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Research Article

Performance Evaluation of Epoxy-Based Natural Composites Reinforced with Flax and Flax-Ramie Fiber

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ABSTRACT

Growing environmental concerns and regulatory pressure have necessitated the requirement for natural fiber-based composites for various applications. Natural fiber-based composites are increasingly valued for their excellent mechanical properties, including high specific strength and stiffness, as well as their lightweight nature. Additionally, their eco-friendliness and superior vibration-damping and thermal-insulation capabilities make them ideal for sustainable and efficient engineering applications. This paper focuses on the performance evaluation of epoxy reinforced with Flax and flax-ramie fiber hybrid composites. The laminates were developed through the hand layup technique with Flax and Ramie fibers using epoxy resin. The prepared samples were further analyzed under various dynamic and static conditions, including Fast Fourier Transform (FFT) analysis, impact testing, water absorption testing, and density measurement. The flax-ramie hybrid composite shows good dynamic and static properties, including better vibration control, impact resistance, and lower moisture absorption, compared to the flax fiber composite. With a density of 1.17 g/cm^3, the hybrid composite absorbs more energy (10.47 J) and withstands higher impact forces (2.08 N). These characteristics make the hybrid composite more suitable for impact-prone and water-sensitive applications.

1. Introduction

Natural fibers have emerged as a prominent alternative to synthetic materials in diverse industries due to their eco-friendly nature, ease of availability, and excellent mechanical properties (1-5). These fibers, derived from renewable resources, offer benefits such as low cost, biodegradability, and lightweight characteristics, making them an attractive choice for composite materials used in automotive, construction, and aerospace sectors (1). With the increasing emphasis on sustainability and green technology, natural fibers like jute, ramie, hemp, and flax are being extensively studied for their

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potential to replace synthetic counterparts and contribute to cost-effective and environmentally friendly products (2, 3). The unique properties of natural fibers, such as high strength, low density, and superior sound absorption, are driving the transition towards sustainable materials in industrial applications (3).

Flax fiber, extracted from the stem of the flax plant, stands out as a versatile reinforcement in polymer composites due to its biodegradability, cost-effectiveness, and lightweight nature (1). Available in various forms such as yarn, nonwoven mats, and pulp, flax fiber enables the tailoring of composite properties by employing different fiber arrangements and processing techniques (4). Research into flax fiber composites has demonstrated significant potential for sustainable applications, with ongoing studies focusing on optimizing textile preforms, enhancing mechanical performance, and understanding biodegradation mechanisms (6). Ramie fiber, another natural fiber, has shown promise for its ability to improve tensile strength, flexural strength, and impact resistance in composite materials, further supporting its role in hybrid composite systems (5, 6).

Epoxy is a class of synthetic thermosetting polymers widely used for its excellent mechanical properties and strong adhesive qualities (7, 8). Flax fiber composites have been extensively explored for their performance when paired with epoxy resin, which enhances the mechanical properties and durability of these composites. Studies show that the incorporation of ceramic additives like silicon carbide and aluminum oxide enhances the chemical and moisture resistance of flax fiber-reinforced polymers, particularly in alkali-treated samples, which exhibit superior properties (9). Impact testing reveals that energy absorption in flax fiber composites increases slightly at lower energy levels but significantly decreases at higher energy levels due to severe material damage (10). The orientation of fibers in woven flax/Elium thermoplastic bio-composites, such as (±45)6 arrangements, has been linked to higher residual performance after impact (11). Different resin types also influence the tensile, flexural, and impact properties of flax fiber composites, with recyclable and bio-epoxy resins providing notable damage resistance (12). Studies on unidirectional flax fiber-reinforced polymers highlight matrix cracking as the primary damage mechanism under impact loads, with these composites exhibiting less damage compared to traditional carbon fiber composites (13).

Environmental factors like saltwater immersion reduce the mechanical properties of alkali and silane-treated flax composites, emphasizing the role of moisture in performance degradation (14, 15). Hybrid flax composites incorporating graphene nanoparticles demonstrate reduced moisture absorption and diffusion, although prolonged exposure to moisture leads to decreased flexural and inter-laminar shear strength (16). Vibration testing on hybrid carbon-flax composites indicates reduced vibration amplitude and frequency, enhancing their suitability for noise and vibration-damping applications, such as in personal watercraft (17). Additionally, the integration of nanofillers into sisal/flax-fiber-reinforced epoxy composites significantly improves mechanical properties, achieving tensile strength of 59.94 MPa, bending strength of 149.52 MPa, and impact resistance of 37.9 kJ/m^2 in specific configurations (18).

