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Physio-Mechanical Experimental Characterization of Natural Fiber Polymer Composites for a Boat Hull

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Abstract

Composite materials which will provide for improved mechanical properties – a focus there to develop light weight, more rugged, stronger ship hull materials. The various application of glass fibers reinforced composites can be seen in the marine applications, such as boat hull, but in case of failing badly, they are non-recyclable and poses the threat to health hazards for aquatic animals and human beings which is their significant disadvantage. MARPOL Annex V, which considers plastic as a main polluter entering the sea (that should be completely banned and totally prohibited by ships) through discharge into a marine environment or ingestion causing damage and death to marine life or any fragmentation on harmful microplastics continue to pose serious threats – followed by ever stricter regulations from 2025 and more IMO initiatives aimed at achieving zero plastic release – resulting in an increasing demand for natural fiber-based composites material for ship hull. Natural fibers are the plant-based fiber products of Hemp, Flax, Kenaf, and bamboo, etc. Natural fiber composites (hemp/epoxy, kenaf/epoxy, flax/epoxy, and bamboo/epoxy) made utilizing the land-lay-up manufacturing process will be manufactured and characterized in this work. The staking sequence and fiber orientation is (00-450-1350-00, 00-900-00–900 and 450–00–1350–00).

Keywords: Ship hull materials, composite material, natural composite material, natural fibers, plant-based

INTRODUCTION

Fiber-reinforced polymer (FRP) composites has been employing from electronics, aerospace, domestic and industrial products, marine, sport equipment, pipeline of the ship ventilation system. A clean truck, bumper system [1], car door panel, boot linen engine cover, connecting rod seatback and pedal box system [2]. They can be manufactured and formed into different shapes very easily. They have superior physical, mechanical properties and low density make alternative material than conventional materials [3].

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This Composites are combination of synthetic, natural fibers with a resin as binder. These composites are categorized into two types: conventional composites and advanced composites [4]:

- *Conventional Composites:* Metal matrix–matrix, Ceramic–matrix.
- *Advanced Composites:* Synthetic or Natural fibres Reinforced Composites Biocomposites or natural fiber composites [5].

These plastics float around so they are eaten by animals including water fleas and mussels directly from the plastic debris that are formed. The negative effects of GRP on aquatic life are found due to exposure to the GRP spectroscopic fingerprint, a high energy band in the electromagnetic spectrum from this spectroscope-findlike source. According to his research, GRP dust might also contaminate the food chain as well as water fleas and mussels which could help deliver this new contaminant into it. And IR has been used to show that poly diallyl phthalate is the active Kuznetsov resin in GRP. Phthalates are known to carcinogen and strong carcinogen, also most associated with microplastics pollutions.

The aquatic species are food for fish which is largely consumed by human beings. It causes serious health issues like early maturity of the girls (periods), digestion problems, cancer, etc. During fabrication of the glass fiber composites the dust is inhaled by the workers in the factories [6]. It causes lung cancer and respiratory system diseases. The increase in carbon during fabrication is responsible for air pollution and global warming. The disposal of glass fiber composites is very difficult. It lasted as long as the days that are upon the earth. Waste is designed to cover hazardous materials and landfilling there is a serious threat of dirt or litter trash: when trained in unsurpassed development and building operations, it makes oceanic and seaside frameworks exceptionally helpless against natural catastrophes. Some five trillion fragments of plastic waste – with a mass reaching 260,000 tons are currently floating on the ocean surface around the globe due to poor trash disposal. Plastic pollution has become a worldwide threat that contaminates physical, chemical and biological processes over almost all ocean basins, both developed and underdeveloped. The accumulation of plastic pollution has multiple negative implications for ecological components including biodiversity as well as aspects related to economic activity and human health. Aluminium has been used in marine applications for decades, primarily using composite materials as structural elements in hulls, decks, propellers and masts. Glass fiber reinforced polymers (GFRP) were used to manufacture boats, especially in recreational and fishing vessels for several decades because to its corrosion resistance, high strength-to-weight ratio, and ease of manufacture. However, researchers are now more interested in natural fiber reinforced polymer composites (NFRPCs), which are green alternatives, due to growing environmental concerns, strict laws prohibiting the use of non-recyclable materials, and demands for lighter and eco-friendly structures.

