STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 1, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Characterization of Bamboo-Fiber Reinforced Geopolymer Composites

Shekhar Rahane[1], Balaprasad Kurpatwar[2], Mangesh Patil[3], Sweety Jachak[4], Krupal Pawar[5,*]

Abstract

In this project, we plan to produce and assess a new, eco-friendly composite made from geopolymer (from a combination of fly ash and GGBFS), strengthened with chemically treated bamboo fibres for retrofitting earthquake-resistant buildings. Geopolymer is produced by activating a mixture of fly ash and GGBFS with sodium silicate and sodium hydroxide solutions. We have produced and analyzed bamboo fibre-reinforced geopolymer composites as potential materials for seismic retrofitting of structures and obtained very good results. A geopolymer composite was developed using a composition of 70 % fly ash, 30 % GGBFS, 12 M sodium hydroxide, an SS/SH mass ratio of 2.0, and 3 % alkali-silane treated bamboo fibres, each having a random orientation of 30 mm within the matrix. In terms of both mechanical (structural) properties, workability and environmental sustainability, this combination achieved the best compromise. With respect to structural behaviour, the most successful composite displayed a compressive strength of 52.3 MPa, a flexural strength of 8.7 MPa, representing a 71 % increase relative to the unreinforced matrix; and a tensile strength of 4.2 MPa, representing a 100 % increase. Most important, the material switched from a brittle fracture mode to a pseudo-ductile fracture mode, a critical switch to enhance energy absorption and thus seismic retrofitting performance.

Keywords: Composite, geopolymer, fly ash, GGBFS, bamboo fibre.

INTRODUCTION

The damage to buildings caused by seismic activity is extreme, causing loss of life and disruption to economies on an unprecedented scale. Earthquakes of extreme severity occurred in Turkey, Syria, Nepal and Japan. These seismic events have shown how urgently needed retrofitting of structures is required to enhance their capability to survive seismic activity in the future [1]. Retrofitting strategies currently employed rely heavily upon cement based products and steel reinforcement as primary means of strengthening structures; both of which result in large quantities of CO2 being emitted globally [2], while simultaneously, depleting global resources [2]. The construction sector is responsible for nearly 38 percent of CO2 emissions generated globally and, of those emissions, cement production accounts for nearly 8 percent of all CO2 emissions globally [3]. Due to the urgency of the combined issues of seismic safety and sustainability, there is now a great deal of research focused on the development of new materials that can address the dual concerns of environmental sustainability and structural integrity. Low-carbon alternatives to OPC (Ordinary Portland Cement) have been developed

***Author for Correspondence**
Krupal Pawar

[1]Assistant Professor, Department of Basic Sciences, Nutan Maharashtra Institute of Engineering & Technology, SPPU, Pune, Maharashtra, India
[2]Assistant Professor, Department of Mechanical Engineering, Adsul Technical Campus, Chas, SPPU, Ahilyanagar, Maharashtra, India
[3]Assistant Professor, Department of Mechanical Engineering, Adsul Technical Campus, Chas, SPPU, Ahilyanagar, Maharashtra, India
[4]Assistant Professor, Department of Computer Engineering, Guru Gobind Singh College of Engg., Nashik, SPPU, Maharashtra, India
[5]Assistant Professor, Department of Mechanical Engineering, Rajiv Gandhi College of Engineering, Karjule Harya, SPPU, Ahilyanagar, Maharashtra, India

Received Date: January 28, 2026
Accepted Date: February 05, 2026
Published Date: February 15, 2026

Citation: Shekhar Rahane, Balaprasad Kurpatwar, Mangesh Patil, Sweety Jachak, Krupal Pawar. Characterization of Bamboo-Fiber Reinforced Geopolymer Composites. Journal of Polymer & Composites. 2026; 14(Special Issue 1): S1007–S1025p.

through the production of geopolymers created by the alkali activation of aluminosilicate materials [4]. Geopolymers are capable of reducing CO2 emissions related to OPC production by 40–80%, and have enhanced durability and chemical resistance compared to OPC [5]. However, similar to OPC, geopolymers also exhibit brittleness and low tensile strength; reinforcing geopolymers will be required to enhance their mechanical properties for structural applications [6]. One sustainable method to improve the ductility and toughness of geopolymer matrices is through the utilization of natural fiber reinforcement. Among all the available natural fibers, bamboo is of specific interest due to its rapid growth rate, high tensile strength, wide availability and the cultural significance of bamboo in several regions prone to earthquakes [7].

The tensile strength of bamboo varies from 140 to 800 MPa, comparable to certain steel grades, however, it possesses a significantly lower embodied energy and carbon footprint than the majority of steel [8]. Additionally, the hollow cylindrical microstructure of bamboo provides a high strength-to-weight ratio making it extremely suitable for seismic retrofitting where it is essential to minimize added mass [9]. The objective of this investigation is to develop a sustainable seismic safety solution by designing geopolymer-bamboo composite systems for use in retrofitting applications. Global climate objectives mandate the reduction of greenhouse gas emissions from the construction industry to a dramatic level [10].

Substantial reductions in embodied carbon and energy consumption can be achieved through the replacement of cement-based matrices with geopolymer matrices and synthetic fibers with bamboo [11]. Bamboo is one of the fastest growing plant species on earth (see Figure 1) and achieves maturity within 3-5 years, while trees typically achieve maturity after decades [12]. The rapid regrowth and low cultivation requirements of bamboo make it a cost effective reinforcement material, particularly in developing countries that are highly susceptible to seismic activity, but do not have the financial capabilities to implement retrofitting technologies [13].

The synergy between geopolymer technology and bamboo fiber reinforcement enables the creation of a novel composite system that utilizes the unique attributes of each component [14]. The alkaline environment of geopolymers enhances bonding between the fibers and matrix, and the cellular structure of bamboo enables efficient crack bridging and energy absorption during seismic activity [15]. It is estimated that approximately 2.5 billion people reside in geographic regions that cultivate bamboo; many of these individuals reside in geographic regions that are susceptible to frequent seismic activity [16]. Therefore, developing regional retrofitting solutions using locally sourced bamboo can assist in building community resiliency, creating job opportunities and supporting traditional bamboo-based industries [17].

Figure 1. Bamboo trees.
*(**Source:** Original Image)*

Novel Contributions

This study is the first to combine geopolymer composite materials and natural fiber reinforcement, addressing a significant omission in using sustainable materials for seismic retrofitting. Unlike previous research that has looked at the individual elements of geopolymer composites and natural fiber reinforcement, and studied them under ambient curing conditions with either a single type of fiber or matrix, this study provides:

1. A dual-alkali silane surface treatment that was optimized for use with bamboo fibers in geopolymer matrices with high alkalinity, providing an enhanced bond between the fibers and the matrix;
2. A systematic optimization of a geopolymer binder made from a 70/30 by weight mixture of Class F fly ash and Ground Granulated Blast Furnace Slag (GGBFS), which provided a balance of early strength development and long term durability; and
3. Demonstration of a transition from brittle to quasi-ductile fracture modes at the optimum 3% fiber loading, which is important for energy absorption during seismic activity, but has been rare in geopolymer systems.

The study's combined approach is aimed at seismic retrofitting applications — a setting that requires both good mechanical properties and sustainability — distinguishing it from most of the existing research into geopolymer-fiber systems that are generally intended for normal building construction.

LITERATURE REVIEW

Geopolymers represent new types of inorganic polymers produced by the alkali-activated aluminosilicates which produce networks of silicon-oxygen-aluminum tetrahedra. The concept of geopolymers was developed by Davidovits during the 1970s [14]. The geopolymerization reaction is based upon the dissolution of aluminosilicate materials within an alkaline environment, followed by the transport of the resulting soluble compounds to the point of polycondensation, and subsequent hardening into a rigid three dimensional polymer matrix [15].

The general chemical formula representing the composition of geopolymers can be written as follows: Mn[-(SiO2)z-AlO2)n·wH2O, where M represents the alkaline cation (Na+ or K+); n is the degree of polycondensation; z represents the Si/Al molar ratio (usually between 1.5 and 2.5 for best performance); and w represents the water content [16]. Fly ash is the most commonly examined geopolymer precursor because it is a very common by-product of coal burning. It has been determined that Class F fly ash (less than 10% CaO) results in geopolymers with both long-term and high acid resistance strength, whereas Class C fly ash (greater than 10% CaO) is characterized by rapid strength gain [17].

