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Experimental Study on Mechanical Properties of Natural Fiber Reinforced Polymer Composite Materials

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ABSTRACT

The growing emphasis on sustainable materials has led to increased research on natural fiber-reinforced polymer composites (NFRPCs). This study investigates the mechanical properties of NFRPCs fabricated using various natural fibers, including jute, hemp, and sisal, as reinforcements in polymer matrices such as epoxy and polyester. By varying fiber types, orientations, and fiber-to-matrix ratios, the experimental results reveal significant trends in tensile strength, flexural strength, and impact resistance. Moderate Impact Strength: Sample-1 has impact strength of 22.2 J/m, which is nearly 57% lower than Sample-2. The absence of Coir and Flax reduces impact absorption compared to Sample-2. Lowest Impact Strength: Sample-3 has the lowest impact strength (20.4 J/m). Sample-2 has the highest tensile strength (56 MPa), meaning it can withstand the most stress before breaking compare to remaining compositions its 34% more tensile strength. Sample-2 has the highest flexural strength, indicating it is the most resistant to bending forces its value of flexural strength almost 30% more than the remaining samples. To conclude, biopolymers have been found to have the tendency to absorb more moisture than their synthetic counterparts. Moreover, natural composites have proved to perform particularly poorly when immersed in water. The findings demonstrate that natural fiber composites provide a sustainable alternative to synthetic composites, with competitive mechanical performance suitable for lightweight and eco-friendly applications.

Keywords: *Natural fiber, polymer, composite matrix, mechanical property, Tribology properties*.

1. INTRODUCTION

Natural fibers such as jute, hemp, flax, and sisal offer high specific strength, low density, and renewable nature. When combined with polymers, these fibers create composites that have applications in automotive, construction, and packaging industries. This study explores the mechanical properties of NFRPCs with varying compositions, fiber orientations, and fabrication techniques to understand their potential for industrial use. Fiber-reinforced polymer (FRP) composites have gained significant attention in recent decades due to their exceptional mechanical properties, lightweight characteristics, and versatility in applications ranging from aerospace to automotive and construction industries. Among these, natural fiber and graphite fiber polymer composites stand out as promising candidates, offering a balanced combination of sustainability and performance. Natural fibers such as jute, flax, hemp, and sisal are widely recognized for their biodegradability, abundance, and cost-effectiveness. These fibers serve as renewable reinforcements that can reduce the environmental footprint of composite materials. However, they often face challenges related to moisture absorption and relatively lower mechanical strength, which limit their standalone use in high-performance applications.

On the other hand, graphite fibers (a form of carbon fibers) exhibit outstanding mechanical strength, stiffness, and thermal stability. When combined with epoxy resin, graphite fibers enhance the overall structural integrity and load-bearing capacity of the composite. This makes them ideal for use in high-stress and demanding environments. The synergistic combination of natural fibers and graphite fibers in an epoxy matrix leverages the strengths of both materials. The natural fibers provide eco-friendliness and cost-efficiency, while the graphite fibers contribute superior mechanical and thermal properties. Epoxy resin, with its excellent adhesive, chemical and thermal resistance properties, acts as the matrix, ensuring effective stress transfer between the fibers and contributing to the durability this study focuses on the preparation of hybrid natural fiber and graphite fiber polymer composites with an epoxy matrix. By exploring the optimal processing conditions and material combinations, this work aims to develop a composite material that balances sustainability, performance, and affordability, addressing the growing demand for advanced materials in diverse engineering applications. Natural fibers are materials obtained from plants, animals, or minerals that can be spun into threads, yarns, or ropes and used to produce textiles and other products. These fibers are eco-friendly, renewable, and biodegradable, making them a sustainable alternative to synthetic fibers. In the past, natural fibers were used in building and structural applications. More recently, some cellulosic products and wastes have been used as fillers in polymers to achieve cost savings and to impart some desirable properties (Chawla and Bastos, 1979; Kokta, 1988; Lubin, 1982; Maldas and Kokta, 1995; Piggot, 1980; Prasad et al., 1983). Already explored industrial applications include window and door frames, furniture, railroad sleepers, automotive panels and upholstery, gardening items, packaging, shelves etc., applications in aerospace, leisure, construction, and sports, industries and, in general applications that do not require very high mechanical resistance, but, instead, reduce the purchasing and maintenance costs (Faris et al., 2014; Ku et al., 2011; Mantia and Morreale, 2011). Recent work on natural fiber composites reveals that the specific mechanical properties of natural fiber composites are comparable to those of glass fiber reinforced composites. Natural fiber composites, in the form of panels, tubes, sandwich plates, have been used to replace wooden fittings, and fixtures, for furniture, and noise insulating panels in the last decade (Alves et al., 2010; Mei-po et al., 2011).

