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Sustainable Natural Fiber Composites: A Study on Mechanical Performance and Moisture Behavior

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Abstract: *This study investigates the synthesis, mechanical behavior, and performance potential of natural fiber-reinforced epoxy composites as sustainable alternatives to conventional synthetic materials. Emphasis is placed on understanding how different fibers sisal, Aloe-vera, and Bamboo influence the composite's mechanical properties. Composites were fabricated using various processing techniques, including hand lay-up, vacuum infusion, and compression molding. These methods affect fiber distribution and interfacial adhesion, which play a vital role in determining the final mechanical performance. Critical factors such as fiber type, surface treatment, and epoxy matrix formulation were carefully controlled during synthesis. Experimental data show significant variation in mechanical properties based on fiber selection. For instance, aloe vera-reinforced composites demonstrated tensile strength around 26 MPa, with a Young's modulus of 1 GPa and 7.4% elongation at break. In contrast, bamboo-reinforced composites achieved tensile strengths up to 307 MPa, while some reports suggest aloe vera fibers can yield strengths between 350–500 MPa under optimized conditions. Additional parameters such as fiber orientation, matrix compatibility, and fiber-matrix interfacial bonding were found to influence tensile strength, impact resistance, and thermal stability. Aligned fibers in the epoxy matrix significantly improved strength in specific loading directions, underscoring the need for optimized composite design. The results highlight the feasibility of using treated natural fibers to engineer high-performance, eco-friendly epoxy composites for structural applications in automotive, aerospace, and construction industries.*

Keywords: Natural fiber-reinforced composites, Epoxy matrix, Sustainable materials, Mechanical properties

I. INTRODUCTION

Epoxy-reinforced natural fiber composite materials have emerged as a promising alternative to traditional synthetic fiber composites due to their unique combination of mechanical properties, environmental sustainability, and cost-effectiveness. These materials consist of a matrix of epoxy resin reinforced with natural fibers such as jute, hemp, banana, coconut, sisal, or flax. The incorporation of natural fibers enhances the mechanical performance of the composites, making them suitable for a wide range of applications. The utilization of natural fibres obtained from diverse plant sources represents a vital aspect of this research. These renewable resources not only contribute to the reduction of carbon footprint but also extend the range of applications for composites. This review explores the wide array of plant sources available for natural fibre synthesis, emphasizing their significance in fostering sustainability in material development. Fig. 1 illustrates a comparison between natural fibers.

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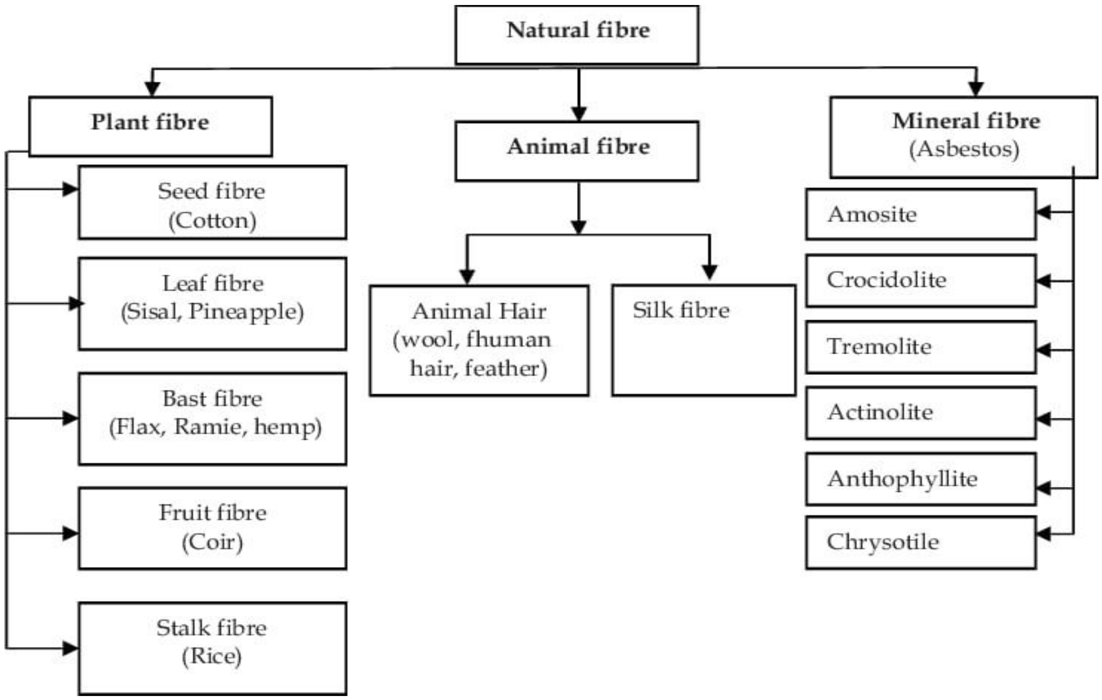