Studies have demonstrated that when 20-40% ground granulated blast furnace slag (GGBFS) is added to fly ash, the rate of geopolymer setting increases dramatically and early-age strength is improved [18-19]. Studies indicate that geopolymers exhibit compressive strengths ranging between 20-100 MPa, similar to, or greater than that of regular concrete [20]. However, they typically display much lower tensile and flexural strengths (approximately 10-15% of their respective compressive strengths) with brittle fracture properties [21]. Studies have demonstrated that geopolymers exhibit increased durability in comparison to OPC-based concretes, including: improved acid resistance due to the absence of calcium hydroxide [22]; resistance to sulfate attack and chloride penetration [23]; and increased high-temperature properties, demonstrating retention of structural integrity at temperatures exceeding 1000°C [24].

The use of natural fibers as a replacement for conventional synthetic reinforcement materials has become popular in recent years due to their biodegradability and renewability. Major benefits associated with using natural fibers include reduced mass relative to glass fibers (1.2–1.6 g/cm³ vs 2.5 g/cm³) and significantly reduced production energy consumption; further, it has been reported that approximately

50% of the total energy required to manufacture glass fiber-reinforced systems can be conserved by using natural fibers and approximately 60% of the total CO^2 emissions generated by glass fiber-reinforced systems can be eliminated [25], [26]. The cellulose content in natural fibers is a primary factor influencing tensile strength, with increased cellulose contents exhibiting improved mechanical performance [27].

In addition to providing mechanical reinforcement, natural fibers provide thermal and acoustic insulation, contributing to improved energy efficiency of buildings [28]. Challenges associated with the use of natural fibers include hydrophilic properties (water absorption, swelling, and degradation), variability in the properties of natural fibers, degradation of natural fibers at elevated temperatures (>200°C), and degradation of lignin and hemicellulose in cementitious matrices at alkaline pH values [29], [30]. Techniques to enhance the properties of natural fibers in alkaline binders include surface modification processes. The sodium hydroxide (NaOH) treatment process has been shown to dissolve hemicellulose, lignin, and pectin, thereby increasing the surface area and cellulose content at the interface [31].

Studies have reported an increase in tensile strength of 21% for sisal fibers treated with 5% NaOH solution and an increase in interfacial shear strength of 35% in cement-based composite materials [32]. Chemical bond formation between hydroxyl groups of the natural fiber and matrix materials occurs through the application of silane coupling agents, enhancing interfacial adhesion [33]. More recent methods include enzymatic treatments and plasma treatments, which alter the surface chemistry of the natural fibers without modifying their bulk properties [34].

Bamboo is composed of cellulose (40–50%), hemicellulose (20–25%), and lignin (20–30%) [35]. Its hierarchical structure, which extends from the macroscopic culm to the microscopic fibrils, contributes to its unique mechanical properties [36]. The outer layers contain tightly packed vascular bundles, whereas the inner layers comprise less densely packed parenchyma cells, creating a gradient of density that generates a stiff outer layer capable of carrying high loads [37]. (See Figure 2.) Bamboo fibers typically display tensile strengths in the range of 140-800 MPa, depending on the species, method of extraction, and test conditions [38].

The modulus of elasticity of bamboo fibers (See Figure 3.) is typically in the range of 10–40 GPa and demonstrates high stiffness-to-weight ratios [39]. The elongation at break of bamboo fibers is in the range of 1.5–3.5%, indicating moderate ductility [40]. Water absorption has a significant effect on the mechanical behavior of bamboo fibers, causing an increase in diameter and micro-cracks in the fiber, resulting in decreased tensile strength [41]. Early research by Ghavami [42] demonstrated that the inclusion of bamboo fibers to reinforced concrete resulted in a significant improvement in flexural toughness and post-cracking load capacity. Subsequent studies demonstrated that bamboo fibers could improve crack control, impact resistance, and energy absorption at fiber volume fractions up to 3% [43].

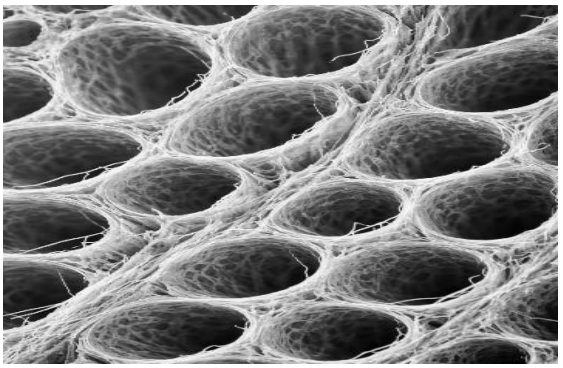

Figure 2. Representative microstructural morphology of bamboo fibers illustrating hollow vascular lumens and layered cell walls at the microscale (~10–50 μm feature size). *(Source: Original Image)*

Figure 3. Bamboo fibers.
(Source. Original Image)

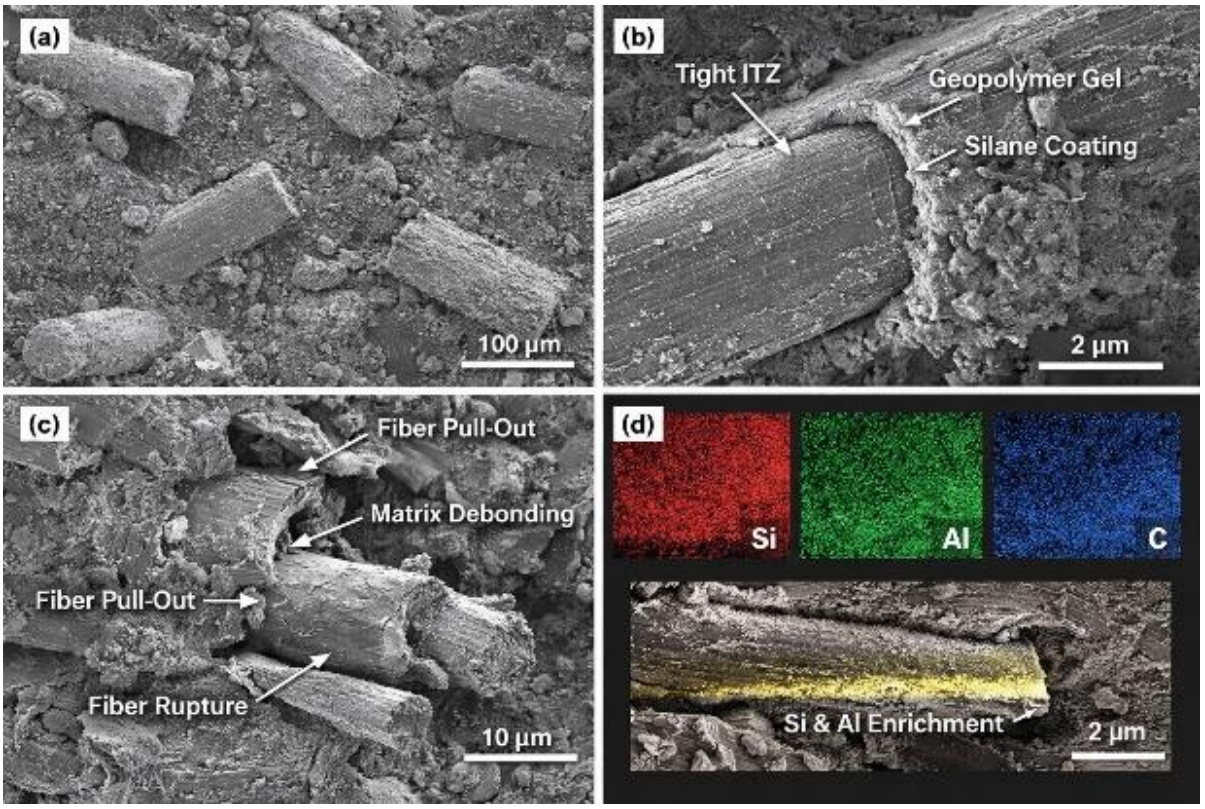

Figure 4. Fiber matrix interactions in geopolymer composite. SEM Higher Magnification of 2000-5000x. *(Source: Original Image)*

A major concern regarding the long-term durability of geopolymers in alkaline environments is the degradation of lignin and hemicellulose, which weaken the bonding at the interface between the fiber and the matrix [44]. Various surface treatments have been investigated, such as alkali treatment, silane coupling agent treatment, and bitumen coating, to minimize this degradation [45].

METHODOLOGY

The detail methodology implemented is shown (Figure 6). The details are described the following section:

Materials Selection and Characterization

The geopolymer precursor blends applied to the study contained Class F Fly Ash provided by a thermal power station and that meets ASTM C618 requirements.

