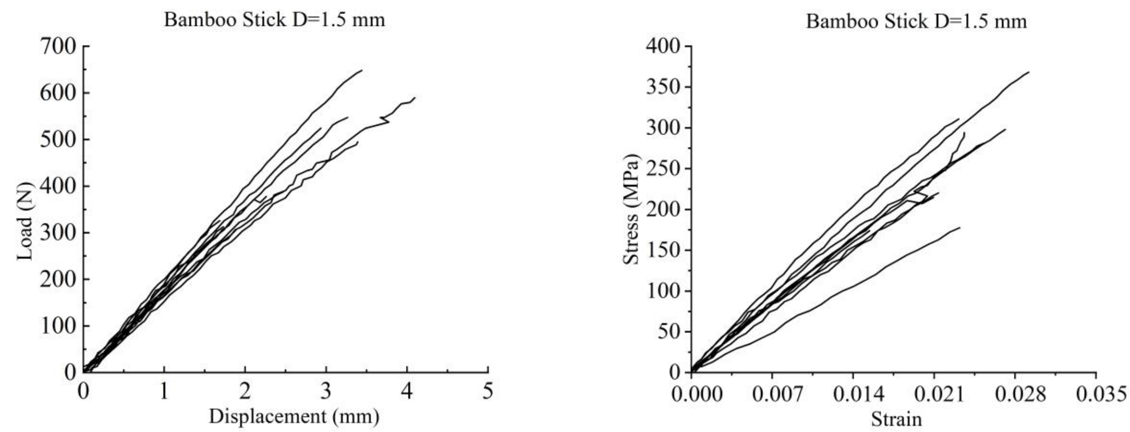


Fig. 4. Presence of nodes in bamboo sticks of 1.5 mm diameter.

Fig. 5 shows linear load-displacement and stress-strain curves of bamboo sticks under tensile load.



(a)



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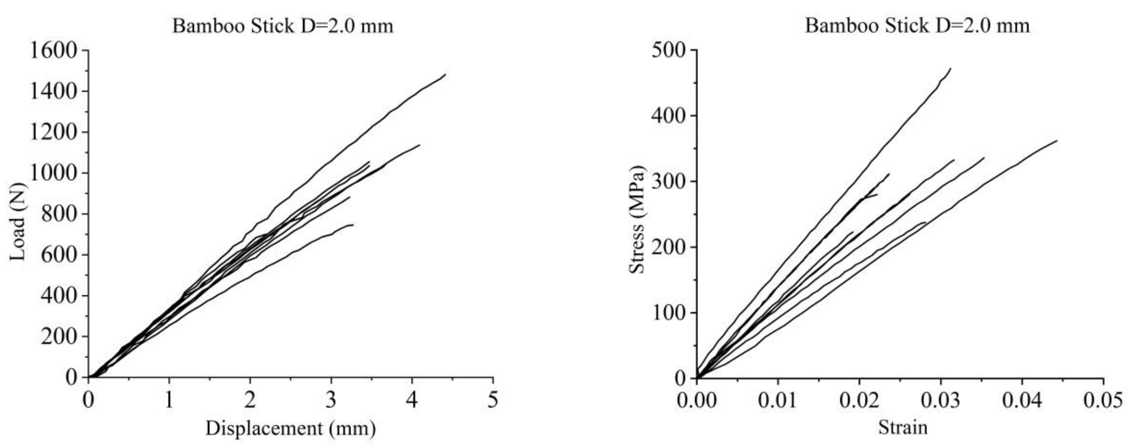


(c)

Fig. 5. Tensile behaviour of bamboo sticks: (a) 1 mm; (b) 1.5 mm; (c) 2 mm.

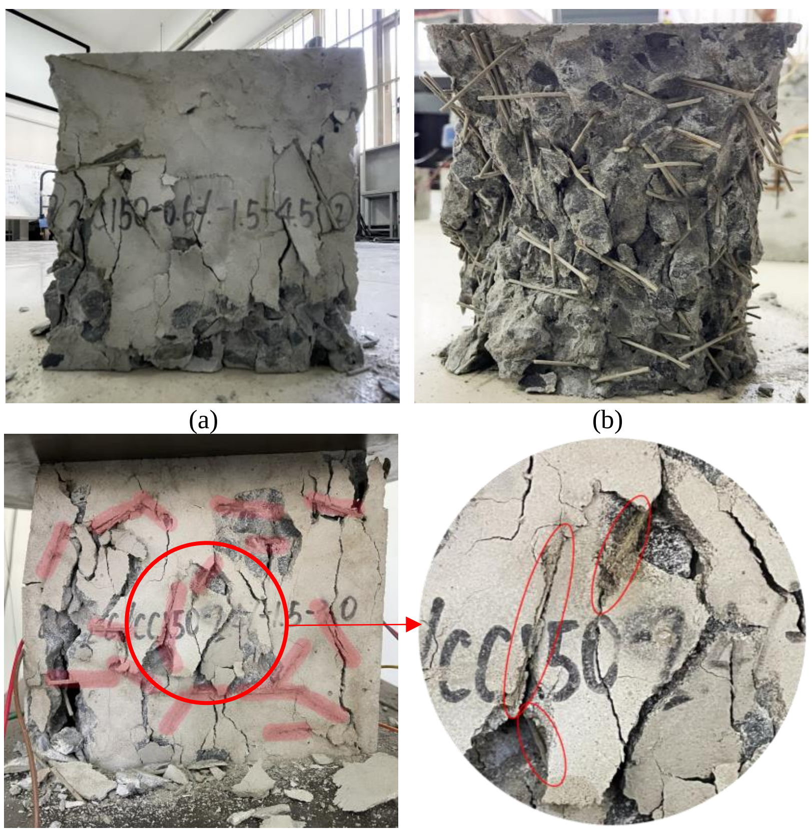
3.2 Compression behaviour of BSRC cubes

The failure pattern of conventional plain concrete was similar to the previous studies [49-52]. First, the vertical cracks appeared on the cube's surface and then grew at an angle of 40-60° to the corners of the specimen, indicating that stresses were concentrating on the surface of the concrete. When the load increased, the surface cracks extended to the inner parts of the specimen, leading to the concrete spalling.

The cracks appeared at 70-80% of the maximum load, leading to final failure when achieving the peak load (Fig. 6).

Fig.6. Failure mode of PC cubes.

All BSRC cubes failed in the same mode regardless of the bamboo sticks ratio and L/D ratio (Fig. 7). When the load achieved 80% of maximum load, the axial cracks appeared on the surface of the specimens, growing from the bottom and the top with increasing load. The major cracks on the surface of BSRC branched into small cracks, leading to the cover spalling. Observation of the specimen's failure patterns showed that the small cracks and corresponding concrete spalling appeared right in the locations of bamboo sticks (Fig. c, d).



(c) (d)

Fig. 7. Failure pattern of BSRC cubes: (a) failure mode of BSRC; (b) loose arrangement of bamboo sticks; (c) location of bamboo sticks (highlighted red); (d) branching on small cracks at the locations of bamboo sticks.

When the peak load was achieved, the specimens failed due to lateral deformation and concrete spalling caused by surface cracks. It is worth noting that BSRC cubes exhibited more branching cracks compared to PC cubes (Fig. 7 a). This may be due to the presence of bamboo sticks, which led to the appearance of voids between cement, aggregates, and sticks. This statement was drawn since some bamboo sticks could be freely removed from the concrete matrix, indicating its loose arrangement (Fig. 7 b).

The compression strength was calculated by the formula (2) according to standard GB/T 50081-2019 [38].

$$f_c = \frac{F_c}{A} \quad (2)$$

Where, f_c – the compression strength, MPa; F_c – the ultimate compression load, N; A – the cross-section area, mm^2. Table 5 shows the compression properties of BSRC and PC cubes.