This study focuses on developing hybrid flax and ramie fiber composites with optimized fiber processing techniques and stacking sequences. The goal is to achieve superior mechanical performance and environmental sustainability for applications in the automotive sector. The novelty of this research lies in evaluating hybrid configurations and incorporating innovative treatments to enhance durability, damage resistance, and eco-friendliness.

2. Methods and Materials

2.1. Materials

2.1.1 Flax Fiber

Flax is a plant species of Linum usitatissimum that includes various cultivars grown primarily for its strong fibers. Flax fibres are typically composed of 64–71% cellulose, 16–18.6% hemicellulose, 1.8–2.3% pectin, and 2–3.8% lignin, as shown in Table 1. The flax fibres, while having a lower environmental impact, exhibit high specific strength, stiffness, thermal insulation, lower density, and energy absorption capacities, making them comparable to other commonly used materials with a similar density range [2]. These qualities make it an excellent reinforcement material for automotive composites, enhancing fuel efficiency, comfort, and safety [3].

2.1.2 Ramie Fiber

Ramie is a vegetal class of *Boehmeria nivea* cultivars grown primarily for its strong and durable fibres. Ramie fibres are typically composed of 68–76% cellulose, 13–16% hemicellulose, 0.6–1% pectin, and 0.6–0.7% lignin, as tabulated in Table 1. The ramie fibres exhibit high specific strength, stiffness, and energy absorption capacities, making them comparable to other commonly used materials with a similar density range [2,3].

Table 1. Composition of fiber content [1][2][3]

Properties	Flax	Ramie
Cellulose content	64-71%	68-76%
Hemi Cellulose	16-18.6%	13-16%
Pectin	1.8-2.3%	0.6-1%
Lignin	2-3.8%	0.6-0.7%

2.1.3 Epoxy and Hardener

Epoxy resins typically consist of two components: a resin and a hardener. The matrix used for fabricating the fiber specimens was epoxy LY-556, which was mixed with hardener HY951 in a 10:1 ratio.

2.2 Methodology

Flax and Ramie fibre with epoxy and hardener are used for fabricating the composite laminates. The materials used for the experiment were prepared by hand layup techniques. The fibrous mats were cut into the required dimensions to prepare samples. Two different kinds of laminates were prepared – one with purely flax fibres and the other with both flax and ramie fibres. In the case of flax reinforced with ramie fibres, the four-layer mats were arranged alternately. Primarily, the epoxy resin was filled over the polypropylene sheets. Each layer of fibrous mat is placed before reaching gel time. The laminate size is limited to 500 x 500 x 3 mm. The fabrication process flow diagram of the composites is shown in Fig. 1.

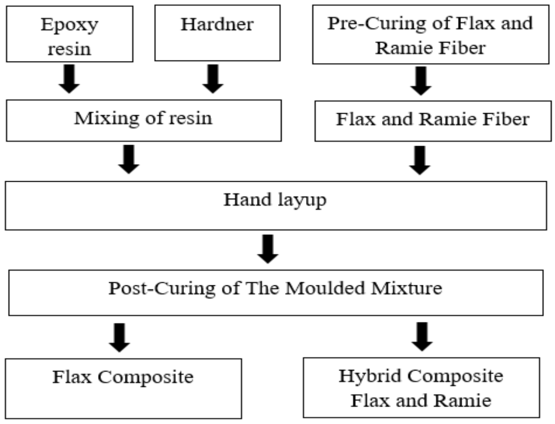


Fig. 1: Experimental Methodology

The laminates were prepared by varying the fibers, specifically flax and flax-ramie hybrid, with a fiber-to-resin ratio of 10:1 using the hand layup method. These fabricated laminates were cut into the test specimen size according to ASTM standards of different tests and were subjected to tests like FFT, impact, moisture absorption, and density tests for understanding the performance of the composite laminates under these testing conditions.

Two specimens were prepared using flax and ramie fibre and epoxy resin by the hand layup method. The epoxy-hardener mixture was first poured onto a polypropylene sheet, followed by placing a layer of fiber on top. Another layer of the matrix was then applied, and the second layer of fiber was added. After all four layers were assembled, the laminate was covered with a polypropylene sheet, placed on a flat surface, and weighted down to ensure proper curing. Due to low atmospheric temperature, the curing process was allowed to proceed for 72 hours. After the curing process, as shown in Fig. 2, test samples were cut to the required dimensions as prescribed in the ASTM standards (20-23).

