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Synergistic Effects of Bamboo and Jute Fiber Integration in Geopolymer Composites

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ABSTRACT

The natural fibers derived from natural products like fruit leaves, tree constituents, and leftovers are now used to synthesize environmentally acceptable materials with excellent mechanical qualities. Geopolymers, on the other hand, behave like materials based on Portland cement in terms of fragility and limited ductility. The assessment of bamboo-reinforcement is the main objective of this work. To investigate the effect of fiber content and type on the mechanical properties of the resulting geopolymer composites, samples were synthesized with varying bamboo fiber concentrations ranging from 0.4 to 4.0 wt.%. The three-point bending, splitting tensile, and compression testing made up the mechanical characterization process. The bending mechanical test done by the point method suggested a continuous relation between fiber content and flexural strength. The outcome of all mechanical tests, like tensile and compression tests, demonstrated result obtaining maximum fiber strength. Conversely, the compressive, splitting tensile, and flexural strengths of geopolymers with 2% wt.% bamboo fiber-reinforcement increased to 65%, 45%, and 232%, respectively. In all mechanical tests, the inclusion of bamboo fiber in optimal proportion altered the failure mode of the samples from brittle to more ductile behavior.

Keywords: Bamboo fiber; Jute fiber; Geopolymer composite; Mechanical properties; Environmental assessment.

1. INTRODUCTION

Geopolymer composites possess superior mechanical qualities compared to materials based on ordinary Portland cement (Cheng *et al*. 2001; Cheng *et al.* 2003; Pacheco-Torgal *et al.* 2008; Reig *et al.* 2013a; Atiş *et al.* 2015). Atiş *et al.* (2015) synthesized a fly ash-based mortar for geopolymer, which achieved a compressive strength of up to 130 MPa within a day. Cheng *et al.* (2003) synthesized a geopolymer matrix with a first-day compressive strength of 80 MPa, using ground granulated furnace slag. The production of geopolymers based on tungsten mine tailings was reported by Pacheco-Torgal *et al.* (2010), which resulted with compressive strength of 40 MPa on the 27th day. Mo *et al.* (2014) observed that industrial minerals like pozzolan and metakaolin have compressive strengths of 65 MPa and 100 MPa on the seventh and 28th day, respectively. They have also been used to synthesize high strength geopolymers. Sun *et al.* (2008) analyzed the matrices of geopolymer, which have less Tensile Strength (TS) and brittleness, just like other cementitious materials.

Arisoy *et al.* (2008) reported that, compared with conventional cementitious materials, geopolymers exhibit improved tensile performance and enhanced ductility when reinforced with both synthetic and natural fibers. The odd infusion of short fibers into a cementitious matrix enhances its toughness through energy intake mechanisms, ductility by allowing multi-cracking, and strength by transferring stress across cracks.

Most studies on fiber-reinforced geopolymers have used fabricated fibers, including basalt fibers (Dias *et al.* 2005; Li *et al.* 2009), fibers made up of steel (Zhao *et al.* 2007), all types of synthetic fibers (Natali *et al.* 2011), polypropylene derived fibers (Puertas *et al.* 2003), and polyvinyl alcohol derived fibers (Sun *et al.* 2008; Li *et al.* 2009). Natural fiber reinforcing of geopolymer matrices has drawn increased interest recently as environmental concerns about developing novel intensity-effective materials with reduced CO_2 emissions have grown (Silva *et al.* 2010; Yan *et al.* 2012; Correia *et al.* 2013). Correia *et al.* (2013) investigated the use of fibers from bamboo and pineapple leaves to strengthen metakaolin-based geopolymers in this regard. While comparing to the unreinforced matrix, they discovered that a 4% wt.% fiber content have a detrimental impact on all the strength like tensile and compressive with splitting strength much higher. By comparing

unreinforced matrices strengths, bamboo fibers raised splitting tensile and flexural strength by 100% and 110 % appropriately. Sá Ribeiro *et al.* (2016) were again adequate to enhance the mechanical characteristics of geopolymers. In their work, a composite material with increased flexural strength (FS) up to 450% more than the control sample was mixed with 6% (wt.%) of water, alkali-studied bamboo fibers and fiber fillet. Correia *et al.* (2013) compared the control matrix. The presence of fibers resulted in roughly 50% reduction in compressive strength, which is comparable to the findings of all fibers. In fly-ash based geopolymer composites, Korniejenko *et al.* (2016) investigated the resulting compressive and FSs by comparing the unreinforced matrices. The results display that the compressive strength was enhanced by 27% with the addition of cotton, bamboo, and coir fibers. Conversely, geopolymer composites with added raffia fibers had reduced compressive strengths. It was observed that the inclusion of fibers like raffia, coir, bamboo and cottons resulted in 45 % reduction in FS. Chen *et al.* (2014) studied the mechanical characteristics of geopolymer with alkali-pretreated sweet sorghum fiber. Ghosh *et al.* (2016) estimated that burnt clay brick leftovers make up 30% of the 850 million tons of construction and demolition debris that the European Union alone produces annually.

The goals of this study were to assess the use of instinctive fibers like cellulosic, namely bamboo and jute in the formation polymers made from brick fired powder Any potential adverse effects on the mechanical properties that could arise from the exposure of fibers to extremely alkaline surroundings from a very earlier time and extended oven-heating time were examined. For this reason, a thorough experimental characterization was conducted. It involved determining the ideal number of fibers to use while considering the workability of mixture and analyzing the feedback of matrices to all mechanical strengths, after multiple days of manufacturing.

2. MATERIALS AND METHODOLOGY

In varying proportions, cellulose, hemicellulose, and lignin constitute the major components of most natural fibers. The Food and Agriculture Organization views jute and bamboo fibers as future fibers because of their advantages to the environment. This serves as the reason they were chosen for this study. An acre of jute plants is thought to emit 11 tons of oxygen and absorb roughly 15 tons of CO_2 however, bamboo crops consume higher CO_2. Then the organic wastes generated during the manufacturing of bamboo fiber can be used in sectors, including the production of fertilizer, animal feed, and bioenergy (Bledzki *et al.* 2015). According to reports, sisal fibers include 43-56% lignin, 20-25% hemicellulose, and 6-8% cellulose, by weight, whereas jute fibers constitute of 60-65% cellulose, 18-25% hemicellulose, and 11-13% lignin by weight (Li *et al.* 2000). The density of fibers ranges from 1.30 to 1.45 g/cm^3, but the density of bamboo fibers is approximately 1.45 g/cm^3 (Dhinakarraj *et al.* 2023). For this investigation, bamboo and jute fibers were cut from commercially available ropes into 10 mm lengths, yielding aspect ratios of 190 and 75, respectively. The SEM was used to examine the longitudinal and cross-sectional morphologies of both fibers (Phologolo *et al.* 2012). The findings are shown in Fig. 1. According to longitudinal micrographs, Figs. 1(a) and (b) show bamboo fibers have tougher surfaces than jute fibers, which may improve the fiber's adherence to the geopolymer matrix. All fibers made up of cells derived from linked fibers resembled adhesive substance, as seen in Fig. 1.