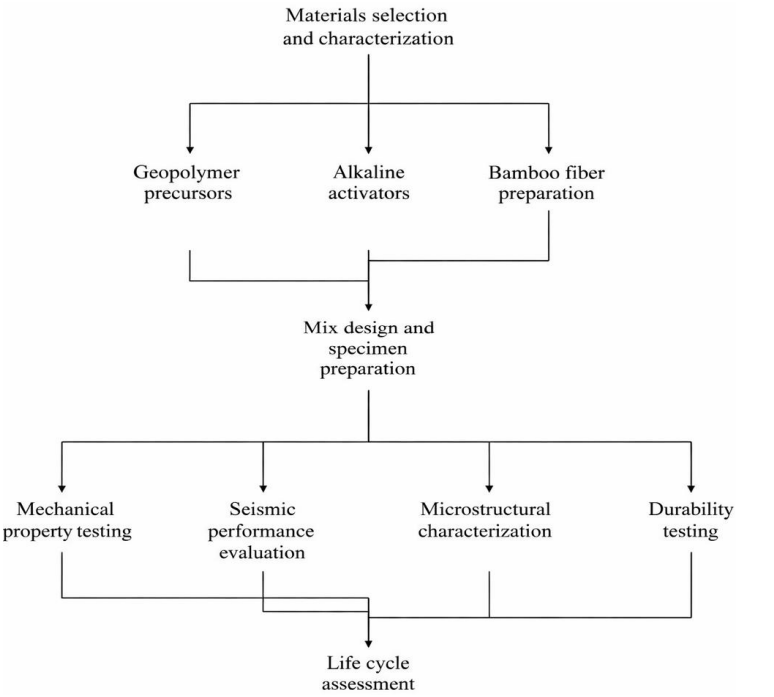

Figure 6. Methodology applied.

The chemical composition of the fly ash is as follows: 58.2% SiO_2, 26.4% Al_2O_3, 6.8% Fe_2O_3 and 3.2% CaO. The fly ash has an average diameter of 12.4 μm, which is primarily in the form of spheres and a BET surface area of 1.84 m^2/g. Ground Granulated Blast Furnace Slag (GGBFS), which is produced from steel production and meets ASTM C989 specifications, had the following chemical composition: 34.2% SiO_2, 14.6% Al_2O_3, 39.8% CaO, 8.4% MgO. The average particle diameter of GGBFS was 18.6 μm and its Blaine fineness is 4250 cm^2/g.

The optimum precursor mixture of 70% fly ash and 30% GGBFS was chosen. The alkaline activator system employed comprised commercially available sodium hydroxide pellets (98% pure) dissolved in deionised water to make 10M, 12M, and 14M solutions. Each of these solutions was made 24 hours before mixing and allowed to cool to room temperature. Commercially available sodium silicate solution with a SiO_2/Na_2O ratio of 2.5, containing 29.4% SiO_2, 14.7% Na_2O, and 55.9% water, was also used as the activator, with sodium silicate/sodium hydroxide weight ratios of 1.5, 2.0, and 2.5 evaluated. All of the mixes had an activator-to-precursor weight ratio of 0.40. Bamboo fibers of the species Bambusa balcooa were mechanically chemically extracted.

The process of mechanical chemical extraction involved longitudinal splitting, hammer milling, and disk refining with gap sizes of 1.0–0.3 mm. The bamboo fibers produced were approximately 15–35 mm in length and 0.2–0.5 mm in diameter. There were four different treatments of the fibers tested: T0 represented the control.

It entailed washing the fibers with deionised water and then drying them at 60°C for 24 hours. Treatment T1 entailed alkaline treatment of the fibers with 5% NaOH for 24 hours, and subsequent washing and drying of the fibers. Treatment T2 involved first performing T1 on the fibers, and subsequently treating them with a 2% γ-aminopropyltriethoxysilane solution in a 95:5 ethanol-water solution for two hours and drying the fibers at 80°C for 4 hours.

Treatment T3 involved subjecting the fibers to steam explosion at 180°C and 1.2 MPa for ten minutes followed by rapid decompression and drying. The tensile strength of individual fibers ranged from 361 MPa to 384 MPa and elastic modulus values ranged from 18.2 to 22.6 GPa, while densities of the fibers varied from 0.68 to 0.74 g/cm^3.

The chemical analysis of the bamboo fibers indicated a range of cellulose content from 49–52%, a range of lignin content from 21–24%, and a range of hemicellulose content from 18–21%. (See Table 1, Table 2 & Table 3)

Mix Design and Specimen Preparation

An L27 orthogonal array based on the Taguchi method was used to determine the most important factors such as the ratio of Fly Ash/GGBFS, Molar concentration of NaOH, Ratio SS/SH, Type of Fiber Treatment, Volume percentage of fibers between 1 and 5 %, and Orientation of Fibers. (See Table 4. and Table 5). After that Response Surface Methodology (RSM) was used to determine the optimal value of the four most important factors using a Box-Behnken Design (See Table 6). The mixing process was performed in accordance with a standard procedure; precursors dried were mixed for 5 min at 140 rpm, then, the alkaline activator was added slowly over 3 min of slow rotation, then the speed was increased to 285 rpm for 4 min, then 200 rpm for 5 min of fibre dispersion and finally for 2 min at 400 rpm of high speed mixing. Workability of the fresh geopolymer composite was determined using a mini slump cone test and should result in a flow diameter between 180 and 220 mm.

Table 1. Physical and Chemical Properties of Class F Fly Ash.

Property	Value	Test Method / Remarks
Source	Thermal power plant	—
Standard compliance	ASTM C618 (Class F)	—
SiO_2 (%)	58.2	XRF analysis
Al_2O_3 (%)	26.4	XRF analysis
Fe_2O_3 (%)	6.8	XRF analysis
CaO (%)	3.2	XRF analysis
Other oxides (%)	Balance	XRF analysis
Median particle size (μm)	12.4	Laser diffraction
Particle morphology	Predominantly spherical	SEM observation
Specific surface area (m^2/g)	1.84	BET method
Loss on ignition (LOI, %)	2.1	ASTM C311

Table 2. Physical and Chemical Properties of Ground Granulated Blast Furnace Slag (GGBFS).

Property	Value	Test Method / Remarks
Source	Steel manufacturing facility	—
Standard compliance	ASTM C989 (Grade 120)	—
SiO_2 (%)	34.2	XRF analysis
Al_2O_3 (%)	14.6	XRF analysis
CaO (%)	39.8	XRF analysis
MgO (%)	8.4	XRF analysis
Minor constituents (%)	Balance	XRF analysis
Median particle size (μm)	18.6	Laser diffraction
Blaine fineness (cm^2/g)	4250	ASTM C204
Hydraulic activity index (28 days, %)	98	ASTM C989
Basicity coefficient $(CaO+MgO)/(SiO_2+Al_2O_3)$	0.99	Calculated

Table 3. Selected Geopolymer Precursor Blend Composition.

Component	Mass Fraction (%)	Justification
Fly ash	70	High silica content, spherical morphology, improved workability
GGBFS	30	High calcium content, enhanced early-age reactivity and strength
Total	100	Optimized precursor blend

Table 4. Coding of Factors for Taguchi L27 Design (Screening Stage).

Factor Code	Experimental Factor	Level 1	Level 2	Level 3
A	Fly ash : GGBFS ratio	100:00:00	70:30:00	50:50:00
B	NaOH molarity (M)	10	12	14
C	SS/SH ratio	1.5	2	2.5
D	Fiber treatment	T0	T1	T2*
E	Fiber content (vol. %)	1	3	5
F	Fiber orientation	Random	Aligned	—

Table 5. Factor levels (coded and actual values).

Factor	−1	0	1
A: Fly ash : GGBFS	100:00:00	70:30:00	50:50:00
B: NaOH molarity (M)	10	12	14
C: SS/SH ratio	1.5	2	2.5
D: Fiber content (vol.%)	1	3	5

Table 6. RSM Box–Behnken Design (Optimization Stage).

Run	A	B	C	D	Run	A	B	C	D
1	−1	−1	0	0	15	1	0	0	−1
2	−1	1	0	0	16	1	0	0	1
3	1	−1	0	0	17	0	−1	0	−1
4	1	1	0	0	18	0	−1	0	1
5	−1	0	−1	0	19	0	1	0	−1
6	−1	0	1	0	20	0	1	0	1
7	1	0	−1	0	21	0	0	−1	−1
8	1	0	1	0	22	0	0	−1	1
9	0	−1	−1	0	23	0	0	1	−1
10	0	−1	1	0	24	0	0	1	1
11	0	1	−1	0	25	0	0	0	0
12	0	1	1	0	26	0	0	0	0
13	−1	0	0	−1	27	0	0	0	0
14	−1	0	0	1					

Specimens were produced as needed for their respective tests, i.e., Compressive Strength, Flexural Strength, Tensile Testing. (See Figure 5) For all tested mechanical properties, six specimens were manufactured for each mixture.