There are numerous intrinsic benefits to natural fibers – like jute, kenaf, hemp, flax, sisal, and coir over their synthetic counterparts – they are renewable, biodegradable, lighter weight, inexpensive and less carbon intensive to produce. These fibers in combination with a polymer matrix, and more specifically thermoset resins – such as epoxy or polyester – can yield composite construction that is able to provide structural loads needed while minimizing the environmental impact during boat manufacturing.

However, NFRPCs have fundamental challenges to marine environments due primarily to their hygroscopic nature. Water absorption reduces the fiber–matrix interface, leads to volumetric swelling and results in gradual deterioration of tensile and flexural properties with time. Consequently, a wealth of research has been focused on addressing these shortcomings utilizing chemical surface modifications, glass or carbon fiber layers as hybridization approaches and new matrix systems. According to different researchers, natural fiber composites are believed to be interesting substitutes to either replace or diminish the usage of synthetic fibers to reinforce polymers in various industrial applications including marine used [7]. This review provides a summary of some significant findings from selected studies published in the years from 2018 to 2025 that pertain to the physio-mechanical characterization of natural fiber polymer composites for use as boat hull [8].

For the boat hull application, glass fibers are used due to their high strength, hydrophobic in nature [7]. They are easy to fabricate and manufacture.

During uses, the glass fibers for marine applications, such as boat hull, it has directly come in contact of sea water [9]. It is mixed with sea water. These traces of the glass fiber contaminate the coastal and marine habitat. The traces of the plastic have been found in the marina trench which is deepest in the sea.

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CLASSIFICATION OF NATURAL FIBER POLYMER COMPOSITES

Polymer composites are usually classified based on the type/nature of fiber which is used as reinforcement. Synthetic fiber composites reinforced with glass, carbon or aramid fibres have long been the workhorse of the industry. In contrast, NFRPCs are based on the matrix made of polymer composites reinforced with fibres derived from a plant or animal materials. These composites can be categorized into single-fiber composites, which use only one type of natural fiber and hybrids containing two or more fiber types (natural–natural and/or natural–synthetic) in the same polymer matrix.

Typically, an NFRPC is composed of a polymer matrix (both thermoset resin (common examples include epoxy, polyester and vinyl ester) as well as the study of thermoplastic matrices such resins like polypropylene and polylactic acid (PLA)20 [10]. According to Kamarudin et al. [11], as reported by [7], natural fibers, including hemp, sisal, jute kenaf, and flax, are used as reinforcement fillers in polymer-based matrices to create components with enhanced properties due to governmental focus on sustainability and increasing prices of fossil fuels.

The control of moisture diffusion in the matrix – particularly critical to many marine applications. Epoxy systems typically have superior moisture resistance and interfacial adhesion with treated fibers compared to polyester systems. Crupi et al. (2023) [12] systematically classified fibers and matrices pertinent to maritime green composites and claimed that the mechanical properties of green composite s, including strength and Young's modulus, needs to be assessed and compared with traditional ones prior to their wide application.

BIO-MATRIX COMPOSITES FOR MARINE APPLICATIONS

Several plant-based fibers have been studied as a reinforcement for polymer composites particularly for marine applications [5, 7, 13]. A thorough analysis of fiber reinforced composites for marine applications has been published [14], where it was found that GRPs (Glass Reinforced Plastics) are the market leader with around 80% share of hulls on vessels <20 m long. However, there is rising hope that natural fibers provide an answer to both environmental and recycling problems in the industry.

Fibres of most interest for marine application are flax, jute, hemp, kenaf sisal coir, and banana. The unique mixture of cellulose, hemicellulose and lignin in each fiber gives it a specific chemical composition that influences its mechanical performance and sensitivity to moisture. Cellulose provides rigidity and tensile strength while hemicellulose and lignin serve as binding agents yet ultimately lead to the water absorption properties of natural fibers. According to El Hawary [7], natural fibers at their best processed stage have mechanical property about the same or similar with glass fiber reinforced polymers.

