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Exploring the Mechanical Characteristics of Three Natural Composite Materials (Kenaf, Sisal, and Banana with Almond shell, Glass, and Silicon carbide fillers): A Comparative Evaluation

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Abstract

The current global demand for lightweight, long-lasting, and economically efficient materials is of unprecedented magnitude. Industry sectors including aircraft, automotive, construction, and sports are constantly adapting to fulfil these requirements. Natural composites refer to materials obtained from natural sources that utilise two or more separate components to form a material with improved characteristics. In numerous industries, natural composites offer a potential and ecologically sound alternative to synthetic materials by harnessing the characteristics of natural resources to develop high-performance, sustainable solutions. The addition of fillers to the matrix of composites serves to augment the characteristics of the composite, including but not limited to strength, stiffness, and durability. Their job is of utmost importance in customising the composite material to suit certain applications and performance criteria. The incorporation of glass, silicon carbide, and almond shell fillers in natural composites yields improved mechanical, thermal, and environmental characteristics, therefore offering adaptable and environmentally friendly options for multiple uses. Comparing the performance of natural fibres such kenaf, sisal, and banana with almond shell, glass, and silicon carbide fillers in composites requires assessing their mechanical characteristics, environmental impact, cost-effectiveness, and appropriateness for different uses. The present study aimed to compare natural fibres and assess their mechanical properties for potential use in feasible uses. A comparison of the data obtained from the tensile test reveals that material 2 with Banana: Sisal: Glass: Epoxy has a tensile strength that is 432.46% higher than that of material 1 with Kenaf: Sisal: Almond shell: Epoxy. According to the findings of the additional mechanical tests, the material 3 that contained Kenaf, Banana, Silicon, and Epoxy resulted in a 260% increase in flexural strength, a 14.44% rise in hardness, and a 17.17% increase in impact energy when compared to other compositions.

Keywords: Natural composites, kenaf, sisal, banana, almond shell, glass, silicon carbide.

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INTRODUCTION

Composite materials epitomise a formidable breakthrough in the field of materials research, providing extraordinary performance, longevity, and design adaptability. With the continuous progress of technology and the growing significance of sustainability, composites will persist in playing a crucial part in diverse industries, so propelling the realisation of novel opportunities and applications.

Composites are materials formed by merging two or more separate and unique components that maintain their individual distinctiveness on a large scale, resulting in a material with superior qualities compared to the individual components. Classification of these materials can be determined by their matrix material, reinforcing type, and structure [1,2].

Polymer Matrix Composites (PMCs) are lightweight structural materials extensively employed in consumer products and transportation. High strength and temperature-resistant Metal Matrix Composites (MMCs) are utilised in the aerospace and automotive industries. Ceramic Matrix Composites (CMCs) are heat and wear resistant materials which find utility in high-temperature industrial applications. Fibre-reinforced composites are robust and rigid materials employed in structural elements. Sustainable and environmentally friendly natural fibre composites are suitable for use in industries such as automotive and construction. Each composite material is designed to fulfil precise performance, environmental, and economical demands based on its intended use [3].

A natural composite is a material composed of natural fibres or fillers combined with a natural or synthetic matrix. These composites are specifically engineered to possess more sustainability, biodegradability, and environmental friendliness compared to traditional composites. They utilise sustainable resources and frequently provide a favourable equilibrium between mechanical characteristics, ecological footprint, and cost efficiency. The use of natural composites is expanding as viable and ecologically sound substitutes for conventional composites. Their combination of green advantages, cost-effectiveness, and performance renders them well-suited for use in various sectors such as automotive, construction, packaging, and related industries. Through the incorporation of natural fibres and fillers into composite materials, industries are progressing towards environmentally sound and sustainable manufacturing methods [4-6].

Natural kenaf fibre is made from the stalks of the Hibiscus cannabinus plant, a relative of jute and cotton. Owing to its exceptional mechanical characteristics, low weight, and favourable environmental effects, it is a widely preferred material for usage in paper, textile, and composite goods. Important Kenaf Fibre Properties: Low Density and High Tensile Strength, Biodegradable, Sustainable, Renewable, Absorbs Moisture, Maintains Thermal Stability. Kenaf fibre is a multipurpose, environmentally friendly substance that has several uses, particularly in the manufacture of paper, textiles, and composite materials. Because of its robust mechanical qualities, low weight, and sustainability, it's a great option for companies looking for environmentally friendly substitutes for conventional synthetic materials [7].