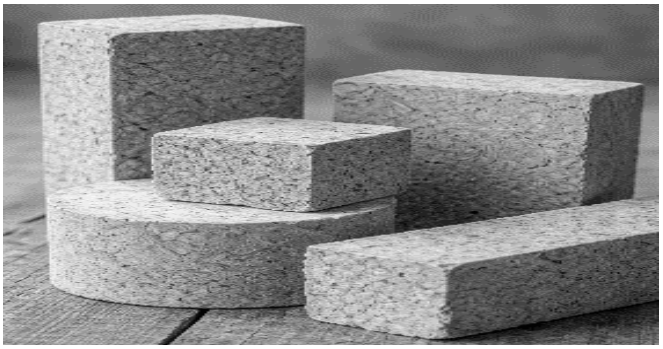

Figure 5. Sample Specimens.
(Source: Original Image)

In each case, the fresh mixture was filled in two layers into the mold and vibrated for 30 s at 50 Hz. After 24 h, the specimens were removed from the mold and stored under controlled conditions at 23 ± 2 °C and 50 ± 5 % r.h. in plastic foil. The mechanical testing of the specimens took place after 7, 14, 28 and 56 d in order to obtain the complete picture of the strength development of the composite over time.

Mechanical Properties Testing

The mechanical properties of the composite material were evaluated by performing standard mechanical property tests in order to provide a consistent basis for comparison of test data. The compression test samples were tested in accordance with ASTM C109 using a 2000 kN Universal Testing Machine that utilized a loading rate of 0.36 MPa/sec. Longitudinal and transverse strain measurements were made utilizing high precision electrical resistance strain gauges (0.01% precision, 10 mm gauge length). The flexural performance of the composite material was determined in accordance with ASTM C293 and was evaluated using a three-point bending apparatus with a 25 kN load cell and a LVDT (±0.001 mm resolution), which was used to determine deflection as a function of applied force.

The crosshead of the three-point bending apparatus was moved at a constant speed of 0.05 mm/min. (See Figure 17) Tensile testing of the composite material utilized two custom designed gripping fixtures, which were used to prevent slippage of the test specimen during testing. The tensile testing was also performed at a constant crosshead speed of 0.5 mm/min. An LVDT clip-on extensometer (±0.02% accuracy, 25 mm gauge length) was used to measure the strain developed in the test specimen during the course of the tensile test. In addition, Brazilian split-tension tests were performed on cylindrical test specimens (100 × 200 mm diameter and height) in accordance with ASTM C496. The Brazilian split-tension test is an indirect method for evaluating the tensile strength of concrete; however, it has been shown to be effective in determining the tensile strength of cement-based materials. The loads were applied to the test specimens at a rate of 0.7–1.4 MPa/min.

RESULTS AND DISCUSSION

Matrix Optimization

Evaluation of different blending ratios for the precursors revealed that a 70:30 fly ash to GGBFS composition produced the best combination of mechanical and rheological properties. The 70:30 blend was found to produce the greatest 28-day compressive strength of 48.6 MPa when evaluated at a fixed activator composition (12 M NaOH and SS/SH of 2.0). This represented an 18% improvement in 28-day compressive strength over the pure fly ash system (41.2 MPa) and an 8% improvement over the 50:50 blend (45.1 MPa). These improvements were primarily due to the synergistic interactions between the spherical morphology and reactive silica content of the fly ash and the high calcium content of the GGBFS. This resulted in improved workability and facilitated C-S-H gel formation. Additionally, the setting times for the blends were greatly improved. Pure fly ash systems had extended setting times (420 minutes for the initial set and 780 minutes for the final set). Conversely, the 70:30 blend set at reasonable times (68 minutes for the initial set and 165 minutes for the final set) (See Figures 7–10).

The effect of activator concentration on compressive strength was also examined. Compressive strength increased from 42.3 MPa at an activator concentration of 10M to 48.6 MPa at an activator concentration of 12M, then decreased to 46.1 MPa at an activator concentration of 14M. Excessively high activator concentrations caused accelerated setting times, entrapped water, increased pore volume, and decreased mini-slump flow from 195mm (at 10M) to 142mm (at 14M). Analysis via Fourier Transform Infrared Spectroscopy (FTIR) revealed increased polymerization of the geopolymer paste at increasing activator concentrations, as evidenced by a shift in the 1000cm^{-1} Si-O-T band to lower wavenumbers. However, excessive polymerization occurred in the 14M samples as evidenced by the presence of sodium carbonate peaks, indicative of undesirable secondary reactions. Evaluating the optimal sodium silicate-to-hydroxide (SS/SH) ratio also demonstrated a similar balance between compressive strength and rheology.

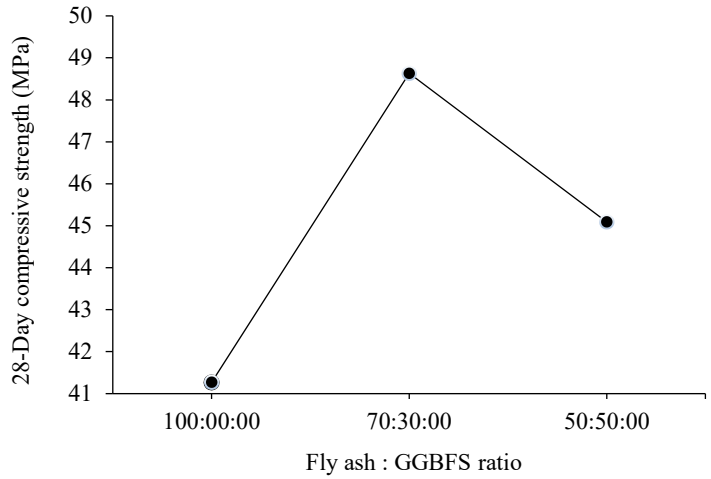

Figure 7. Variation of 28-day compressive strength with fly ash–GGBFS ratio at fixed activator concentration (12M NaOH, SS/SH = 2.0).

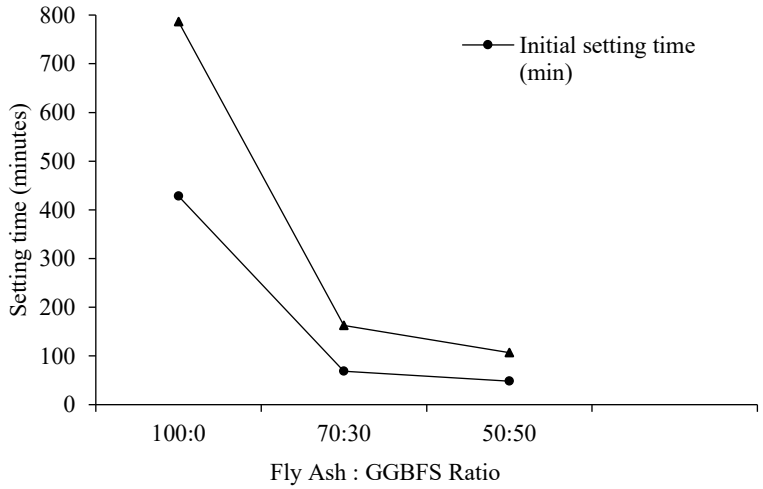

Figure 8. Influence of GGBFS incorporation on initial and final setting times of fly ash–slag geopolymer binders.

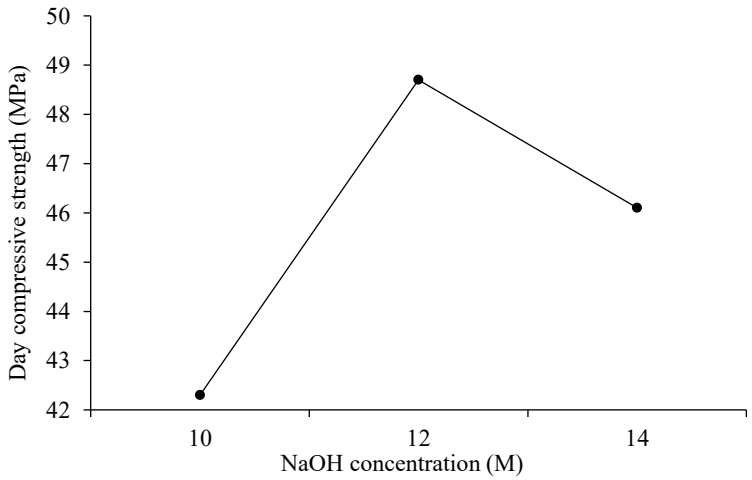

Figure 9. Effect of NaOH activator concentration on 28-day compressive strength of fly ash–GGBFS (70:30) geopolymer composites (SS/SH = 2.0).