1. Materials

a) **Natural Fibers**: Choose natural fibers such as jute, hemp, flax, sisal, kenaf, or coir based on the availability and mechanical performance.

b) **Polymer Matrices**: Epoxy and polyester resins were used due to their superior bonding with fibers and widespread application.

c) **Fiber Treatment**: Fibers were treated with alkali (NaOH) to enhance interfacial adhesion with the matrix.

Fig: 1 Raw Materials used for the Investigation (a) Jute fiber (b) flax fiber (c) sisal fibre (d) coir fibre (e) carbon fibre (f) Glycerol

2. Methods

3.1 Multi-layer natural fiber composite binding process

The binding process for multi-layer natural fiber composites involves assembling layers of natural fibers and a compatible matrix material (e.g., resin) to form a cohesive composite structure. Below is a step-by-step explanation of the typical process:

3.2 Material Selection

- **Fibers:** Choose natural fibers such as jute, hemp, flax, sisal, kenaf, or coir based on the desired mechanical and thermal properties.
- **Matrix Material:** Select a compatible matrix, such as thermosetting resins (e.g., epoxy, polyester) or thermoplastics (e.g., polypropylene, polylactic acid). Biodegradable or bio-based resins are often used for eco-friendly applications.

3.3 Fiber Preparation

- **Cleaning:** Remove impurities from the fibers to improve adhesion with the matrix.
- **Drying:** Ensure the fibers are dry to avoid issues like poor bonding and voids.
- **Surface Treatment:** Treat fibers with chemical agents (e.g., alkali treatment) or physical methods (e.g., plasma treatment) to enhance interfacial bonding with the matrix.

3.4 Preparation of Composite Fiber Material Using a Vacuum Oven

A **vacuum oven** is commonly used in the processing of polymer composite fibers to remove trapped air, improve fiber-matrix bonding, and enhance the mechanical properties of the final composite. Below is a step-by-step guide on preparing fiber-reinforced polymer (FRP) composites using a vacuum oven. Surface Preparation & Molding Setup: Clean the mold to remove dust, oil, and debris. Apply a release agent to prevent sticking. Cut fiber fabric to the required dimensions. Resin Preparation & Impregnation: Mix the resin and hardener in the correct ratio. Apply vacuum (typically 0.8 to 0.9 bar). Set the appropriate curing temperature based on the resin type: Epoxy resin: 80–120°C Polyester resin: 60–90°C, PEEK (thermoplastic): 250–400°C, Maintain curing for the specified time (e.g., 2–6 hours). Gradually cool the composite inside the oven to avoid thermal stress. Post-Curing & Finishing: Remove the composite from the oven and vacuum bag. Trim excess material and perform surface finishing (sanding, polishing). Conduct mechanical testing (impact, tensile, flexural tests) to evaluate quality.

Twin-screw extruder is widely used for compounding **natural fiber-reinforced polymer composites (NFCs)**. It allows continuous processing, better fiber dispersion, and improved polymer-fiber adhesion. The extruder blends natural fibers with thermoplastic or thermosetting polymers to produce composite pellets or sheets. **Fiber Pre-Treatment:** Natural fibers absorb moisture, which can cause **poor adhesion and degradation** at high processing temperatures. **Drying:** Heat fibers at **80–110°C** in an oven for **4–8 hours** to remove moisture. **Chemical treatment (optional): Alkaline treatment (NaOH, 5–10%)** removes lignin and increases fiber roughness for better bonding. **Silane or MAPP coupling agents** improve adhesion with the polymer. **Acetylation** enhances fiber compatibility with hydrophobic matrices.