Fig. 1: Composite Materials Types of reinforcements in composites

Natural fibers and glass fibers are two common types of fibers used in composite production, each with unique properties and applications. Natural fibers, sourced from plants or animals, offer sustainability and biodegradability, making them environmentally friendly. In the automotive industry, epoxy-reinforced natural fiber composites can be used for interior components, such as door panels and dashboards, reducing the weight of vehicles and improving fuel efficiency. Moreover, the use of natural fibers offers potential for reducing the carbon footprint of the automotive sector.

Pickering et al. (2008) The most common classification for natural fibres is by botanical type. Using this system, there are six basic types of natural fibres: bast fibres such as jute, flax, hemp, ramie, and kenaf; leaf fibres such as banana, sisal, agave, and pineapple; seed fibres such as coir, cotton, and kapok; core fibres such as kenaf, hemp, and jute; grass and reed such as wheat, corn, and rice. Bast fibres come from the inner bark or phloem of dicotyledonous plants and provide structural strength and rigidity to the plant stem. These fibres lay under a thin bark and exist as fibre bundles or strands and run parallel to the length of the stem. Vimal et al. (2015) studied mechanical properties of modified fibre reinforced epoxy composites. They used two types of fibre treatment- Succinylation and Phthalicylation with different concentrations. Fibre was treated one by one in a chemical solution and then found phthalicylated fibre has shown good flexural properties. Couture et al. (2016) used UD flax/PLA and UD flax-paper with a PLA matrix for fabrication of unidirectional composite. Compression moulding technique was used to develop composite. The mechanical properties of composites made with UD flax and UD flax-paper were compared. The tensile and flexural properties of the flax/PLA were obtained better than flax- paper/PLA. UD flax paper obtained high impact strength. Seshanandan et al. (2016) studied the effect of nano titanium oxide additives on the properties of hybrid jute-glass composites. Hand layup technique was used to fabricate the composite. Hybrid jute-glass frp composites were manufactured with glass fibre chopped strand mat, woven jute mat, polyester resin and nano titanium oxide. All mechanical properties were enhanced due to use of nano titanium filler. Kumar et al. (2022) Natural composites materials were developed by using hand layup process. Initially a mould in workshop with the help of various types of carpentry tools with good surface finishing and dimensional accuracy. Matrix material used in this experiment is epoxy resin and for curing, hardener was used in a proper ratio. Hardener were poured in epoxy with helps of cylindrical glass beaker and properly mixed by ultrasonic mixture in the large size cylindrical glass beaker of weight ratio, respectively. Mould releasing agent such as wax coated on Teflon sheet was kept at the bottom of the mould to easily remove the composites plate after solidification. Then epoxy-hardener mixture was applied on the mould and these mixtures were spread with the help of hand brush. After complication of all the process finally 30 kg weight were put on it and leave it for about 24 hours for curing. Singh et al. (2022) Bidirectional Aloe vera natural fibre material which are biodegradable, eco- friendly, light in weight are bought from Go-Green product ltd. Chennai, India, Processing techniques of bidirectional aloe vera fibre mat are indicated in Figure. The important properties of aloe vera fibre as per the supplier are presented in Table.

