Investigation of Mechanical Behaviour of Specially Treated PLA-Based Natural Hybrid Fibre Composite

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Abstract This research work aims to prepare the banana (B), sisal (S), and glass (G)-based hybrid composite for wet and dry characterization. The composites were fabricated by two different methods, and the fibres were treated with the solutions. In the first method, 1% volumetric concentration of sodium hydroxide was mixed with purified water solution and the next was 0.5% sodium hydroxide with 0.5% potassium manganate mixed with purified water solution. The composite was fabricated layer by layer, and the layer models (G/S/S/SG, G/B/B/B/G, and G/SB/SB/SB/G) were synthesized by a compressive moulding technique. Microscopic analysis was carried out on composite specimens and presented to confirm the internal structure and bonding. The outcomes revealed that the G-SB-SB-SB-G hybrid composite treated

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A. K. Shukla et al. (eds.), *Recent Advances in Mechanical Engineering*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-96-7480-0_29

with the NaOH with $KMnO_4$ solution exhibited improved mechanical properties and high moisture resistance.

Keywords Banana fibre · Dry composite · Moisture absorbability · Statistical analysis · Wet composite

1 Introduction

Materials are one of the necessary and essential resources for many applications [1]. It is impossible to think about zero waste, but the accumulation of waste can be minimized. The research value will be raised while converting waste into the most useful product. Some of the natural fibres are readily available on a global scale as well as plentiful farm waste such as banana, sisal, and so on. Researchers have performed multiple attempts to harness them which utilizing such fibres in composite material synthesizing is one of the hot and spicy studies [2]. The PLA-based composites were used for automotive interiors, biodegradable packaging, construction materials, consumer goods, electronics casings, agricultural products, sports equipment, medical implants, technical textiles, aerospace components, and small-scale wind turbine blades [3]. Epoxy resin as a matrix is frequently found in several polymer composite materials that use fibreglass due to its perfect combination and familiarity in the production of fibres with glass, sisal, and banana-based composite materials [4, 5]. The authors employed an epoxide resin matrix to synthesize the E-glass and bamboo fibre-reinforced hybrid composite and performed the mechanical and morphological characteristics [6]. They reported that the length of the fibres and their content impact their mechanical characteristics such as flexural and tensile strengths and optimize the length of fibres as 15 mm and the fibre content is 16 wt.% in the matrix. Evaluation of different properties of composite materials with a hybrid of aloe vera and glass fibres (18%) reinforcement in epoxide resin and polyester resin matrices (82%) and tested in shock, transverse and flexural loads and ensured that the reinforcement improves mechanical characteristics [7]. The authors utilized polyester resin matrix to establish the glass/banana composites with various layer fashion, as well as various contents of malic acid, treated banana fibres (fibre wt% of 20, 25, 30, 35, 40, and 45%), and artificial glass fibres [8]. The improvement in the treated banana fibres enhances the tensile and bending characteristics. Saravanan and Gnanavel synthesized in the matrix of LY556 epoxide resin and the fibres of glass/banana hybrid composites. They used 7% NaOH treated 15 mm long banana fibres (30, 40, and 50% of wt. ratio) and preserved end layers of the composite panel were glass fibres and found that the growth of banana fibre content has improved its tensile characteristics in comparison to jute based composite of the same fashion [9]. In a study, properties of sisal fibre/phenol–formaldehyde and glass/sisal fibre/phenol–formaldehyde composites were studied and concluded that glass enhanced mechanical and thermal characteristics [10]. To reduce the acoustic transmission in the automotive application compounds of hemp, bamboo and banana fibres (35%), polyester