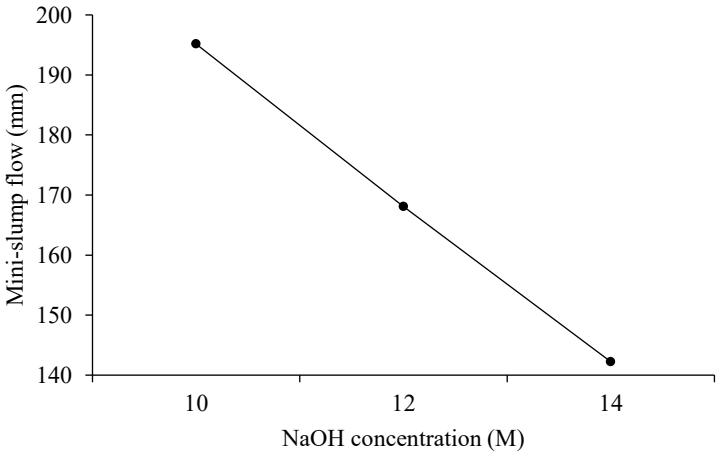

Figure 10. Variation of mini-slump flow with NaOH concentration, indicating reduced workability at higher alkalinity.

Compressive strength increased from 44.2 MPa at an SS/SH ratio of 1.5 to 48.6 MPa at a SS/SH ratio of 2.0 and reached 51.3 MPa at a SS/SH ratio of 2.5. At higher SS/SH ratios there is greater soluble silica available to produce a denser aluminosilicate network. The 29Si Nuclear Magnetic Resonance (NMR) spectra of the geopolymer paste indicated an increase in the number of Q4(3Al) and Q4(4Al) sites, corresponding to the denser network. However, excessive viscosity at a SS/SH of 2.5 hindered fiber dispersion and prolonged the setting time (124 minutes compared to 68 minutes at a SS/SH of 2.0). Therefore, based on the results of this study, the optimized geopolymer matrix composition was determined to be 70 wt.% fly ash, 30 wt.% GGBFS, activated with 12M NaOH and an SS/SH ratio of 2.0 at an activator-to-precursor mass ratio of 0.40 (See Figures 11–12).

Optimization of Fiber Parameters

A study conducted by researchers to evaluate how varying percentages of treated bamboo fibers within composite materials affected the mechanical performance of composites revealed an inconsistent relationship between fiber percentage and mechanical performance. The addition of treated bamboo fibers resulted in a non-linear increase in the mechanical properties of the composite. Specifically, the addition of treated bamboo fibers at concentrations of 0–5% by volume resulted in increases in all mechanical properties measured. Compressive strength increased from 48.6 MPa at 0% fiber content to a maximum of 52.3 MPa at 3% fiber content; however, the addition of excess amounts of fiber resulted in decreases in compressive strength to 47.8 MPa at 5% fiber content. Excess amounts of fiber caused agglomeration, resulting in increased porosity and processing difficulties.

The addition of treated bamboo fibers resulted in a significant increase in flexural strength; specifically, flexural strength increased from 5.1 MPa at 0% fiber content to 8.7 MPa at 3% fiber content, representing a 71% increase in flexural strength. However, at higher fiber content, the addition of treated bamboo fibers resulted in the creation of weak planes formed as a result of fiber clustering and thus resulted in decreases in flexural strength. Tensile properties were the most significantly enhanced as a result of the addition of treated bamboo fibers.

The addition of treated bamboo fibers resulted in a doubling of the direct tensile strength from 2.1 MPa (unreinforced) to 4.2 MPa at 3% fiber content. Post-crack behavior also transitioned from brittle fracture to ductile strain hardening. Specifically, strain capacity at peak load increased from 0.08% to 0.31%. Toughness indices following ASTM C1018 were also greatly increased; specifically, I_5 increased from 1.0 to 4.8, and I_{10} and I_{30} increased from 1.0 to 8.2 and 15.7, respectively, indicating a great deal of post-crack load retention and energy absorption. Therefore, it was concluded that 3% fiber content is the optimal fiber content for use in composites (See Figures 13–15).

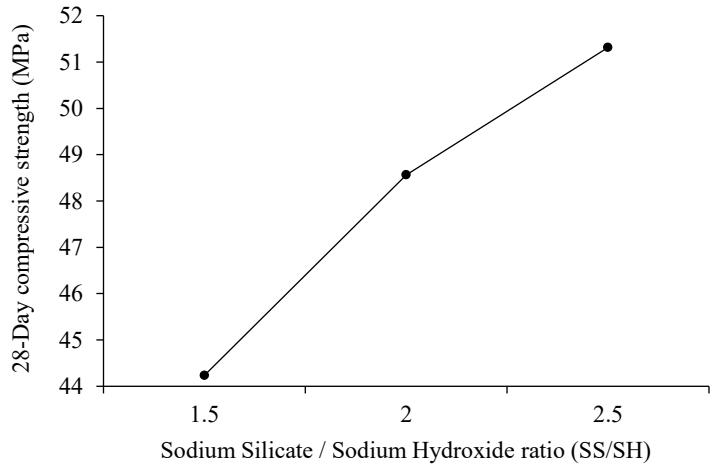

Figure 11. Effect of sodium silicate to sodium hydroxide ratio on 28-day compressive strength of fly ash–GGBFS (70:30) geopolymer composites activated with 12M NaOH.

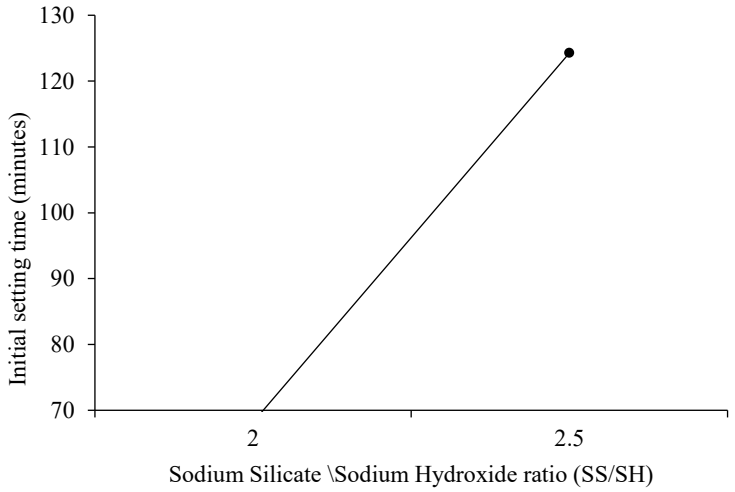

Figure 12. Influence of SS/SH ratio on initial setting time of geopolymer binders, highlighting workability constraints at higher sodium silicate contents.

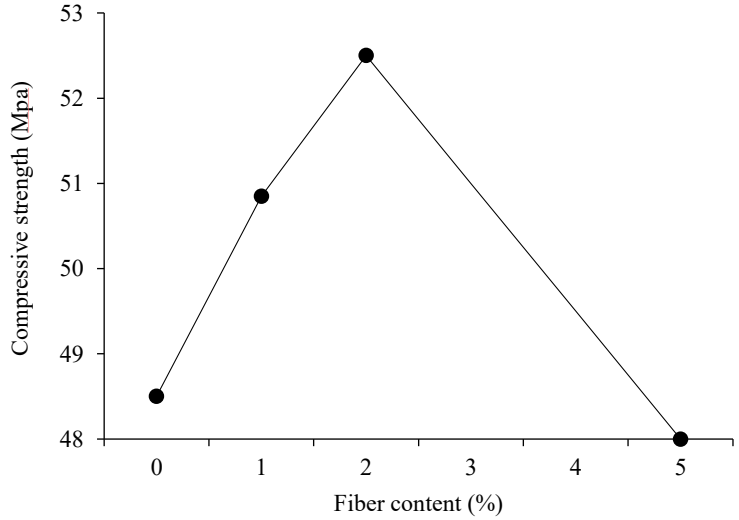

Figure 13. Variation of compressive strength with treated bamboo fiber content.