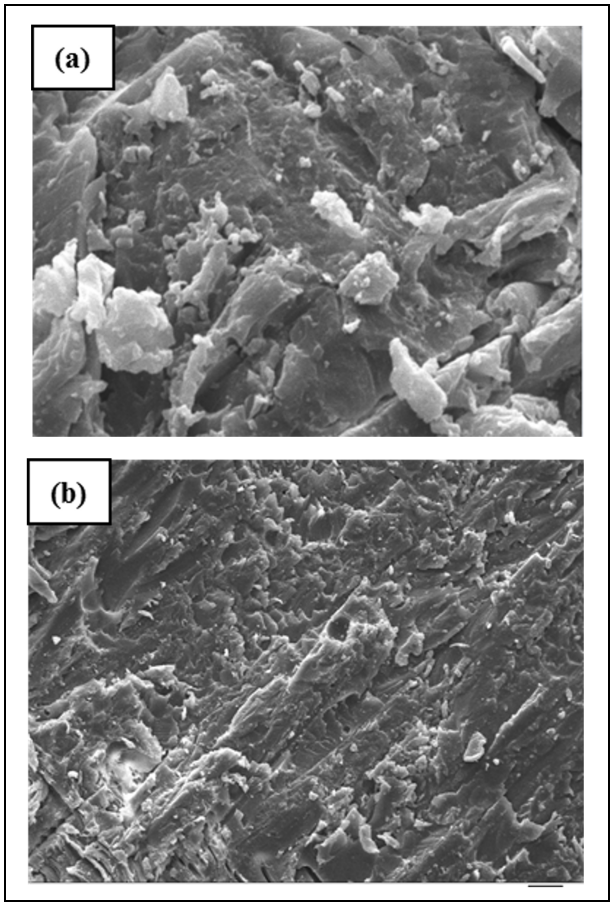


Fig. 1: SEM images of natural fibers used for reinforcement geopolymer matrix based on FCBP (a) Jute fiber longitudinal view and (b) Bamboo fiber longitudinal view

Water consumption and water contact angle experiments were performed on bamboo and jute fibers to find their wettability. Before the experiments, both fibers were dried for 24 hours at 65 °C. The dried fibers were then wrapped in water for a whole day to assess water consumption. The fibers were able to achieve a saturated surface dry (SSD) state, after the extra water was removed from their surface using absorbent paper. Equation (1) was used to measure the water consumption quantity (A), here w and d represent mass of the fibers

under non-wet circumstances and at the SSD state, appropriately.

Absorption of water (A), % = ((w-d)/d) ×100 … (1)

In contrast, a glass slide was used for influence angle testing, and several fibers were arranged together to make a horizontal exterior that was roughly 1.6 mm broad. The flattened group of fibers was studied with an individual droplet of 0.5 mL distilled water, and after 1, 10, 20, and 30 seconds, the connection angle was studied with a Ramé-hart contact angle goniometer. According to the water absorption test findings, bamboo and jute fibers had values of 125% ± 5% and 102% ± 13%, respectively. This suggests that bamboo has a higher water consumption scope than jute. Additionally, experiments that use water as connection angles as seen in Fig. 2 show that bamboo fibers are noticeably higher hydrophilic than jute fibers. Even after being exposed to the water droplet for 30 seconds, jute fibers still had a connection angle of 70°. Conversely, after 1 second of exposure, bamboo fibers showed a lower initial connection angle of 45°, which quickly reduced. It was observed that the water droplet was fully absorbed by the material within ten seconds of placement, making it impossible to measure the contact angle.

According to these findings, bamboo fibers have a higher affinity for water than jute fibers, which is important for forming a strong positive contact between the fiber and the water-based geopolymer matrix (Ranjbar *et al.* 2016). Using MTS machine with capacity of 5 kN the tensile test was analyzed and a 6 mm/min move rate was used to examine the TSs of bamboo and jute fibers.