(35%), and polypropylene (30%) were involved to synthesize a composite [11]. In a research work, an unplasticized polyvinyl chloride resin matrix composing composites with banana pseudo-stem and reported and the reinforcement, the enhanced impact and hardness characteristics of the composite [12]. The use of an epoxide matrix with 10% NaOH-treated sisal/hemp fibres to produce a composite by the compressive moulding method was done [13]. The authors optimized that 40 wt% of fibres have enhanced rapture strength to 82.07 MPa and tensile strength to 53.13 MPa. Authors pointed out that the composite jute-banana-glass displays the best mechanical characteristics (flexural, impact, and tensile) in comparison to the composite of jute-sisal-glass with a common matrix of epoxy resin AW106 [14]. The study suggested that for achieving the best tensile properties sisal fibre reinforcement and for obtaining the best flexural properties, jute fibre reinforcement can be preferred in the epoxy resin matrix [15]. It was also noticed that though natural fibres have benefits than artificial ones, the problem of poor adhesion exists in natural fibres. Such adhesive properties can be enhanced by suitable pretreatment of them [16].

The sisal and banana fibres were pretreated with sodium hydroxide and used for synthesizing composites. They composed short and random orientations of NaOH-treated sisal and banana fibres composite in the unsaturated isophthalic polyester resin matrix by compression moulding technique to investigate free vibration and flexural behaviours. It was found that the pretreatment enhanced interfacial bonding among matrix and fibres and thereby properties of free vibration also[17]. The author's study focused on the investigation of the influence of woven E-glass fibres in the sisal, banana fibres randomly oriented used hybrid composites in three layers (G/B/G, G/S/G, and G/BS/G) and five layers (G/B/G/B/G, G/S/G/S/G, and G/BS/G/BS/G) fashion [18]. The benchmark specimens were single-layer composites of banana (B), sisal (S), and banana and sisal (BS) and found that the tensile strength by a factor improved by 2.34 for three layers and 4.13 for five layers. However, such is not supported for flexural and impact properties. In another study, authors used 5% NaOH-treated sisal (40 and 25%) and banana (10 and 25%) fibres with random orientation in epoxy resin (50 and 50%) by hand layup technique and concluded that increase of banana fibres reduces the tensile strength and improves flexural and toughness properties. Banana fibres were treated with 5% NaOH solution for 240 min and dried in the oven for 24 h at 105 °C. For the sisal fibres refinement, they used the hot NaOH solution of 80 °C temperature and dried at 60 °C in a vacuum before washing the fibres. But in the current investigation two different solutions; 1% NaOH solution and 0.5% NaOH and 0.5% $KMnO_4$ solutions for 4 h and dried in the courtyard for 2 h in the morning sun rays from 8:30 AM to 10:30 AM. The epoxy 758 resin matrix is used for synthesizing B/G/S, G/S/B, and S/B/G composites, in which G/S/B exhibits the highest tensile strength of 21.06 MPa, but S/B/G holds only 10.42 MPa. The S/B/G absorbs 8.4 J of energy in impact investigation. B/G/S exhibits good flexural strength of 0.35 KN, and G/S/B demonstrates a flexural strength of 0.35. This research aims to fabricate well-defined composites of glass/sisal, glass/banana, and glass/sisal and banana composite with the epoxy resin matrix. Use of selective fibres of 50 mm long, two different natural fibre refinement techniques, the alternate fashion of vertical and horizontal orientation of fibres, predefined layers and their sequence and limit of a maximum of five layers, and start and finish layers are glass fibres were considered. The characterization which includes moisture absorption, UTS, tensile modulus, bending strength, bending modulus, impact strength, scanning electron microscope (SEM) examination, and dynamic mechanical analysis was focused to identify the wide range of applications of these composites.