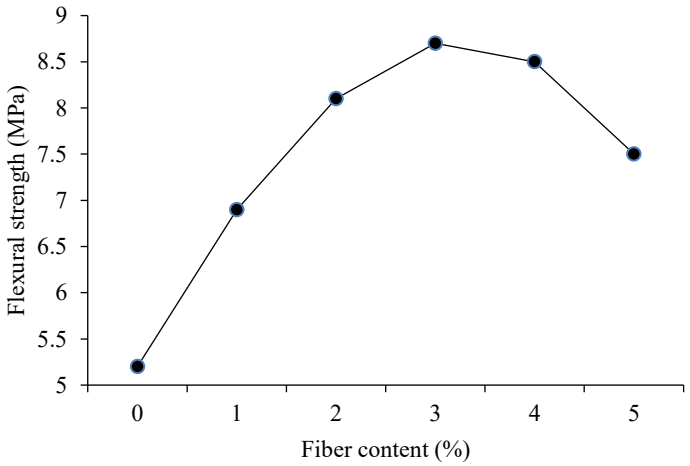

Figure 14. Effect of fiber volume fraction on flexural strength of geopolymer composites.

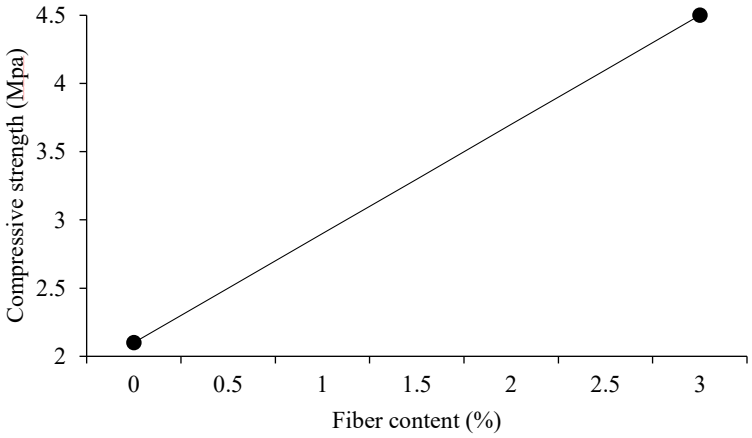

Figure 15. Influence of fiber reinforcement on direct tensile strength

In order to investigate the effect of fiber length on the mechanical properties of composites, researchers evaluated the effects of fiber length at a fixed 3% volume fraction of treated bamboo fibers. Results indicated that compressive strength remained relatively constant between 49.8 and 52.3 MPa for fiber lengths of 10, 20, 30, and 40 mm. In contrast, flexural performance exhibited noticeable variations; specifically, flexural strength increased from 7.2 MPa (10 mm) to 8.7 MPa (30 mm), after which flexural strength decreased to 8.1 MPa at 40 mm. Long fibers are beneficial for enhancing crack bridging and stress transfer; however, longer fibers can suffer from dispersion difficulties. Utilizing the Kelly-Tyson model, the critical fiber length was determined to be approximately 17 mm, making the 30 mm fiber, which is 1.8 times the critical length, ideal. Additionally, aspect ratios ranging from 25 to 100 (assuming a 0.4 mm fiber diameter) support 30 mm as the optimal length, in accordance with literature benchmarks of 50-75 (See Figures 16 and 17).

The results of the investigation into fiber orientation effects on the mechanical performance of treated bamboo fiber-reinforced composites demonstrated that random fiber orientation produces isotropic behavior with consistent flexural and tensile strengths of 8.7 MPa and 4.2 MPa, respectively, and with low variability. Aligned fibers parallel to the direction of loading improve flexural and tensile strengths to 12.4 MPa and 6.8 MPa, respectively; however, aligned fibers perpendicular to the direction of loading significantly reduce performance, yielding 5.2 MPa in flexure and 2.6 MPa in tension with greater variability than random orientation. (See Figure 18) Consequently, random fiber orientation was determined to be the most suitable orientation, providing predictable and stable performance under the multidirectional stress states common in seismic retrofitting environments.

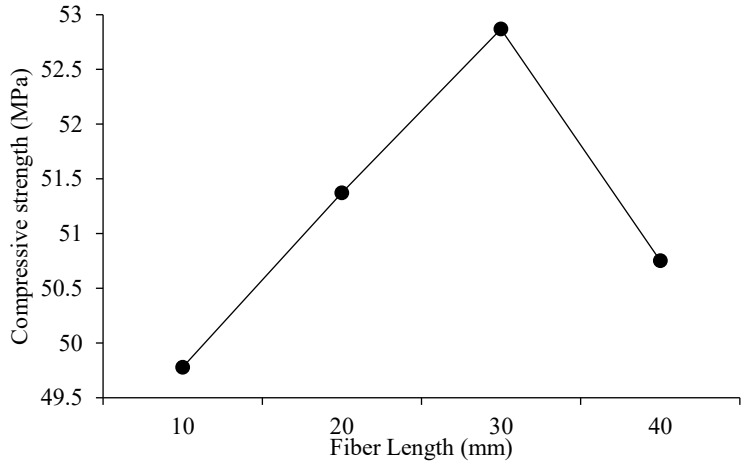

Figure 16. Influence of fiber length on compressive strength of geopolymer composites at 3% fiber volume fraction.

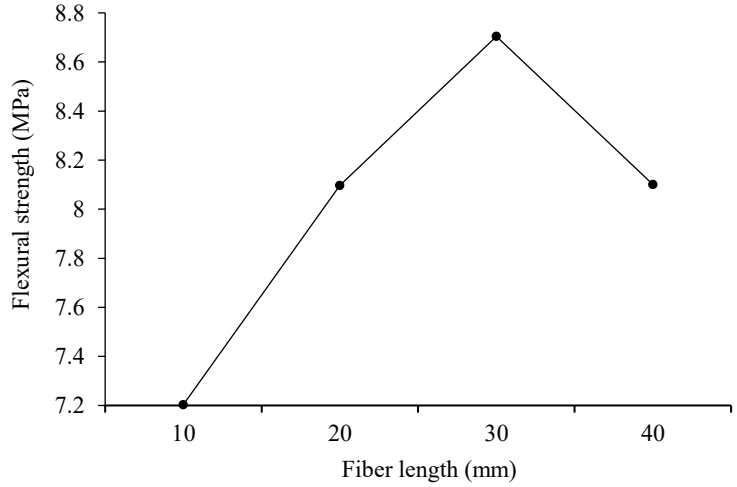

Figure 17. Effect of fiber length on flexural strength, highlighting optimal performance at 30 mm.

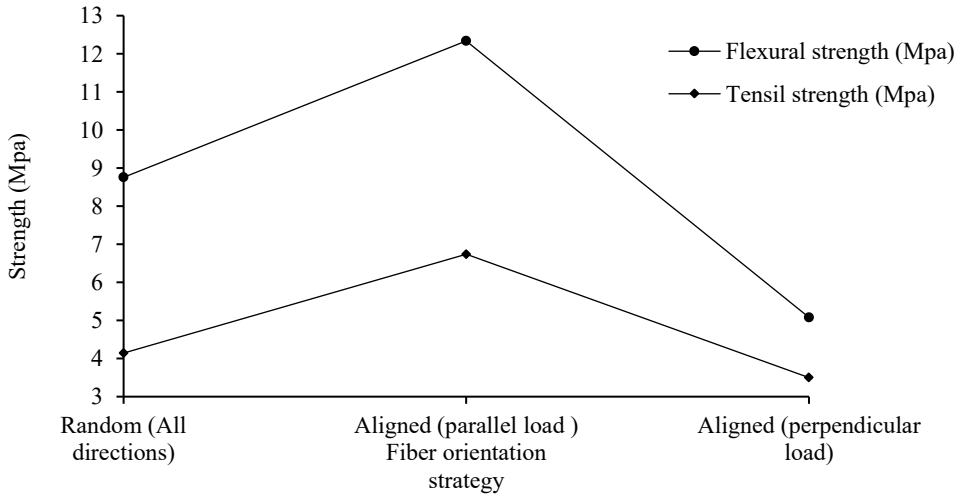

Figure 18. Influence of fiber orientation on flexural and tensile strengths of geopolymer composites, comparing random three-dimensional distribution and aligned unidirectional configurations under parallel and perpendicular loading.