To use the hand layup process to create the fiber mixing of the reinforced hybrid composite made of alovera and sisal fibers. Utilizing various testing techniques to determine the composite's mechanical characteristics. Preserving the required weight, stiffness, and strength specifications while perhaps becoming more affordable than conventional materials. To investigate the behavior of created composites in absorbing moisture Gupta et al. (2017) The sisal leaf fibres are bundles as long as the leaf, 12 m long. The ultimate fibres of sisal average 3 mm (1±8 mm) long and 20 m (8±41 m) wide. Sisal or sisal hemp is an agave, Agave sisalana, which grows with sword-shaped leaves about 1.5±2 m tall. It is indigenous to the Western hemisphere, particularly Mexico. The name comes from the Yucatan port of Sisal from which the fibre was first exported. The sisal plant has a 7±10year lifespan and typically produces 100+250 dark to pale green leaves in the formed in a rosette on the trunk. Each leaf is approximately 1±2 m long, 10±15 cm wide, and 6 mm. Lee et al. (2012) Natural plant fibres have unequivocally contributed economic prosperity and sustainability in our daily lives. Particularly, bamboo fibres have been used for industrial applications as diverse as textiles, paper, and construction. Recent renewed interest in bamboo fibre (BF) is primarily targeted for the replacement or reduction in use of glass fibre from non-renewable resources. In this review, various mechanical, chemical, and biological approaches for the preparation and separation of macro-, micro-, and nanosized fibres from raw bamboo are summarized. The differences in the mechanical, thermal, and other properties of fibres from different materials are linked to their size, aspect ratio, surface charge and groups, and their function in nature. Bio composites made of BF are considered to be green, environmentally responsible eco-products. Different processing parameters such as fibre extraction, surface modification, and synthesis of the composites affect the characteristics of composites

II. METHODOLOGY

This chapter examined several techniques for creating composite materials. The analysis revealed that hand layup production process is simple and appropriate for the creation of composite materials. As a result, we completed the hand layup for creating a natural fiber composite using three distinct fibers.

Hand lay-up Methods

Hand lay-up is the simplest and oldest open molding method for fabricating composites. At first, dry fibers in the form of woven, knitted, stitched, or bond fabrics are manually placed in the mold, and a brush is used to apply the resin matrix on the reinforcing material. Subsequently, hand rollers are used to roll the wet composite to ensure an enhanced interaction between the reinforcement and the matrix, to facilitate a uniform resin distribution, and to obtain the required thickness. Finally, the laminates are left to cure under standard atmospheric conditions. Generally, this process is divided into four steps: mold preparation, gel coating, lay-up, and curing. Curing is the process of hardening the fiber-reinforced resin composite without external heat. Fig. 2 show process of hand-lay-up.