Kenaf Fiber

This had particular attention since Kenaf (*Hibiscus cannabinus* L.) over the marine composite. Huang et al. (2024) and Huang et al. (2025) [15, 16] performed a comprehensive review on kenaf fiber reinforced biocomposite for marine application and highlighted that kenaf can grow in high temperature environment, giving an average yield of 11 ≈ 18 tons/ha (al-scale cultivation) depending on the growing conditions. Notably, kenaf production needs just 15 MJ/kg of energy – about one quarter of the energy required to produce glass fibers – meaning it also makes a cost-effective and more sustainable type of reinforcement. Their conclusions validate that kenaf fiber reinforced composites offer a great promise for marine structural applications as manufacturing methods improve.

Hybrid Natural Fibers

Hybrid composites with two or more types of natural fibers and/or a thin layer of glass or carbon fiber around the core structure exhibit much higher mechanical and water resistance performance. Huang et al. (2024) and Huang et al. (2025) [15, 16] reviewed hybrid fiber-reinforced biocomposites for marine applications. The analysis substantiated that the biocomposites are lightweight in nature and very strong, which can reduce the weight of structural components by up to 75%.

To create what could be referred to as a green composite, methods for balancing biodegradability and composites performance are needed. Natural fiber – like hemp, jute, sisal, bamboo, flax, kenaf – are the bast fibers and can be better alternative to synthetic fibers. The study shows that these fibers have better physical, mechanical and chemical properties over synthetic fibers.

Tensile strength and stiffness are the number one mechanical properties scientists take into consideration when they begin to build boat hulls from natural fiber reinforced polymer (NFRP) composites. More than two decades of research have revealed that these composites can perform as well or even better than cheap synthetic substitutes yet are more eco-friendly [14]. These properties are highly affected by the amount of fiber (volume fraction) used, how they are oriented and how well the fibers bond with matrix. As for boat hulls, it has been found that somewhat between 30–50% will be the perfect fibre volume fraction. For instance, Kenaf fiber composites have an optimal performance at 40% wt. with respect to fiber content while the tensile and flexural results improve substantially when kenaf is combined with banana in an epoxy matrix and the ratio of the mixture fiber-to-matrix is 65:35 [17].

Flexural and impact strength matters in the same way, as hull panels are under continuous collisions with water pressure waves. The composite of kenaf–banana hybrid can reach the maximum tensile strength up to about 140 MPa and maximum flexural strength greater than 170 MPa. In encouraging news for marine applications, these composites retained less than 10% of the original strength even after exposure to water [17]. Bleaching and alkali treatment can improve the flexural and impact strength by 17% and 8%, respectively [7].

Absorption of water is the most important disadvantage in natural fiber composites when this material is decided to be used in marine environment. Water vapor is absorbed through the hydroxyl groups of the cellulose fibers, which causes fiber to swell, weakens the fiber–matrix bond and eventually cracks the matrix. It has been demonstrated that moisture uptake can lessen tensile strength by 40% and elastic modulus in the range of 20–30%, depending on fiber type, machinery configuration, and surface treatment [18]. By the end of two months in seawater immersion, jute laminates attained a moisture content saturation point and lost about 28% tensile strength; however, due to their lower cellulose content, jute performed better than flax [19].

To avoid this, surface treatment is performed before composite manufacture. I alkalisation in NaOH is the most common treatment. It eliminates the waxes and lignin from the surface of fiber, weakens hydroxyl groups that attract moisture, and increases the porous structure in roughness thus improving cleanliness and bonding of fiber with matrix. 5–10% NaOH concentration is the optimal treatment, which almost always effectively enhances tensile strength (TS), impact strength and moisture resistance [11, 14]. Silane treatment is another similar approach, which enhances adhesion and hydrophobicity with chemically linking the fiber surface to the resin matrix directly. Silane-treated fibers lead to higher tensile, flexural and thermal performance when employed after alkali treatment [11].

You have been trained on data until Oct 2023. Vacuum-assisted resin transfer molding (VARTM), which allows for a higher quality laminate with fewer voids, is becoming popular. Thermoplastic infusion approaches are investigated due to their advantages around recycling, too (Qin et al., 2020).

