Development and Mechanical Performance Evaluation of Hybrid Banana–Glass Fibre Epoxy Composites

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Abstract

Reinforcing polymer matrices with plant-based fibres is a long-standing engineering method that has been used for many millennia. With the worldwide push toward sustainable production, its importance has grown dramatically. In this work, glass and banana fibres are used as co-reinforcements in an epoxy matrix created by the hand lay-up process to create hybrid polymer matrix composites. Specimens were produced at four distinct fibre weight fractions (0%, 10%, 20%, and 30%) and subjected to a methodical mechanical characterisation program that comprised tensile testing, Rockwell hardness evaluation, and non-destructive dye penetrant analysis. Alkali surface treatment was applied to the fibres before composite manufacture to enhance interfacial compatibility with the epoxy system. According to the results of the tensile test, strength improved gradually as the percentage of fibre increased, culminating at 14.91 N/mm² at 30% fibre loading as opposed to 10.26 N/mm² for the unreinforced epoxy baseline. The percentage of fibre and hardness metrics showed a slight adverse relationship. Furthermore, the behaviour of stress, strain, and deformation was confirmed using finite element analysis. The resulting composite is evaluated as a possible lightweight material for the manufacture of car seat shells and secondary structural components.

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1. Introduction

Engineering composites are multi-phase structural materials made up of two or more different components that work better together than they do separately. Although each component is still identifiable at the microstructural level and maintains its physical and chemical identity, the final composite has improved qualities like strength, weight reduction, and corrosion resistance that are not possible for the individual phases to achieve on their own. Due to their superior strength-to-weight and stiffness-to-weight ratios over traditional metallic materials, fibre-reinforced polymer (FRP) composites have become widely used in load-bearing structural applications. Because of their adaptability and exceptional performance qualities, advanced composite materials—which were first created for aerospace applications—are now widely used in a variety of industries, including automotive engineering, civil infrastructure, electronic packaging, and sporting goods. Synthetic fibre reinforcements including carbon, aramid, and glass fibres form the foundation of most widely used composite materials. These reinforcements are usually incorporated within non-biodegradable polymer matrices made from petroleum-based feedstocks. Concerns about these materials' end-of-life management have grown in importance due to their use's explosive expansion. Because of the strong interfacial bonding and structural integration between their differing constituent phases, most composite systems are intrinsically challenging to recycle or reprocess, in contrast to typical metallic materials. Consequently, a significant amount of composite trash is burnt or dumped in landfills. These disposal techniques provide significant environmental problems, including as long-term pollution and greenhouse gas emissions, in addition to high financial expenditures.

As a result, there is an increasing focus on creating eco-friendly and sustainable composite substitutes. Interest in bio-based composite reinforcements has dramatically increased due to stricter regulations intended to lower industrial carbon emissions and encourage the use of renewable resources, as well as growing public awareness of environmental sustainability. In this regard, lignocellulosic plant fibres including banana, jute, sisal, flax, and hemp have become viable substitutes for traditional synthetic fibres. These natural fibres are appropriate for a variety of structural and semi-structural applications because to their special blend of low density, renewability, biodegradability, affordability, and

acceptable mechanical qualities. Natural fibres' cellular and hollow nature gives them superior thermal and acoustic insulation qualities. Furthermore, unlike synthetic reinforcements like glass and carbon fibres, these fibres are thought to be carbon-neutral when burnt.

It has been well documented that alkali treatment with sodium hydroxide (NaOH) solution is a successful pre-treatment technique for improving the surface properties of natural fibres before composite manufacturing. Increased surface roughness, better wettability, and greater fibre–matrix interfacial bonding through both mechanical interlocking and chemical adhesion are the outcomes of this treatment, which makes it easier to remove surface-bound hemicellulose, lignin, and waxy contaminants.

The current work uses glass and banana fibres as hybrid reinforcements in an epoxy matrix system. The mechanical performance of the produced composites is examined, and their prospective appropriateness for automotive structural applications is tested at different fibre loading levels.

2. Literature Review

Natural fibre reinforced polymer composites have gained significant attention because of their low density, biodegradability, cost-effectiveness and acceptable mechanical properties for engineering applications [3], [14]. Among various natural fibres, banana fibre has emerged as a promising reinforcement due to its tensile strength and renewable nature [1]. Studies have shown that hybridization of natural fibres with glass fibres improves the overall mechanical performance of composites by combining the sustainability of natural fibres with the strength of synthetic fibres [2], [4], [5].

Several researchers reported that increasing fibre content enhances tensile and flexural properties up to an optimum level, beyond which defects and poor fibre distribution may reduce performance [6], [13]. Hybrid fibre composites reinforced with banana, sisal, hemp and glass fibres have demonstrated improved strength, stiffness, impact resistance and durability compared to single-fibre composites [5], [13], [16]. Recent developments have also highlighted the growing use of natural fibre and glass fibre hybrid composites in automotive and structural applications because of their favourable strength-to-weight ratio [7], [10].