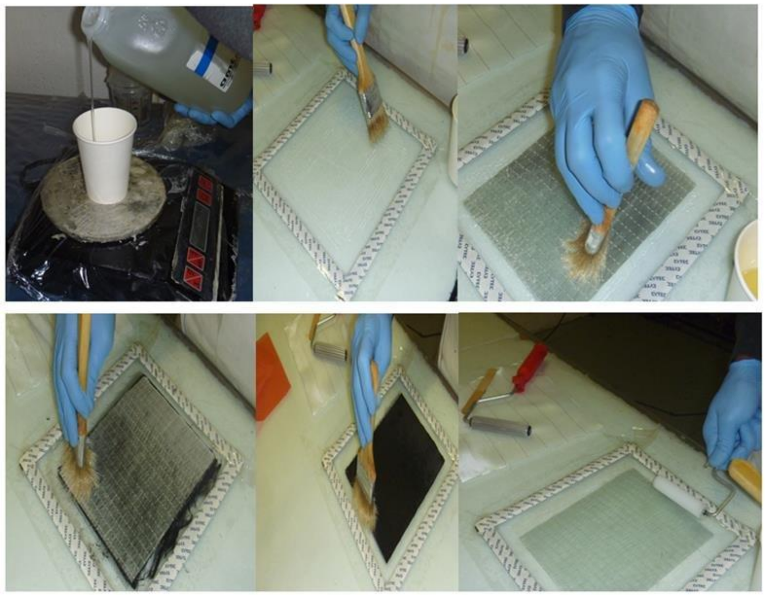

Fig. 2: Hand-lay-up process

Vacuum bag

This method is an extension of the wet lay-up process in that the pressure is applied to the laminate once laid-up in order to improve its consolidation. Vacuum bag molding is the primary composite manufacturing process for making laminated structures and is very common in the aerospace industry. It has limited use in the automotive industry since it is a labor-intensive process and may involve long cycle times. This is done by sealing a flexible plastic film or an elastomeric membrane (silicon, nylon or polyimide) commonly called as "vacuum bag" over the wet laid-up laminate and onto the tool. The air under the bag is extracted by a vacuum pump and thus up to one atmosphere of pressure can be applied to the laminate to consolidate it, while ensuring removal of air pockets to maximum extent. Thus, the vacuum bag technique is an improvement over the contact moulding process in that, it provides a near void free composite with greater control over the thickness and fibre fraction of the molded product. Further, in the vacuum bag moulding technique, several processing aids like a porous peel ply, a perforated plastic film (a porous plastic film) and a non-woven fabric breather are placed between the vacuum bagand the wet layup to facilitate removal of excess resin from inside out under the influence of a uniformly distributed vacuum. Fig. 3 below shows a schematic of the above process.

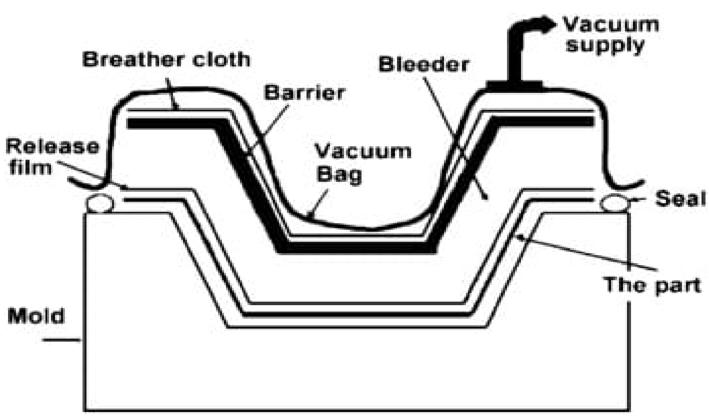

Fig. 3: Vacuum bag process.

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III. EXPERIMENTAL WORK

Materials used for fabrication of composite

Epoxy resin is a two-part polymer material, typically used as an adhesive or coating. It's created by mixing a resin and a hardener, which then undergo a chemical reaction to form a strong, durable substance as shown in Fig. 4. Epoxy resins are known for their strong adhesion, chemical resistance, and versatile applications in various industries. The hardener is typically an agent that reacts with the resin (often epoxy) to cause it to cure or solidify, forming a strong bond between the natural fibers and the resin matrix. Common hardeners used include hy-951, h-192, and others. These hardeners are often used in specific ratios with the resin to achieve optimal curing and strength properties. We use ratio for resin and hardener is 2:1.

Fig. 4: Epoxy resin and hardener.

Bamboo plants have a giant structure and grow very quickly, yielding within 4–5 years of their planting. The height of this plant reaches up to 60 m within three months. Bamboo is mainly produced in Asia, and Central and South America. Bamboo fiber is a regenerated cellulose fiber. It is a common fact that bamboo can thrive naturally without using any pesticide. The fiber is seldom eaten by pests or infected by pathogens. So, scientists found that bamboo owns a unique anti-bacterium as shown in Fig. 5

Fig. 5: Bamboo fibers.

Aloe vera fibers can be used in composite materials as a reinforcing agent or for surface modification. The fibers can be extracted from the Aloe vera plant, treated, and incorporated into a polymer matrix. This helps to create composites with improved mechanical properties, such as increased strength and reduced degradation. Aloe vera fibers can be used in composite materials as a reinforcing agent or for surface modification. The fibers can be extracted from the Aloe vera plant, treated, and incorporated into a polymer matrix. This helps to create composites with improved mechanical properties, such as increased strength and reduced degradation. Fig. 6.

Fig. 6: Aloe Vera

Sisal fiber-reinforced composites often exhibit superior impact strength compared to other natural fiber composites, making them suitable for applications requiring good impact resistance. Natural, plant-based fiber that can be used as a reinforcement in polymer composites, offering a sustainable and relatively inexpensive alternative to synthetic fibers. Sisal fiber-reinforced composites exhibit good impact strength, moderate tensile and flexural properties, and have the potential to be used in applications requiring high impact resistance shown in Fig. 7.