Organic sisal fibre is derived from the leaves of the Agave sisalana plant, which is indigenous to Mexico but is currently grown in many tropical and subtropical areas. Sisal fibre’s strength, resilience, and adaptability make it one of the most commonly used natural fibres. Sisal fibre possesses a number of important properties, including excellent tensile strength, moderate stiffness, durability, and biodegradability. Sisal fibre is a multipurpose, environmentally friendly material that is used in many different industries, such as composites, building, textiles, and agriculture. It is a useful substitute for synthetic fibres like glass and plastic because of its great strength, resilience, and sustainability. For many products and applications, sisal is still an affordable and environmentally friendly option, despite potential problems with moisture absorption and UV deterioration.

Organic banana fibre is derived from the pseudo stem of the banana plant, a species of Musa. It is renowned for its robustness, resilience, and environmentally beneficial qualities. It is a byproduct of growing bananas and provides synthetic fibres with an environmentally friendly substitute. High strength, light weight, biodegradability, moisture absorption, lustre and appearance, thermal resistance, and renewable resource represent a few of the main characteristics of banana fibre. Strong, resilient, and eco-friendly, banana fibre finds use in a variety of products, including packaging, agricultural goods, textiles, and composites. Its biodegradability and sustainability make it a desirable substitute for synthetic materials, especially in sectors looking to lessen their environmental effect. Notwithstanding certain difficulties associated with processing and moisture sensitivity, banana fibre has enormous potential for environmentally friendly developments in a variety of applications [8].

Materials added to the composite matrix to change or improve its properties, lower costs, or emphasise particular features like strength, stiffness, or weight are known as fillers in composites. Their incorporation may have an impact on the mechanical, thermal, and electrical properties of the composite material. They may be synthetic or natural. In composite design, fillers are frequently essential because they improve performance without appreciably raising prices.

In composites, fillers are essential for altering and improving the material's characteristics. Manufacturers can customise composites for particular uses by choosing the appropriate filler, which lowers production costs and improves performance in areas like strength, weight, durability, or conductivity. The large range of fillers accessible allows for versatility in the design of composites for a variety of industries, including consumer products, automotive, aerospace, and construction. Natural fillers like almond shells and high-performance materials like silicon carbide are examples of available fillers [9].

Natural and sustainable, almond shell filler is a byproduct of processing almonds in agriculture. Previously regarded as trash, these shells are now utilised as a filler in the production of composites, especially biodegradable and environmentally friendly composites. Because they are more readily available, less expensive, and better for the environment than synthetic fillers, almond shell fillers are becoming more and more popular. They also help with waste management. Their mechanical qualities might not be as good as those of synthetic fillers, but their environmental advantages and appropriateness for low-load, biodegradable composites make them a desirable option for businesses looking to cut back on carbon emissions. In the automotive, construction, packaging, and consumer products industries, almond shell fillers are expected to witness a rise in utilisation due to the growing need for sustainable materials.

Glass fillers are frequently employed to improve the mechanical, thermal, and electrical properties of composite materials. They might be glass fibres, glass beads, or glass powder, and they are usually mixed with polymer matrices to make materials that are robust, long-lasting, and light. Glass fillers are widely employed in the automotive, aerospace, construction, and electronics industries due to their exceptional performance features. Although glass fillers have many advantages, issues like brittleness and moisture sensitivity need to be taken into consideration when choosing materials and processing methods.

In general, silicon fillers consist of silicon or silicon-derived compounds such as silicon carbide (SiC) or silica (SiO_2). Silicon fillers are renowned for their exceptional hardness, thermal conductivity, and chemical stability, rendering them highly advantageous in a wide range of industrial sectors. Silicon carbide, a filler recognised for its exceptional durability and thermal conductivity, is commonly included in composites to enhance wear resistance, hardness, and high-temperature performance. The inclusion of silicon fillers, namely silicon carbide and silica, provides notable benefits in improving the mechanical, thermal, and chemical characteristics of composite materials. Owing to their exceptional hardness, thermal stability, and wear resistance, these fillers find extensive application in sectors like automotive, aerospace, electronics, and construction. Nevertheless, it is crucial to meticulously control the expensive nature and possible fragility of composites during their design and manufacturing to guarantee the best possible performance in selected applications [10].