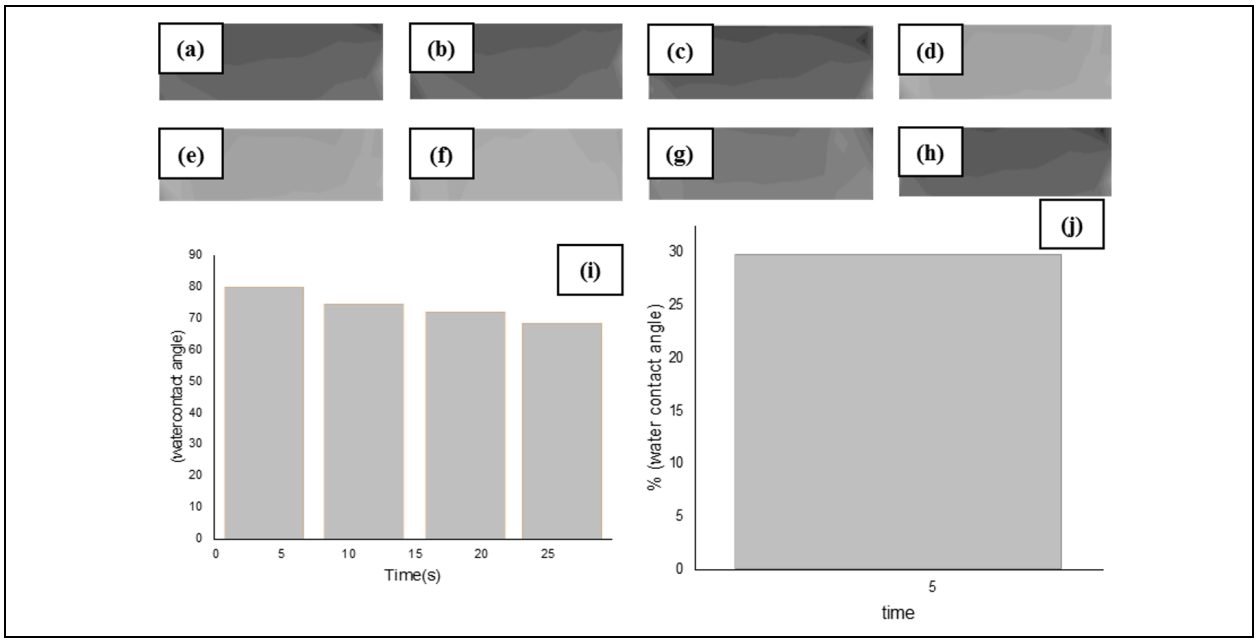


Fig. 2: Fiber test for water contacts and time variation for jute and bamboo

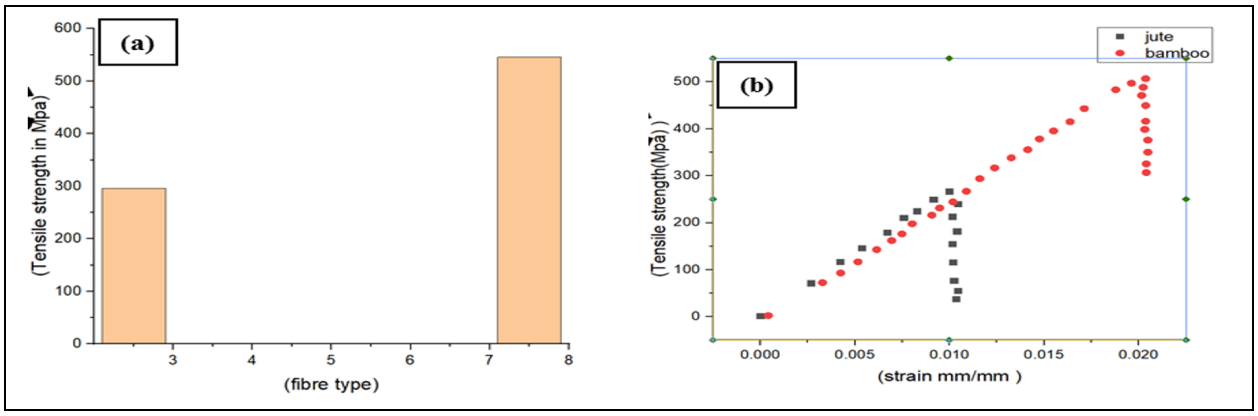


Fig. 3: Individual jute and bamboo fibers: (a) Tensile strength and (b) Tensile stress *versus* strain

Tensile testing on single fibers was carried out in accordance with ASTM D3822 criteria (Silva *et al.* 2020b). The scale of the enforced load to the fiber's moderate transversal area was used to compute the tensile stresses. To represent all comparative curves like strain and stress, the ratio between the grasp distance and the crosshead displacements was measured. The TS tests for both types of fibers are displayed in Fig. 3a. Six types of sample fibers were analyzed. Bamboo fibers had TS of 508 MPa, while jute fibers had a strength of 276 MPa. Fig. 3b shows the tensile stress *versus* strain curves for all fibers. Jute fibers had an E-modulus of 28 GPa, while bamboo had comparatively low rate of 26 GPa. Bamboo fibers conferred 98% higher prolongation quantity than jute fibers. The potential reactivity of raw material is enhanced by the Fired Clay Brick Powder (FCBP) (Fig. 4a) as evidenced by the average diameter magnitude of 18.15 µm. The SEM micrograph of FCBP displayed in Fig. 4b demonstrates irregular and crystal-like morphology.

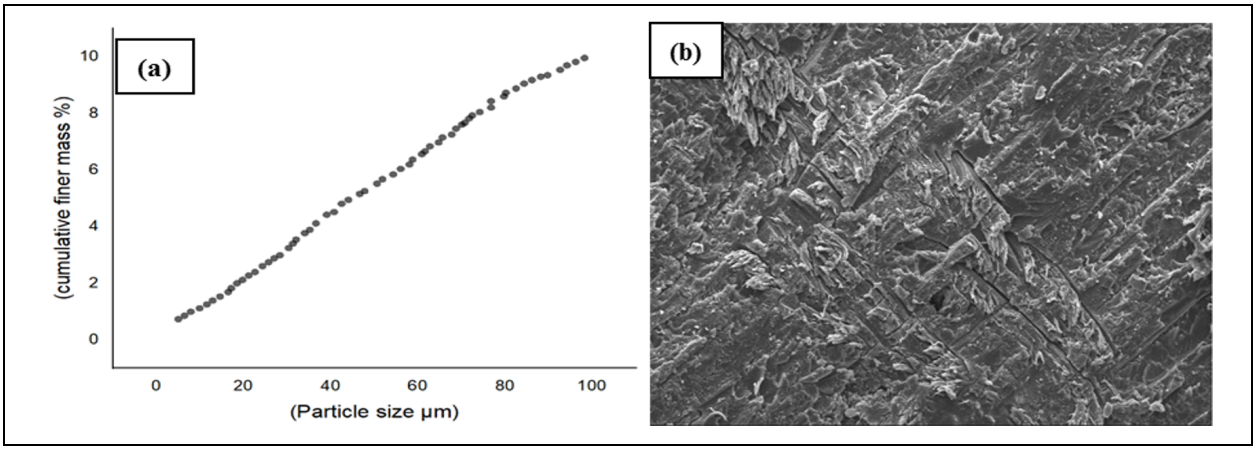


Fig. 4: (a) Particle size distribution and (b) Scanning electron micrograph of FCBP

Table 1. FCBP chemical composition of by XRF method

Oxide Content (w/ w %)							
Sio_2	**Al_2O_3**	**Fe_2O_3**	**K_2O**	**MgO**	**CaO**	**Na_2O**	**other**
52.45	19.85	8.10	2.64	1.86	1.52	1.29	10.43

The X-ray fluorescence examination of the FCBP revealed a chemical composition with an immense concentration of SiO_2, Al_2O_3, and Fe_2O_3 (Table 1), confirming the right conditions of geopolymer synthesis (Silva *et al.* 2019). A sodium silicate solution, purified water and NaOH pearls (99% weight and purity) were combined to prepare the alkaline activating solution. By substance, the sodium silicate solution is composed of 28% SiO_2, 8% Na_2O, and 64% H_2O.