Fig. 7: Sisal fabric.

Composite Fabrication

Hand lay-up is the simplest and oldest open molding method for fabricating composites. At first, dry fibers in the form of woven, knitted, stitched, or bond fabrics are manually placed in the mold, and a brush is used to apply the resin matrix on the reinforcing material. Subsequently, hand rollers are used to roll the wet composite to ensure an enhanced interaction between the reinforcement and the matrix, to facilitate a uniform resin distribution, and to obtain the required thickness. Finally, the laminates are left to cure under standard atmospheric conditions. Generally, this process is divided into four steps: mold preparation, gel coating, lay-up, and curing. Curing is the process of hardening the fiber-reinforced resin composite without external heat.

The molding of NFCs typically involves processes such as compression molding, injection molding, or resin transfer molding. During molding, the natural fibres are combined with either thermoplastic or thermoset resins, and the mixture is placed in a mound under heat and pressure to form the desired shape. The selection of the molding technique depends on the type of fibre, matrix material, and the end-use application. Fig. 8 show this process. Composite materials (resin and fibers) are placed in an open mold, where they cure or harden while exposed to the air. Tooling cost for open molds is often inexpensive, making it possible to use this technique for prototype and short production runs. Approx. we used mold size 15×20cm.

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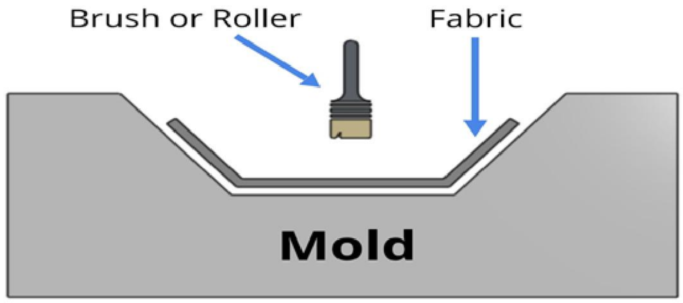

Fig. 8: Molding process

Sample Preparation

scroll saw is a small electric or pedal-operated saw used to cut intricate curves in wood, metal, or other materials. The fineness of its blade allows it to cut more delicately than a power jigsaw, and more easily than a hand coping saw or fretsaw. Like those tools, it is capable of creating curved cuts with angled edges, by tilting the body of the saw or its table along the axis of the cut. Scroll saws are often used to cut intricate curves and joints, a task they can complete quickly and with great accuracy. They can also be used to cut dovetail joints and are a common tool for thicker intarsia projects. When a fine blade is used, the kerf of a scroll saw is almost invisible. precision-cutting intricate curves and patterns on thin stock. As shown in Fig. 9 & 10.

Fig. 9: Scroll Saw Machine

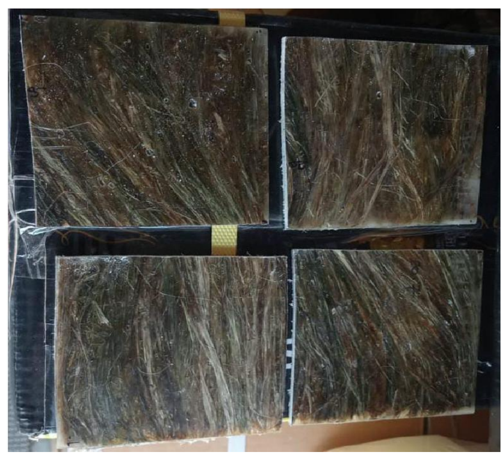

Fig. 10: Sample After Cutting

IV. RESULT AND DISCUSSION

Water Absorption Testing

Water absorption testing is a critical evaluation method for natural fiber composites, such as those made from bamboo and Alveroa (often spelled Alvarez or Alvero in different contexts). These tests help assess how the material behaves when exposed to moisture, which is important for determining durability, structural integrity, and suitability for different applications, especially in environments prone to humidity or wet conditions. For bamboo and Alvaro natural fibre composites, the testing method can generally follow a standard procedure, though there may be slight adjustments based on the material's composition. Below is an outline of how water absorption testing for these materials can be conducted. Sample Preparation: cut the samples prepare standardized test specimens (usually 10 cm x 10 cm or according to relevant standards). Dry the samples: Ensure that the samples are completely dried before testing for 24-48 hours until they reach a constant weight shown in Fig. 13.