In many industrial applications, adhesives, coatings, and composite materials, epoxy resin and binders are essential ingredients. They enhance the qualities of different items in different ways, typically in complimentary but separate ways. Epoxy resin is a thermosetting polymer that finds extensive application as a major component in paints and flooring systems, as well as a matrix ingredient in composites, adhesives, and coatings. It is renowned for having outstanding adhesive qualities, a high mechanical strength, and chemical resistance. A binder is a substance that keeps other ingredients in a composition together. The binder in construction materials, adhesives, coatings, and composites makes ensuring that the filler or reinforcing components stay in place and that the finished product has the appropriate mechanical and physical qualities.

MATERIALS AND METHODS

The present study involved the production of composite sheets using natural fibres such as Kenaf, Sisal, and Banana, together with different fillers including almond shell, glass, and silicon carbide. The hand layup technique is employed in manufacturing.

Kenaf has a density falling between 1.2 and 1.5 g/cm³, which results in its low weight. Cellulose, accounting for 45-57% of kenaf fibre, is the primary structural element that enhances the strength of the fibre. Approximately 21-23% hemicellulose content contributes to flexibility. 15-19% lignin content imparts rigidity to the fibre [11,12].

The density of sisal fibre is around 1.45 g/cm³, which renders it lighter. The cellulose content of Sisal fibre is between 65-78%, which imparts the fibre with its strength and rigidity. The hemicellulose content ranges from 10% to 14% and enhances fibre flexibility. A lignin content of 8-10% imparts stiffness but also impacts biodegradability.

The density of banana fibre is around 11.35 g/cm³, which renders it lightweight and has similar properties to other natural fibres. The cellulose content in banana fibre is 60-65%, which imparts strength and stiffness to the fibre. Hemicellulose contents range from 15% to 17%, which enhance the elasticity and moisture absorption characteristics of the fibre. A lignin content of 5-10% provides stiffness but also increases the fragility of the fibre. Figure 1 shows the different varieties of fibres used for current study [13].

The density of almond shell powder is rather lower, usually ranging from 1.2 to 1.4 g/cm³, so enabling a reduction in the total weight of composite materials. Almond shells exhibit a high degree of stability at moderate temperatures, undergoing breakdown at the range of 200-250°C. Almond shells are predominantly composed of lignin, cellulose, and hemicellulose. The cellulose content is 25-30%, which enhances both strength and rigidity.

The lignin content is 25-35%, contributing to stiffness and enhancing water resistance. Hemicellulose content ranges from 25% to 30%, contributing to the material's elasticity. Approximately 1-3% of almond shells are composed of ash, which can impact the thermal and chemical stability of the filler.

The density of glass fillers is rather high, usually ranging from 2.4 to 2.6 g/cm³, therefore contributing to an increase in the weight of the composite material. A Young's modulus ranging from 70 to 90 GPa imparts significant stiffness and rigidity to the composite material. Glass fillers exhibit exceptional thermal stability and are capable of withstanding temperatures of 800°C or above, rendering them well-suited for high-temperature applications.

Figure 1. Natural fibres used for the present study.

The density of silicon carbide is 3.2 g/cm³, which is relatively high and can make composite materials heavier overall. Silicon carbide (SiC) has exceptional thermal conductivity, ranging from 120 to 270 W/m³K, making it well-suited for applications that need efficient heat dissipation. Silicon carbide fillers enhance the tensile strength and rigidity of the composite by contributing to a high Young's modulus of roughly 410 GPa.

For this study, three distinct composite specimens with various fillers were employed. For obtaining balanced strength and toughness, Specimen 1 has natural fibres like kenaf and sisal along with almond shell as filler with a composition ratio of Kenaf: Sisal: Almond shell: Epoxy = 25%: 25%: 15%: 35%; specimen 2 contains natural fibres like banana and sisal along with glass fibre as fillers with a composition ratio of Banana: Sisal: Glass: Epoxy = 25%: 25%: 20%: 30%; and specimen 3 contains natural fibres like kenaf and banana along with silicon fibre as fillers with a composition ratio of Kenaf: Banana: Silicon: Epoxy = 25%: 25%: 15%: 35%. To create composite materials, these materials were manufactured utilising the hand lay-up process. Figure 2 shows the different specimens prepared for the mechanical testing among the varieties of specimens prepared for the investigations [14,15].