Tab. 5. Compression properties of PC and BSRC cubes

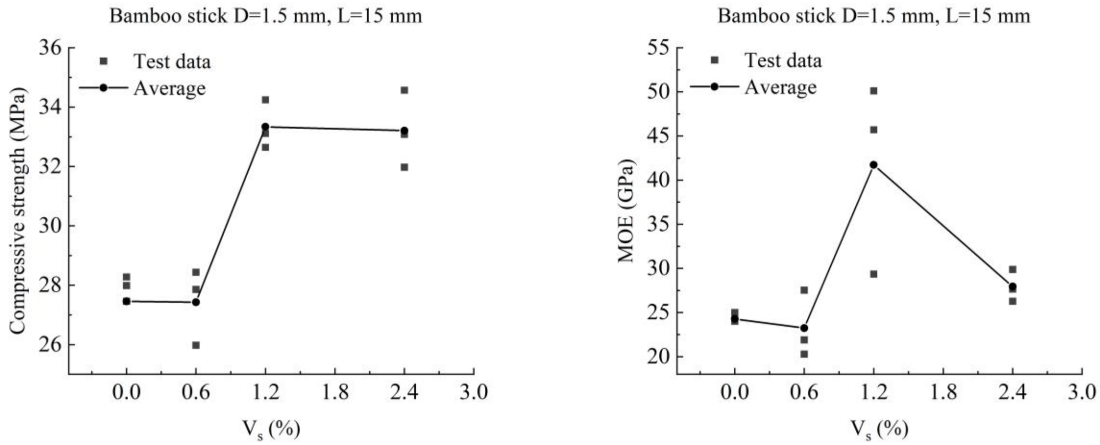
Specimen	Compressive strength				Elastic modulus				Poisson's ratio			
	f_c, MPa	STD	COV	CHV	E_c, GPa	STD	COV	CHV	υ	STD	COV	CHV
C	27.46	4.74	0.01	19.66	24.27	3.72	0.15	18.15	0.26	0.15	0.42	0.11
C0.6-1.5-15	27.42	1.29	0.05	25.31	23.23	3.81	0.16	16.97	0.23	0.05	0.19	0.16
C0.6-1.5-30	28.35	0.11	0.01	28.16	21.31	3.21	0.15	16.03	0.16	0.06	0.39	0.06
C0.6-1.5-45	32.22	1.07	0.03	30.46	24.43	6.46	0.26	13.81	0.34	0.11	0.32	0.16
C1.2-1.0-10	36.52	0.68	0.02	35.41	48.62	0.79	0.02	47.32	0.38	0.09	0.23	0.23
C1.2-1.5-15	33.33	0.82	0.02	31.98	41.72	10.94	0.26	23.73	0.40	0.03	0.07	0.36
C1.2-2.0-20	33.67	0.75	0.02	32.44	49.88	0.68	0.01	48.76	0.41	0.07	0.17	0.30
C1.2-1.0-20	31.56	2.82	0.09	26.93	25.53	3.74	0.15	19.38	0.31	0.05	0.15	0.23
C1.2-1.5-30	29.02	3.59	0.12	23.11	36.19	6.72	0.19	25.13	0.28	0.06	0.20	0.19
C1.2-2.0-40	31.05	1.18	0.04	29.11	29.24	9.67	0.33	13.33	0.36	0.12	0.33	0.16
C1.2-1.0-30	28.59	2.52	0.09	24.45	49.54	0.85	0.02	48.15	0.41	0.02	0.06	0.37
C1.2-1.5-45	30.22	1.90	0.06	27.08	44.58	6.16	0.14	34.45	0.28	0.01	0.01	0.28
C1.2-2.0-60	32.72	3.06	0.09	27.69	49.77	0.70	0.01	48.63	0.32	0.12	0.37	0.13
C2.4-1.5-15	33.21	1.30	0.04	31.07	27.93	1.82	0.07	24.94	0.32	0.17	0.55	0.03
C2.4-1.5-30	26.49	0.54	0.02	25.61	26.61	9.30	0.35	11.32	0.31	0.14	0.46	0.08
C2.4-1.5-45	29.63	2.39	0.08	25.69	25.83	8.67	0.34	11.58	0.35	0.15	0.43	0.10

Note: f_c – compression strength, MPa; E_c – compression modulus of elasticity, GPa; υ – Poisson's ratio.

As can be seen, compression strength and MOE of the control PC cubes constituted 27.46 MPa and 24.27 GPa, respectively. The compression strength and MOE for BSRC cubes with V_s of 0.6% constituted 27.42 MPa and 23.23 GPa, 28.35 MPa and 21.31 GPa, 32.22 MPa and 24.43 GPa for L/D ratios 10, 20, 30, respectively. BSRC cubes with V_s of 1.2% showed slightly increased strength and elastic modulus values for decreased bamboo stick diameter and lengths, while the properties of BSRC with V_s of 2.4% decreased. It should be noted that specimens with bamboo sticks ratio of 1.2% and increased bamboo stick diameters and lengths showed lower compressive strength values compared to cubes with decreased bamboo stick diameters.

3.2.1 Bamboo stick volume ratio effect on the compressive behaviour of BSRC cubes

In this part, the effect of V_s on the compressive behaviour of BSRC cubes was analyzed. For the analysis, specimens with 0.6%, 1.2%, and 2.4% of bamboo sticks with a diameter of 1.5 mm and lengths of 15 mm, 30 mm, and 45 mm were compared. Fig. 8 shows the changing trend in the compressive strength and MOE of BSRC cubes compared to PC cubes.



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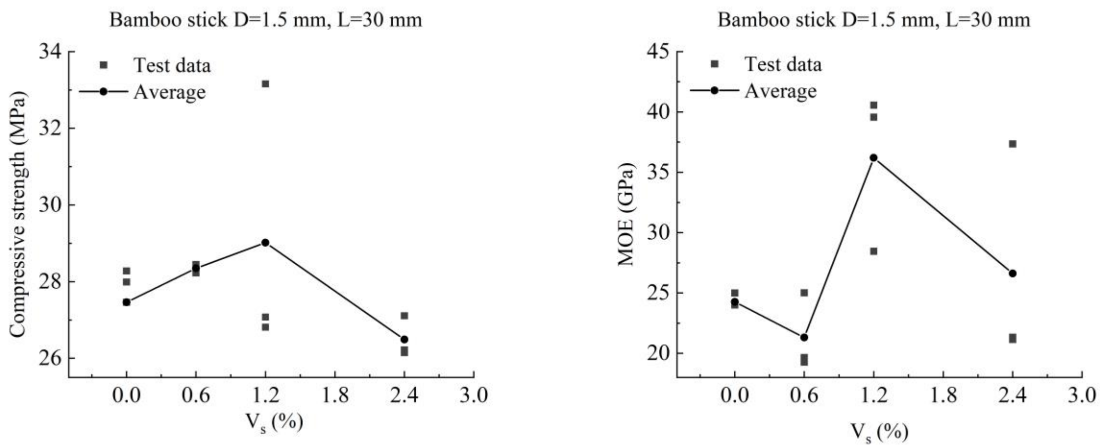

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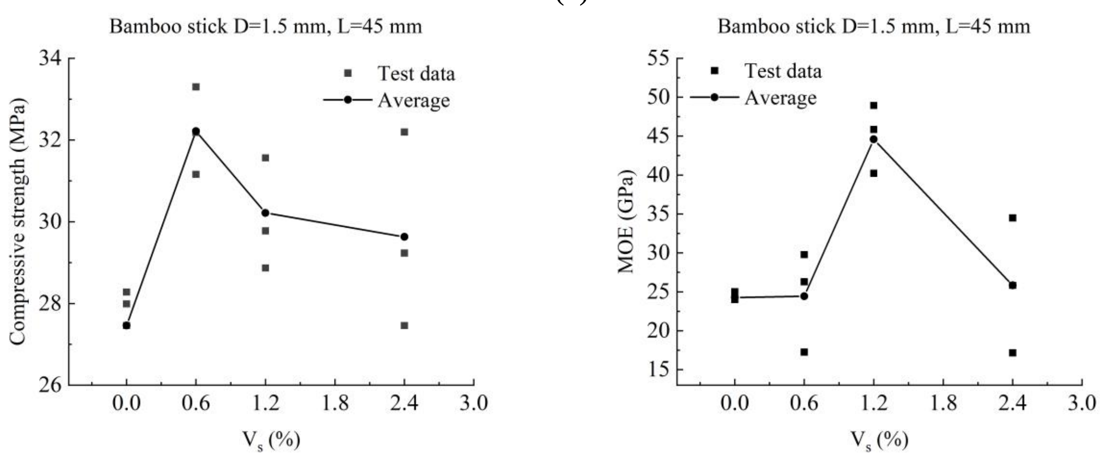


(c)

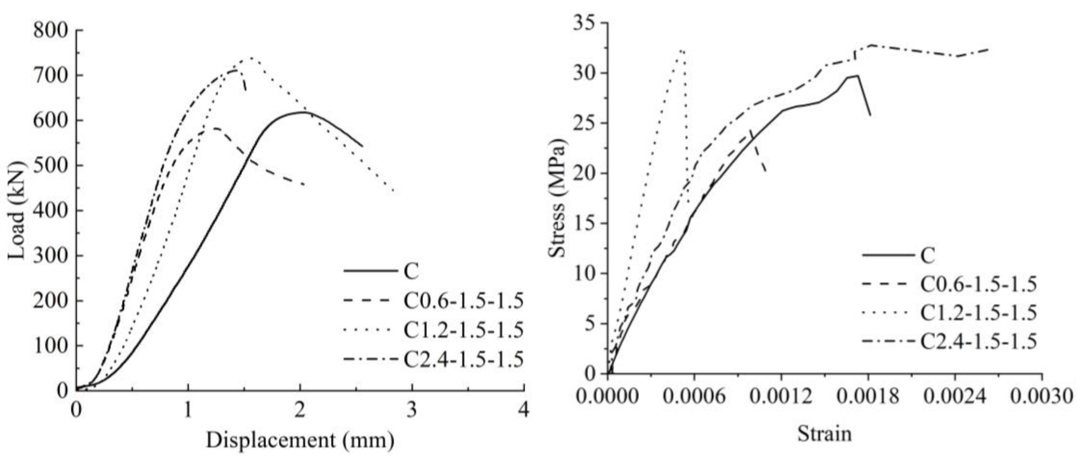
Fig. 8. Compressive strength and MOE of PC and BSRC: (a) L/D 10; (b) L/D 20; (c) L/D 30.