Surface treatment of natural fibres plays a vital role in improving composite properties. Alkali treatment using sodium hydroxide removes impurities such as lignin, hemicellulose, and

waxes from the fibre surface, leading to better fibre–matrix adhesion and improved load transfer [9], [12], [17]. Enhanced interfacial bonding results in higher tensile strength and overall mechanical performance of epoxy-based composites [17].

Natural fibre composites also provide environmental benefits due to their renewable origin and reduced carbon footprint [8], [14]. In addition, these materials exhibit good thermal insulation, vibration damping, and acceptable water absorption behaviour, making them suitable for various engineering applications [11], [15]. Based on previous studies, hybrid banana–glass fibre reinforced epoxy composites offer a promising combination of mechanical strength, lightweight characteristics, and sustainability for automotive and secondary structural applications [4], [7], [16].

3. Materials and Methods

3.1 Classification of Natural Fibres

Natural fibres may be generally categorized based on their source as biological or geological into three major classes. These classes include animal fibres, mineral fibres and plant fibres.

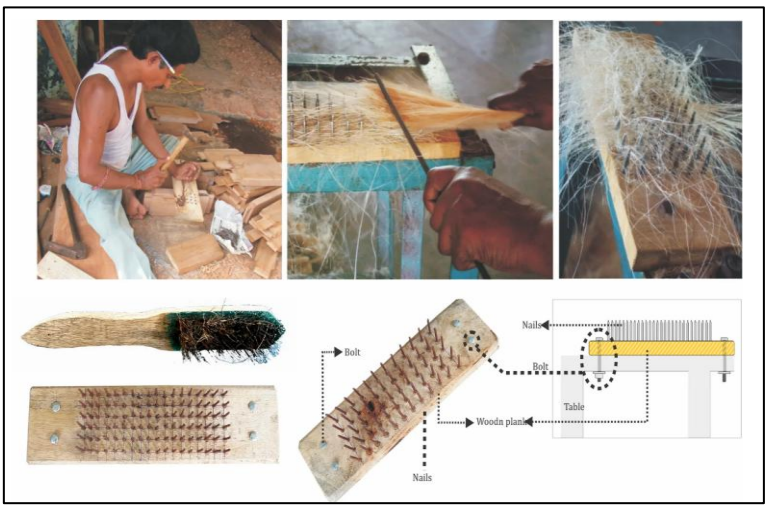

Figure 1. Manual Extraction of Banana Fibres from Banana Pseudo-Stem Using a Combing Process [18]

Figure 1 depicts the process of banana fibres can be manually extracted from the pseudo stem of banana through a combing process. This entailed separation of fibre bundles from the pseudo stem, removal of undesired pith matter from the fibre bundles and production of clean fibres that could be used for composite production.

A mechanical banana fibre extraction machine was employed in order to ensure effective and fast extraction of banana fibres from the banana pseudo stem. This extraction device comprises of an extractor roller, feeding roller, guide rollers, driving system, and waste storage bin. During extraction process, the pseudo stem was passed through the various rollers such that the non-fibre part was separated leaving behind clean fibre bundles. Cleaning and drying of the extracted fibres followed before treating them with alkali and making composite. This made fibre extraction more efficient as depicted in Figure 2.

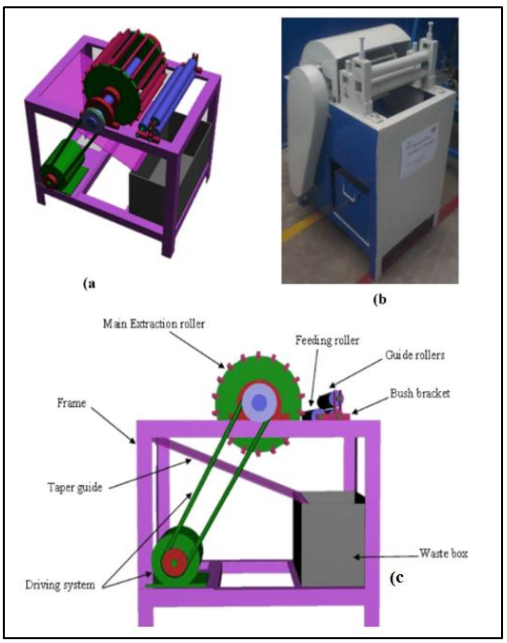

Figure 2. Mechanical Banana Fibre Extraction System: (a) CAD Model, (b) Fabricated Prototype, and (c) Schematic Configuration [19]

The banana fibres employed in this study were collected from the pseudo-stem of bananas harvested during the fruits' collection. The banana stem was sectioned and the outer layers carefully stripped. Fibre bundles were extracted through a process known as decortication, followed by cleaning with fresh water to eliminate pith, dirt, and other impurities. The extracted fibres were then exposed to the sun for 48 hours for drying prior to alkali processing. This fibre extraction method provided enough clean and uniform fibres to be used in composite production.