(a) (b)

(c) (d)

(e)

Fig. 2: Laminate sample fabrication process. Mixing of resin and hardener (a) application of resin on binding sheet (b) laying of first layer of fiber (c) application of resin on the fiber, and the process is continued until the achievement of optimal thickness (d) laminate after curing (e)

2.3 Density

The density of the composite laminate was found by using Archimedes' principle as per the ASTM D792 standards. This provides a measure of the material's mass per unit volume, which is essential. A specimen with the dimensions 60 x 60 x 3 mm is prepared. The setup mainly consisted of a weighing balance and immersion medium (distilled water). The specimens' weight is first recorded in air and then immersed in distilled water, as shown in Fig. 3, and then the weight of the submerged specimen is recorded.

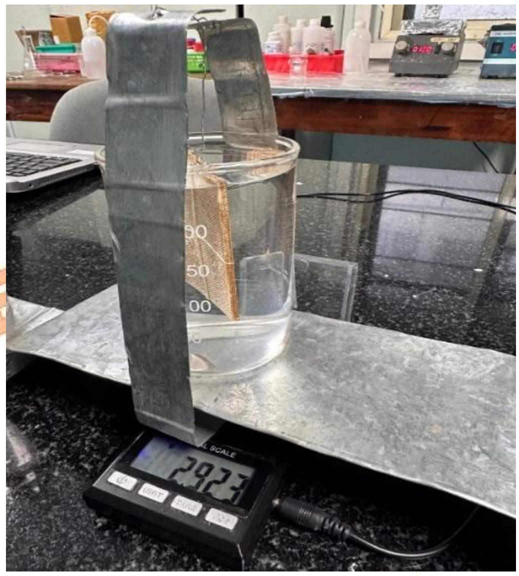


Fig. 3: Weight of composite in water

Density is calculated using,

(1) Specific Gravity (SG)

$$SG = \frac{Weight\ in\ Air}{Weight\ in\ Air - Weight\ in\ Liquid} \quad (1)$$

(2) Density

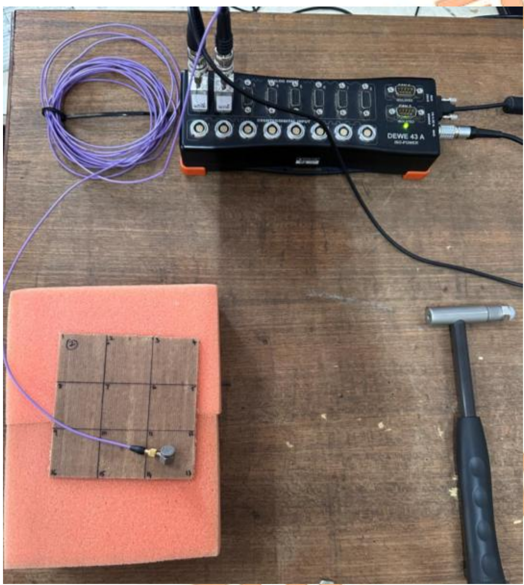
$$Density = SG \times Density\ of\ Liquid \quad (2)$$

2.4 FFT

The modal test using FFT with an 8-channel analyser is an essential method for evaluating the dynamic properties of composite materials, particularly those used in automotive applications. This test identifies key vibrational characteristics such as natural frequencies, damping ratios, and mode shapes, which help predict how the material will perform under real-world vibrational loads, like those experienced in automotive dashboards under Free-Free and Cantilever conditions, as shown in Fig. 4. Understanding these properties ensures the composite's reliability and performance.

During the test, the composite specimen is mounted on a fixture as shown in Fig. 5, and accelerometers are attached at a specific point. Controlled vibrations are introduced using a modal hammer, while the 8-channel analyser collects response data from an accelerometer. This setup captures both localized and overall vibrational behaviour, providing a comprehensive view of the material's performance.

The collected data is processed using FFT to convert it into the frequency domain, where natural frequencies are identified, and mode shapes and damping characteristics are analyzed. The multi-channel capability enhances accuracy, making it particularly useful for complex composite structures. This testing was conducted in line with ASTM E756 standards.