2 Materials and Methods

2.1 Constituents of the Hybrid Composites

The natural fibres of sisal and banana stems were utilized to form the composite material which is prepared from the high-graded fibres with pre-defined orientation style. The major components of the suggested hybrid composites are also classified as natural fibres, synthetic fibre, and paste for connecting them [19]. The primary natural fibres are: banana and sisal [20]. The matrix of 3554B grade hardener and 3554A grade bio epoxy resin is used as a matrix for attaching layers and their contents. The fibres of banana and sisal have been mined from plants with extreme care and have ensured their best quality. Banana fibres (Fig. 1a) are mined very carefully from the stem of the banana tree by the successive process of rolling, combing, cleaning with water, cleaning with compressed air, and drying with sun rays. The naturally cultivated high-quality sisal leaves have been gathered and handled by decortications and dried at solar radiation to obtain high-quality sisal fibres (Fig. 1b). Mechanically outstanding glass fibre (Fig. 1c) is preferable to artificial fibre. All the fibres are said to have been evenly cut into 50 mm long. The basic properties of the fibres are shown in Table 1.

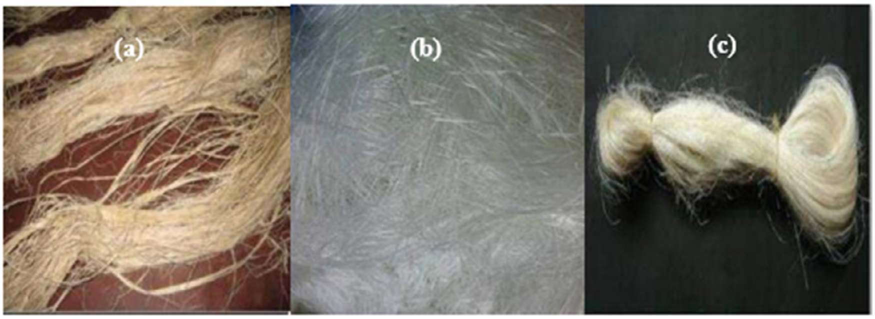

Fig. 1 **a** Carefully extracted banana fibres, **b** high-quality sisal fibre, **c** branded glass fibre

Table 1 Attractive properties of favoured fibres

Fibre	Young's modulus (GPa)	Flexural modulus (GPa)	Tensile strength (MPa)	Density (g/cm^3)
Banana fibre	27–32	20–25	550–800	1.3–1.35
Sisal fibre	9–22	8–16	350–700	1.33–1.5
Glass fibre	72–73	70–72	3100–3800	2.5–2.6

2.2 Refinement of Natural Fibres

In the continuation of research, the improvement of strength has been acquired through low-cost chemical processing. It was undoubtedly justified in earlier studies that sodium hydroxide–water solution treatment has led to better mechanical characteristics [21]. In this study, two different types of treatment have been described for natural fibres.

2.3 Refinement by Treatment–A

The chemical concentration ratio is for every kilogramme solution containing 990 g mass of purified water and 10 g mass of sodium hydroxide. A specially mined high-class banana, as well as sisal fibres, has been dripping in the solution for 4 h; then the soaked fibres are allowed to dry in the courtyard for 2 h in the morning sun rays from 8:30 AM to 10:30 AM. Sun-dried fibres have been positioned and cut into a uniform length of 5 cm. The fabrications of composites that make use of these fibres are designated as class-a G/S/B hybrid composites.

2.4 Refinement by Treatment-B

The chemical concentration ratio is for every kilogramme solution containing a 990-g mass of purified water, a 5-g mass of sodium hydroxide, and a 5-g mass of potassium manganate (VII). A specially mined high-class banana, as well as sisal fibres, was soaked in the solution for 4 h, and then the soaked fibres were allowed to dry out at the courtyard for 2 h in the morning sun rays from 8:30 AM to 10:30 AM. The dried fibres were arranged and cut into a uniform length of 5 cm. The fabrications of composites using these fibres are denoted as class-b G/S/B hybrid composites.

2.5 Synthesis of G/S/B Hybrid Composites

Figure 2 illustrates the research plan for arranging layers of composites in the horizontal and vertical directions. Table 2 illustrates the layer-by-layer detailed data of three significant classifications of layer fashion of composite. Square-shaped chromium-plated mild steel moulds (of side 30 cm) have been positioned on the compression testing machine (CTM) table. The wax has been applied to moulds for non-sticking of the composite and is the easiest way to release the composite from the mould. The 50 mm long fibres were positioned by orientation scheduled in composite layer fashion. The instantaneously mixed bio epoxy resin with hardener paste is being applied among layers to hold on layers as well as their natural/synthetic fibre.