RESULTS AND DISCUSSION

Tensile, hardness, flexural and impact tests were performed to assess and compare the mechanical characteristics of three structurally distinct materials, namely natural composite sheets. Specimens were prepared and tested in accordance with ASTM standards [16-18].

Table 1 gives the summary of results obtained under different mechanical testing conducted with ASTM standards.

Figure 2. Banana / sisal / kenaf composite specimens prepared for testing.

Table 1. Mechanical Testing Results.

Material and composition ratio	Sample	Tensile strength (MPa)	Flexural strength (MPa)	Hardness (HRC)	Impact energy (KJ/m^2)
Kenaf: Sisal: Almond shell: Epoxy(25%: 25%: 15%: 35%)	Sample 1	6.5	26	85	104.75
	Sample 2	6.7	25	90	106.42
	Sample 3	7.02	26	95	104.16
Banana: Sisal: Glass: Epoxy (25%: 25%: 20%: 30%)	Sample 1	35.5	85	98	105.8
	Sample 2	36.1	80	99	106.75
	Sample 3	36.07	90	97	107.01
Kenaf: Banana: Silicon: Epoxy (25%: 25%: 15%: 35%)	Sample 1	12	95	103	121.5
	Sample 2	12.58	85	100	124.25
	Sample 3	12.5	90	106	124.48

Tensile Test

Because of the orientation of the fibres or fillers, composite materials frequently display varying mechanical properties in different directions. Characterising this directional dependence is aided by tensile testing. The highest stress a composite can withstand before failing is measured by its tensile strength. Tensile examination ASTM D-638 has been carried out on the specimens.

The different values of ultimate tensile strength obtained during the tensile test have been shown in figure 3. The average value of three material's respective tensile strengths were 6.74 MPa for material 1, 35.89 MPa for material 2, and 12.36 MPa for material 3. The intrinsic glass filler property in material 2 along with the natural qualities of banana and sisal mat produced a greater ultimate tensile strength value. In contrast to materials without glass fillers, the natural toughness and flexibility of banana and sisal fibres, along with the inherent qualities of glass fillers, such as high tensile strength, stiffness, and interfacial bonding, create a synergistic hybrid composite with noticeably higher tensile strength.

Flexural Test

Composite materials are put through a flexural strength test to see how well they can withstand deformation and failure under bending loads. The highest stress a material can withstand in a bending arrangement before failing is known as its flexural strength. For flexural strength test ASTM D 790 standard was followed in this study.

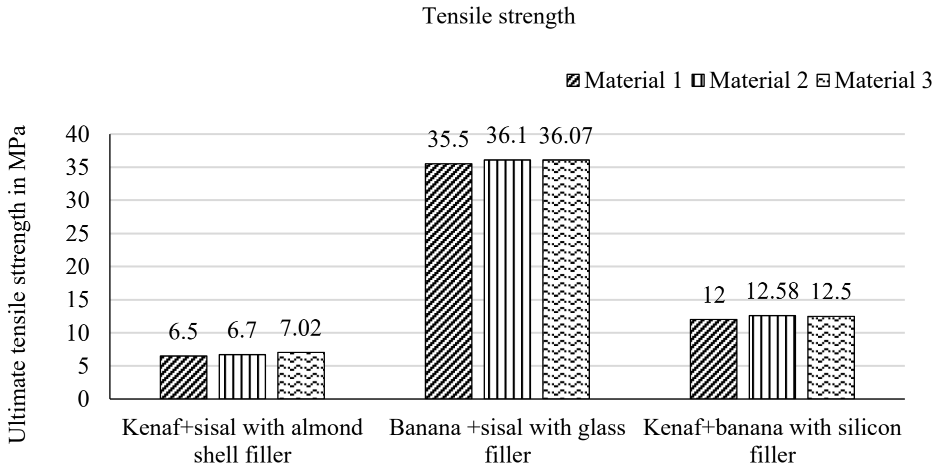

Figure 3. Tensile Test results of banana / sisal / kenaf composite specimens.