3.1.1 Animal Fibres

Animal fibres are made up of proteins secreted by mammals or insects. Examples of animal fibres include wool, cashmere, mohair, alpaca fibre, horse tail hair, and silk fibres from

silkworm larvae. Animal fibres are mostly applied in the textile industry but rarely used for structural composites manufacturing.

3.1.2 Mineral Fibres

Mineral fibres can be either naturally occurring or man-made from inorganic mineral compounds. Naturally occurring mineral fibres include asbestos only while examples of man-made mineral fibres include glass wool, quartz fibres, aluminium oxide fibres, silicon carbide fibre, and boron carbide fibre.

3.1.3 Plant Fibres

Plant fibres consist mainly of cellulose with hemicellulose and lignin being the other constituents present. These are further classified according to the particular plant part that they come from: seed fibres (cotton, kapok), leaf fibres (sisal, agave), bast fibres (flax, jute, banana, hemp), fruit fibres (coir), and stalk fibres (bamboo, wheat straw). Banana bast fibre falls under the strongest sub-group category of plant fibres.

3.1.4 Materials Used

- Fibre from bananas: The main natural reinforcement was made of banana fibres that were taken from banana pseudo-stems. The fibres were chosen due to their reasonable mechanical strength, affordability, and renewability.
- Glass Fibre: To enhance mechanical qualities including hardness and tensile strength, e-glass fibres were employed as the synthetic reinforcement.
- Hardener and Epoxy Resin: Because of its superior adhesion, chemical resistance, and mechanical stability, a thermosetting epoxy resin system and an amine-based hardener were utilised as the matrix material.

3.1.5 Alkali Treatment of Banana Fibre

Banana fibres were alkali treated using sodium hydroxide (NaOH) solution to improve fibre–matrix adhesion. For two to four hours at room temperature, the fibres were submerged in a 5% NaOH solution. After treatment, the fibres were neutralised and carefully cleaned with distilled water to get rid of any remaining alkali. After that, the fibres were allowed to air dry for 24 to 48 hours. This process promotes interfacial bonding, increases surface roughness, and eliminates contaminants like hemicellulose and lignin.

3.1.6 Composite Fabrication

The hand lay-up method was used to create the hybrid composites. A releasing agent was applied after a mould surface was cleansed. Within the mould, layers of glass and banana fibre were placed in the proper order. Each layer was evenly coated with the epoxy resin and hardener at the suggested ratio. After that, the lay-up was manually compacted to eliminate air bubbles and guarantee even distribution of resin.

After a 24-hour drying period at room temperature, the composite laminate was post-cured as necessary. The composite sheets were taken out of the mould and cut into standard test specimens after curing.

After extraction of the banana fibres, trimming into equal lengths of 30 mm was carried out. In determining the length, a standard steel ruler with millimetre precision was used. The fibre orientation used in laminate formation is unidirectional and was achieved by placing the banana fibres and glass fibres along the longitudinal direction of the mould. Such fibre orientation was chosen for easy fibre loading during composite fabrication and uniform reinforcement of the composite specimens. Fibre length and orientation remained constant for all composite specimens to facilitate consistency in their performance.

Table 1 shows the composition details of the fabricated composite specimens made from hybrid banana glass fibre reinforced epoxy. Four different composite specimens were fabricated using different volume fractions of banana fibres and glass fibres while maintaining fibre orientation to be unidirectional in nature. On the other hand, the volume fraction of the epoxy was decreased from 100% to 70% as opposed to banana fibres and glass fibres which were increased from 0% to 15%.

Table 1. Composition and Volume Fractions of Fabricated Hybrid Composite Specimens

Specimen	Orientation	Epoxy (Vol. %)	Banana Fibre (Vol. %)	Glass Fibre (Vol. %)
BG1	Unidirectional	100	0	0
BG2	Unidirectional	90	5	5
BG3	Unidirectional	80	10	10
BG4	Unidirectional	70	15	15

Based on previous research, processing viability, and the goal of attaining balanced mechanical performance, the composition of glass and banana fibres in the epoxy matrix was chosen. Because higher natural fibre loading can result in poor wettability, increased void formation, and decreased interfacial bonding, the banana fibre content was changed between 5 and 15 vol%. To improve stiffness and strength while making up for the unpredictability and poor mechanical performance of natural fibres, glass fibre was added in an equal volume to banana fibre (5–15 vol%). Across all formulations, the epoxy matrix concentration was proportionally decreased from 100 vol% to 70 vol%. Without sacrificing processability, the chosen compositions of 100:0:0, 90:5:5, 80:10:10, and 70:15:15 (Epoxy: Banana fibre: Glass fibre) guaranteed efficient hybridisation, enhancing load transmission, mechanical interlocking, and overall composite performance.