After finishing all five layers, the un-dried composite has been compressed by CTM. This leads to the excessive resin, air gaps/air bubbles eliminated from the hybrid composite and refined with constant thickness. The composite was maintained in CTM for 180–240 min with a unified load of compression to avoid bending when setting up of composite. After 240 min of compression, the composite panels dry on the rooftop for 5–6 days. Similarly, all classes of composite panels have been synthesized.

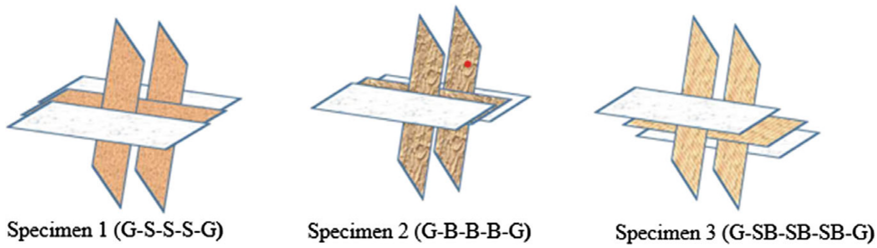

Fig. 2 Research plan for layer fashion of composite

Table 2 Layer fashions of composites

Layers from bottom to top	Specimen 1 (G-S-S-S-G)	Specimen 2 (G-B-B-B-G)	Specimen 3 (G-SB-SB-SB-G)
L1–bottom layer, L2–middle layer 1, L3–middle layer 2, L4–middle layer 3, L5–top layer	Glass fibre (horizontal orientation), sisal fibre (vertical orientation)-sisal fibre (horizontal orientation)—sisal fibre (vertical orientation)-glass fibre (horizontal orientation)	Glass fibre (horizontal orientation), banana fibre (vertical orientation), banana fibre (horizontal orientation), banana fibre (vertical orientation), glass fibre (horizontal orientation)	Glass fibre (horizontal orientation), sisal and banana fibre (vertical orientation), sisal and banana fibre (horizontal orientation), sisal and banana fibre (vertical orientation), glass fibre (horizontal orientation)

3 Characterization

The preparation of any composite material which can be sustained to the decided requirement can be confirmed by the study of mechanical properties and study of water absorption characteristics [4]. These properties confirmed whether the prepared composite material is suitable for the specific application. In this work, the basic mechanical properties of tensile strength, flexural strength, and moisture absorption were studied under wet and dry conditions. The tensile testing was conducted as per the ASTM D3039 standard, and the specimen was prepared by rectangular-shaped specimens with dimensions of 25.4 mm in width, 254 mm in length, and with a length of 152.4 mm. The ASTM D790 standard is used for the flexural testing, and the composite specimens were prepared in the dimensions of 38.1 mm width, 152.4 mm length, and 3 mm thickness.

3.1 Tensile Strength

Table 3 presents the tensile strength of hybrid glass/steel/banana (G/S/B) composite specimens under conditions and treatments A and B. The G-S-S-S-G yield a tensile strength of 55.6 MPa when dry and treated with technique A, which slightly increases to 57.8 MPa with technique B. When in wet conditions, the tensile strength of G-S-S-S-G rises to 56.8 MPa with technique A and to 58.0 MPa with technique B. Similarly, G-S-S-S-G gives an increased result from 58.2 to 59.9 MPa in dry conditions it was transitioning from technique-A to technique-B, and from 59.5 to 60.2 MPa in wet conditions. G-SB-SB-SB-G follows a comparable pattern, with tensile strengths ranging from 60.2 to 61.9 MPa when in dry conditions and further increasing from 60.8 to 62.0 MPa at wet conditions. These outcomes illustrate the varying effects of treatment techniques and moisture conditions on the tensile properties of G/S/B hybrid composites, highlighting potential strategies for optimizing their mechanical performance in different environments.