Extrusion Process Using Twin-Screw Extruder: Screw speed: 50–200 rpm (lower for better fiber retention, higher for better mixing). **Temperature zones:** Zone 1 (Feeder): **150–180°C,** Zone 2 (Mixing): **180–220°C,** Zone 3 (Melt zone): **200–250°C,** Zone 4 (Die exit): **180–200°C. Feeding:** Feed **dried fibers** and **polymer pellets** into the twin-screw extruder. Maintain a **fiber loading of 10–40%** (higher fiber content improves strength but reduces process ability). **Melting & Mixing:** The polymer melts inside the heated extruder barrel. Fibers are **sheared and dispersed** into the polymer melt. Coupling agents promote fiber-polymer bonding. **Degassing & Moisture Removal:** A vacuum vent removes residual moisture and volatile compounds. **Extrusion through Die:** The mixture exits through a die to form **pellets, sheets, or profiles**. **Post-Processing & Final Product Formation: Pelletizing:** Composite strands are cut into pellets for injection molding or further processing. **Sheet Formation:** If a sheet die is used, the extruded sheet is **cooled, calendared, and cut** into final dimensions. **Compression Molding (Optional):** Pellets can be **remelted and molded** into automotive, construction, or packaging components.

3.5 Layer Arrangement

- Arrange fibers in the desired orientation (e.g., unidirectional, woven, or random mat) depending on the application.
- Stack the layers in the desired sequence to form the composite's preform.

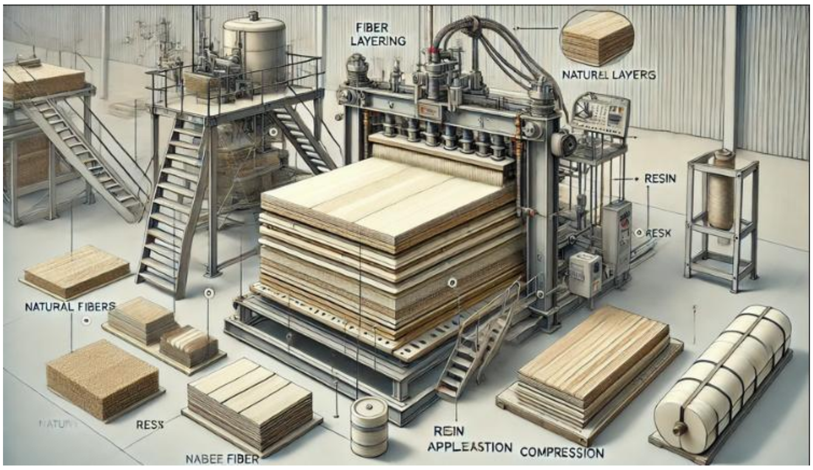

Fig.2. depicting the multi-layer natural fiber composite binding process.

3. Results

3.1 Tribological Properties

Two significant tribological phenomena that arise during the relative motion of solid surfaces are friction and wear. These processes typically result in energy dissipation and material degradation. At high temperatures, the tribological characteristics of phenol formaldehyde composites containing varying sisal fiber volume percentages were examined. While the friction coefficient displayed distinct patterns at different temperatures, the impact of varying fiber quantities on the wear rate and coefficient of friction of sisal fiber/phenol formaldehyde composites was taken into consideration. At higher temperatures, the wear rate rose noticeably. The bulk of the friction stresses are often carried by detached fibers on the composites' worn surface. Defects in the composites are likely to arise at greater fiber content levels because of the fibbers' poorer matrix dispersion. In general, a quantitative figure that describes a material's frictional behaviour is called the coefficient of friction (COF). A friction value in wear testing might be either a steady number determined at the conclusion of the test or an average of the whole test. Wear is the gradual loss of material during sliding from one or both mating surfaces due to chemical and/or mechanical processes. At various operating conditions, the worn surfaces of flax epoxy (FE) and jute fiber reinforced epoxy (JFRE) composite have been noted. The primary cause of deboning, which weakened the interfacial link between the fibers and the matrix, is high thermo mechanical. The strong side force caused microcracks to spread.