2.1 Steps for Experimental Work

As per ASTM C1437-15, flow tests were conducted on newly synthesized FCBP-based geopolymer composites to examine the impact of jute and bamboo fiber content on the workability of the mixture. To do this, fresh material was evenly divided into two coatings and compressed by tamping all layers 20 times in a truncated conical mold with dimensions of 70 mm for the upper diameter, 100 mm for the bottom diameter, and 50 mm for the highness. After a minute, the mold and material setting were taken out for multiple drops more than 25 times. According to the protocols outlined in ASTM 109 (Ramu *et al.* 2023), ASTM C496 and ASTM C348 (Deepanraj *et al.* 2023) tests were carried out to assess the impact of the addition of jute and bamboo fibers on the mechanical properties of FCBP-based geopolymer composites. For all mechanical tests of geopolymer composites, an electromechanical testing apparatus MTS exceed 45.105 with a 100 kN capacity was employed as shown in Fig. 5a. For every mechanical test, the global displacements that matched the load frame were recorded. The displacement rate of the load frame was maintained at 0.5 mm/min. For compression tests, 50 mm-side cubic samples were used (Fig. 5b) and for splitting tests, cylindrical specimens with 40 mm in diameter and 80 mm in height were used (Fig. 5c). Prismatic samples with dimensions of 40 mm for cross-section and 160 mm for length were used for three-point bending tests (Fig. 5d). The distribution and interactions between the bamboo and jute fibers inside the binder mixture were examined using the SEM. With an operating voltage of 30 kV, all SEM imaging of fiber-reinforced fractured samples was carried out by an FEI

Quanta 200 SEM. Since excess water addition has been shown to reduce the mechanical characteristics of geopolymer matrices in prior research, the idea of adding more water to reduce the workability loss caused by fibers was not taken into consideration (Reig *et al.* 2013b). The geopolymer mixes were poured into cubic, cylindrical, and prismatic silicon molds, and the air bubbles were removed by vibrating the molds. Samples were demolded after 24 hours but were maintained in the oven, while the specimens were cured for three days at 65°C. After that, the specimens were stored at room temperature for four more days till mechanical testing was done. To prevent the fibers in Fiber-Reinforced Geopolymer Composites (FRGC) from deteriorating, the oven curing period was restricted to three days. Silva *et al.* (2019) show that since FCBP-based geopolymers require relatively high temperatures during the first phase of formation, curing at room temperature was ignored. An overview of the preparation of FRGCs and curing conditions is included in Table 2, along with the quantity of samples tested used in the mechanical tests.

3. RESULTS AND DISCUSSION

The optical image of geopolymer composites obtained microscopically to examine the FCBP used in this study is shown in Fig. 6. The impact of bamboo and jute fiber incorporation on workability of geopolymer composites as determined by the flowability of the mix is depicted in Fig. 7. Equation (2) was used to calculate the flowability (F), which is the relative difference between the tested average of the matrix base diameter (S_0) and the mold bottom diameter (S).The FRGC flow setup is shown in Fig. 7a. The findings displayed in Fig. 7b suggest that there is a direct correlation between the fiber content and flowability of both FRGCs. On the other hand, bamboo-FRGCs showed a smaller decrease in workability for the same fiber percentage. For instance, bamboo-FRGC had a 50% greater flow capacity than jute-FRGC at a 2% fiber content.

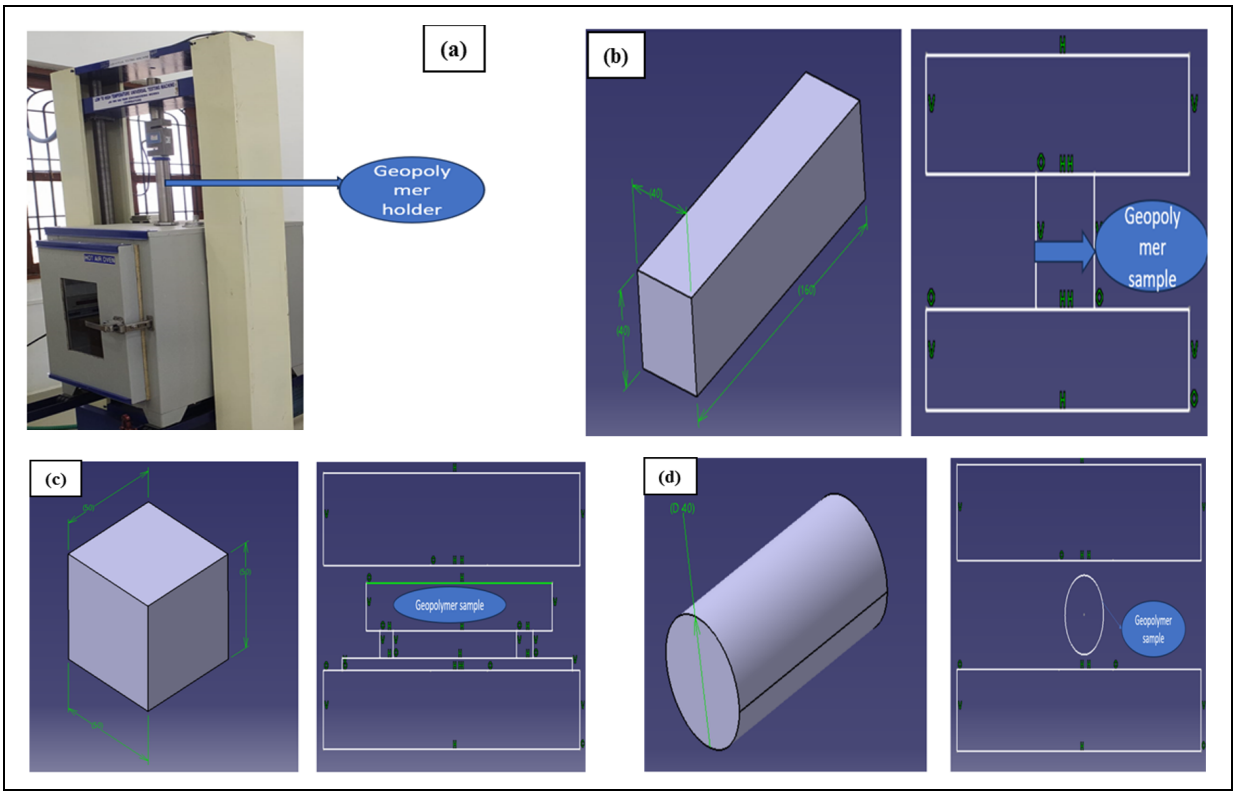


Fig. 5: (a) UTM (b) Geopolymer cure sample (c) Geopolymer cylindrical sample and (d) Prismatic sample and tensile testing test (units in mm)