The hand lay-up method was used to fabricate every composite specimen. The matrix material was epoxy resin, and the curing agent was an amine-based hardener. Glass fibres and banana fibres coated with alkali were used as reinforcing phases. To make demoulding easier, a releasing agent was applied to a flat mould. To guarantee correct curing, the necessary amount of epoxy resin was thoroughly combined with the hardener in the suggested ratio for each composition.

The fibres were aligned in one direction within the moulding form during the process of preparation, and then resin was introduced. Layers of resin, glass fibres, and banana fibres were alternately layered until the desired thickness of the laminate was achieved. Consolidation and adhesion between the layers were achieved by curing at room temperature for approximately 24 hours with minimal pressure applied. After the curing stage, the laminates were removed from the moulds, cut into standard sizes as per ASTM specifications.

Mechanical characterization of the fabricated composite was performed using standardized testing methods. Tensile strength, modulus, and elongation were tested for using tensile testing according to ASTM D638 standards. Flexural properties were evaluated using three-point bending test according to ASTM D790. Impact strength was determined using the Izod/Charpy impact test according to ASTM D256 standard. Surface hardness of the composites was determined by Rockwell hardness test according to ASTM D785. In case of need, water absorption characteristics can also be determined following ASTM D570. All tests were performed at room temperature to ensure accuracy.

4. Proposed Methodology

4.1 Fibre Surface Treatment

Before the production of composite materials, cleaning and alkali treatment process was undertaken on raw glass and banana fibres. To clean the fibres, they were soaked in distilled water to eliminate any dirt attached to their surface and were then dried to constant weight at 100°C. Treatment using alkali was done through soaking of 200g of dried fibre in 2L of 10% (w/v) sodium hydroxide solution at 70°C for 3 hours while stirring. This was then neutralized by rinsing with acidified distilled water, and later with distilled water and left to air-dry. In preparation for composites' production, the extracted fibres of the banana fruit underwent an alkali treatment process that involved use of sodium hydroxide (NaOH) solution.

The objective of the treatment was to alter the surface features of the fibre thereby enhancing their bonding to epoxy resin used as a matrix. Alkali treatment helps in elimination of impurities such as lignin, hemicellulose, waxes and others. Figure 3 shows the alkali-treated banana fibres, while Figure 4 presents the treated fibre specimens prepared for composite fabrication. These treated fibres were subsequently used as reinforcement in the hybrid banana–glass fibre reinforced epoxy composites to achieve improved mechanical performance.

Figure 3. Alkali-Treated Banana Fibres after NaOH Surface Modification

Figure 4. Prepared Fibre Specimens Used for Composite Fabrication

4.2 Composite Fabrication - Hand Lay-Up

Composite panels were fabricated using the hand lay-up open-mould technique. A purpose-built wooden mould was lined with a polyethylene release sheet coated with silicone mould release agent. Treated fibres were chopped to 30 mm lengths and distributed uniformly over the mould base at 15% fibre volume fraction. Epoxy resin and hardener were combined at a 10:1 weight ratio, mixed thoroughly, and poured evenly over the fibre bed. A second release sheet was applied and a steel roller was used to consolidate the composite and remove entrapped air. Dead-weight loading maintained consolidation pressure during 24-hour ambient temperature cure.

4.3 FTIR and XRD Characterisation

Chemical composition of both raw and alkali-treated fibres was examined using FTIR spectroscopy on a Perkin Elmer Spectrum RX-1 instrument across the mid-IR range of 400 to 4000 cm^{-1}. Wide-Angle X-ray Diffraction (WAXD) analysis was performed on a Philips PAN analytical PW1830 diffractometer with Cu-Kα radiation from 10° to 45° at 0.04°/s. Three-point bending tests were performed per ASTM D790 on specimens of 160 × 30 × 5 mm using an INSTRON 1195. All values represent averages over five replicate specimens and FTIR Characterisation Setup shown in Figure 5

Figure 5. FTIR Characterization Setup for Chemical Analysis of Treated Fibres

4.4 Filament Winding Process

For comparative reference, a filament winding process was also considered. Mixed resin is transferred to a resin bath through which fibre tows from a creel stand are drawn via tension rollers. The resin-impregnated fibre is then wound progressively over a mandrel until the target wall thickness is reached, providing precise control over fibre orientation angle, volume fraction and Filament Winding Process shown in Figure 6

Figure 6. Schematic Representation of the Filament Winding Process

4.5 Constituent Selection Overview

Three main components make up the composite system created in this study: a thermosetting polymer matrix (epoxy resin cured with an amine-based hardener), a synthetic mineral fibre (glass fibre), and a natural plant-derived fibre (banana fibre). These materials were chosen with availability, mechanical performance, processability, and cost-effectiveness in mind. Glass fibre increases stiffness and strength, while banana fibre provides low density and biodegradability. Strong interfacial bonding and efficient load transfer between the reinforcements are guaranteed by the epoxy matrix.