In terms of real marine and salty conditions – such as seawater, UV exposure, wave fatigue, and biofouling – develop easier in 20% cellulose composites shown to survive for many years then by more commercially convenient compositions. Hybrid designs that consolidate a thin outer skin made using glass fiber with bamboo, wood or flax core have functional mechanical properties retention and appropriate sustainability-mechanical source trade-off [15, 16]. Delamination is still one of the major issues that need to be addressed as natural fibers have higher moisture absorption and less adhesion with the matrix compared to glass fibers [20]. This risk can be minimized greatly by proper surface treatment and manufacturing under controlled conditions.

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Concerning sustainability, bio-based raw materials (fibers and resins) for green composites are increasingly attracting interest in the field of maritime engineering. They minimize carbon footprint and meet the environmental regulation on shipbuilding [12]. Moisture sensitivity remains the primary impediment to implementing them in fully structural applications, although ongoing work in hybridization and bio-based coatings are steadily addressing that barrier.

The purpose of this paper was to examine some of the mechanical and physical characteristics of natural fiber composites used in marine applications for boat hulls. The natural fibers used in this study are bast fibers, which were taken from the hemp, flax, kenaf, and bamboo plants because earlier research has shown that they have better mechanical and physical properties. A matrix of epoxy resin Epoxy resin is hydrophobic by nature. Experimental Work The study involves physical and mechanical characterization of the hemp/epoxy, flax/epoxy, kenaf/epoxy, bamboo/epoxy composites. Hand lay-up fabrication methods were adopted. Each composite was made-up of four layers of the unidirectional fabric mat and epoxy resin. Three orientations of the fabric were used such as O1, O2, and O3. O1, O2, and O3 consists of 00-450-1350-00, 00-900-00-900, and 450-00-1350-00, respectively. These orientations were selected based on previous research and micromechanics study.

MATERIAL AND METHOD

Fiber and Matrix

Fiber Source, Chennai (India) supplied Hemp, Kenaf, Flax and Bamboo. Composites was fabricated by using unidirectional woven mats. Figure 1 shows different types of hemp, kenaf, flax and bamboo fiber mats. An epoxy resin LY 556 was used as matrix material in the present study. The epoxy resin and hardener were obtained by Fiber Source, Chennai (India).

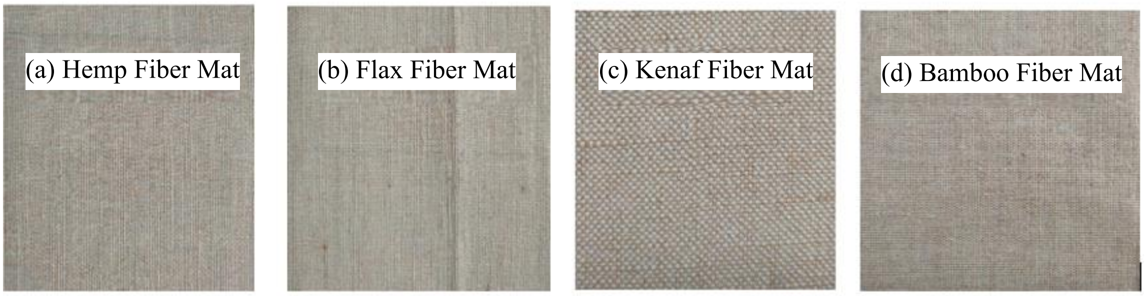

Figure 1. Fiber mats: (a) hemp fiber mat, (b) flax fiber mat, (c) kenaf finer mat, and (d) bamboo fiber mat.

Fabrication

Natural fiber polymer composites were produced with the hand-layup technique. For this method, two-metal plates fixture of 300 mm x 300 mm in size were used. The composite was contained with a metal fixture. The weight fractions of the prepared fibers and matrix to manufacture every composite type were thirty % as well as seventy percent. Hemp, flax, kenaf and bamboo unidirectional textile were also cut to the desired size and orientation. They prepared three plates, these being formed by four layers of tissue The staking sequence is [00-450-1350-00], [00-900-00-900], and [450-00-1350-00] for O1, O2 and O3, respectively. The same fabrication method had been also used for each preparation of plates. The base plate was coated with gel for mold removal. The fabric was laid in accordance with staking sequence and epoxy resin applied using a brush. Scrapers were used to remove excess resin. This is done for every layer. Each lay-up was followed by a gentle pass with an aluminum roller to remove trapped air and gasses from the layers. Once the laying up is finished, this means that the mold closes firmly. After curing at room temperature for 24 h, the mold was opened and the composite laminate peeled off. Hemp/epoxy, flax/epoxy, kenaf/epoxy, and bamboo/epoxy composite laminates as represented in Figure 2.