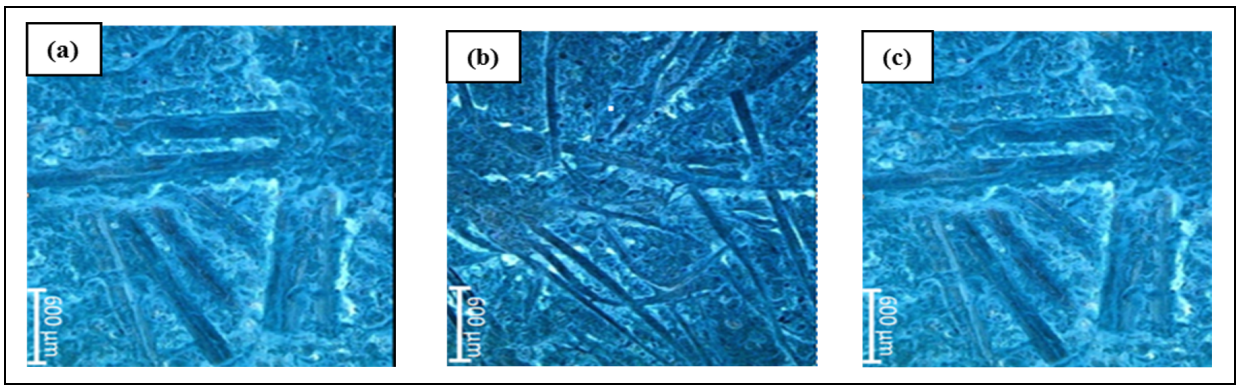


Fig. 6: Optical microscope images of geopolymer composites: (a) Control matrix (b) Jute FRGC and (c) Bamboo FRGC

Table 2. Curing and testing condition of FRGC

Type of fibre	Fibre addition wt.%	Sampling tests	Millimoles per mole	Na_2O (wt.%)	Water/binder wt./wt.	Time and curative temperature	Curing fixes up total
Control grid	-	8	0.558	7.98	0.28	3 days and 70 °C	7 days
Jute	0.49	8	0.60	8	0.27	3 d and 70 °C	7 days
	1.00	8					
	1.50	8					
	2.00	8					
Bamboo	0.50	8	0.60	8	0.27	3 d and 70 °C	7 days
	1.00	8					
	1.50	8					
	2.00	8					
	2.50	8					
	3.00	8					

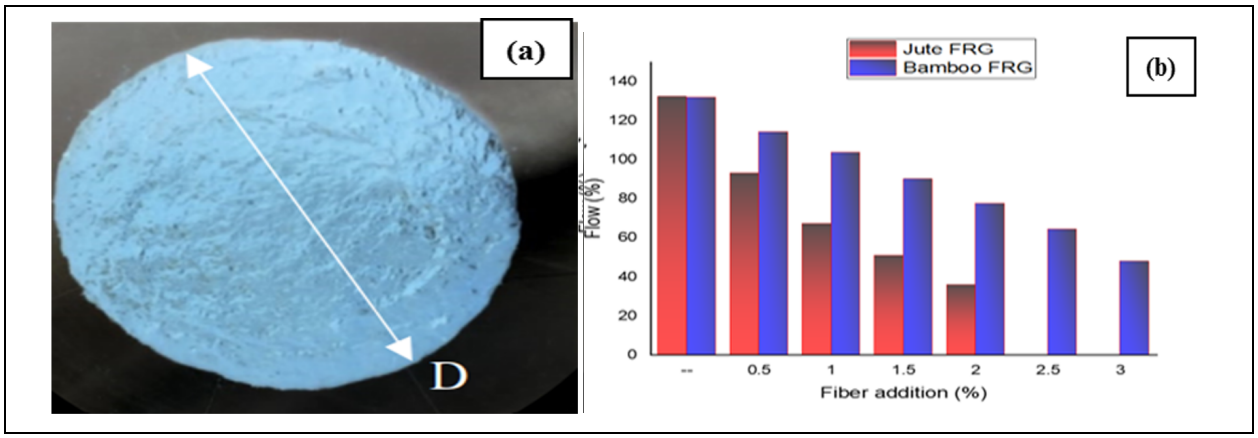


Fig. 7: FRGC flow tests: (a) FRGC flow setup (b) Results for flowability of jute and bamboo fibers

As observed by Yazici *et al.* (2007), who noted the workability of reinforced material decreases as the additive proportion increases, which can be attributed to the low aspect ratio of the bamboo fibers. This test made it possible to determine the maximum percentages of bamboo (3%) and jute (2%) that could be added to the combinations.

$$F = (S\text{-}S_0)/S_0)\times 100 \quad \ldots (2)$$

It was not possible to analyze a higher amount of fiber. The results of reinforced bamboo and jute fibers with FRGCs appropriately are displayed in Fig. 8(a) and (b). Fig. 8 shows that a fiber content of 2% leads to an increase in bulk density for both bamboo FRGC and jute, in contrast to other research that report an inversely comparable relation between the bulk density and the

fiber content (Alomayri *et al.* 2013; Chen *et al.* 2014; Ranjbar *et al.* 2016).

This study differs significantly from earlier publications because no additional water was supplied to make up for the workability that was lost when fibers were introduced. Large amounts of intergranular holes would form in the microstructure because of an inevitable inclusion of additional water to the blend and its consecutive dispersal during curing, which would lower the bulk density of the composites (Alomayri *et al.* 2013).

Higher manufacturing compaction owing to the workability loss and increased fresh mixture viscosity from fiber addition can account for the initial density gain observed in both FRGCs relative to the regulation matrix. Nonetheless, the bulk density of both FRGCs decreases as the fiber content exceeds 1% (wt.%).

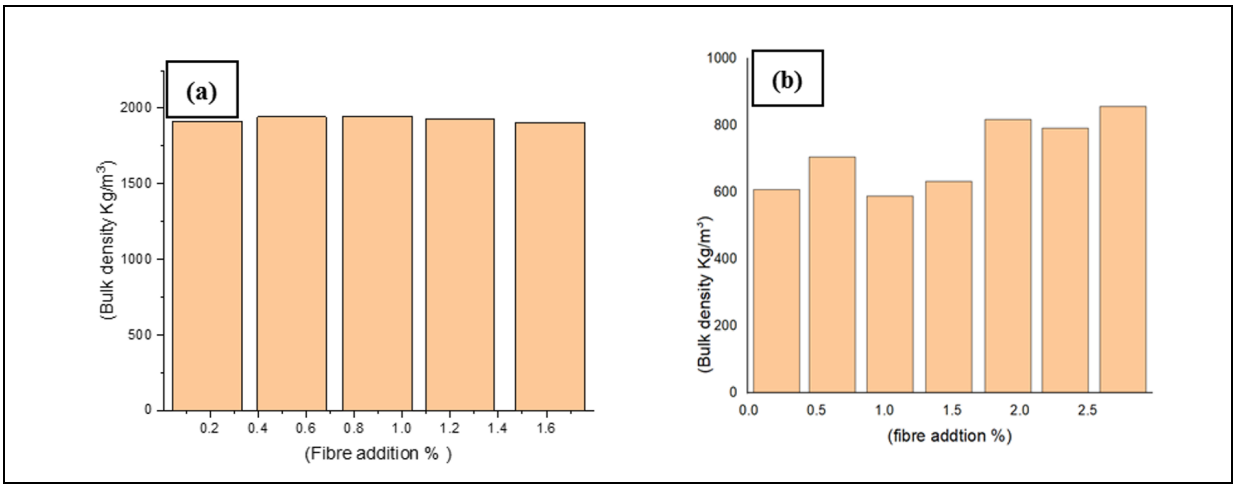


Fig. 8: Test results of geopolymer composites (a) Jute fibers and (b) Bamboo fibers