Comprehensive Mechanical Characterization

The incorporation of 3% randomly oriented, T2-treated 30 mm long bamboo fibers into an optimized 70:30 fly ash to GGBFS activated with 12M NaOH and an SS/SH ratio of 2.0 resulted in significant improvements in the mechanical and deformation behavior of the resulting composite. A 28-day compressive strength average of 52.3 ± 1.8 MPa was achieved with linearly elastic stress–strain behavior up to approximately 40% of the ultimate strength being exhibited. An elastic modulus of 22.4 ± 1.1 GPa was determined for the fiber-reinforced composite, a 15% increase above that of the unreinforced geopolymer matrix due to the effects of fiber-induced confinement. Peak strain increased to 0.31% from 0.24% in the unreinforced matrix, providing a 39% increase in deformation capacity; the post-peak strength retention of the reinforced specimens was also greatly improved, with the reinforced specimens retaining 60% of the peak load at 0.5% strain compared with 35% for the unreinforced matrix. The Poisson's ratio of both materials remained consistent at 0.21 ± 0.02. The failure mode of the unreinforced matrix changed from a brittle failure mode where the specimen failed catastrophically upon reaching maximum compressive strength to a progressive crushing with interconnected cracking when the bamboo fibers bridged cracks and prevented catastrophic collapse. The flexural performance of the composite was also greatly enhanced with a 28-day flexural strength of 8.7 ± 0.6 MPa. Linear behavior was exhibited on the load-deflection curve until the first crack at 6.2 MPa; beyond this point, the crack bridging provided by the bamboo fibers allowed for a controlled increase in load capacity. (See Figure 19).

In contrast, the unreinforced specimens experienced an abrupt post-peak decrease in load capacity; the reinforced composite, however, experienced a slow decrease in stiffness and substantially greater flexural toughness, producing 4.82N·m or an increase of nearly 640% over the unreinforced value of 0.65N·m. The modulus of rupture to compressive strength ratio increased to 16.6% as opposed to 10.5% for the unreinforced material demonstrating the composite's ability to provide a much better enhancement of tensile related properties for use in seismic applications. Direct tensile testing provided additional evidence of these improvements with a direct tensile strength of 4.2 ± 0.3MPa and an elastic response until initial matrix cracking at ~2.8MPa. Following the onset of matrix cracking, micro-cracks formed but the fibers maintained load resistance through pullout and fracture mechanisms, allowing for a pseudo-ductile response with a peak stress at 0.31% strain. The split tensile strength was 3.8 ± 0.3 MPa or 90% of the direct tensile strength. Fracture energy measured using the RILEM protocol was 1.84 N/m or 12 fold (900%) the value obtained for the unreinforced geopolymer. Collectively these enhancements represent significant increases in crack resistance, energy absorption and ductility, each of which is important in mitigating seismic loads. (See Figure 20)

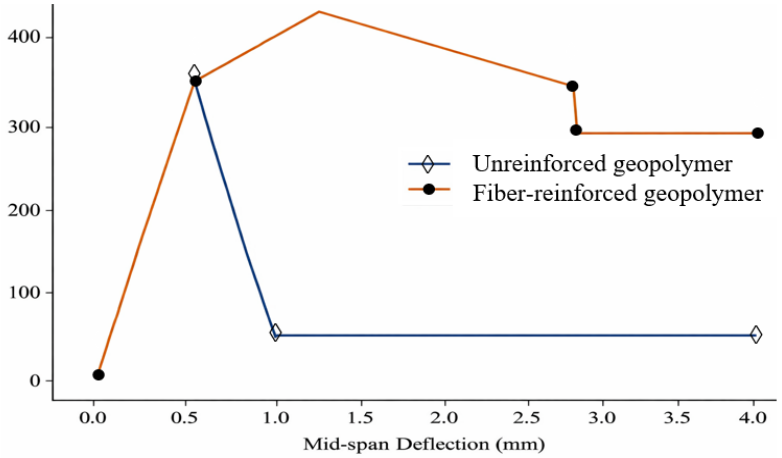

Figure 19. Representative load-deflection response of fiber-reinforced and unreinforced geopolymer composites under three-point bending, showing enhanced post-crack load carrying capacity and flexural toughness due to fiber bridging.

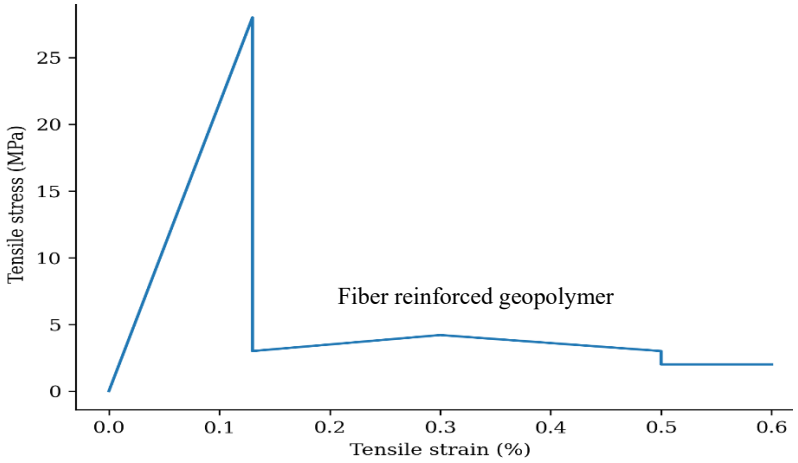

Figure 20. Representative direct tensile stress-strain response of fiber-reinforced geopolymer composite, illustrating strain-hardening behavior, enhanced deformation capacity, and gradual post-peak softening due to fiber bridging.

Comparative Analysis with Previous Geopolymer Composite Studies

Significant increases in mechanical characteristics have been identified in this research over prior reports of geopolymer-natural fiber composite materials. Compressive strengths of 52.3 MPa were developed with a 3% volume fraction of bamboo fibers and are comparable to those values published in other works: Alomayri et al. (2014) used a 45 MPa value for cotton fibers added into fly ash geopolymers at the same or near the same volumes as this work and Silva et al. (2017) reached 48 MPa in metakaolin based geopolymers using sisal fibers. Significantly greater than the normal 40-50% increases in flexural strength (from 6.1 MPa to 8.7 MPa) were also found.

The 100% increase in tensile strength (to 4.2 MPa) was especially impressive in comparison to the 55% increase in flax fibers added into fly ash geopolymers at a 5% volume fraction by Korniejenko et al. (2018). The improved performance of the bamboo-fiber reinforced geopolymers can be due to the following three reasons: (i) Bamboo has a hierarchical microstructure (See Figure 4) which improves the mechanical bond to the fibers; (ii) A combination of two alkalis (NaOH and KOH) and the addition of an organosilane to the geopolymer matrix minimized the degradation of the fibers during processing while improving the adhesion between the fibers and the geopolymer matrix; (iii) Geopolymerization in the alkaline matrix occurs faster around the surface of the fibers because of the synergism created by blending fly ash and GGBFS. The transition of the fracture mode from brittle to pseudo-ductile, found in this work, is a significant advancement that addresses the primary limitation identified in the recent reviews by Ranjbar and Zhang (2020), as it appears that many geopolymer-fiber composites, even after adding fiber, fail predominantly through brittle fracture modes.

CONCLUSIONS

This study has produced and characterized sustainable bamboo fiber reinforced geopolymer composites for use in seismic retrofitting of structures, producing significant results. The most successful combination was that of 70% fly ash, 30% GGBFS, 12M sodium hydroxide, an SS/SH ratio of 2.0, and 3% alkali-silane treated bamboo fibers of 30mm length randomly oriented through the matrix. The combination provided the best balance of both the structural properties (mechanical), workability, and the environmental sustainability.

From a structural standpoint, the most successful composite exhibited a compressive strength of 52.3 MPa, a flexural strength of 8.7 MPa which is an increase of 71% relative to the unreinforced matrix, and a tensile strength of 4.2 MPa or an increase of 100%. Most importantly, the material transitioned from a brittle fracture mode to a pseudo-ductile mode, a critical transition to improve energy absorption and overall seismic retrofitting performance.