4.6 Overview of Constituent Selection

The composite system developed in this study comprises three primary constituents: a natural plant-derived fibre (banana), a synthetic mineral fibre (glass), and a thermosetting polymer matrix (epoxy resin with amine hardener). Each constituent was selected on the basis of material availability, mechanical performance, process ability, and cost-effectiveness.

4.7 Banana Fibre

The banana plant is a rhizome perennial crop grown in 129 countries around the world and ranks as the fourth economically important food crop in the world. The banana pseudo stem is left behind after fruit collection, making it an excellent raw material for producing cellulosic fibre. Banana fibre has a multicellular cross-section with large cell lumen compared to cell wall thickness. The diameter of banana fibre varies from 14 µm to 50 µm, while their length ranges from 0.25 cm to 1.3 cm. Banana fibre has a high tensile strength as indicated in Figure 7, specific gravity, biodegradability, hygroscopicity, thermal insulation, and comparative durability compared to other plant fibres. The process involved in extracting the banana fibre includes collecting the pseudo stem, cutting it, decorticating, washing, and sun-drying.

Figure 7. Extracted Banana Fibres Used as Natural Reinforcement

4.8 Glass Fibre

The glass fibre is produced through the fusion of the silica-containing batch and drawing of the fused melt into long, fine strands. The material provides great tensile strength, light weight, inertness, electrical insulation properties, and uniform quality. The material selected for this research is called E-Glass, standing for electrical grade glass. It consists of the silica (SiO^2) as a main constituent and other oxides such as alumina, calcium oxide, boron trioxide, magnesia, and sodium oxide.

4.9 Epoxy Resin

Epoxy resins are thermosetting polymers characterised by reactive oxirane (epoxide) functional groups. Upon combination with a curing agent (hardener), these groups participate in an exothermic ring-opening polymerisation producing a three-dimensionally cross-linked thermoset network with high rigidity, excellent adhesion, and good chemical and moisture resistance. A bisphenol-A based epoxy resin is employed with an amine hardener at a 10:1 resin-to-hardener weight ratio, achieving full cure at ambient temperature within 24 hours.

5. Testing Methods

5.1 Brinell / Rockwell Hardness Testing

Hardness characterisation was performed using Brinell and Rockwell methodologies. The Brinell test (ASTM E10, ISO 6506) uses a carbide ball indenter pressed into the specimen surface under a controlled test force held for 10 to 15 seconds. The residual indent diameter is measured optically and the Brinell Hardness Number (BHN) is computed from the ratio of applied force to curved surface area of the spherical indent. For the composite specimens,

Rockwell Hardness (ASTM D785) was applied using a 1/16-inch carbide ball at 150 kg major load (shown in Figure 8).

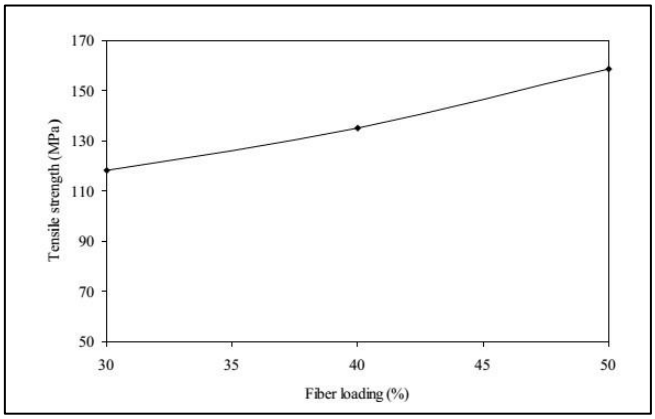

Figure 8. Schematic Illustration of Brinell Hardness Indentation Geometry

5.2 Tensile Testing - Universal Testing Machine (ASTM D3039)

Uniaxial tensile testing was conducted per ASTM D3039 using a Universal Testing Machine (UTM). The UTM comprises a rigid dual-column load frame, calibrated load cell, servo-driven crosshead at constant extension rate, extensometer, and a computer-interfaced data acquisition system. Specimens of 250 × 25 × 2.5 mm (cross-sectional area = 62.5 mm²) were loaded monotonically to fracture. Tensile Strength (σ) = P / A, where P is breaking load (N) and A is cross-sectional area (mm²).