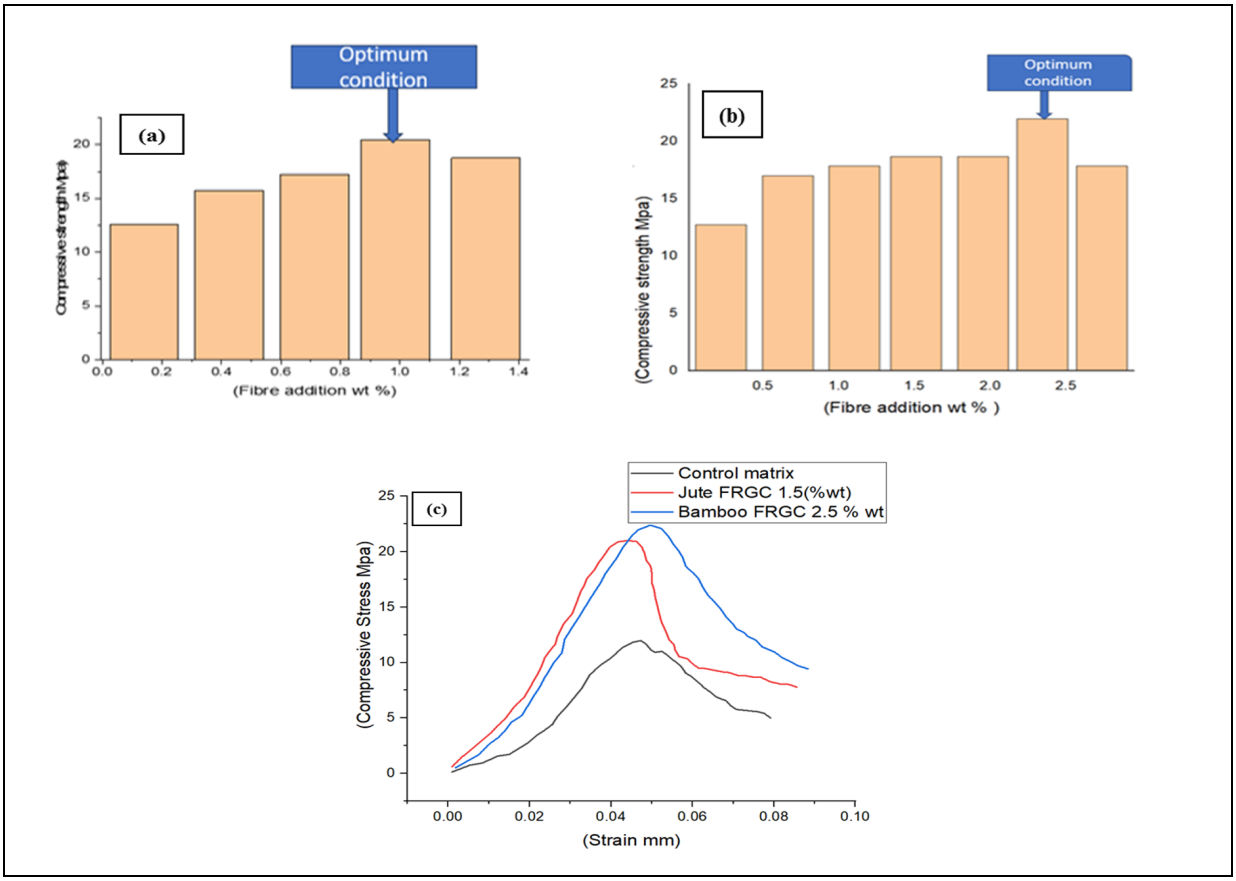


Fig. 9: Compression test results: (a) Jute reinforced (b) Bamboo reinforced and (c) Compression *versus* strain curves

Even with increased compaction energy used during manufacture, there may be a loss of bulk density due to fiber agglomeration during mixing at high fiber concentrations. Intergranular holes formed by fiber agglomeration in composites may potentially be detrimental to the mechanical features of the material (Alomayri *et al.* 2013). The outcomes of the compressive analysis for uniaxial area conducted on the FRGCs and control samples are displayed in Fig. 9. The geopolymer composite compression strength behaves better than the control sample, as seen in Fig. 9(a) and (b). Furthermore, the data shows a tendency toward increased strength with increasing fiber content, up to a point where decline is seen, indicating that the kind of fiber determines the maximum strength. When the fiber content was 1.5% (wt.%) in the instance, jute-FRGC seventh day compression strength captured maximum of 21.02 MPa, indicating a 64% improvement over the control. However, when correlated to the control matrix, bamboo-FRGC specimen with 2.8% of weight fibers showed the largest enhancement of 78% on the seventh day reaching 22.1 MPa. For both varieties of FGRC, higher fiber concentrations resulted in a decline in compressive strength. Fig. 9c displays control matrix of the compression stress *versus* strain curves, the ideal jute-FRGC containing 2.0 wt.% fiber, and bamboo- FRGC containing 2.5 wt.% fiber. Both the jute and bamboo-FRGCs show higher E-moduli, 103% for jute and 76% for bamboo when correlated to the control matrix.