Practical Implementation Considerations

Although laboratory test results indicate a great deal of promise for bamboo-fiber reinforced geopolymer composites in seismic retrofitting, there are many technical barriers which need to be resolved before such an application can become widespread. Technical barriers related to durability include: the potential for fibers to degrade over time due to continuous exposure to an alkaline environment; the potential for the material to undergo dimensional changes as it experiences varying levels of moisture content; and the potential for the material's performance to decrease as it undergoes freeze/thaw cycles in moderate climates. The alkali-silane treatment does provide some degree of protection against some of the potential issues noted above, however, it is essential to conduct accelerated aging tests on specimens treated using the treatment described herein, to determine the specimen's ability to withstand realistic environmental conditions, for a given amount of time. Production barriers that exist at a large scale include:

(i) producing bamboo fibers with a high level of consistency regarding fiber length, diameter and quality, regardless of the type of bamboo used or the season of harvesting;
(ii) Developing manufacturing processes that produce geopolymer composites that have good fiber distribution at an economical price;
(iii) Developing quality assurance programs to monitor activator solutions and curing regimens; and
(iv) Finding ways to extend the workable time of geopolymer mixtures so that they may be more competitive economically with traditional cementitious materials.

It is also important to verify long term performance through field demonstration projects that have a full structural health monitoring system in place, to validate laboratory findings when subjected to realistic seismic loads. In addition, it is necessary to develop standard testing protocols, design guides and building codes specifically for bamboo-geopolymer composite systems to make them more acceptable to the construction industry. An additional consideration that needs to be evaluated is whether the increased cost associated with treating the fibers and activating the geopolymer mixture is offset by the long term benefits of reduced maintenance requirements, longer service life and enhanced environmental sustainability. Therefore, addressing the previously mentioned implementation barriers will require significant research and pilot scale demonstrations to effectively transition this promising technology into practical seismic retrofitting applications.

Acknowledgments

The author wish to thanks all authors for collaborative research done and contributing their skills to enhance the research article quality.

REFERENCES

1. Rossetto T, Ioannou I, Grant DN. Existing empirical vulnerability and fragility functions: Compendium and guide for selection. GEM Technical Report. GEM Foundation, Pavia, Italy; 2013.
2. Petek Gursel A, Masanet E, Horvath A, Stadel A. Life-cycle inventory analysis of concrete production: A critical review. Cem Concr Compos. 2014; 51:38–48.
3. International Energy Agency. Global Status Report for Buildings and Construction 2019. Paris, France: IEA; 2019.
4. Davidovits J. Geopolymer chemistry and applications. 4th ed. Saint-Quentin: Institut Géopolymère; 2015.
5. Provis JL, van Deventer JSJ. Geopolymers: Structures, processing, properties and industrial applications. Oxford: Woodhead Publishing; 2009.
6. Hardjito D, Rangan BV. Development and properties of low-calcium fly ash-based geopolymer concrete. Research Report GC1. Curtin University of Technology, Perth, Australia; 2005.
7. Silva FA, Chawla N, Toledo Filho RD. Tensile behavior of high performance natural (sisal) fibers. Compos Sci Technol. 2008;68(15-16):3438–3443.

8. Janssen JJA. Mechanical properties of bamboo [dissertation]. Eindhoven: Eindhoven University of Technology; 1981.
9. Ghavami K. Bamboo as reinforcement in structural concrete elements. Cem Concr Compos. 2005;27(6):637-649.
10. International Network for Bamboo and Rattan. Bamboo and climate change mitigation. INBAR Policy Brief. Beijing, China; 2010.
11. Lobovikov D, Paudel S, Piazza M, Ren H, Wu J. World bamboo resources: A thematic study. Non-Wood Forest Products. no. 18. Rome: FAO; 2007.
12. McLellan BC, Williams RP, Lay J, van Riessen A, Corder GD. Costs and carbon emissions for geopolymer pastes. J Clean Prod. 2011;19(9-10):1080–1090.
13. Osorio L, Trujillo E, Van Vuure AW, Verpoest I. Morphological aspects and mechanical properties of single bamboo fibers. J Reinf Plast Compos. 2011;30(5):396–408.
14. Davidovits J. Geopolymers: Inorganic polymeric new materials. J Therm Anal. 1991;37(8):1633–1656.
15. Duxson P, et al. Geopolymer technology: The current state of the art. J Mater Sci. 2007;42(9):2917–2933.
16. Palomo A, et al. Chemical stability of cementitious materials based on metakaolin. Cem Concr Res. 1999;29(7):997–1004.
17. Singh B, Ishwarya G, Gupta M, Bhattacharyya SK. Geopolymer concrete: A review. Constr Build Mater. 2015;85:78–90.
18. Yip CK, Lukey GC, van Deventer JSJ. The coexistence of geopolymeric gel and calcium silicate hydrate. Cem Concr Res. 2005;35(9):1688–1697.
19. Olivia M, Nikraz H. Properties of fly ash geopolymer concrete designed by Taguchi method. Mater Des. 2012;36:191–198.
20. Sumajouw DMJ, Hardjito D, Wallah SE, Rangan BV. Fly ash-based geopolymer concrete: Study of slender reinforced columns. J Mater Sci. 2007;42(9):3124–3130.
21. Rashad AM. A comprehensive overview about the influence of different additives on alkali-activated slag. Constr Build Mater. 2013;47:29–55.
22. Bakharev T. Durability of geopolymer materials in sodium and magnesium sulfate solutions. Cem Concr Res. 2005;35(6):1233–1246.
23. Duxson P, et al. The effect of alkali and Si/Al ratio on mechanical properties of metakaolin-based geopolymers. Colloids Surf A. 2007;292(1):8–20.
24. Kong DLY, Sanjayan JG. Effect of elevated temperatures on geopolymer paste, mortar and concrete. Cem Concr Res. 2010;40(2):334–339.
25. Bledzki AK, Gassan J. Composites reinforced with cellulose based fibres. Prog Polym Sci. 1999;24(2):221–274.
26. Wötzel M, Wirth R, Flake M. Life cycle studies on hemp fibre reinforced components. Angew Makromol Chem. 1999;272(1):121–127.
27. Satyanarayana KG, Arizaga GGC, Wypych F. Biodegradable composites based on lignocellulosic fibers. Prog Polym Sci. 2009;34(9):982–1021.
28. Asdrubali S, D'Alessandro F, Schiavoni S. A review of unconventional sustainable building insulation materials. Sustain Mater Technol. 2015;4:1–17.
29. John MJ, Thomas S. Biofibres and biocomposites. Carbohydr Polym. 2008;71(3):343–364.
30. Toledo Filho RD, Scrivener K, England GL, Ghavami K. Durability of alkali-sensitive sisal and coconut fibres. Cem Concr Compos. 2000;22(2):127–143.
31. Kabir MM, Wang H, Lau KT, Cardona F. Chemical treatments on plant-based natural fibre reinforced polymer composites. Compos B Eng. 2012;43(7):2883–2892.
32. Li X, Tabil LG, Panigrahi S. Chemical treatments of natural fiber for use in natural fiber-reinforced composites. J Polym Environ. 2007;15(1):25–33.
33. Yousif BF, El-Tayeb NSM. The effect of oil palm fibers as reinforcement on tribological performance. Surf Rev Lett. 2007;14(6):1095–1102.
34. Zafeiropoulos NE, et al. Engineering and characterisation of the interface in flax

fibre/polypropylene composite materials. Compos A Appl Sci Manuf. 2002;33(8):1083–1093.
35. Azzini F, Ciaramello GS, Salgado ACO. Bamboos from the Merostachys, Chusquea, and Guadua genera as pulp sources. Bragantia. 1987;46(2):379–391.
36. Liese W. The anatomy of bamboo culms. Technical Report. Beijing, China: INBAR; 1998.
37. Nogata S, Takahashi H. Intelligent functionally graded material: Bamboo. Compos Eng. 1995;5(7):743–751.
38. Amada S, Untao S. Fracture properties of bamboo. Compos B Eng. 2001;32(5):451–459.
39. Chung KK, Yu SH. Mechanical properties of structural bamboo for bamboo scaffoldings. Eng Struct. 2002;24(4):429–442.
40. Sharma B, et al. Engineered bamboo for structural applications. Constr Build Mater. 2015;81:66–73.
41. Sharma B, et al. Thermal conductivity of engineered bamboo composites. J Mater Sci. 2015;50(21):7004–7013.
42. Ghavami K. Ultimate load behavior of bamboo-reinforced lightweight concrete beams. Cem Concr Compos. 1995;17(4):281–288.
43. Rahman MM, et al. Performance evaluation of bamboo reinforced concrete beam. Int J Eng Technol. 2011;11(4):142–146.
44. Janssen JJA. Bamboo in building structures [dissertation]. Eindhoven: Eindhoven University of Technology; 1981.
45. Shah DU, Ramage M, Ulrike F, Scherman O. Environmental resin for bamboo composites. University of Cambridge Research Report. UK; 2016.