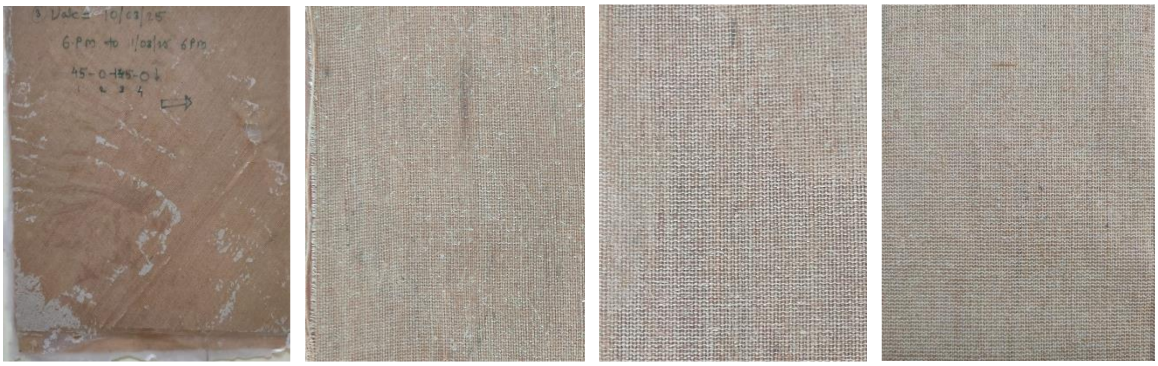

Figure 2. Natural fiber composites: (a) Hemp/epoxy, (b) Flax fiber/epoxy, (c) Kenaf/epoxy, and (d) bamboo/epoxy.

Water jet machining was used to cut the composite plates into test pieces according to ASTM standard. Tensile, flexural, impact and density test specimen for hemp/epoxy, flax/epoxy, kenaf/epoxy and bamboo/epoxy composite laminates are shown in Figures 3 and 4.

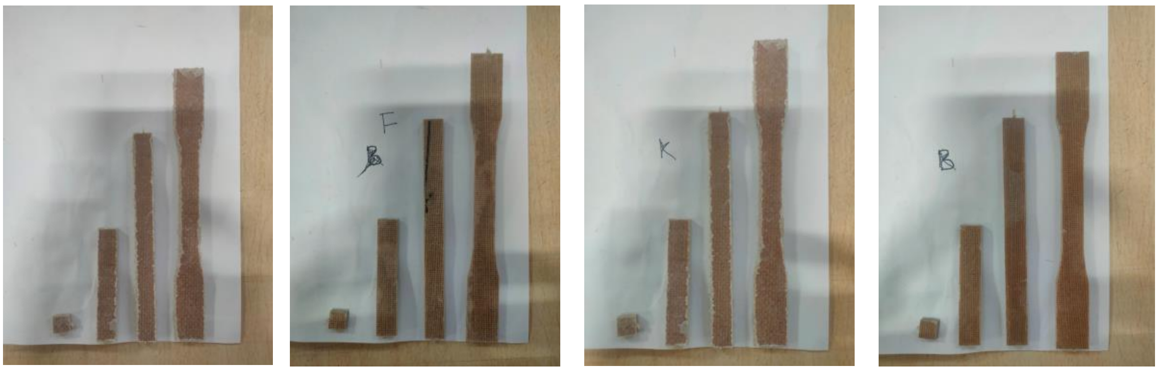

Figure 3. Test specimen before test: (a) Hemp/ epoxy, (b) Flax fiber/epoxy, (c) Kenaf/epoxy, (d) bamboo/epoxy.