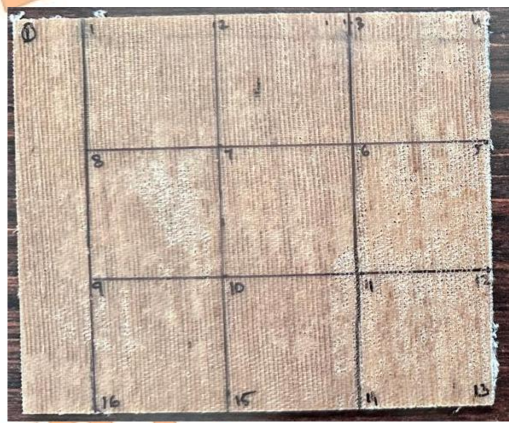


(a)

(b)

Fig 4: FFT modal test of specimens using Free-Free(a) and Cantilever(b) conditions.

(a)



(b)

Fig 5: FFT Tests setup for Free-Free (a) and Cantilever (b) conditions

2.5 *Impact Test*

An impact test is conducted to determine the composite's durability and yield strength using the ASTM D7136 standard for drop tests. The specimen with the dimensions 100 x 100 x 3 mm, as shown in Fig. 7, is kept in the high-speed impact machine. A conical impactor is dropped from the 0.5 m, allowing it to free-fall and impact the specimen. The impact energy is recorded by the machine.

2.6 Water Absorption Test

The water absorption test is used to evaluate the amount of water absorbed by natural fibre composite materials when exposed to a humid environment or immersed in water. The test is carried out as per ASTM D5229 standards. A specimen with dimensions 60 x 60 x 3 mm was dried at an atmospheric temperature of 24°C and humidity of 83% until any pre-existing moisture dries out; the dry weight is then recorded. The specimen is then immersed in distilled water as shown in Fig. 6 and weighed at specific intervals of 24h, 48h, 72h, and 92h after blotting the surface moisture. Water absorption (WA) is calculated using,

$$WA(\%) = \frac{Weight\ (wet) - Weight\ (dry)}{Weight(dry)} x\ 100$$

Fig. 6: Specimens immersed in distilled water

3. Results and Discussion

3.1 Density

Two composite specimens, Flax Composite and Flax-Ramie Hybrid Composite, were evaluated based on their densities to determine their suitability for various applications. The results, depicted in the graph as shown in Fig. 7, show that the Flax Composite had a higher density of 1.36 g/cm^3, while the Flax-Ramie Hybrid Composite was lighter, with a density of 1.17 g/cm^3. The lower density of the hybrid composite suggests its potential advantage in applications where weight reduction is essential (13,15,19).

Additionally, while the dry weight of the Flax Composite was 10.97 g, the Flax-Ramie Hybrid Composite was slightly heavier at 11.75 g. However, the Flax-Ramie Hybrid showed a lower weight in water (1.77 g) compared to the Flax Composite (2.92 g), indicating differences in porosity and water retention, which could affect the material's mechanical properties and performance (1,4,8).

In comparing these composites, it is notable that flax composites typically exhibit higher density due to their closely packed structure (9,11). On the other hand, ramie fiber contributes to reduced porosity in hybrid composites, as highlighted by its superior tensile and bending strength when combined with other fibers (2,3,5). Furthermore, flax-ramie hybrid composites benefit from their balanced combination of mechanical performance and moisture resistance, as demonstrated in phenol-formaldehyde-based systems (15,19).

Studies have consistently shown that hybrid composites, particularly those incorporating flax and ramie fibers, offer improved mechanical and water resistance properties. These advantages align with findings where hybridization optimizes the trade-off between density, moisture absorption, and mechanical strength (4,19,20).