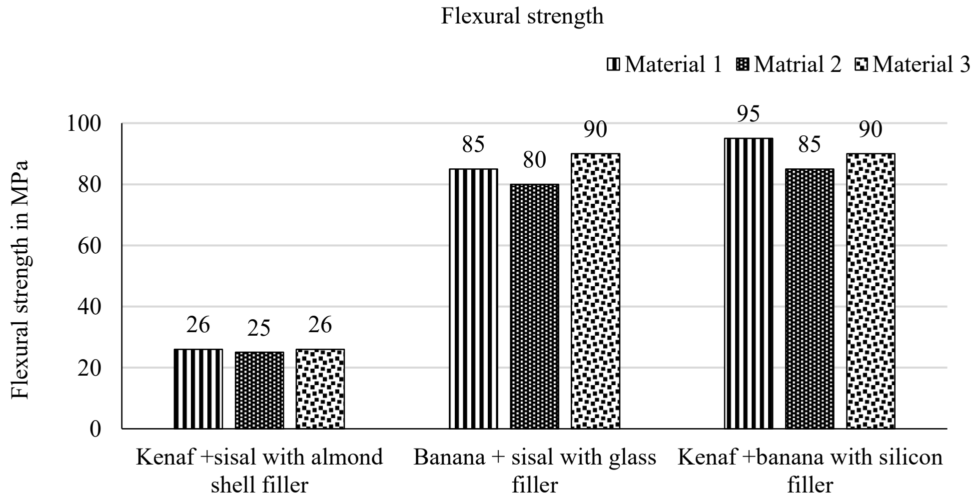

Figure 4. Flexural test results of banana / sisal / kenaf composite specimens.

As a result of the flexural test, the various values of flexural strength that were obtained are displayed in figure 4. The results of the flexural test showed that the mean values for the material 1 had a strength of 25 MPa, material 2 had a strength of 85 MPa, and material 3 had 90 MPa. By combining the enriched qualities of silicon carbide filler with the availability of kenaf and banana fibres, material 3 is determined to have the highest flexural strength of all the materials tested. Material 3 possesses outstanding flexural strength as a result of the unique mix of high-stiffness kenaf fibres, strong banana fibres, and rigid silicon carbide fillers. The effective distribution of stresses, resistance to fracture propagation, and enhancement of the composite's capacity to withstand bending loads without failure are all outcomes of the coactive interaction between natural fibres and synthetic fillers.

Hardness Test

Composite materials' hardness, which indicates their resistance to localised deformation (such indentation or surface penetration), is assessed using the Rockwell Hardness Test. In situations where wear resistance is crucial, this test is crucial for evaluating the durability and surface integrity of composites. This test was conducted in accordance with ASTM D785 standards [19-20].

The results of the hardness test are presented in figure 5, which summarises the various levels of hardness that were achieved. The specimens underwent a hardness test and resulted with the average value with 90 HRC in material 1, 98 HRC in material 2, and 103 HRC in material 3. According to the results of the other mechanical tests, substance 3 has the higher hardness value. The combination of kenaf fibre, banana fibre, and silicon filler produced material 3 with a greater hardness value of 103 HRC compared to materials 1 (90 HRC) and 2 (98 HRC). This can be due to the fact that material 3 contains silicon filler. Individually and in conjunction with one another, these components contribute to an increase in the material's stiffness, an improvement in bonding, and better microstructural properties that are resistant to deformation and provide an overall improvement in the material's hardness. Material 3, which contains a larger concentration of fibres and silicon filler, is anticipated to have superior mechanical qualities, including a higher level of hardness, in comparison to the other materials that were considered for testing.

Figure 5. Hardness test results of banana / sisal / kenaf composite specimens.