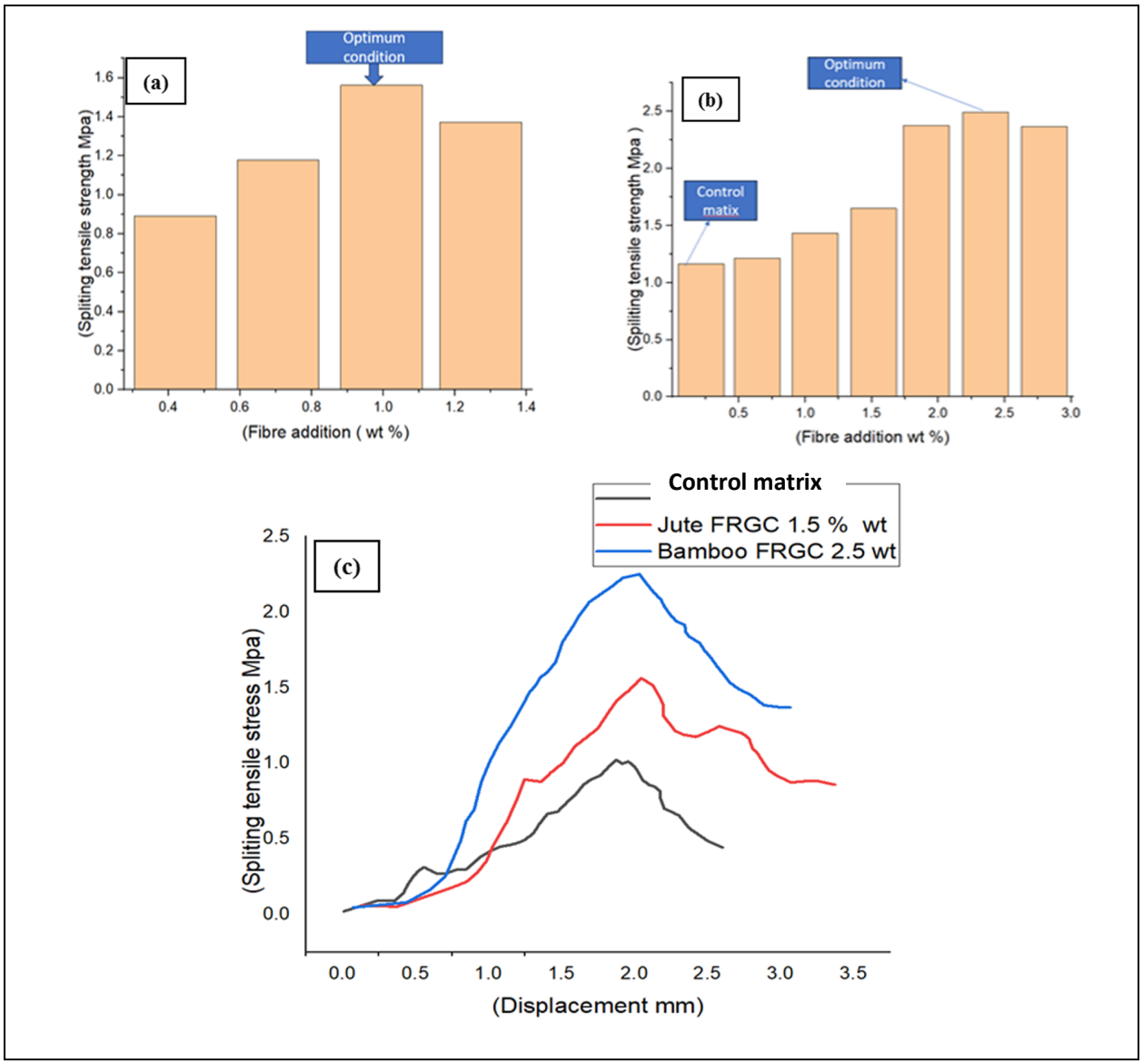


Fig. 10: Splitting analysis test results : (a) jute; (b) Bamboo reinforced and (c) Tensile strength stress *versus* displacement curves

During the compression tests, the control matrix (no fiber-reinforcement) exhibited a brittle failure mode with the production of tiny free pieces (Fig. 9c). However, it is evident from the modes of failure of FRGCs containing bamboo and jute fibers that they exhibit more ductility. Fig. 10 displays the splitting test results. Fig.10(a) and (b) show that the tested matrices behaved better under tensile loads when bamboo and jute fibers were included. Both FRGCs demonstrated that during compression testing, the presence of fibers considerably altered the failure behaviour, reducing specimen fragmentation up to an optimal standard, consistent with the observed compressive strength results.

The inclusion of 2.0% (wt.%) of fibers to FRGC jute produced maximum value of 1.7 MPa TS, surpassing strength of the control matrix by 45%. This is the same optimal value found in the compression testing. With 2.5% (wt.%) more fiber added, the TS of FRGCs expanded to 2.4 MPa which is 114% greater than the control matrix. When compared to the FRGCs control matrix, the ideal fiber content showed improved tensile toughness (Fig. 10). The range under the displacement curve *versus* splitting tensile stress represents the tensile toughness. Comparing 2.5% bamboo FRGC and 2.0% jute FRGC to the control matrix, the tensile toughness of the two samples increased by 92% and 181%, respectively. Lastly, higher failure mode of ductile was revealed by FRGC splitting test when compared to the control grids. Therefore, fibers permit payload transmission from the fractured location to alternative flawless segment of the sample. The FRGCs exhibit multi-cracking fracture behavior. These findings concur with those of Sun *et al.* (2008) and Chen *et al.* (2014), who described how the inclusion of short fibers causes fly ash-based geopolymer matrices to change from having brittle to ductile behavior.