As can be seen from Fig. 8 a, adding 0.6% of sticks did not change the compressive strength and decreased the MOE of BSRC. With the addition of 1.2% of sticks, the strength and MOE values of the specimens respectively increased by 21.38% and 71.9% compared to plain specimens.. The addition of 0.6% of sticks with an L/D ratio of 10 had a negligible effect on the compressive properties, while 1.2% of sticks with an L/D ratio of 10 led to a significant improvement. At the same time, the addition of 2.4% caused lower improvements compared to that of BSRC with 1.2% of sticks. The improvement constituted 20.94% and 15.08% for strength and elastic modulus, respectively. This can be explained by the fact that the higher volume ratio of sticks led to bond strength deterioration between cement, aggregates, and bamboo sticks, which caused lower strength and MOE values.

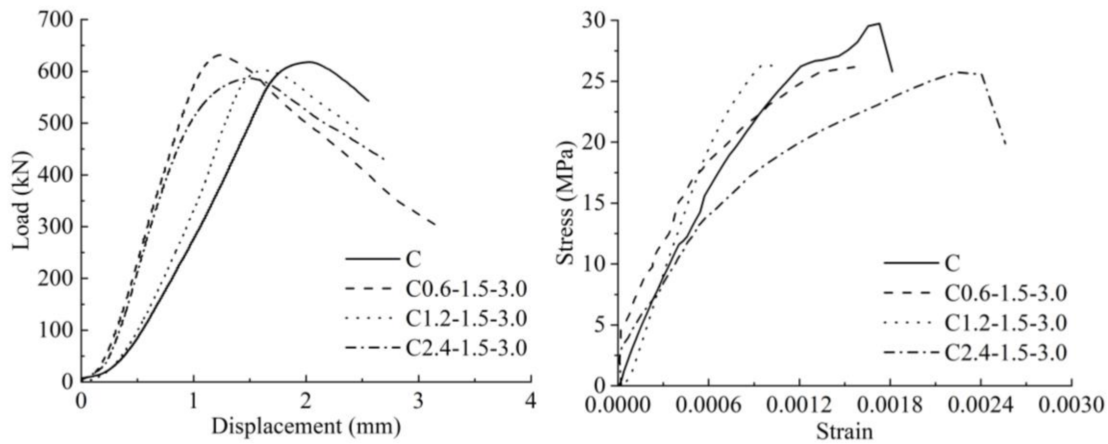
Fig. 8 b shows the compressive strength and MOE values of BSRC specimens with bamboo sticks of L/D=20. Similarly, the effect of 0.6% of sticks on strength and MOE values was negligible. Strength improvement for the specimens constituted 3.24%, while MOE decreased by 12.2% compared to PC specimens. The addition of 1.2% of sticks with an L/D ratio of 20 improved strength and MOE by 5.68% and 49.11% compared to plain specimens. It can be seen, that the increased length of sticks led to a decrease in the compressive properties of BSRC with 1.2% of sticks. Most likely, the increase in length led to an increase in the volume of the sticks, which also negatively affected the adhesion strength between the cement and aggregates, followed by a decrease in the compression strength. Further increase in V_s to 2.4% and bamboo sticks length to 30 mm caused compressive strength to decrease by 3.53% and MOE to increase by 11% compared to PC specimens. The deterioration in strength was caused by the decrease in bond strength between cement and aggregates. At the same time, increased stiffness might be caused by the increased energy absorption capacity of bamboo sticks with increased length [53, 54].

Fig. 8 c shows that increase in bamboo stick length to 45 mm led to an increase in the compressive strength of BSRC with 0.6%, 1.2% and 2.4% of sticks by 17.33%, 10.05%, and 7.9%, respectively. Increasing bamboo stick length positively affected the compressive strength of BSRC with a lower stick volume ratio (0.6%), however, it was still inferior to the strength improvement achieved by the addition of 1.2% of sticks with an L/D ratio of 10. At the same time, an increase in the length of bamboo sticks didn't affect MOE values of BSRC with 0.6% and 2.4% of sticks much, while MOE of cubes with 1.2% of sticks with L/D=30 improved by 83.68% compared to PC cubes.

Similar findings were drawn by Kumarasamy et al. [30]. Their study showed that the compressive strength of BFRC specimens increased with the addition of fibres at 0.5%, 1%, 1.5%, and 2%, but it decreased at 2.5% of fibres. Kumarasamy et al. [30] reported that the compressive strength of PC and BFRC cubes with 1.5% of bamboo fibres constituted 36.23 MPa and 36.87 MPa, respectively. However, Terai et al. [31] reported that the compressive strength of BSRC members significantly decreased with an increased volume fraction of sticks, since the bond stress between the cement matrix and aggregates was reduced because of the adding sticks. Fig. 9 shows the load-displacement and stress-strain relationships of BSRC compared to PC cubes. The effect of the bamboo stick volume ratio was investigated.



(a)



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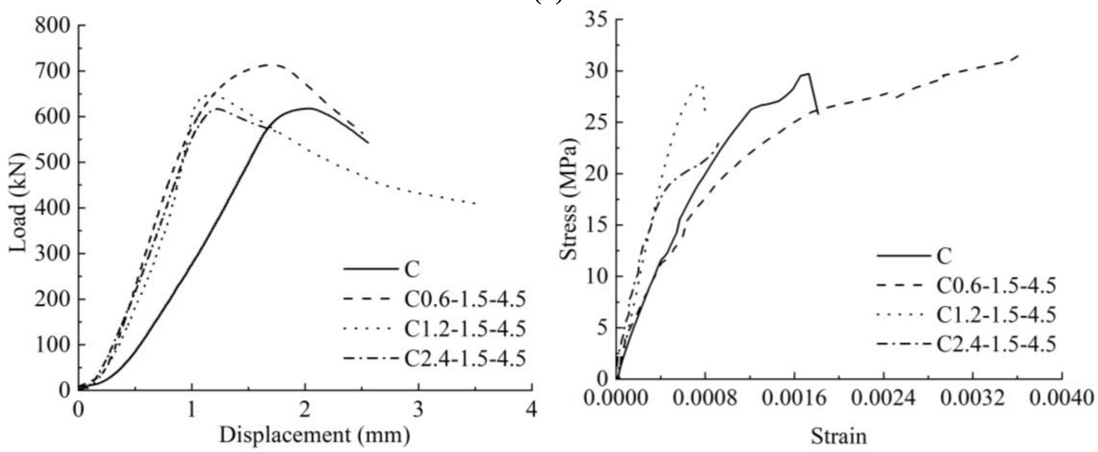


(c)

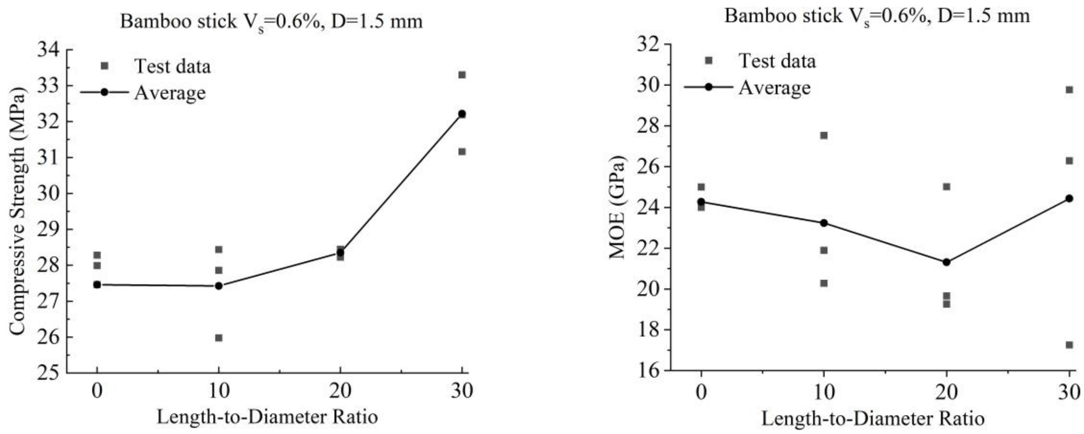
Fig. 9. Load-displacement and stress-strain curves of PC and BSRC cubes: (a) L/D ratio 10; (b) L/D ratio 20; (c) L/D ratio 30.

The diameter of bamboo sticks in BSRC cubes constituted 1.5 mm. Compared to plain concrete cubes, the ultimate loads and fewer deformations were observed for BSRC with 1.2% and 2.4% of sticks with an L/D ratio of 10 for the same amount of load, while 0.6% of sticks did not significantly affect the compressive behaviour of the composite (Fig. 9 a). The stress-strain curve of the specimens with 1.2% of sticks was almost linear, while cubes with 2.4% of sticks showed linear and non-linear behaviour before failure. As can be seen from Fig. 9 b, an increase in the bamboo stick L/D ratio to 20 decreased the fracture load values and stiffness of the specimens regardless of the bamboo stick ratio. Stress-strain curves for BSRC with V_s of 0.6% and 1.2% were almost linear. Similar to the specimens with an L/D ratio of 10, BSRC with V_s of 2.4% and an L/D ratio of 20 showed linear and non-linear behaviour before failure.