Table 3 Tensile strength of the hybrid composites

Category of hybrid composite	Dry specimen treated by		Wet specimen treated by	
	Technique-A (MPa)	Technique-B (MPa)	Technique-A (MPa)	Technique-B (MPa)
G-S-S-S-G	55.6	57.8	56.8	58
G-S-S-S-G	58.2	59.9	59.5	60.2
G-SB-SB-SB-G	60.2	61.9	60.8	62

Table 4 Flexural strength of the hybrid composites

Category of hybrid composite	Dry specimen treated by		Wet specimen treated by	
	Technique-A (MPa)	Technique-B (MPa)	Technique-A (MPa)	Technique-B (MPa)
G-S-S-S-G	1478	1582	1530	1589
G-B-B-B-G	1320	1457	1414	1495
G-SB-SB-SB-G	1549	1654	1590	1689

3.2 Flexural Strength

Table 4 shows the result of the flexural strength analysis of hybrid composites; the flexural test results indicate that the G-SB-SB-SB-G hybrid composite yields the highest tensile strength values among the three configurations under both dry and wet conditions.

The composite specimens, the composite subjected to technique B which consisting of a 5% NaOH and 0.5% $KMnO_4$ solution attained a peak tensile strength of 1654 MPa. This was followed by the G-S-S-S-G composite treated with Technique B, reaching 1582 MPa, and the G-B-B-B-G composite treated with Technique B, achieving 1457 MPa. Similarly, the wet specimens of G-SB-SB-SB-G treated with Technique-B yield the highest tensile strength at 1689 MPa and the G-S-S-S-G and G-B-B-B-G composites treated with Technique-B exhibiting lower values of 1589 MPa and 1495 MPa, respectively. The consistent superiority of the technique-B treatment over technique-A (1% NaOH solution) across all composite configurations in both dry and wet conditions highlights the efficacy of the combined NaOH and $KMnO_4$ treatment in enhancing the fibre-matrix interfacial bonding and elevating the mechanical properties of the hybrid composites.

3.3 Moisture Absorption

The part of samples has been heated at 50–60 °C to discard the content of moisture in the aggregate sample panels. Then, they were measured by all measurements and the weight of each specimen's panel. The specimen's panels were submerged in a purified water bath for five days. The weight gain and dimensional gain have been noticed in each 12-h gap. The rapid enhancements were noticed at the first several observations but then progressively stabilized. On the final day which is the fifth day, there is no longer betterment in weight gain and dimensions (Table 5). Consequently, it is understood that the test is nearly completed. The final values have been used to evaluate the net absorption of moisture in grammes and elongation.

Table 5 Moisture absorbability rate of the composites

Composite	Water absorbed in grammes of composite specimen	
	Treated by Technique-A	Treated by Technique-B
Banana fibre	5.9	4.7
Sisal fibre	5.7	4.4
Glass fibre	5.2	4

3.4 SEM Analysis G/SB/SB/SB/G Treatment-B Hybrid Composites

The morphological analysis is used to confirm the internal structural and bonding of the composite Figs. 3 and 4 show the SEM images of G/SB/SB/SB/G Treatment-B hybrid composites.

Figure 3 demonstrates the view of the manufactured G/SB/SB/SB/G class-b G/S/B hybrid composites material; it explains continuous fibres and the void formed on the surface of the specimens. The analysis of Scanning Electron Microscopy (SEM) demonstrates the inner structure and the inner surface have been discovered to be broken and the fragmented surface materials. Figure 5 clearly shows the fracture of fibre and a partial scattering of fibres in the framework of the composite of the G/SB/SB/SB/G fashioned G/S/B hybrid composite material. The figure does clearly show a rapture of the fibres in the tested composite, the composite of the G/SB/SB/SB/G fashioned G/S/B hybrid composite material fractured by tensile strength, and there is a breaking point with disintegration of fibres in the composite material.