4.2 SEM Characterization of Natural Fiber Polymer Composites

SEM results help obtain a clear picture of crack propagation properties and the state of fiber during failure. SEM characterization of flax reinforced laminates shows the brittle character of the fracture at a microscopic level with significant presence of pull-out, with weak interface and the presence of fibrillation. Fractrography studies on Jute/sisal/flax fiber reinforced hybrid polyester composites, showing the fracture behavior of the composite, indicate that a better fiber–matrix adhesion exists in the hybrid composite due to the interlocking of fibers. The fracture surface morphologies of natural fibers/carbon fiber reinforced hybrid composites that were subjected to tensile and flexural tests are shown in images below of the hybrid composite with untreated natural fibers/carbon fiber reinforced hybrid composites that were subjected to tensile and flexural tests are shown in Fig below of the hybrid composites with the untreated fiber that was tested at RT; the surface morphology was rough and exhibited typical long fiber pull-out. When the samples were tested at 40^0C, voids due to fiber pull-out could be observed. These images indicate that weak interfacial bonding exists between the untreated natural fibers/carbon fiber fibers and the epoxy matrix. Porous structure with lumen, where the resin did not penetrate into the bundles of fibers. However, when the samples were tested at 60^0C, deboning of the fiber–matrix interface was observed, as shown in Fig, this is because the temperature approached the T_g value of the composites. Finally, softening of the epoxy matrix can be clearly observed in the fracture-surface image of the sample that was tested at 80^0C.

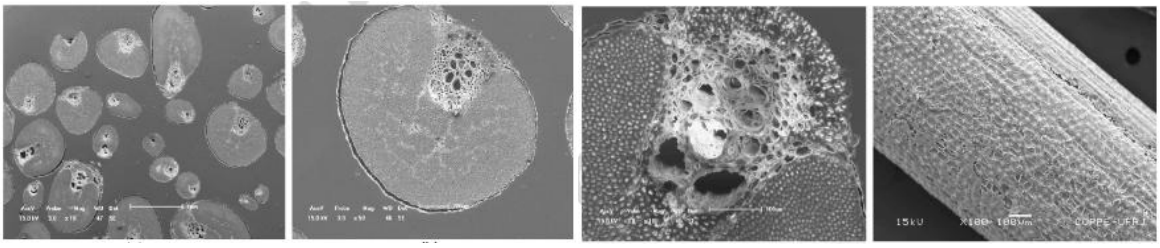

Fig.3. Scanning electron micrographs showing the morphology of fibers

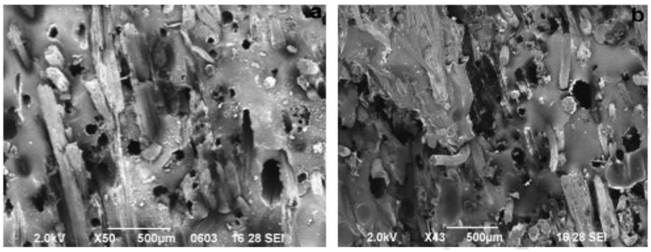

Fig.4. SEM micrograph of the flexural fractured specimen

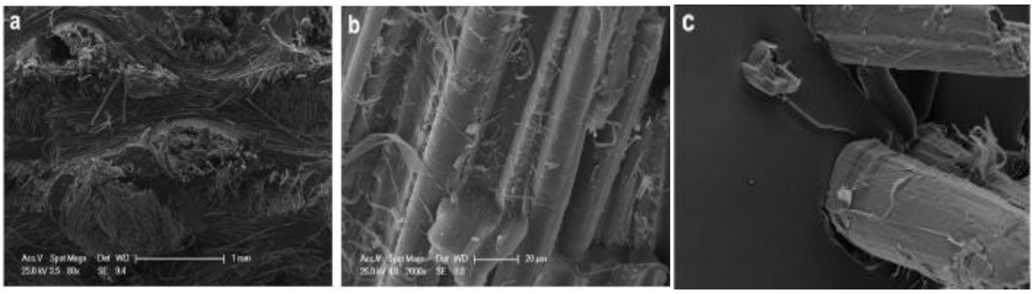

Fig.5. SEM images of the fracture surface of (a) Jute (b) sisal (c) flax fiber reinforce

4.3 Density

To compare the density (g/cc) of three different polymer composite specimens, we need to consider the composition of each composite, including the polymer matrix and reinforcing materials (fibers, fillers, or nanoparticles). Below is a general comparison based on common polymer composites.