According to Fig. 9 c, the specimens with 1.2% and 2.4% of sticks showed fewer strains than PC and BSRC specimens with 0.6% of sticks for the same load. At the same time, its behaviour was almost linear and brittle with a sharp descending stage after failure. The specimens with 0.6% of sticks and an L/D ratio of 30 showed the highest fracture load and smooth stress-strain curve with pronounced linear and non-linear stages before failure. The specimens with 2.4% of sticks also showed improved stiffness compared to PC cubes but low fracture load. This can be explained by the increased energy absorption of sticks caused by the increased length of sticks. At the same time, the excessive amount of sticks and increased length led to the deterioration of bond strength between concrete aggregates leading to weak strength.

3.2.2 Bamboo stick length effect on the compressive behaviour of BSRC cubes

In this part, the effect of the bamboo stick length on the compressive behaviour of BSRC cubes was analyzed. For the analysis, specimens with 0.6%, 1.2%, and 2.4% of bamboo sticks with a diameter of 1.5 mm and lengths of 15 mm, 30 mm, and 45 mm were compared. Fig. 10 shows the changing trend in compression strength and MOE of BSRC cubes compared to PC cubes.



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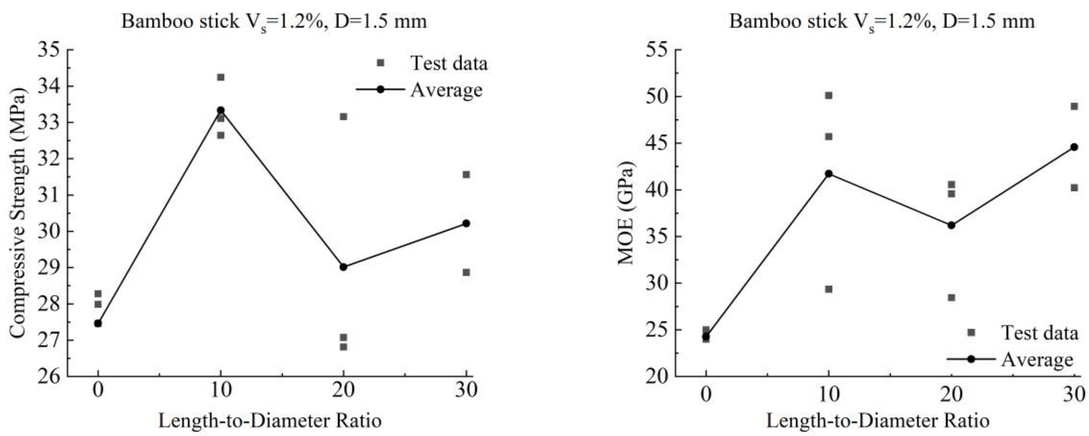

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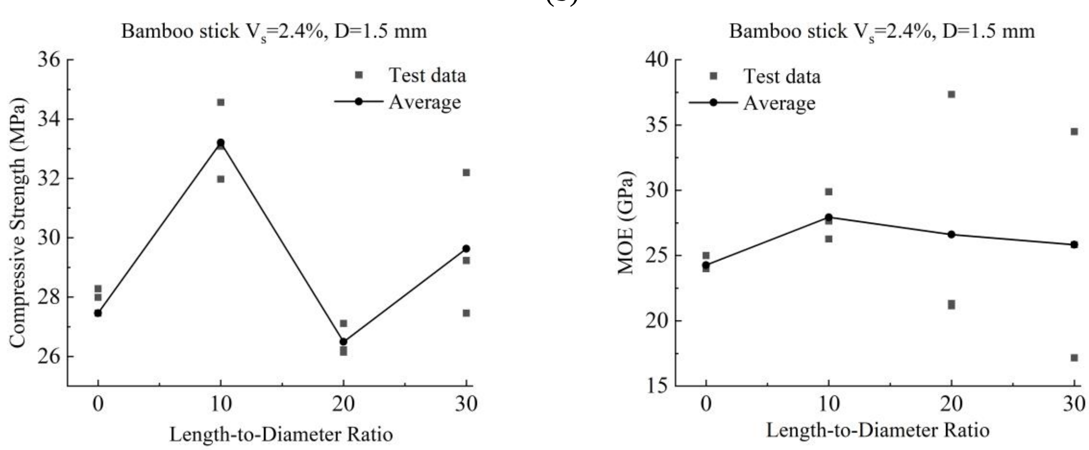


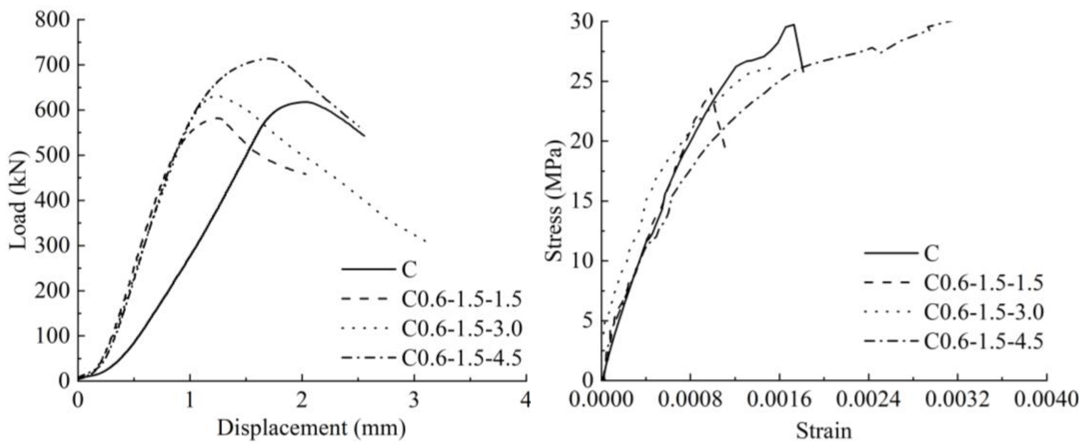
(c)

Fig. 10. Load-displacement and stress-strain curves of PC and BSRC cubes: (a) 0.6%; (b) 1.2%; (c) 2.4%.

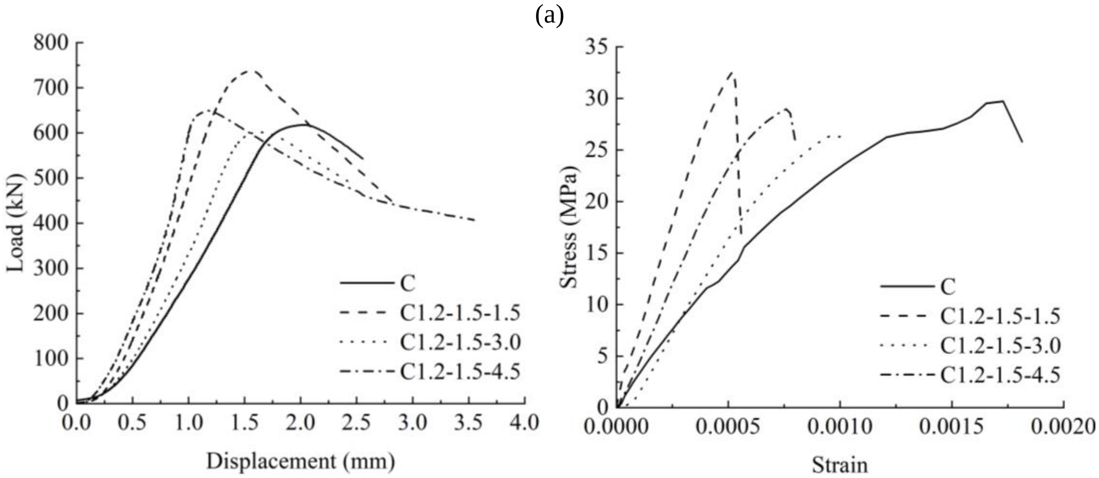
As can be seen from Fig. 10 a, an increase in bamboo stick length led to an increase in the compressive strength of BSRC with V_s of 0.6%. Specimens with V_s of 1.2% and 2.4% showed a similar changing trend: the compressive strength values increased only for sticks with a length of 10 mm. When the L/D ratio of sticks increased to 20, the strength values significantly decreased and increased slightly for sticks with an L/D ratio of 30. The stiffness of the composites with V_s of 0.6% decreased by adding sticks with L/D ratios of 10 and 20 and increased for sticks with L/D=30. MOE values of specimens with V_s of 1.2% were highest for sticks with L/D ratios of 10 and 30. The stiffness of cubes with 2.4% of sticks increased only at L/D=10.

Fig. 11 shows the average load-displacement and stress-strain curves of PC and BSRC specimens, considering the same stick volume ratios and different L/D ratios. The diameter of bamboo sticks in BSRC cubes constituted 1.5 mm, while the length of sticks differed by 15 mm, 30 mm, and 45 mm. As can be seen from Fig. 11 a, an increase in the length of bamboo sticks improved the fracture load of the specimens with 0.6% of sticks, while an ultimate load of BSRC with L/D ratios of 10 and 20 did not differ much from the control specimens. The stress-strain curves of the specimens with 0.6% of sticks and L/D ratios 10–20 were almost linear, showing a negligible improvement in strain development. The specimens with an L/D ratio of 30 led specimens to enter a non-linear stage before failure and develop more deformations for the same amount of load.

Better compression performance was observed in the specimens with 1.2% of bamboo sticks. As shown in Fig. 11 b, BSRC with sticks of L/D=10 showed the highest fracture load. The stress-strain curves shows that specimens with 1.2% of sticks improved strain development regardless of the L/D ratio. Specimens with sticks of L/D ratios 20 and 30 showed lower fracture loads and were less stiff than that of L/D ratio 10.