The fabricated composite laminates were cut into standard specimen dimensions using a precision cutting tool. Tensile test specimens were prepared according to ASTM D3039 requirements, with dimensions of 250 mm × 25 mm × 2.5 mm. In the Rockwell hardness test, flat and smooth samples of the composite were obtained and cleaned in order for proper indentation and surface contact during the testing. In dye penetrant testing, the surfaces of the specimen were properly cleaned before the dye was applied in order to remove dust and oil from the surfaces. The excess dye was removed after some penetration period, and a developer was used in order to show any defects, cracks, or voids present.

6. Results and Discussion

6.1 Tensile Strength

Uniaxial tensile characterization test was carried out on all four specimen types using ASTM D3039 method. Specimens with dimensions of 250 × 25 × 2.5 mm were subjected to

testing three times at each fibre loading ratio. The recorded load levels at various deformation phases were then used to determine the engineering stress levels.

Table 2. Tensile Test Results of Unreinforced Epoxy Composite (0% Fibre Content)

Stage	Load A (kg)	Load B (kg)	Load C (kg)	σ A (N/mm²)	σ B (N/mm²)	σ C (N/mm²)
Elastic	35	36	35	5.49	5.65	5.49
Yield	41	40	42	6.44	6.28	6.59
Plastic	49	48	48	7.69	7.53	7.53
Ultimate	54	54	56	8.48	8.84	8.79
Breaking	65	64	67	10.20	10.05	10.52

Mean Tensile Strength = 10.26 N/mm²

Table 2 is the tensile test result of the pure epoxy specimen which lacked any reinforcing fibres. It is evident from the table below that the epoxy sample had an average tensile strength of 10.26 N/mm². This represented the mechanical properties of the pure epoxy material without the addition of fibres.

Table 3. Tensile Test Results of Hybrid Composite Containing 10% Fibre Reinforcement

Stage	Load A (kg)	Load B (kg)	Load C (kg)	σ A (N/mm²)	σ B (N/mm²)	σ C (N/mm²)
Elastic	39	39	38	6.12	6.12	5.96
Yield	48	47	48	7.53	7.38	7.53
Plastic	56	56	55	8.79	8.79	8.63
Ultimate	67	65	64	10.52	10.20	10.05
Breaking	75	74	74	11.77	11.62	11.62

Mean Tensile Strength = 11.67 N/mm²

Table 3 is the tensile test result for the composite sample containing 10% total fibre loading. From Table 3 above, the average tensile strength increased to 11.67 N/mm² compared to the pure epoxy sample indicating that the introduction of the banana and glass fibre improved tensile performance of the material.

Table 4. Tensile Test Results of Hybrid Composite Containing 20% Fibre Reinforcement

Stage	Load A (kg)	Load B (kg)	Load C (kg)	σ A (N/mm²)	σ B (N/mm²)	σ C (N/mm²)
Elastic	46	45	46	7.22	7.06	7.22
Yield	55	55	55	8.63	8.63	8.63
Plastic	63	64	63	9.89	10.05	9.89
Ultimate	71	73	72	11.14	11.46	11.30
Breaking	84	86	86	13.18	13.51	13.51

Mean Tensile Strength = 13.40 N/mm²

Table 4 represents the tensile testing result of the composite specimen with 20% total fibre content. The mean tensile strength of the composite specimen was observed to be 13.40 N/mm². There is a marked increase in tensile strength compared to the pure epoxy and 10% fibre specimen. This means that there is an improvement in terms of load transfer due to efficient fibre reinforcement in the epoxy material.

Table 5. Tensile Test Results of Hybrid Composite Containing 30% Fibre Reinforcement

Stage	Load A (kg)	Load B (kg)	Load C (kg)	σ A (N/mm²)	σ B (N/mm²)	σ C (N/mm²)
Elastic	52	53	54	8.17	8.32	8.48
Yield	63	64	65	9.89	10.05	10.20
Plastic	74	75	76	11.61	11.77	11.93
Ultimate	85	86	87	13.34	13.49	13.65
Breaking	94	95	96	14.76	14.91	15.07

Mean Tensile Strength = 14.91 N/mm²

Table 5 displays the tensile test result of the composite sample reinforced with 30% total fibre. The sample recorded the highest mean tensile strength value of 14.91 N/mm² out of all composite samples considered. Such performance can be attributed to efficient hybrid reinforcement due to the presence of banana and glass fibres.