Table: 1 Density of various polymer composite samples

Specimen	Polymer Matrix	Reinforcement	Density (g/cc)
Specimen 1	Epoxy Resin	Natural fiber (Jute + sisal) + Graphite Fiber	1.16
Specimen 2	Epoxy Resin	Natural fiber (Jute + sisal + Coir + Flax) + Graphite Fiber	1.29
Specimen 3	Epoxy Resin	Natural fiber (Flax + Coir) + Graphite Fiber	1.24

If you have specific polymer composites in mind, please provide details, and I can refine the density comparison accordingly. Sample-1 is the lightest, making it suitable for applications where weight reduction is a priority. Sample-2 has the highest density, likely leading to better mechanical properties. Sample-3 falls in between, providing a balance of moderate weight and good strength.

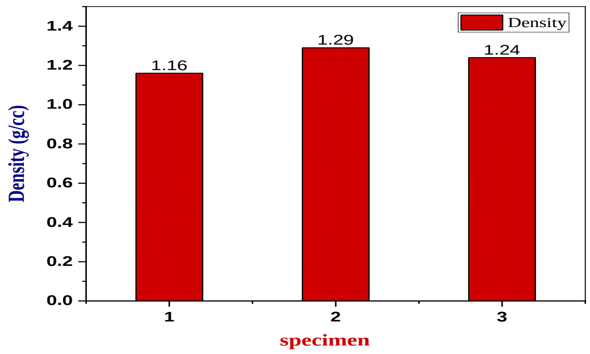

Fig.6. Density of various polymer composite samples

4.4 Impact Energy

The **impact energy** of a **polymer composite fiber** refers to the energy required to fracture or damage the composite under sudden loading conditions. This is a crucial parameter in assessing the toughness and durability of fiber-reinforced polymer (FRP) composites used in applications such as aerospace, automotive, and protective materials.

Table: 2 Impact Energy of various polymer composite samples.

Specimen	**Polymer Matrix**	**Reinforcement**	**Impact Energy (kJ/m^2)**
Specimen 1	Epoxy Resin	Natural fiber (Jute + sisal) + Graphite Fiber	22.2
Specimen 2	Epoxy Resin	Natural fiber (Jute + sisal + Coir + Flax) + Graphite Fiber	51.6
Specimen 3	Epoxy Resin	Natural fiber (Flax + Coir) + Graphite Fiber	20.4

Highest Impact Strength: Sample-2 has the highest impact strength (51.6 J/m). The presence of four natural fibers creates a synergistic reinforcement effect, leading to better energy absorption during impact. Moderate Impact Strength: Sample-1 has impact strength of 22.2 J/m, which is nearly 57% lower than Sample-2. The absence of Coir and Flax reduces impact absorption compared to Sample-2. Lowest Impact Strength: Sample-3 has the lowest impact strength (20.4 J/m). Jute and Sisal are missing, which may reduce fiber-fiber bonding strength and energy dissipation. Sample-2 shows superior impact resistance, likely due to the diverse fiber combination enhancing load transfer and energy absorption. Sample-1 and Sample-3 have lower impact strength, indicating that fewer fiber types result in lower toughness. Adding multiple natural fibers improves composite toughness, as seen in Sample-2.