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Fig. 13: Water absorption testing.

Flexural Testing

The flexural properties of the natural fiber composite specimens shown in Table 1, made from bamboo, aloe vera, and jute fibers with epoxy resin, were evaluated using a Universal Testing Machine as per ISO 178:2019 standards. The test results revealed an average flexural strength of 35,79 MPa and an average flexural modulus of 3368 MPa, indicating a reasonably high load-bearing capacity and stiffness. The variations in flexural strength across specimens could be attributed to differences in dimensions and fiber dispersion within the matrix. Specimen I demonstrated the highest flexural strength, likely due toits balanced width and thickness, ensuring optimal load distribution. These findings highlight the composite's potential suitability for applications requiring moderate mechanical strength and rigidity, showcasing the effectiveness of natural fibers in enhancing the epoxy resin's properties. The flexural test conducted on natural fiber composite panels made with bamboo, aloe vera, and jute fibers, using epoxy resin as the matrix, yielded significant findings. The average flexural strength was 35.79 MPa, and the flexural modulus was 3368 MPa, indicating good structural rigidity and load-bearing capacity. The specimens, tested under ISO 178:2019 standards at a speed of 2 mm/min, showed consistent performance across varying dimensions, with minor deviations. Notably, the first specimen achieved the highest flexural strength of 51.67 MPa, highlighting potential variability based on specimen dimensions and material distribution. The results confirm the potential of these natural fiber composites for applications in building materials, offering an eco-friendly alternative with satisfactory mechanical properties. These findings emphasize the composites suitability for lightweight and sustainable construction solutions. Fig. 14 show the graph.

Table 1: The flexural properties of the natural fiber composite specimens

Sample	Width (mm)	Thickness (mm)	Flexural strength (MPA)	Flexural modulus (MPA)
1	10.25	4.13	51.67	6142
2.	10.42	4.70	28.62	2460
3.	11.14	4.17	31.27	3021
4.	10.81	4.77	35.55	2936
5.	10.29	4.50	31.87	2281
Average	**10.58**	**4.45**	**35.79**	**3368**

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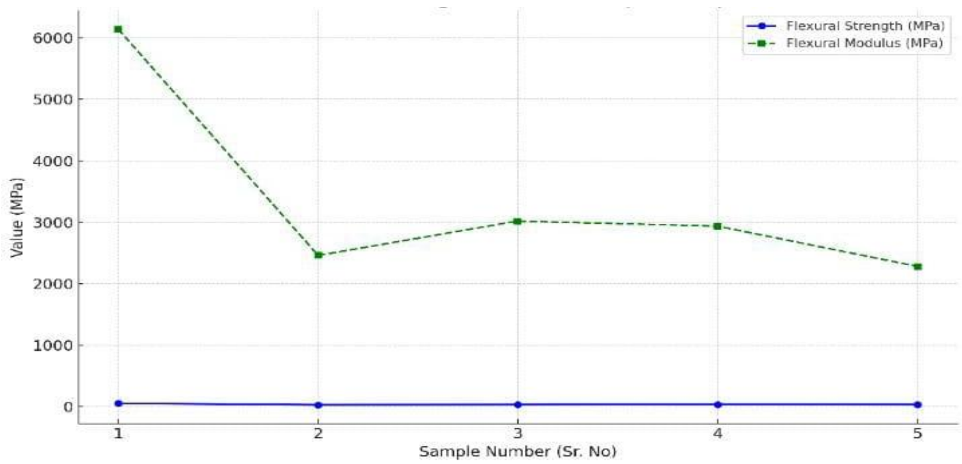

Fig. 14: Flexural strength graph.