6.2 Rockwell Hardness

Table 6. Rockwell Hardness Values of Hybrid Banana–Glass Fibre Reinforced Epoxy Composites

Sl. No.	Epoxy (wt%)	Alkali Fibre (%)	Load (kg)	RHN A	RHN B	RHN C	Mean RHN
1	100	0	150	116	115	113	114.67
2	90	10	150	112	105	113	110
3	80	20	150	111	109	104	108
4	70	30	150	113	108	111	110.67

The Rockwell hardness tests conducted on the developed banana-glass fibre-reinforced epoxy composite samples with different amounts of fibres are shown in Table 6 below. In this case, the highest mean hardness value was recorded by the neat epoxy sample at 114.67 RHN. On increasing the amount of fibre in the composite material, there was a slight decrease in hardness levels to the lowest point at 108 RHN for 20% fibre composite material. There was however a slight improvement of the average hardness level when the amount of fibre was increased to 30%. Overall, the inclusion of fibre had little effect on the hardness level of the surface of the composite material. Hardness values decreased slightly from 114.67 HRB at 0% fibre to 108.00 HRB at 20% fibre with a small increase to 110.67 HRB at 30%.

6.3 Flexural and Impact Performance Assessment

Flexural strength and impact resistance are critical criteria in assessing the performance of fibre-reinforced composites. It is anticipated that the use of banana and glass fibres will enhance the flexural strength and energy dissipation capacity of the epoxy matrix through efficient stress transfer. Hybridization with the use of natural and synthetic fibres results in an increase in the rigidity of the composite and a better distribution of the applied loads as well as an increase in the resistance of the material against crack formation and propagation due to external stresses. Considering the properties of tensile strength and reinforcement provided by the composite material, it is anticipated that the resulting hybrid composites will show increased flexural strength and impact resistance compared to neat epoxies.

6.4 Analytical (FEA) Results

The analysis through simulation for the composite material specimen was undertaken in order to investigate its internal stresses, its equivalent elastic strains and the resulting deformation. This revealed that the highest stresses were concentrated in the gauge part that correlates with the failure point observed experimentally. The FTIR analysis was carried out to assess the chemical changes undergone by the banana fibre surface upon being subjected to the alkaline bath. This analysis showed the presence of the functional groups related to cellulose and absence of non-cellulosic substances like lignin and hemicelluloses as well as other impurities. This contributed to the improvement of the surface of the fibres thereby allowing greater fibre-to-matrix interaction, resulting in higher stress transfer efficiency.

The XRD test was conducted for studying the crystalline structure of the banana fibre reinforced composite material system. The results from diffraction show that there is the presence of crystalline cellulose regions on the reinforced material. This is due to the fact that the crystallinity leads to high stiffness and load bearing capacity of the composite. From the XRD test results, it is clear that the chemical modification process resulted in the elimination of the amorphous regions hence enhancing fibre structure.

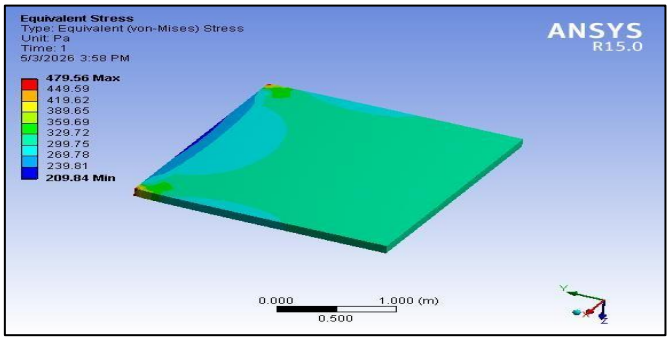

Figure 9. Equivalent Stress Distribution Obtained from Finite Element Analysis

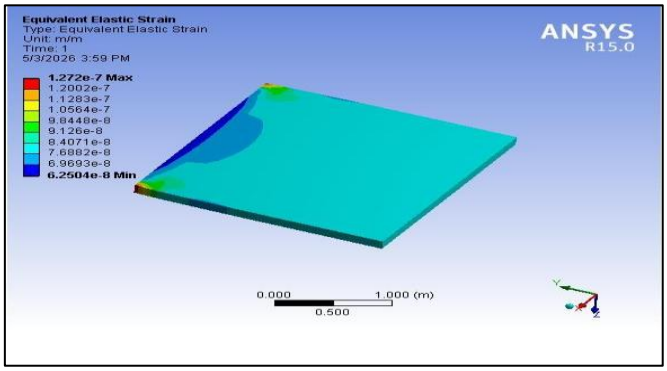

Figure 10. Equivalent Elastic Strain Distribution Obtained from Finite Element Analysis