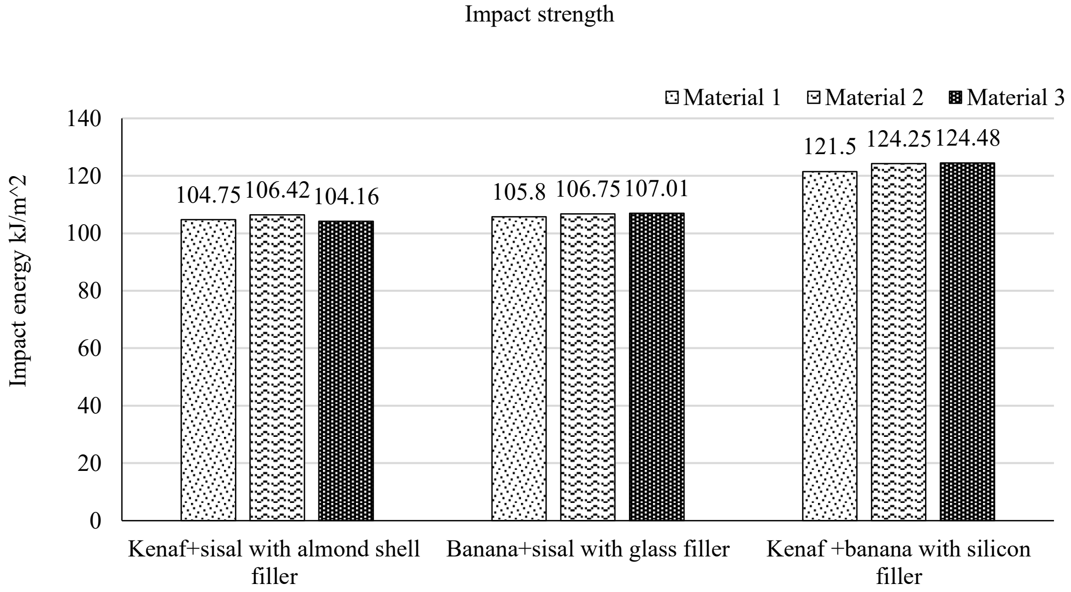

Figure 6. Impact test results of banana / sisal / kenaf composite specimens.

Impact Test

When composites are exposed to abrupt, high-energy forces or impacts, the impact test evaluates the material's capacity to absorb energy and withstand damage. When assessing a composite's toughness and resistance to delamination, crack propagation, or catastrophic failure under dynamic loading circumstances, it is crucial. The Izod Impact Test was conducted in accordance with ASTM D256 standards.

The outcomes of the impact test are depicted in figure 6, which provides a summary of the different amounts of impact energy that were attained. The impact test performed on the three materials yielded the mean results of 105.33 kJ/m^2 for material 1, 106.52 kJ/m^2 for material 2, and 123.41 kJ/m^2 for material 3, in a manner similar to those of the flexural test. The high impact energy in the material 3 was a direct outcome of the rich characteristics of the silicon carbide filler. The similar trends in both impact and flexural test results for the three materials indicate that material 3, with its combination of kenaf and banana fibers and silicon fillers, has superior toughness and energy absorption capacity. The fibers enhance the ductility and stress distribution, while the silicon fillers improve the matrix strength and bonding, resulting in better energy absorption in both static and dynamic loading conditions. This synergy of fibers and fillers contributes to the higher energy absorption seen in material 3 during both impact and flexural testing.

Microscopic Examination

Figures 7, 8, and 9 show the microscopic examination of three structurally distinct materials analysed using an optical microscope. From the optical images, it is evident that the bonding between the structural materials and the epoxy resin is continuous and firmly held by the resin layer. A homogeneous distribution of the natural composite sheets is uniformly observed throughout the fabricated materials. In Figure 3, it is evident that kenaf, sisal, and almond shell materials are strongly bonded with the epoxy resin via an adhesive mechanism. In some regions of the kenaf layer, the resin is visibly projected. Figure 4 demonstrates that banana, sisal, and glass materials are bonded with the resin layer without any gaps or interruptions, also by an adhesive mechanism. Figure 5 shows that the bonding between kenaf, banana, silicon, and the resin layers is thoroughly mixed, with no signs of agglomeration observed in the fabricated material. Thus, the microscopic examination validates the strong bonding between the structural materials and the resin layer, providing a foundation to proceed with mechanical testing.

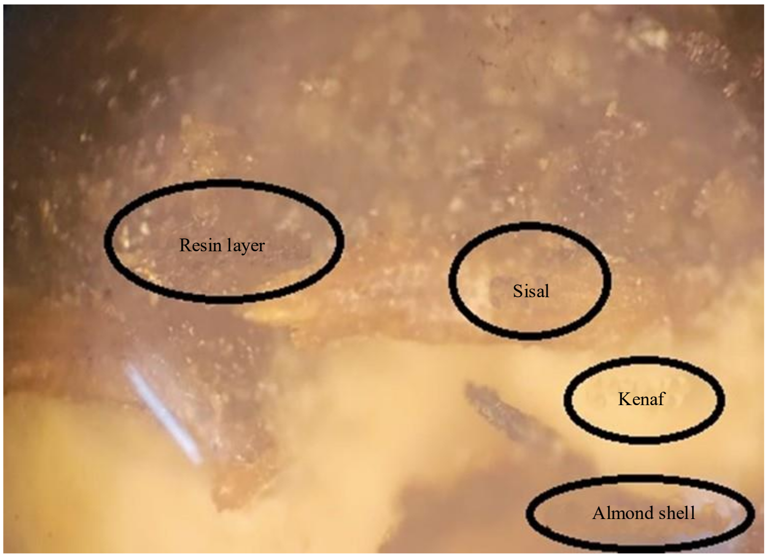

Figure 7. Microscopic image of kenaf: sisal: almond shell: epoxy (25%: 25%: 15%: 35%).