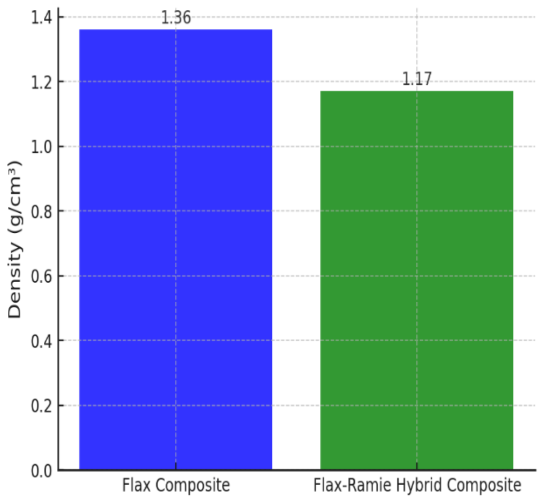


Fig 7: Density of fiber-reinforced epoxy composite

3.2 FFT

The modal tests of flax fiber and flax-ramie hybrid composites under free-free and cantilever conditions reveal distinct vibration characteristics. For the flax fiber composite, natural frequencies range from 90.7 Hz to 909.6 Hz, with damping ratios reaching up to 0.188. This suggests effective vibration control in certain modes, but optimization is needed in higher frequency ranges. In contrast, the flax-ramie hybrid composite demonstrates natural frequencies between 133.95 Hz and 868.08 Hz, with a maximum damping ratio of 0.181 in free-free conditions, though generally lower under cantilever conditions. These findings align with earlier studies that suggest flax and ramie hybrid composites exhibit improved mechanical properties and dynamic performance due to their hybrid configuration, enhancing vibration resistance (19,5).

In the graph shown in Fig. 8, a comparative analysis of natural frequencies and damping ratios for both composites under free-free and cantilever conditions is presented. The natural frequencies (solid lines) and corresponding damping ratios (dashed lines) are plotted across ten modes. It is observed that the cantilever condition generally resulted in higher frequencies, especially for the flax-ramie hybrid composite, while the flax fiber composite displayed more consistent frequencies under free-free conditions. These observations are consistent with studies that highlight the influence of boundary conditions on the vibrational performance of fiber-reinforced composites (3, 4).

Damping ratios varied across modes, with the flax fiber composite exhibiting higher damping values in initial modes and the hybrid composite maintaining lower damping overall. This comparison highlights how material composition and test conditions influence dynamic behavior, underscoring the potential of each composite for specific applications based on their mechanical properties.

Such behavior emphasizes the advantage of hybrid composites in balancing dynamic performance and structural damping, as reported in recent investigations (2,8).

3.3 Impact Test

The impact test results indicate that the flax fiber composite absorbs an average of 10.23 J of energy with an impact force of 1.82 N and a consistent displacement of 5.70 mm. This shows moderate impact resistance but some variability, suggesting the need for reinforcement in critical applications where higher performance is required. These findings align with previous studies reporting moderate impact resistance for flax fiber composites, attributed to the inherent properties of flax fibers (10,11).

In contrast, the flax-ramie hybrid composite demonstrates slightly better performance, with an average absorbed energy of 10.47 J, an impact force of 2.08 N, and a displacement that varies slightly between 5.57 mm and 5.81 mm. This indicates a consistent ability to absorb energy while maintaining structural integrity, making it more suitable for impact-prone applications. Similar findings in earlier works have highlighted the benefits of hybrid composites, such as improved energy absorption and impact resistance due to the synergistic effect of combining flax and ramie fibers (19,4).