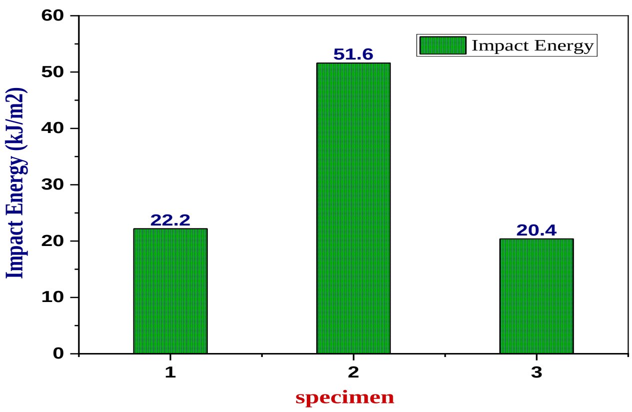

Fig.7. Impact Energy of various polymer composite samples

4.5 Tensile strength

The tensile strength of composites increased with higher fiber content up to 30% but showed a decline at 40%, likely due to poor fiber dispersion and agglomeration. Jute fiber composites exhibited the highest tensile strength, followed by flax and sisal. The unidirectional orientation provided better tensile properties than random orientation.

Table: 3 Tensile strength of various polymer composite samples.

Specimen	Polymer Matrix	Reinforcement	Tensile strength(MPa)
Specimen 1	Epoxy Resin	Natural fiber (Jute + sisal) + Graphite Fiber	39
Specimen 2	Epoxy Resin	Natural fiber (Jute + sisal + Coir + Flax) + Graphite Fiber	56
Specimen 3	Epoxy Resin	Natural fiber (Flax + Coir) + Graphite Fiber	37

Sample-2 has the highest tensile strength (56 MPa), meaning it can withstand the most stress before breaking. Sample-1 has moderate strength (39 MPa), performing better than Sample-3 but lower than Sample-2. Sample-3 has the lowest tensile strength (37 MPa), suggesting it may have a weaker reinforcement or polymer matrix compared to the others.

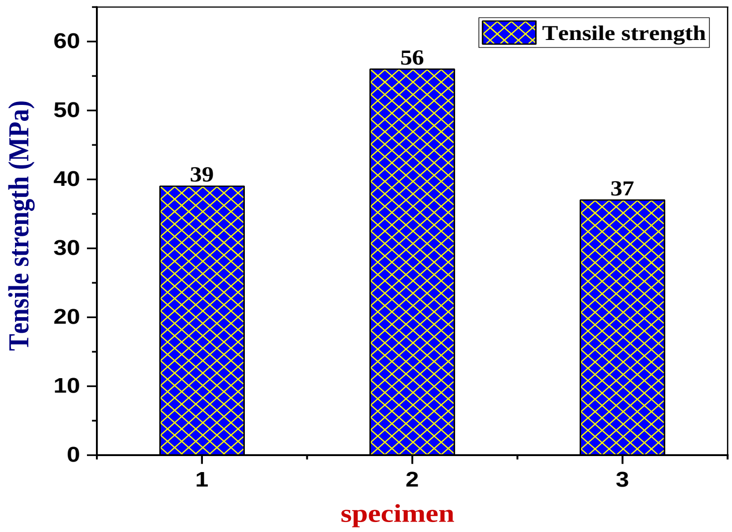

Fig.8. Tensile strength of various polymer composite samples

4.6 Youngs Modulus

Natural fiber composites offer moderate stiffness with sustainability benefits but have lower mechanical performance compared to synthetic fibers. Carbon fiber composites provide exceptional stiffness and strength, making them ideal for high-performance applications but come at a higher cost. The choice between natural fiber and carbon fiber composites depends on factors such as cost, environmental considerations, mechanical requirements, and end-use applications. Understanding the Young's modulus of these fiber-reinforced epoxy composites is essential for optimizing their structural performance and ensuring their suitability for specific engineering applications.

Table: 4 Youngs Modulus of various polymer composite samples.

Specimen	Polymer Matrix	Reinforcement	Youngs modulus(GPa)
Specimen 1	Epoxy Resin	Natural fiber (Jute + sisal) + Graphite Fiber	2.38
Specimen 2	Epoxy Resin	Natural fiber (Jute + sisal + Coir + Flax) + Graphite Fiber	3.36
Specimen 3	Epoxy Resin	Natural fiber (Flax + Coir) + Graphite Fiber	1.6

Sample-2 has the highest Young's modulus (3.36 GPa), indicating it is the stiffest composite. Likely, this sample has high-stiffness reinforcements (e.g., carbon fiber). Sample-1 (2.38 GPa) has moderate stiffness, suggesting a balance between flexibility and rigidity, possibly due to a lower reinforcement percentage or a different fiber type. Sample-3 (1.60 GPa) has the lowest stiffness, meaning it is the most flexible. This could be due to natural fiber reinforcements or a more flexible polymer matrix.