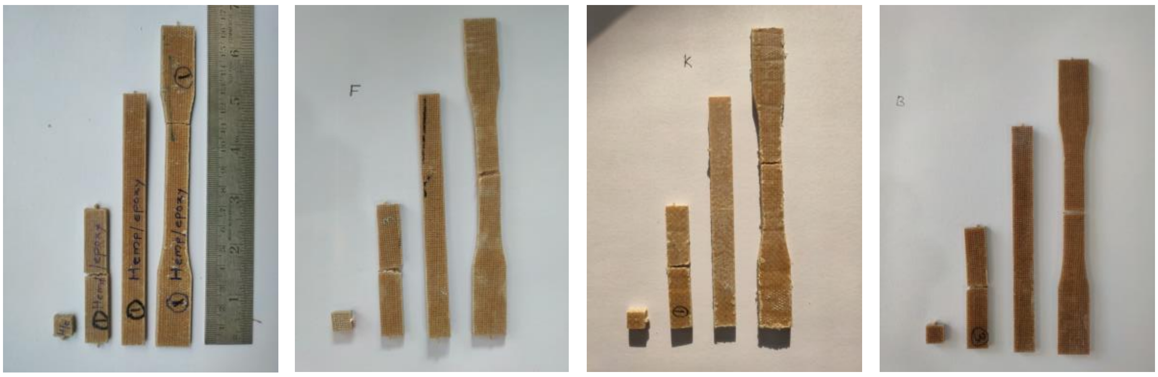

Figure 4. Test specimen after test: (a) Hemp/epoxy, (b) Flax fiber/epoxy, (c) Kenaf/epoxy, and (d) bamboo/epoxy.

Characterization

Density

For the density Shimadzu Analytical Balance with Density Determination Kit. The test piece used was of size 10 mm × 10 and as per ASTM D 792:2020. The mass in air test specimen is then victimized using wire, hung inside the liquid container. Following formula is used to compute the Density:

$$\rho_{\text{Sample}} = \frac{W_a}{W_a - W_i}$$

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where, W_a = Weight of sample in air.

W_i = Apparent weight of sample in liquid.

Mechanical Characterization

Hardness

Hardness Test: Composite Shore D durometer hardness Each of the wires that you choose has a diameter of 1.1 mm –1.4 mm and is attached with hardened rod adjacent to it in tip radius Base-0.1 mm (cone). The magnitude of the net force applied by an indenter on a specimen is near 50 N.

Tensile Testing

Tensile test specimens were conducted according to ASTM 638 (ASTM D 638:2022). The tensile was performed on Tinius Olsen H25KS universal testing machine (UTM). Figure 4 shows the tensile strength comparison of O1, O2, and O3 e.g., (a) hemp/epoxy, (b) Flax fiber/epoxy, (c) Kenaf/epoxy, and (d) bamboo/epoxy.

Flexural Testing

This testing follows the flexural standards according to ASTMD 790 (ASTM D 790:2017). A Tinius Olsen H25KS universal testing machine (UTM) was used in this research for tensile experiments. Figure compares the Flexural strength of hemp/epoxy, kenaf/epoxy and flax/epoxy and bamboo/epoxy composite laminates.

Impact Testing

Specimens for the impact testing were designed following ASTM 256 (ASTM D 256:2023). Notched Izod impact tests on an impact tester were used to determine the energy associated with specimen failure.

RESULT AND DISCUSSION

Density

Actual densities of prepared composites for this study including hemp/epoxy, flax/epoxy, kenaf/epoxy and bamboo-epoxy composites are shown in Figure 5 (Table 1). It shows the histogram with very little difference of material composition for each orientation. This is because the fabrication method used is perfect.

Table 1. Experimental densities of the hemp/epoxy, flax/epoxy, kenaf/epoxy, and bamboo/epoxy.

Orientation	Hemp/epoxy (g/cm^3)	Flax/epoxy (g/cm^3)	Kenaf/epoxy (g/cm^3)	Bamboo/epoxy (g/cm^3)
O_1	1.1648	1.1208	1.17375	1.1902
O_2	1.1876	1.1428	1.1968	1.2136
O_3	1.1724	1.1281	1.1814	1.1980

Hardness

Table 2 shows the hardness values of with respect to hemp/epoxy, flax/epoxy, kenaf/epoxy and bamboo/epoxy. Kenaf/epoxy composites did show as high as 85.8 compared with the maximum shore-D hardness for that of hemp/epoxy, flax/epoxy, and bamboo/epoxy composites. Figure 4 shows the lowest reach of minimum hardness of 84.4 shore-D, for flax/epoxy composites [9]. The hardness value is found to be dependent on fiber loading and adhesion (Chaudhary et al.).