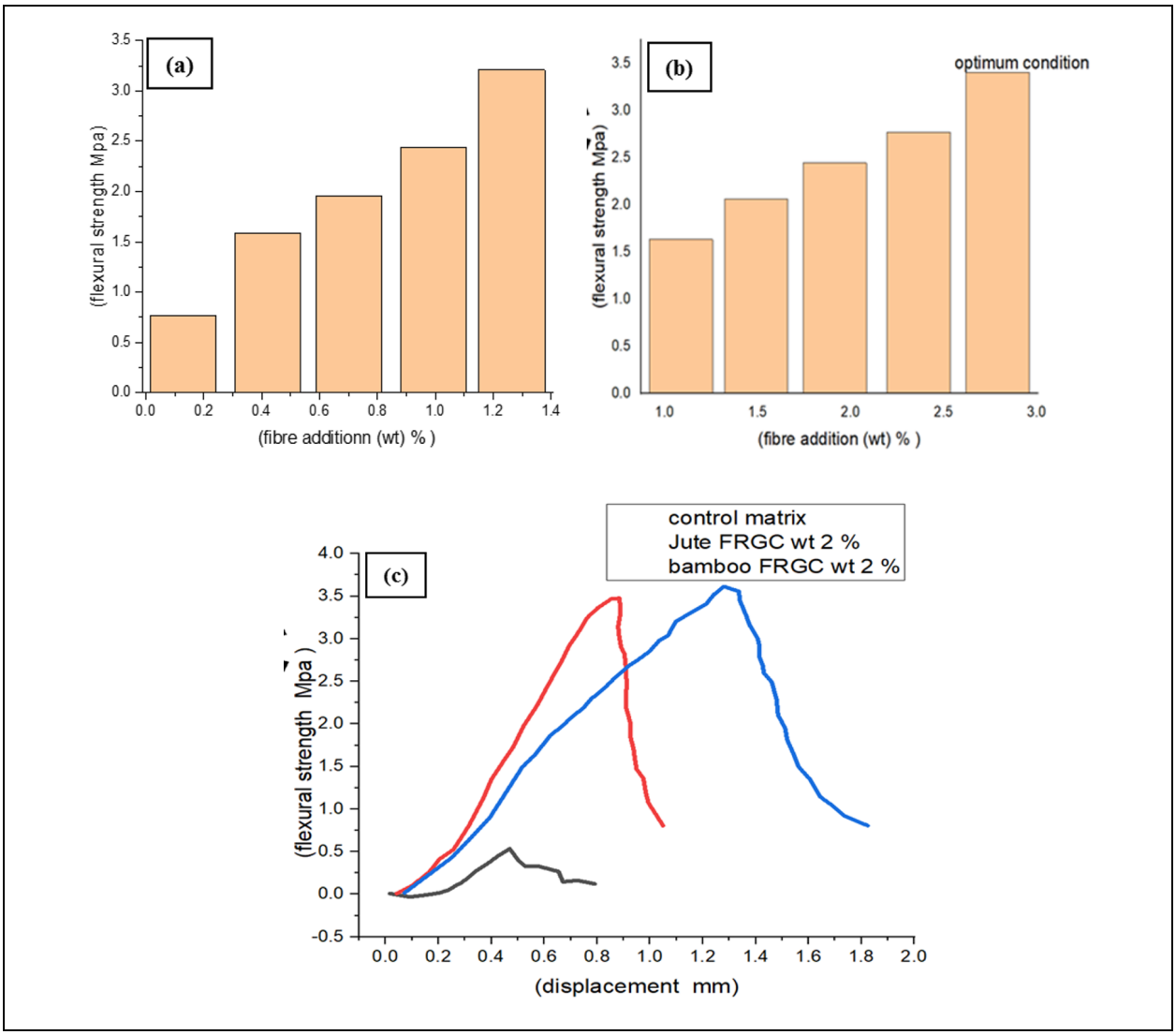


Fig. 11: Three-point bending test results: (a) Jute with reinforced (b) Bamboo fibers and (c) Flexural strength stress *versus* displacement curves

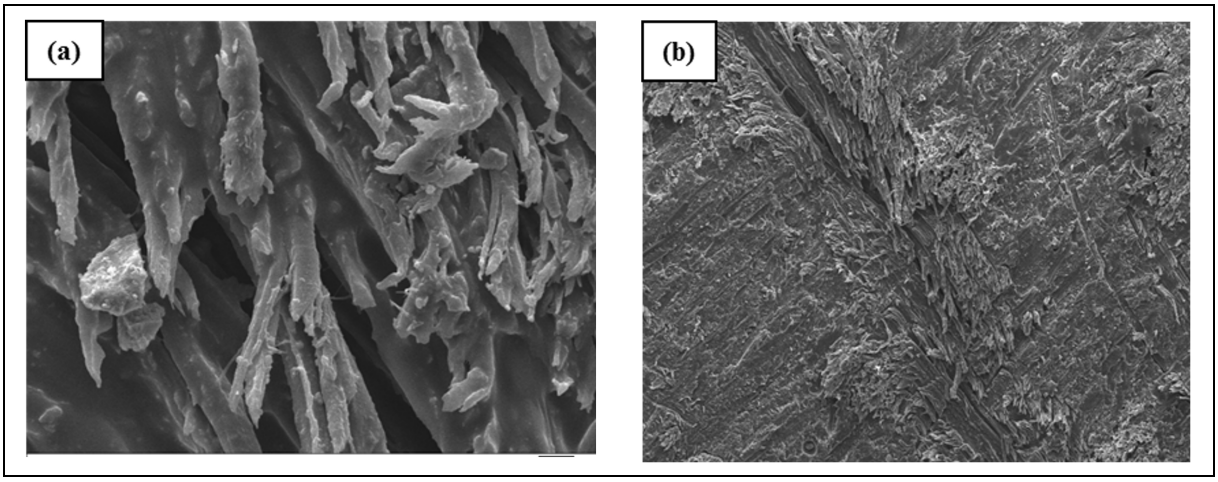


Fig. 12: Cracked FRGCS: (a) Jute fiber grid bonding in FRGC and (b) Bamboo fiber matrix in FRGC

Fig. 11 displays the outcomes of the variable three-point bending investigation. The flexural strength of produced geopolymer composites clearly demonstrates the impact of bamboo and jute fiber-reinforcement. Fig. 11(a) and (b) show that for both varieties of FRGCs, a continuous relation between the fiber content and FS was seen, in contrast to the findings of the compression and splitting tensile tests. With a fiber percentage of 2% (wt.%), FRGCs had the higher FS of 3.3 MPa, which is 329% greater than the control matrix. According to the studies by Sun *et al.* (2008) and Chen *et al.* (2014), it has been suggested that the improvement in FS observed in FRGCs is due to the ability of the fibers to carry higher tensile stresses across cracks. Fig. 11c, also depicts the failure posture of the control matrix, 3% FRGC jute and 4% bamboo-FRGC in the final case. When geopolymer composite is reinforced with fibers, the inclusion of both fibers significantly alters the failure behavior, changing it from a sudden brittle crack to a composed, further adhesive failure. The displacement curve demonstrated the control matrix of flexural modulus and FRFGs. The mechanical behavior of FRGCs was dependent on the structure of the geopolymer matrix as well as the kind and quantity of natural fibers (Ardanuy *et al.* 2015; Thirumalvalavan *et al.* 2023). Jute and bamboo fibers exhibited strong adhesion to the FCBP-based geopolymer matrix, as evidenced by the SEM images presented in Fig. 12(a) and (b), respectively.

4. CONCLUSION

Geopolymer based on powdered natural fiber-reinforced burned clay bricks was developed as a possible building material with good mechanical qualities and minimal environmental impact. They exhibited improved mechanical behavior when combined with short jute and bamboo fibers. The raw and hard characteristics of the fiber-reinforced geopolymer composites depend on the kind and quantity of fibers combined with FCBP. When compared to the control matrix (unreinforced FCBP-based geopolymer), fiber content which is derived from jute FRGC with 1.5% by weight demonstrated biggest improvement in tensile and compressive strengths by 64% and 45%, respectively. When compared to the control matrix, bamboo-FRGCs performed best at a 2.5% (wt.%) fiber content, improving the TS by 112% and the compressive strength by 76%. All of strain and stress curves and the failure condition of the specimens showed that the inclusion of fibers encouraged reinforced samples. A continuous link among the FS and natural fiber of FRGC was revealed by three-point bending tests. With 2% fiber content, the FS of FRGC jute was 3.3 MPa which is equivalent to a 329% increase over the unreinforced matrix. Thus, bamboo-FRGCs outperformed unreinforced FCBP-based geopolymer, exhibiting a 3.5 MPa FS at 3% fiber content by 360%.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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