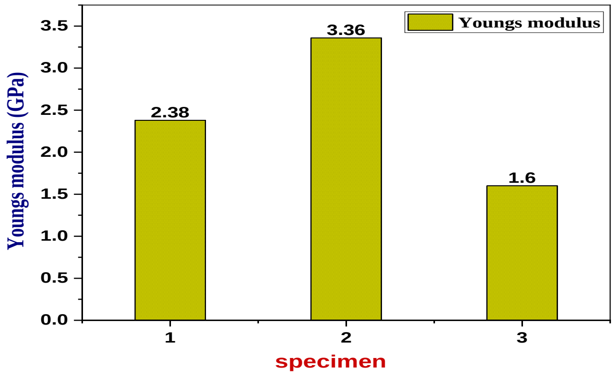

Fig.9. Youngs modulus of various polymer composite samples.

4.7 Flexural strength

While **natural fiber-reinforced epoxy composites** offer an eco-friendly and cost-effective alternative, they exhibit lower flexural strength compared to **carbon fiber-reinforced epoxy composites.** Carbon fiber composites are preferred for high-performance applications due to their outstanding mechanical properties. However, NFRCs are gaining popularity in sustainable applications where moderate strength and biodegradability are prioritized.

Table: 5 Flexural strength of various polymer composite samples

Specimen	Polymer Matrix	Reinforcement	Flexural strength(MPa)
Specimen 1	Epoxy Resin	Natural fiber (Jute + sisal) + Graphite Fiber	62
Specimen 2	Epoxy Resin	Natural fiber (Jute + sisal + Coir + Flax) + Graphite Fiber	89
Specimen 3	Epoxy Resin	Natural fiber (Flax + Coir) + Graphite Fiber	57

Sample-2 (89 MPa) has the highest flexural strength, indicating it is the most resistant to bending forces. It likely contains a strong reinforcement. Sample-1 (62 MPa) has a moderate flexural strength, suggesting a balanced composite with decent reinforcement. Sample-3 (57 MPa) has the lowest flexural strength, making it the least resistant to bending forces. This could be due to a lower reinforcement percentage, the use of natural fibers, or a weaker matrix.

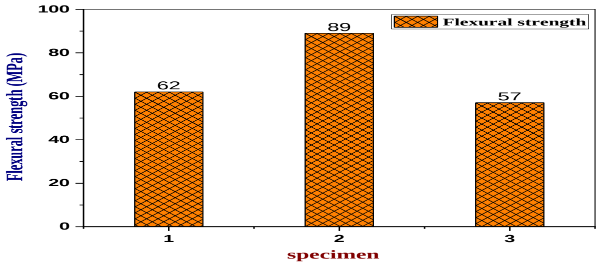

Fig.10. Flexural strength of various polymer composite samples

4.8 Flexural modulus

The **flexural modulus** of a composite polymer indicates its stiffness or resistance to bending under an applied force. It is measured in **gigapascals (GPa)** and varies based on the fiber type, polymer matrix, and fiber-matrix interaction.

Table: 6 Flexural modulus of various polymer composite samples.

Specimen	Polymer Matrix	Reinforcement	Flexural modulus(GPa)
Specimen 1	Epoxy Resin	Natural fiber (Jute + sisal) + Graphite Fiber	3.5
Specimen 2	Epoxy Resin	Natural fiber (Jute + sisal + Coir + Flax) + Graphite Fiber	5.6
Specimen 3	Epoxy Resin	Natural fiber (Flax + Coir) + Graphite Fiber	2.9

Sample-2 has the highest stiffness; making it more suitable for applications requiring high flexural strength. Sample-3 has the lowest stiffness, making it more flexible, which may be useful for applications needing impact absorption. Sample-1 is intermediate, balancing stiffness and flexibility.