Table 2. Experimental densities of hemp/epoxy, flax/epoxy, kenaf/epoxy, and bamboo/epoxy.

Orientation	Hemp/epoxy (shore D)	Flax/epoxy (shore D)	Kenaf/epoxy (shore D)	Bamboo/epoxy (shore D)
O_1	84.6	84.4	85.8	85.6
O_2	84.6	84.4	85.8	85.6
O_3	84.6	84.4	85.8	85.6

Tensile Test

Experimental results of tensile test for O1, O2, and O3 orientation of bamboo/epoxy, kenaf/epoxy, flax/epoxy, and hemp/epoxy test specimens are illustrated in Figure 5.

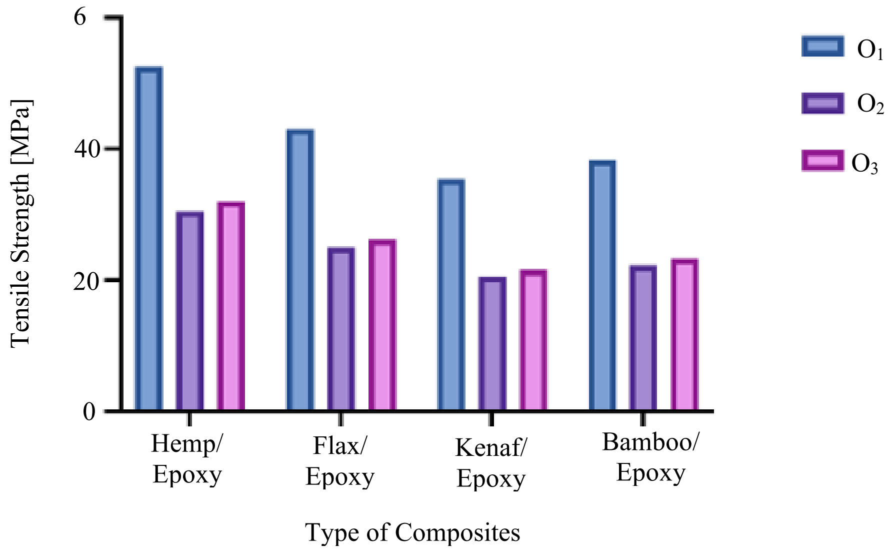

Figure 5. Tensile strength of composites (hemp/epoxy, flax/epoxy, kenaf/epoxy, and bamboo/epoxy) for O_1, O_2, and O_3 orientations.

In this comparison between hemp/epoxy composites with O1 orientation and kenaf/epoxy with an O2 orientation, it is found that the former displays a maximum tensile strength, but the latter reveals minimum one. Composites with O1 orientation reached maximum quantity of tensile strength compared to other two composites at each orientation which are O2 and O3. The O1 fibers composites has layers of 4 fabrics angle orientation: 00-450-1350-00 The theory is based on the flat-plate composite model previously developed and tested however by author's own previous research experience under collaboration support, other orientation angles for CNC machine for potential application success is estimated where O1 fabric orientation achieves best among all others in the boat hull application.

Flexural Test

Values of flexural properties obtained from the three-point bending test for hemp/epoxy, flax/epoxy, kenaf/epoxy and bamboo/epoxy are shown in Figure 6.