(a)



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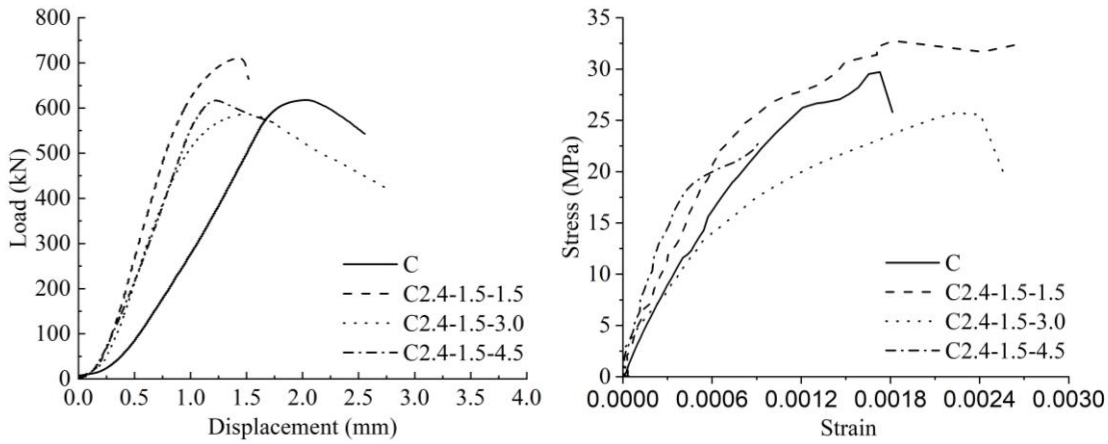


(c)

Fig. 11. Load-displacement and stress-strain curves of PC and BSRC cubes: (a) V_s 0.6%; (b) V_s 1.2%; (c) V_s 2.4%.

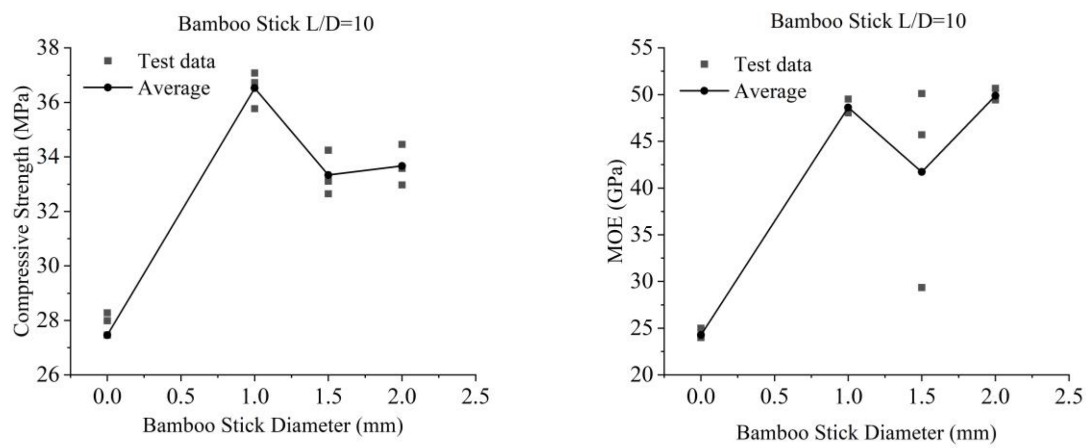
At the same time, the stress-strain curve of BSRC with 1.2% of sticks and an L/D ratio of 10 was almost linear, while curves of L/D=20–30 were linear with a short non-linear stage before failure, indicating that there is a proportional relationship between the length of the sticks, energy absorption, and stiffness.

As shown in Fig. 11 c, the fracture loads of BSRC cubes with 2.4% of sticks with an L/D ratio of 10 were also improved. Specimens with sticks of L/D ratios of 10 and 30 showed fewer deformations for the same amount of load, while the group with an L/D ratio of 20 developed more strains compared to PC cubes. All the specimens showed obvious linear and non-linear stages before failure.

Based on the observations, the L/D ratios of sticks affect the compressive performance of BSRC. The results were in line with previous studies, stating that the length of fibres significantly impacted composites mechanical properties [54-56]. It was found that in the specimens with V_s of 0.6%, the increase in length of sticks to 45 mm increases the fracture load and stiffness of the composite. However, the lower lengths of bamboo sticks did not significantly improve the composite compared to PC specimens. In specimens with 2.4% of sticks, an increase in the length of sticks led to a decrease in fracture load and stiffness, while the lower length of sticks could sustain higher load increments with fewer deformations. However, the excessive amount of bamboo sticks (2.4%) caused lower bond strength between concrete aggregates, and the corresponding fracture load and MOE also decreased. The best performance was observed for BSRC, with 1.2% of sticks and an L/D ratio of 10. These changes are most likely caused by a change in the volume of the fibrous material, which change the behaviour of the composite. According to observation, the volume of the sticks had the same effect on the mechanical properties of the material as the stick volume ratio. The mechanical properties of the composites increase with a certain volume ratio of sticks, when it is exceeded or reduced, the strength and rigidity of the material deteriorate. The same pattern was observed with an increase in the length of the sticks.

3.2.3 Bamboo stick diameter effect on the compressive behaviour of BSRC cubes

To evaluate the effect of the diameter of bamboo sticks on the compressive performance of BSRC, specimens with V_s of 1.2% and bamboo sticks diameters of 1 mm, 1.5 mm, and 2 mm were analyzed. Fig. 12 shows the changing trends in the compressive strength and MOE of BSRC compared to PC.



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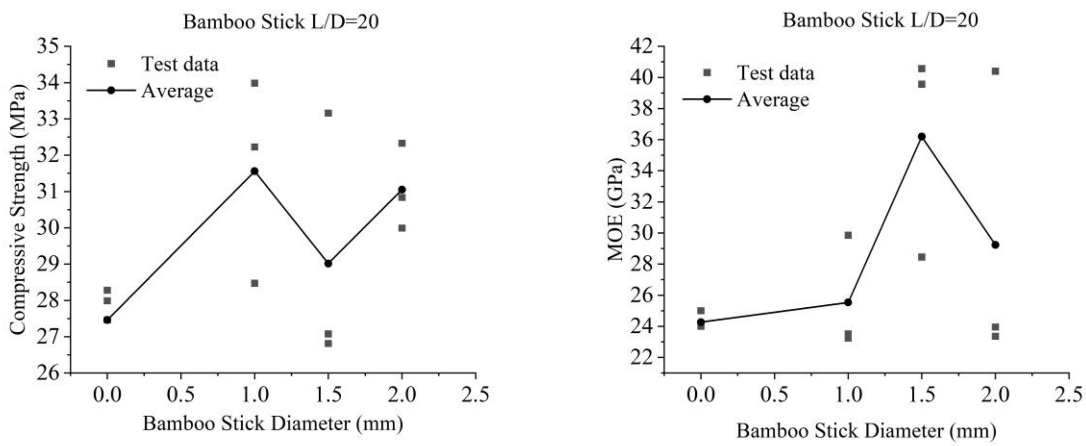

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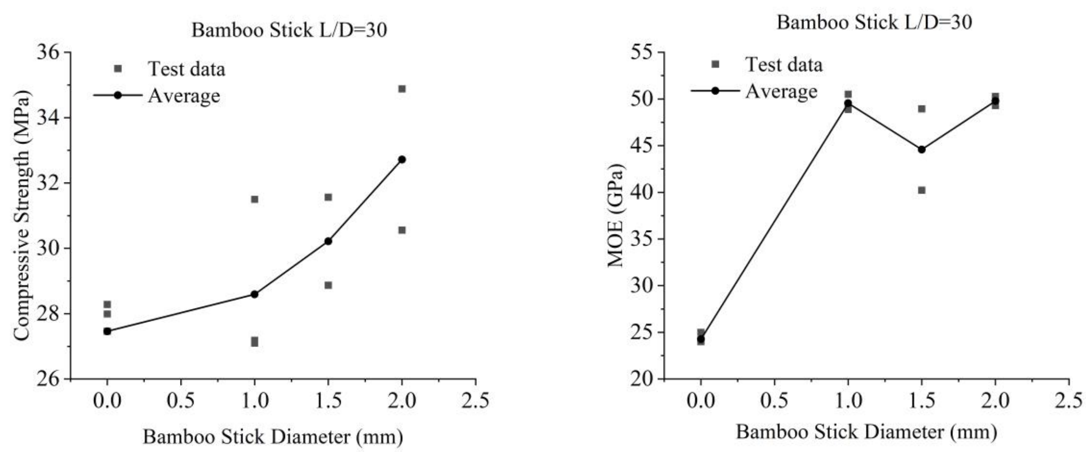


(c)

Fig. 12. Compressive strength and MOE of BSRC compared to PC cubes: (a) D=1 mm; (b) D=1.5 mm; (c) D=2 mm.