Figure 8. Microscopic image of banana: sisal: glass: epoxy (25%: 25%: 20%: 30%).

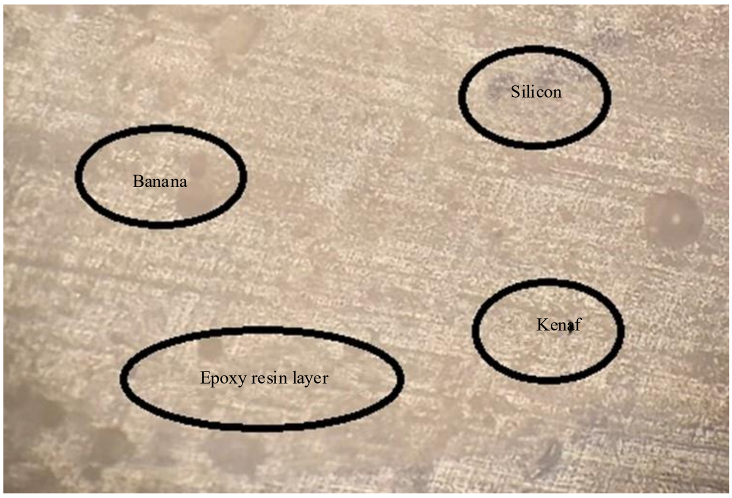

Figure 9. Microscopic image of kenaf: banana: silicon: epoxy (25%: 25%: 15%: 35%).

CONCLUSIONS

Kenaf and Sisal with Almond Shell Filler, Banana and Sisal with Glass Filler, and Kenaf and Banana with Silicon Filler were the three natural fibre composite materials that were analysed in this study. The mechanical properties of each of these materials were examined. The tensile strength, flexural strength, impact energy, and hardness of the material were the primary areas of inspection.

- In terms of total mechanical performance, Kenaf + Sisal with Almond Shell Filler had the lowest performance. Both the tensile strength (about 6.5–7.02 MPa) and the flexural strength (around 25–26 MPa) were rather low. However, the impact energy (approximately 104–106 KJ/m^2) remained identical across all samples, and the hardness rose. It is possible that this material is good for applications that require low-cost solutions and moderate impact resistance; nevertheless, it is not perfect for structural applications that require great strength.
- The material composed of banana and sisal with glass filler exhibited a higher tensile strength (about 35–36 MPa) in comparison to the other materials. Additionally, it exhibited a moderate flexural strength (around 80–90 MPa) and steady impact energy (approximately 105–107 KJ/m^2). Because of its high hardness values (97–99 HRC), this material is extremely durable and is an excellent choice for applications that require both strength and resistance to wear.
- It was determined that the substance with the best overall performance was Kenaf + Banana with Silicon Filler mix. The flexural strength (85–95 MPa), impact energy (121.5–124.48 KJ/m^2), and significant hardness (103–106 HRC) of this material were the highest demonstrated by any other material. The tensile strength of this material was lower than that of the glass-filled composite, which was approximately 12–12.58 MPa. However, because to its great impact energy and flexural performance, it is extremely suitable for applications that require superior toughness and energy absorption due to its exceptional performance.

In conclusion, Kenaf + Banana with Silicon Filler is the most promising material. It possesses exceptional flexural strength, impact energy, and hardness, which makes it a suitable material for applications that require high performance. As a result of its tensile strength and endurance, Banana + Sisal with Glass Filler is another material that represents a strong contender. While this is going on, Kenaf + Sisal with Almond Shell Filler demonstrates potential for use in non-structural, low-load applications where cost and mild impact performance are the most important considerations.

The significance of filler selection in boosting the mechanical properties of natural fibre composites for certain applications is brought to light by this investigation.

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