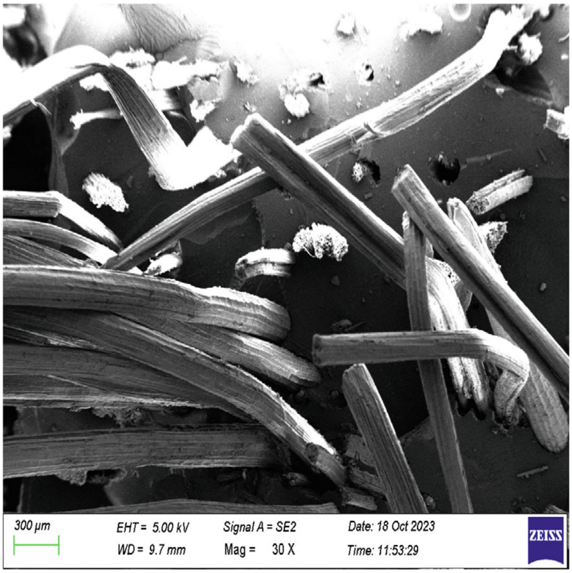

Fig. 3 SEM of G-SB-SB-SB-G hybrid composite

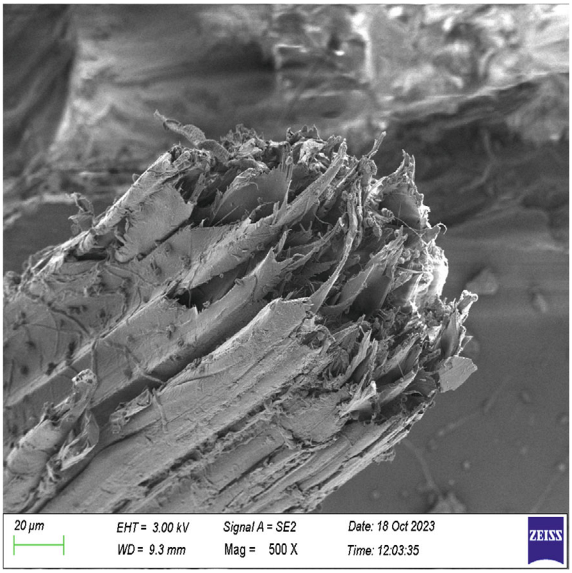

Fig. 4 Tensile tested SEM of G-SB-SB-SB-G hybrid composite

4 Conclusion

This research study contributes to the development of sustainable high-performance hybrid natural fibres composites by utilizing sisal (S) and banana (B), in combination with glass (G) fibres, which is easily recyclable, environment-friendly, inexpensive, and easy to obtain. The three different hybrid natural fibre composites are made with the configurations of G-S-S-S-G, G-B-B-B-G, and G-SB-SB-SB-G which were characterized by dry and wet applications. The composite material is prepared to achieve desired characteristics such as power and low humidity absorbability, and to reduce the absorbability capacity, two different fibre treatment techniques were used, i.e. Treatment-A using 1% NaOH solution and Treatment-B using a solution of 5% NaOH of 0.5% $KMnO_4$. These treatments also improve the fibre-matrix interfacial bonding with good strength. The moisture absorption and morphological characteristics were studied for the three different types of hybrid composites these composites have a great finish, and encompass a good variety of strengths and desirable characteristics. The findings suggest that the G-SB-SB-SB-G hybrid composite treated with the NaOH with $KMnO_4$ solution (Treatment B) exhibits improved mechanical properties and moisture resistance due to better fibre-matrix interfacial bonding. The SEM analysis and moisture absorption also confirm that G-SB-SB-SB-G hybrid composite is better in all aspects.

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