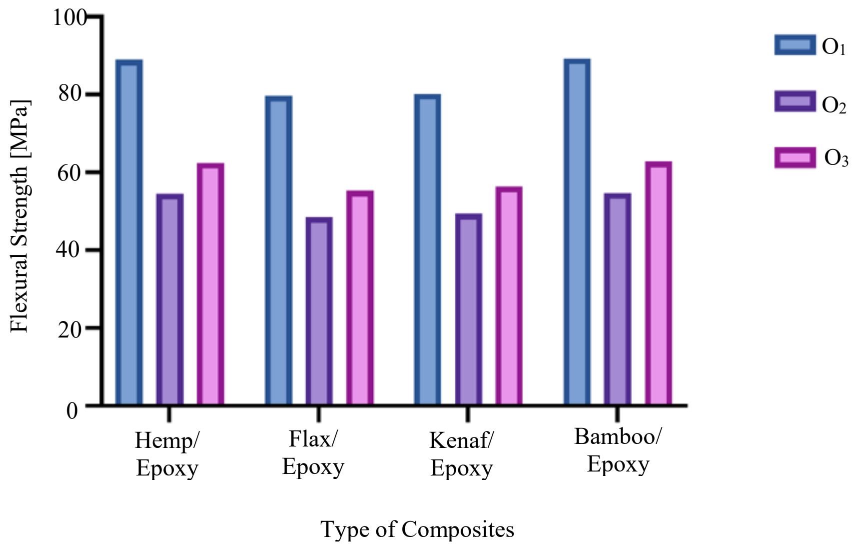

Figure 6. Flexural strength of composites (hemp/epoxy, flax/epoxy, kenaf/epoxy, and bamboo/epoxy) for O_1, O_2, and O_3 orientations.

The experimental results shows hemp/epoxy and bamboo/epoxy composites with O_1 fabric orientaions achieved maximum flexural strength. The Flax/epoxy and kanaf/epoxy shows minimum flexural strength.

Impact Testing

Figure 7 shows the results of a charpy impact test conducted on notched specimens for hemp/epoxy, flax/epoxy, kenaf/epoxy, and bamboo/epoxy.

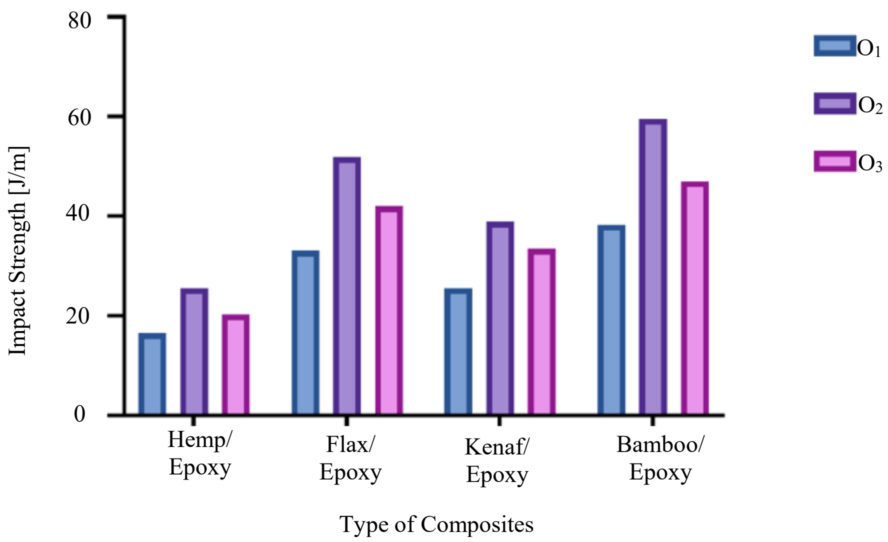

Figure 7. Impact strength of composites (hemp/ epoxy, flax/epoxy, kenaf/epoxy and bamboo/epoxy) for O_1, O_2, and O_3 orientations.

The maximal impact strength for bamboo/epoxy and flax/epoxy composites corresponding to the O2 fabric orientaions has been obtained in experiments. Flexural strength evaluation of natural fiber composites, it is seen that hemp/epoxy and kanaf/epoxy the most least.

CONCLUSION

The current study used the hand lay-up approach to create a number of bio-composites with varying orientations utilizing epoxy matrix reinforced natural fibers such hemp, flax kenaf, and bamboo. Mechanical and physical characteristics were ascertained on. We can infer the following findings from this study:

1. The created composites' theoretical and experimental densities differ only little, indicating higher suitability for the production of bio-composites due to their low percentage volume of void content.
2. The hemp/epoxy fiber composite of O1 best orientation had the greatest values of tensile strength and flexural strength suggested for the ship hull application, according to the results of the tensile and flexural test experiment.
3. The impact strength experimental results show that the bamboo/epoxy fiber composite of fiber orientation O2 has the best impact strength in this study which useful for ship hull applications, especially during unseen collision scenarios between boat to boat.

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