Compression Test

A compression test was conducted on five composite samples using a Universal Testing Machine (UTM) with equipment ID AC/MC/40, following the ISO 604:2002 standard as shown in Table 2. The test was performed on 26th March 2025, with a testing speed of 2 mm/min. The machine was last calibrated on 9th August 2024, and its next calibration is due on 8th August 2025. Each of the five samples had different dimensions. Sample 1 measured 10.40 × 4.80 × 10.75 cm and withstood a maximum load of 2348 N. Sample 2, sized 11.04 × 4.82 × 10.37 cm, sustained a load of 2263 N. Sample 3, with dimensions of 10.30 × 4.85 × 10.50 cm, endured 2440 N. Sample 4, sized 9.71 × 5.00 × 11.20 cm, handled 2544 N, while Sample 5, with dimensions of 11.53 × 5.00 × 10.02 cm, sustained the highest load of 5156 N. The average maximum load across all samples was calculated to be 2546.2 N. fig. 15: show compression test graph.

Table 2: Compression test

Sample no.	Sample dimensions (cm)	Max load (N)
1	10.40 x 4.80 x 10.75	2263
2	11.04 x 4.82 x 10.37	2263
3	10.30 x 4.85 x 10.50	2440
4	9.71 x 5.00 x 11.20	2544
5	11.53 x 5.00 x 10.02	51256
Average		**2546.2**

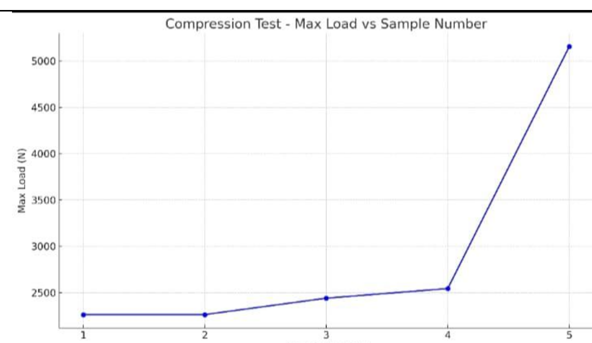

Fig. 15: compression test graph

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Composite manufacturing processes involve combining two or more different materials to create a composite material with enhanced properties. These processes can be broadly categorized into prepreg-based methods (like manual layup, automated tape laying, and fiber placement) and resin infusion methods (like resin transfer molding, vacuum-assisted resin transfer molding, and resin film infusion). The resulting composite material exhibits improved strength, durability, lightweight, and resistance to environmental factors.

V. CONCLUSION

The evolution of natural fiber-reinforced epoxy composites represents a significant leap forward in the development of high-performance, environmentally sustainable materials. This method builds upon the traditional wet lay-up process, with the added application of pressure to enhance fiber-resin bonding, resulting in composites with superior mechanical properties. Recent advancements have demonstrated the compatibility of natural fibers such as flax, jute, hemp, bamboo, sisal, and aloe-vera with epoxy resins, yielding composite materials that excel in mechanical strength, thermal resistance, and eco-friendliness. These natural fibers possess inherent characteristics like high tensile strength, low density, biodegradability, and renewability, which contribute to their growing popularity in composite manufacturing. Compared to conventional synthetic fiber composites, natural fiber composites can offer several advantages. For instance, incorporating natural fibers into epoxy matrices has been shown to improve tensile strength by up to 50%, and thermal stability can increase by as much as 20%. These improvements are particularly significant for applications requiring lightweight yet durable materials.

In the automotive sector, natural fiber composites are used in manufacturing components such as door panels, seat backs, dashboards, and interior trims. These materials can reduce the overall weight of vehicles by up to 30%, which leads to better fuel efficiency and lower emissions without compromising mechanical performance. The construction industry also benefits from the use of these composites, where they serve as high-strength, lightweight panels, insulation materials, and even structural elements in eco-conscious buildings. Due to their low density and impressive load-bearing capabilities, they are ideal for applications requiring both strength and reduced material weight. While still in the early stages of exploration, the aerospace industry is beginning to recognize the potential of natural fiber-reinforced composites, particularly for non-critical components where weight reduction is a priority. These materials could significantly contribute to energy savings and performance improvements in aviation by lowering aircraft mass.

To further capitalize on the potential of natural fiber composites, future research must focus on:

Optimizing fabrication techniques, such as compression molding, vacuum-assisted resin transfer molding (VARTM), and pultrusion, to improve cost-effectiveness and production scalability. Understanding long-term durability under various environmental conditions (e.g., humidity, UV exposure, temperature changes) to ensure reliability. Expanding the scope of applications, including marine, sports equipment, and consumer goods industries.

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