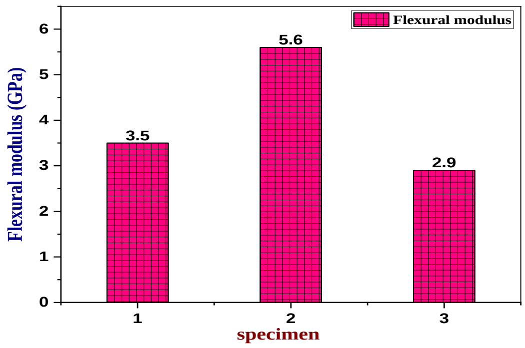

Fig.11. Flexural modulus of various polymer composite samples

4.9 Moisture absorption behaviour

The effects of fiber content and fiber surface modifications on the flexural, impact and water absorption properties of the composites were investigated. They found that acrylic acid treatment resulted in improved mechanical and water absorption properties of the composites, compared to the alkali treatment and to the absence of any fiber modification. The influence of sea water ageing on the properties of bio-composites. They showed that the weakening of the interface between flax fiber and carbon fiber matrix is one of the main factors triggering the damage mechanism induced by water absorption. The water absorption properties of coir and sisal fiber reinforced Epoxy composites, using water at three different temperatures, of 23, 50, and 70^0C, were analyzed. A decrease in the tensile properties of the composites was demonstrated, showing a great loss in mechanical properties of the water-saturated samples, compared to the dry samples. To conclude, biopolymers have been found to have the tendency to absorb more moisture than their synthetic counterparts. Moreover, natural composites have proved to perform particularly poorly when immersed in water. The strength of a sisal/carbon composite was 13–31% lower when fully immersed into liquid than at 95% RH.

5. Conclusions

This experimental study highlights the potential of natural fiber-reinforced polymer composites as sustainable alternatives to synthetic materials. Key findings include: Because of their bio renewable nature and environmentally friendly nature, natural fibers provide a number of advantages over synthetic materials in reinforcing composites. As a result, they can be used efficiently in a variety of applications. The current essay examines the reliability of natural fibers and their composites in this context. Our survey examines numerous findings from the published literature on the mechanical characteristics of natural fibers, including their tensile, impact, and interlinear qualities, as well as their water absorption and tribological qualities and those of natural fiber composites, in order to evaluate the dependability of natural fibers. Because they are biodegradable, plant-based natural fiber composites have shown themselves to be a significant substitute for synthetic fiber reinforced polymer matrix composites. Reducing the usage of synthetic fibers and greenhouse gas emissions can be achieved by using more natural fiber as reinforcement for composite materials. In terms of tensile strength, impact strength, interlinear shear strength, heat, water absorption, and tribological characteristics, natural fiber composites are similar to synthetic fiber composites. The type of resin, the fiber's origin (fruit, stem, leaf, etc.), the reinforcement type (powder form, short fiber, continuous fiber), the fiber orientation (unidirectional or multidirectional), and the manufacturing method (hand layup, compression molding, injection molding, etc.) all affect the composites' characteristics. The desire for more environmentally friendly materials in the modern world has led researchers to focus on natural cellulosic fibers, which have been successfully employed as reinforcements in a variety of applications in place of synthetic fibers. A thorough analysis of the many characteristics of natural fibers and how they are described using different methods is provided in this work. This information may benefit new researchers in the field and offer insight into natural fiber composites. Additionally, a thorough examination of various surface modification techniques for natural fibers and processing methods for composite fabrication may be included in the future. It is also possible to talk about the application of different thermoset and thermoplastic polymers and how they affect composites. However, there are still a number of issues with using natural fibers in polymer composites, including the composites' poor thermal characteristics and excessive water absorption. Furthermore, there are a few less studied areas, like the plant-based composites' acoustic insulating qualities, thermal conductivity, and electric resistance. Future studies must focus on environmentally benign materials that have enough qualities to take the place of synthetic polymer composites in order to open up new application areas.

Future research should explore hybrid composites, long-term durability, and environmental performance under real-world conditions to broaden the application scope of NFRPCs.

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