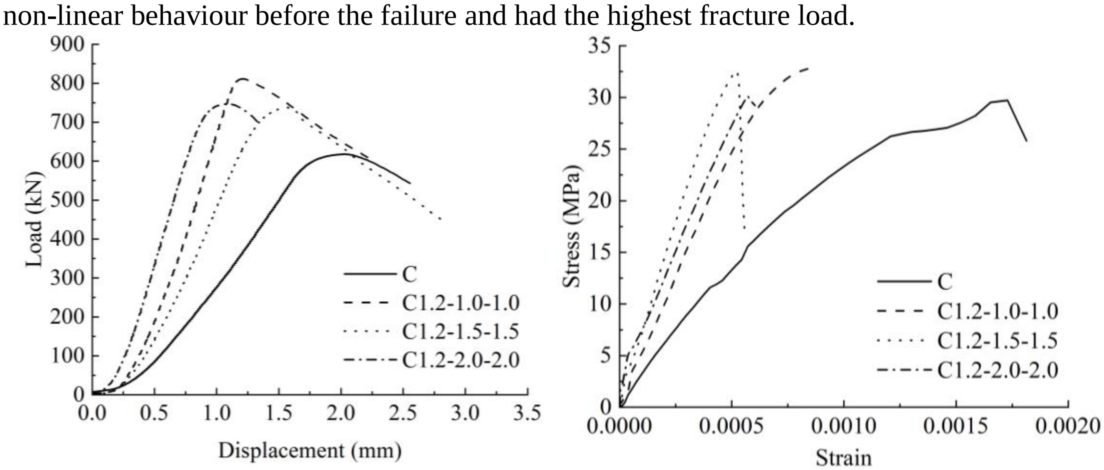
As shown in Fig. 12 a, the compressive strength and MOE of BSRC with 1 mm diameter bamboo sticks increased by 32.99% and 100.33% compared to PC cubes. The compressive properties of the specimens decreased when the diameter of bamboo sticks increased to 1.5 mm. The strength and elastic modulus improvement constituted 21.38% and 71.9% compared to plain specimens. When the diameter of sticks increased to 2 mm, the compressive strength and MOE improved by 22.61% and 105.52% compared to PC cubes. It should be noted that with an increase in the diameter, the length of sticks also increased and constituted 15 mm and 20 mm for 1.5 mm and 2 mm diameter sticks, respectively. Based on this, it can be concluded that the mechanical properties of BSRC decreased when the diameter and length of the bamboo stick constituted 1.5 mm and 15 mm, which decreased the bonding strength between the aggregates. At the same time, the 20 mm length of a bamboo stick with a 2 mm diameter improved the compressive strength and stiffness of the composite since an increased length improved the energy absorption of the sticks.

According to Fig. 12 b, similar changes in the compressive strength occurred in specimens with L/D=20. At the same time, the stiffness of BSRC with bamboo sticks of 1 mm diameter and 20 mm length and cubes with sticks of 2 mm diameter and 40 mm length, improved by 5.19% and 20.48% compared to PC cubes. The specimens with bamboo sticks of 1.5 mm diameter and 30 mm length increased stiffness by 49.11% compared to plain concrete cubes. At the same time, the compressive strength of cubes with 1.5 mm diameter sticks significantly decreased compared to that of cubes with 1 mm and 2 mm diameter sticks.

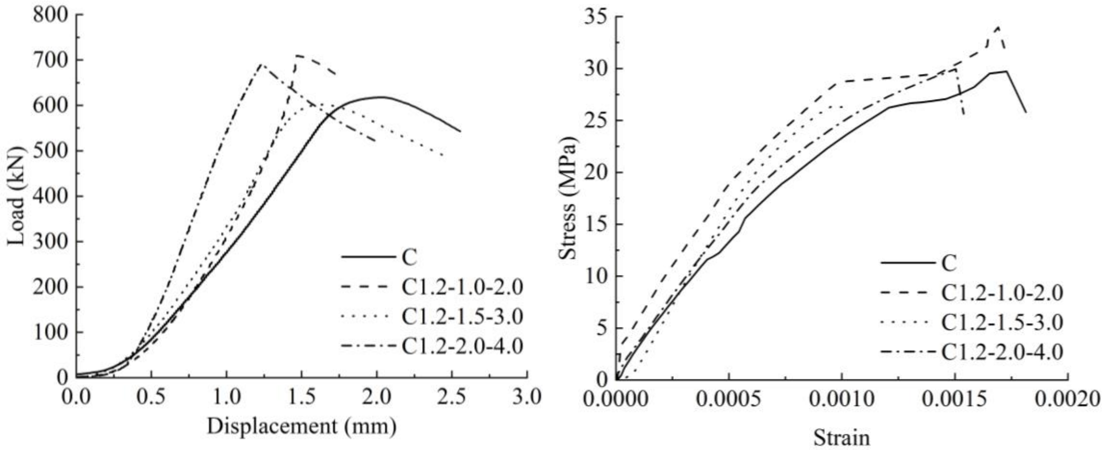
Fig. 12 c shows the increasing trend of the compressive strength in cubes with bamboo sticks of L/D=30. Compared to plain cubes, the strength values increased by 4.12%, 10.05%, and 19.16% for the specimens with 1 mm, 1.5 mm, and 2 mm diameter bamboo sticks. MOE values increased significantly by 104.12%, 85.07%, and 105.07%, showing the highest values compared to PC and BSRC cubes with L/D of 10 and 20.

Based on the results, the best compressive performance was observed for BSRC with a 1.2% of bamboo stick volume ratio and L/D ratio of 10 and 30. The best compressive strength and MOE values were achieved by adding bamboo sticks of 1 mm diameter and 10 mm length, 1.5 mm diameter and 15 mm length, 2 mm diameter and 20 mm length, and 2 mm diameter and 60 mm length. For mentioned specimens, the compressive strength and elastic modulus values increased by 32.99% and 100.33%, 21.38% and 71.9%, 22.61% and 105.52%, and 19.16% and 105.07%, respectively. Based on the analysis, it can be concluded that the diameter and length of bamboo sticks affected the mechanical performance of the BSRC composite. Thin and long bamboo sticks significantly improve the strength and stiffness of the composite, and the improvement can respectively achieve up to 19.16–32.99% and 71.9–105.52% compared to that of plain concrete. Thick and short sticks improve the strength and elastic modulus by 4.12–14.93% and 5.19–83.68%, respectively.

Fig. 13 shows the average load-displacement and stress-strain curves of BSRC cubes with 1.2% of sticks with diameters of 1 mm, 1.5 mm, and 2 mm. As can be seen from Fig. 13 a, all the BSRC cubes had increased fracture loads and fewer strains for the same load as PC specimens. At the same time, the specimens with stick diameters of 1.5–2 mm were almost linear. BSRC, with a 1 mm stick diameter, showed short non-linear behaviour before the failure and had the highest fracture load.



(a)



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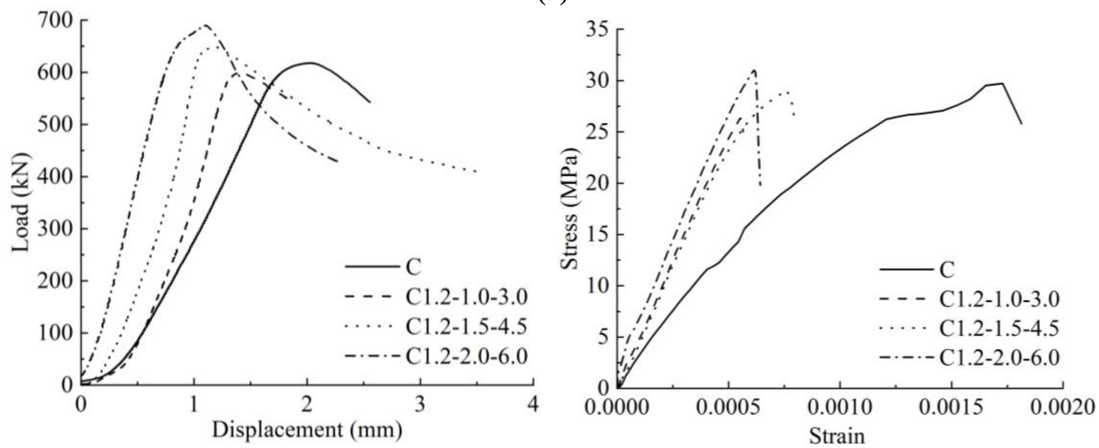

(c)

Fig. 13. Load-displacement and stress-strain curves of PC and BSRC cubes with 1.2% of sticks with different diameters: (a) L/D=10; (b) L/D=20; (c) L/D=30.

According to Fig. 13 b, BSRC cubes with sticks of 1 mm diameter and an L/D ratio of 20 also showed a high stiffness and fracture load compared to PC cubes and BSRC with sticks of 1.5–2 mm diameter. In addition, cubes with 1 mm diameter sticks showed stress-strain curves with pronounced linear and non-linear stages.

Similarly, an increase in the L/D ratio to 30 led to improved strain development for BSRC cubes regardless of bamboo stick diameters. However, the stress-strain curves of the specimens behaved almost linearly with brittle failure. At the same time, fracture loads of BSRC with 1 mm diameter sticks were lower compared to that of cubes with 1.5–2 mm diameter sticks.