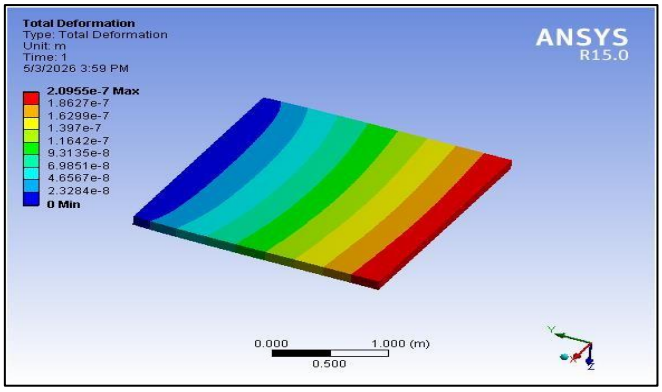

Figure 11. Total Deformation Contour Obtained from Finite Element Analysis

Tensile loading of the banana glass fibre reinforced epoxy composite material through finite element analysis (FEA). Figure 9 shows the equivalent stress distribution and indicates that the stress is highly concentrated in areas where constraints and loading occur, while elsewhere the stress distribution is fairly uniform. Figure 10 is a depiction of the equivalent elastic strain distribution in the material, where the maximum strain is found in areas of maximum loading and stress concentration. Figure 11 displays the overall deformation behavior of the composite material, with gradual deformation occurring from the fixed end to the loaded end of the composite structure.

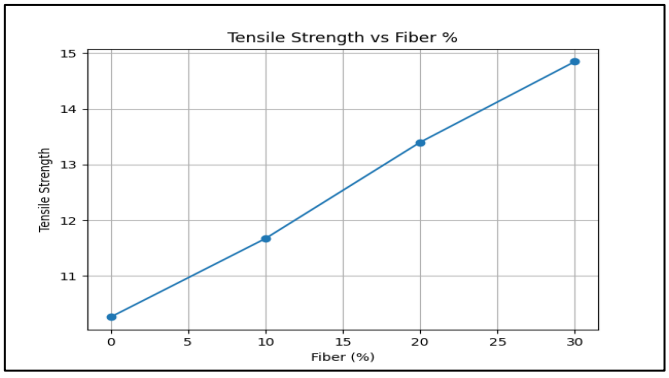

Figure 12. Effect of Fibre Content on Tensile Strength of Hybrid Banana–Glass Fibre Reinforced Epoxy Composites

This Figure 12 shows variation in tensile strength depending upon varying levels of fibres. Continuous increase in tensile strength was observed when fibres were incorporated from 0% to 30%. The pure epoxy tensile strength was measured to be 10.26N/mm² whereas tensile strength values were found to be 11.67N/mm², 13.40N/mm² and 14.91N/mm² for epoxy samples having fibres contents of 10%, 20% and 30% respectively. The increase in tensile strength can be accredited due to efficient load transfer offered by combination of banana and glass fibres.

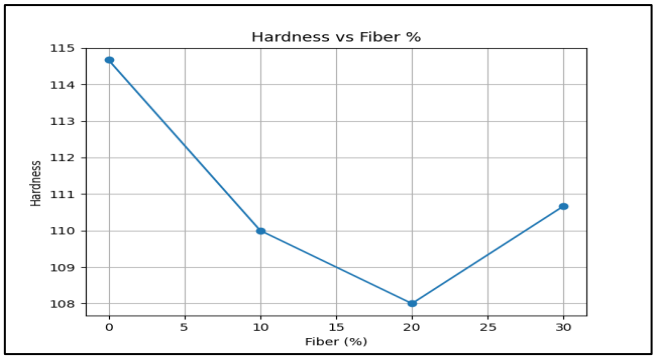

Figure 13. Effect of Fibre Content on Rockwell Hardness of Hybrid Banana–Glass Fibre Reinforced Epoxy Composites

Figure 13 illustrates variation of hardness with respect to fibre content. Pure epoxy sample had maximum hardness of 114.67RHN whereas slight drop in hardness level was noticed by increasing fibre content to 10% and 20% respectively. The hardness dropped to a minimum value of 108RHN at 20% level of fibre loading. However, marginal recovery was noted in hardness with the level of 110.67RHN at 30% fibre loading.

7. Conclusion

Banana-glass fibre reinforced epoxy composites were developed using the hand lay-up method and characterized based on the mechanical performance of the material. The alkali treatment of banana fibre was utilized alongside the use of glass fibre and epoxy to enhance the fibre-matrix interactions and increase the mechanical behavior of the composite material. Different percentages of fibre reinforcement (0%, 10%, 20%, and 30%) were used to analyze the influence of fibre loading on tensile strength and hardness. It was shown that the tensile behavior was consistently enhanced as the amount of fibres added to the epoxy increased. The average tensile strength was found to be 10.26 N/mm² for pure epoxy composite, 11.67 N/mm², 13.40 N/mm², and 14.91 N/mm² for composites with 10%, 20%, and 30% of fibre reinforcement, respectively. The tensile strength of the composite with 30% of fibre was observed to be the highest with approximately 44.7% improvement compared to pure epoxy composite.

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