3.3 Fitting equation

3.3.1 Compressive strength of BSRC cubes

Due to the novelty of the current research, there are still no attempts to develop calculation models for describing the compression behaviour of BSRC cubes. In previous studies, multiple attempts were made to predict the compressive strength of steel fibre reinforced concrete composites. The researchers adopted several approaches, including linear and nonlinear regression methods [57-63], Artificial Neural Network [64], Central Composite Design and Box Behnken Design [65]. In this research, the IBM SPSS Statistics 20 tool was used to develop a fitting equation for the compression strength of BSRC specimens using the linear regression model. First, a correlation analysis using Pearson's correlation method was carried out to evaluate the dependence level between compression strength values and the following parameters as MOE, bamboo stick volume ratio, and bamboo stick length-to-diameter ratio. Table 6 shows the correlation analysis results.

Tab. 6. Correlation analysis considering MOE, bamboo stick volume fraction, and length-to-diameter ratio.

Parameters		MOE	V_s ratio	L/D ratio
f_c	Pearson Correlation	0.227	0.023	– 0.095
	Sig. (2-tailed)	0.286	0.909	0.636
	N	24	27	27

A Pearson's correlation coefficient should lay between -1 and 1, which indicates the tested parameters are linearly related, whereas 0 indicates no correlation. The closer the value to 1 or -1, the higher the correlation. According to the results, only MOE had quite a significant correlation with the compressive strength of BSRC. The L/D ratio and V_s ratio showed a very low correlation to strength values. It can be caused by non-homogeneous MOE and strength values of BSRC cubes for each group of L/D ratio and V_s ratio. Poor adhesion of bamboo to the concrete matrix, dimensional instability of bamboo sticks, the appearance of voids, and weakening of bond strength between cement and aggregates caused a hard-to-predict and hard-to-control mechanical behaviour of BSRC. In this regard, it was decided to consider only 2 parameters as influencing factors of compression strength for 1 certain group of specimens. Since bamboo sticks V_s had a major effect on strength values, it was decided to adopt it along with the MOE ratio of BSRC to PC ($MOE_{BSRC/PC}$) for a new correlation analysis for each L/D ratio of BSRC. The values of $MOE_{BSRC/PC}$ ratio were considered in order to take into account changes in MOE values of BSRC based on MOE values of PC caused by the addition of bamboo sticks.

Tab. 7. Correlation analysis considering V_s ratio and $MOE_{BSRC/PC}$

Parameters		$MOE_{BSRC/PC}$	V_s
f_{c10}	Pearson Correlation	0.607	0.704
	Sig. (2-tailed)	0.148	0.34
	N	7	9
f_{c20}	Pearson Correlation	0.591	– 0.502
	Sig. (2-tailed)	0.163	0.252
	N	7	7
f_{c30}	Pearson Correlation	– 0.319	– 0.834
	Sig. (2-tailed)	0.020	0.486
	N	7	7

Note: f_{c10}, f_{c20}, f_{c30} – compression strength of BSRC with sticks L/D ratio of 10, 20, and 30, respectively.

A new correlation analysis, including V_s ratio and $MOE_{BSRC/PC}$ ratio of each L/D group, was carried out (Table 7). As can be seen, the correlation between the compression strength, $MOE_{BSRC/PC}$ and V_s ratio constituted 0.607 and 0.704, 0.591 and -0.502, -0.319 and -0.834, for BSRC with stick L/D ratio of 10, 20, and 30, respectively. Based on linear regression, the fitting equations for the compression strength were developed, provided that V_s ratio and MOE of concrete are known. The fitting equation for the compression strength of BSRC cubes with bamboo sticks L/D ratio of 10 is as follows:

$$f_{c10} = 20.382 + \left(1.566 \frac{V_s}{V_o} + 0.000256 E_{c0} \right) \tag{3}$$

where, f_{c10} – the compression strength of BSRC with bamboo stick L/D ratio of 10, MPa; E_{c0} – is the modulus of elasticity of PC with concrete grade 30, MPa; V_s – bamboo sticks volume ratio, %; V_0 = 0.6%, representing the basic bamboo sticks volume ratio. R^2 of the fitting equation is 0.89 or 89%.

The compression strength of BSRC with bamboo stick L/D ratio of 20 is as follows:

$$f_{c20} = 20.816 - (1.362\frac{V_s}{V_o} + 0.000464E_{c0}) \quad (4)$$

where, f_{c20} – the compression strength of BSRC with bamboo stick L/D ratio of 20, MPa. R^2 of the fitting equation is 0.98 or 98%.

The compression strength of BSRC with bamboo stick L/D ratio of 30 is as follows:

$$f_{c30} = 35.194 - \left(1.262\frac{V_s}{V_0} - 0.0001E_{c0}\right) \quad (5)$$

where, f_{c30} – the compression strength of BSRC with bamboo stick L/D ratio of 30, MPa. R^2 of the fitting equation is 0.86 or 86%. Table 8 shows the comparison of experimental and calculated compression strength values.

Tab. 8. Experimental and calculated values of the compression strength of BSRC cubes

Specimen	f_c experimental, MPa	f_c calculated, MPa	Error, %
C0.6-1.5-15	28.44	28.16	0.97
C0.6-1.5-15	25.98	28.16	8.41
C0.6-1.5-15	27.86	28.16	1.09
C1.2-1-10	36.52	31.65	13.35
C1.2-1.5-15	32.64	31.65	3.03
C1.2-2.0-20	33.67	31.65	6.00
C2.4-1.5-15	33.08	32.86	0.68
C2.4-1.5-15	31.98	32.86	2.76
C2.4-1.5-15	34.57	32.86	4.94
C0.6-1.5-30	28.38	30.72	8.24
C0.6-1.5-30	28.45	30.72	7.98
C0.6-1.5-30	28.23	30.72	8.82
C1.2-1-20	31.56	29.35	7.00
C1.2-1.5-30	27.07	29.35	8.42
C1.2-2.0-40	31.05	29.35	5.48
C2.4-1.5-30	26.15	26.63	1.85
C2.4-1.5-30	26.22	26.63	1.57
C2.4-1.5-30	27.11	26.63	1.77
C0.6-1.5-45	33.30	31.51	5.39
C0.6-1.5-45	32.19	31.51	2.12
C0.6-1.5-45	31.16	31.51	1.10
C1.2-1-30	28.59	30.24	5.76
C1.2-1.5-45	31.56	30.24	4.18
C1.2-2.0-60	32.72	30.24	7.57
C2.4-1.5-45	29.23	27.72	5.18
C2.4-1.5-45	27.46	27.72	0.94
Mean	30.20	29.95	4.79

The error was calculated by equation (6):

$$Error = \frac{A-B}{B} \times 100\% \tag{6}$$

where, A – the calculated value, B – the experimental value. The average error constituted 4.79%, which indicates the equation's goodness-of-fit.

3.3.2 Stress-strain model of BSRC cubes

Currently, there are no models for determining the stress-strain relationship for the BSRC composite. Due to the different behaviour, which depends on the ratio of sticks in the composite, stick L/D ratio and diameter, it is difficult to offer a single model for the BSRC. However, it is possible to derive a number of common characteristics that determine the stress-strain behaviour of the BSRC. Based on experimental data, not a single group of composites showed an obvious yield point. Some of the specimens showed obvious nonlinear behaviour, while some of the curves were almost linear. In addition, the majority of curves had a short elastic-plastic transition and a short plastic stage before the destruction. There are several models that define the stress-strain behaviour of the materials. The Ramberg-Osgood model is used for those materials with nonlinear behaviour that have elastic, smooth elastic-plastic and plastic stages [66-68]. This model is also widely used for materials that do not have a clear yield point and represented by the following equation (7):

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^n \tag{7}$$

where, ε represents the sum of elastic strain ε_e and plastic strain ε_p (8):

$$\varepsilon = \varepsilon_e + \varepsilon_p \tag{8}$$

which can be expressed as follows (9–10):

$$\varepsilon_e = \frac{\sigma}{E} \tag{9}$$

$$\varepsilon_p = K\left(\frac{\sigma}{E}\right)^n \tag{10}$$

where, σ is stress, E is Young's modulus, and K and n are constants that depend on the material being considered. Taking σ_0 as the reference point in the linear stage of the curve, and ε_0 – as the strain corresponding to the σ_0, and eliminating E, the equation is obtained as follows (11):

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + K\varepsilon_0^{n-1}\left(\frac{\sigma}{\sigma_0}\right)^n \tag{11}$$

Let's express $\alpha = K\varepsilon_0^{n-1}$ and the final model for the stress-strain relationship of BSRC in compression is as follows (12):

$$\begin{cases} \dfrac{\varepsilon}{\varepsilon_0} = \dfrac{\sigma}{\sigma_0} + \alpha\left(\dfrac{\sigma}{\sigma_0}\right)^n, 0 < \varepsilon < \varepsilon_{c0} \\ \sigma = f_c, \varepsilon_{c0} < \varepsilon < \varepsilon_{cu} \end{cases} \tag{12}$$

where, f_c and ε_{c0} are the stress and strain corresponding to the peak load, respectively, and ε_{cu} is the ultimate compressive strain of the composite. Fig. 14 shows the comparison of the experimental and calculated results based on the Ramberg-Osgood stress-strain model.

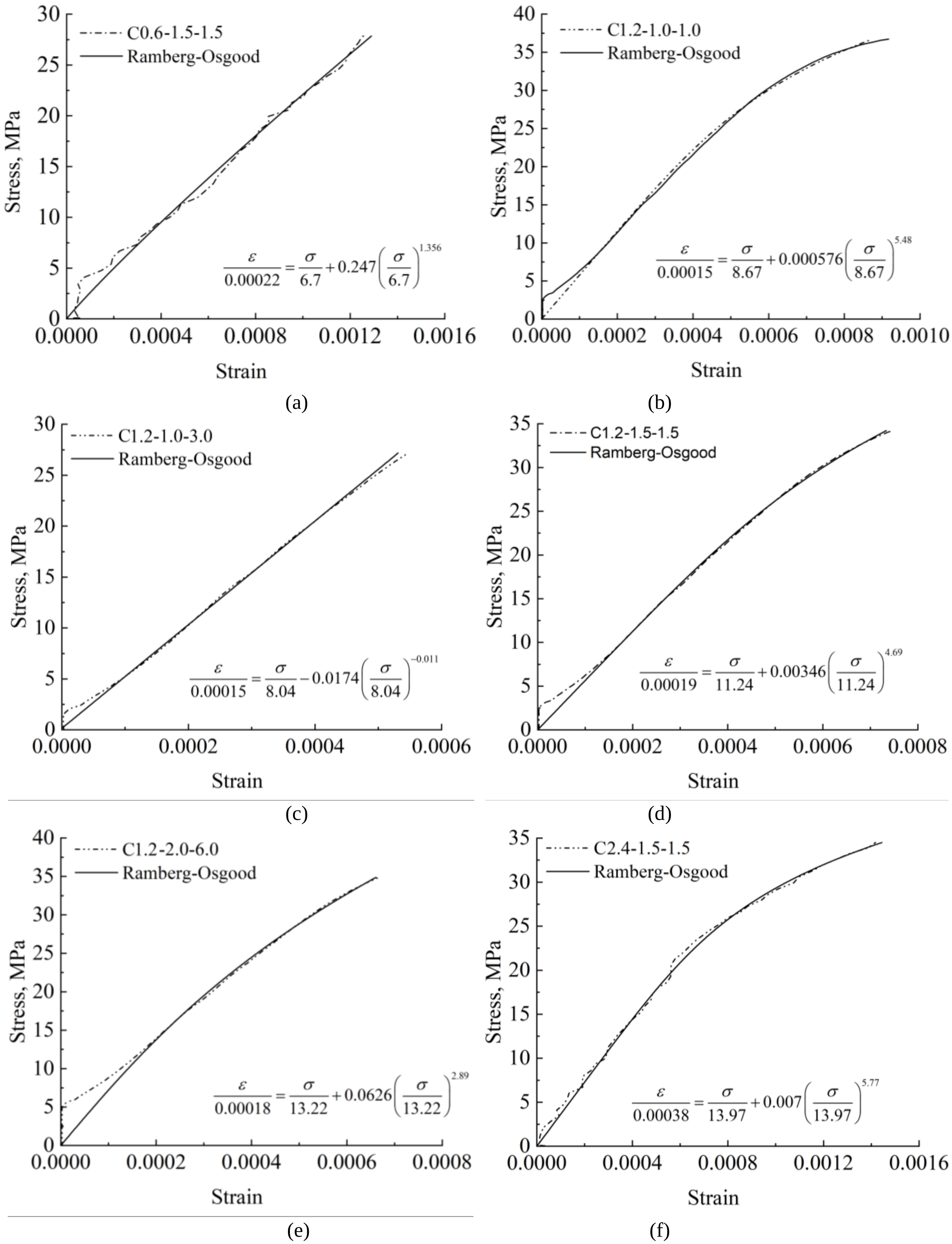

Fig. 14. Experimental and theoretical stress-strain curves of BSRC cubes: (a) C0.6-1.5-15; (b) C1.2-1.5-15; (c) C1.2-1.0-10; (d) C1.2-1.0-30; (e) C1.2-2.0-60; (f) C2.4-1.5-15.

As can be seen, the Ramberg-Osgood model is suitable for describing the stress-strain relationship of BSRC cubes with R^2 constituting 97%.

4 Discussion

In total, 64 BSRC cubes with concrete grade 30 were subjected to compression tests. The bamboo sticks ratio and the sticks' length-to-diameter ratio were used as influencing factors.

It turned out that both the volume ratio of bamboo sticks and the length-to-diameter ratio had a significant impact on the compression strength of the BSRC cubes. The diameter of bamboo sticks also showed a significant impact on compressive properties.

The results of this study are consistent with previous studies. Kumarasamy et al. [69] reported that the compression strength values increased up to 36.54 MPa, and 36.87 MPa for BSRC cylinders with 0.5% and 1.5% bamboo fibres. In this study, the strength values for BSRC cubes with 0.6% and 1.2% of sticks improved up to 32.22 MPa, and 33.33 MPa, respectively. In contrast, Terai et al. [31] reported that the compression strength of BSRC specimens decreased with the addition of 1%, 2%, and 3% of bamboo sticks. This could be caused by different factors, including mistakes in concrete mixing procedure, leading to forming of fibre balls instead of even distribution of fibres. The type of bamboo species used for research and the difference in a concrete mix design and concrete strength grade also could affect the previous research outcomes. For instance, Terai et al. [31] used *Phyllostachys bambusoides*, while Kumarasamy et al. [69] used *Oxytenanthera abyssinica*, and the current study used *Phyllostachys pubescens*. In the previous and current studies, the addition of fibres and sticks higher than 2% led to a decrease in the compression strength of the composite.

It is worth noting that in this study, the bamboo sticks were not subjected to any treatment, causing the dimensional changes of bamboo [27]. During drying, bamboo absorbed moisture leading to an increase in size and pushing back the walls of concrete. When concrete dried, bamboo lost moisture and shrank in size, leaving voids between concrete and bamboo, which led to the poor mechanical performance of the composite. When compressed, the following picture was observed: the bamboo sticks could be completely extruded from the concrete without applying any force, which indicated the free position of the sticks in the matrix. Past studies have also reported a weak bond between bamboo, cement, and aggregates interface that contributed to the shear failure and poor mechanical properties of the composite [36, 70, 71]. For further research, it is recommended to consider the possibility of improving the adhesion and water repellency of bamboo sticks through additional processing.

It was found, that the Ramberg-Osgood model was suitable for describing the stress-strain relationship of BSRC cubes with goodness-of-fit, constituting 97%.

5 Conclusion

In this research, the feasibility of the use of bamboo sticks as a reinforcement of concrete was evaluated. The bamboo stick volume ratio, stick diameter and length-to-diameter ratio were considered as influencing factors. In total, 64 BSRC cubes with bamboo stick diameters of 1 mm, 1.5 mm, and 2 mm, bamboo stick volume ratios of 0.6%, 1.2% and 2.4% and stick length-to-diameter ratios of 10, 20, and 30 were subjected to compression tests. Based on the results, the following conclusions have been drawn:

(1) With the addition of 0.6% of sticks, the compressive strength of the BSRC increased by 3.24% and 17.33% for length-to-diameter ratios 20 and 30, respectively. The compressive strength of specimens improved with the addition of 1.2% and 2.4% of bamboo sticks with the length-to-diameter ratio of 10 by 21.38% and 20.94%, respectively.

(2) The MOE significantly improved only in specimens with 1.2% of sticks and a length-to-diameter ratio of 10 and 30 since the size and amount of bamboo sticks were sufficient to take over the stress from the concrete without impairing the bond between the cement and aggregates.

(3) With an increase in the stick length-to-diameter ratio to 20 and 30, the compressive strength of BSRC with 1.2% and 2.4% of sticks decreased by 10.72–14.85% and 10.78–20.23%, respectively, due to decrease in the bond between the cement matrix and aggregates.

(4) Increase in the diameter of bamboo from 1 mm to 1.5–2 mm decreased the compressive strength values to 8.73–20.54%, respectively. An increase in the length of sticks from 10 mm to 20–60 mm decreased the strength values by 2.82–21.71%, respectively.

(5) BSRC cubes with lower stick length-to-diameter ratios showed load-displacement curves with the elastic and short elastic-plastic region before failure, while specimens with increased stick length-to-diameter ratios were almost linear.

(6) Based on the results of the analysis, 1.2% of bamboo sticks with a diameter of 1 mm and a length-to-diameter ratio of 10 turned out to be the most optimal reinforcement option with the highest compressive strength and MOE values. This amount of bamboo sticks was suitable to maintain sufficient bond strength between cement matrix and aggregates. Further addition of bamboo led to decreasing bonding strength and corresponding low mechanical performance of BSRC.

(7) The Ramberg-Osgood model showed high goodness-of-fit for the stress-strain relationship of BSRC cubes in compression with R^2 97%.

In this study, the bamboo sticks were not subjected to any treatment. The high moisture absorption capacity of bamboo sticks during curing and drying led to dimensional changes in bamboo and the appearance of voids between concrete matrix and bamboo. Therefore, for further research, special water-protective treatment of the sticks is recommended. It should be noted, that additional processing to improve the water-repellent and bonding properties of bamboo sticks may affect the overall environmental performance of BSRC. Therefore, a complete life cycle assessment of BSRC material production is necessary.

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