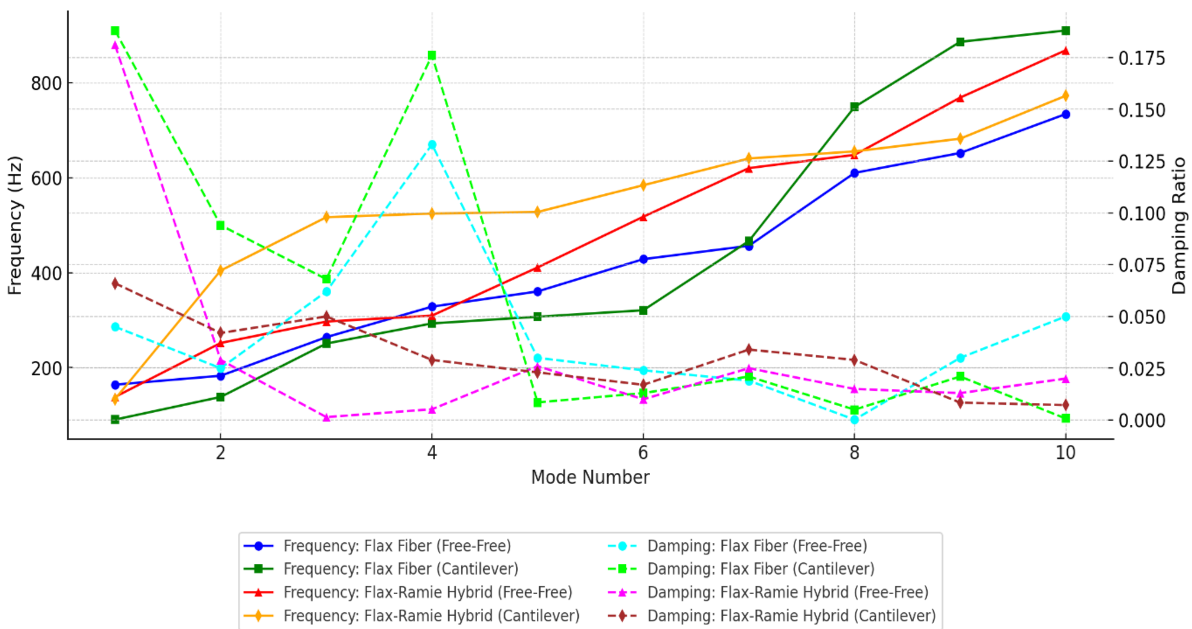
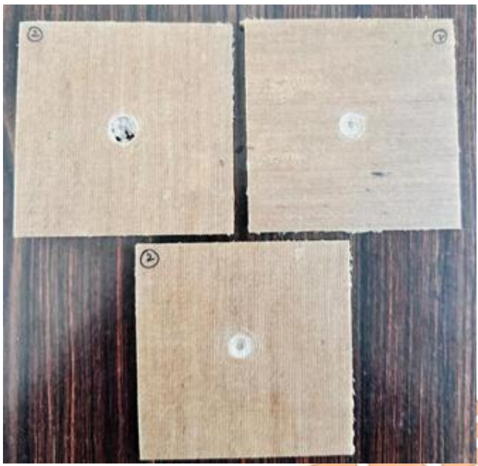
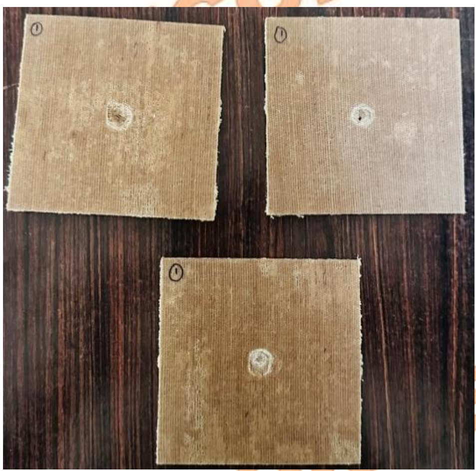


Fig. 8: Frequency and damping ratios of fiber–reinforced epoxy composite



(a)



(b)

Fig. 9: Composite samples before (a) and after (b) impact testing

Below is the graph as shown in Fig. 10, comparing the energy absorption, impact force, and displacement of both composites. The blue and red bars represent the energy absorbed and the impact force, while the green line shows the displacement values. The flax-ramie hybrid composite outperforms the flax fiber composite in both energy absorption and impact force, while maintaining a more consistent displacement, as shown in Fig. 9, highlighting its suitability for applications requiring enhanced impact resistance. These observations are consistent with studies emphasizing the role of fiber hybridization in enhancing impact performance, particularly in dynamic loading conditions (2,3).

3.4 Water Absorption Test

After 72 hours, the flax composite exhibited a significant increase in water content to 33.3%, whereas the water content of the flax and ramie hybrid composite remained unchanged at 11.1%. This trend persisted through 96 hours, with the flax composite maintaining its water content at 33.3% and the hybrid composite remaining at 11.1%. The higher moisture absorption in the flax composite is likely due to its greater porosity, which allows it to retain more water. Porous structures have more spaces that can hold water, thereby increasing absorption. These findings align with prior studies that attribute higher water absorption in flax composites to their porous structure and hydrophilic nature (13,14).

In contrast, the flax-ramie hybrid exhibits lower water absorption, suggesting a less porous and more compact structure. This comparative analysis highlights how porosity affects the material's moisture behavior, underscoring the need to reassess moisture retention when defining specific applications to prevent potential performance or durability issues. The reduced water absorption in the hybrid composite is consistent with findings in hybrid materials, where the combination of fibers can lead to a denser, less porous structure (3,4).

The chemical composition of fibers, particularly lignin and hemicellulose, significantly influences their water absorption properties. Lignin is hydrophobic and resists water uptake, while hemicellulose is more hydrophilic and promotes moisture absorption. As noted in Table 1, flax fibers have a higher hemicellulose content (16-18.6%) compared to ramie (13-16%), which can lead to increased moisture absorption (18).

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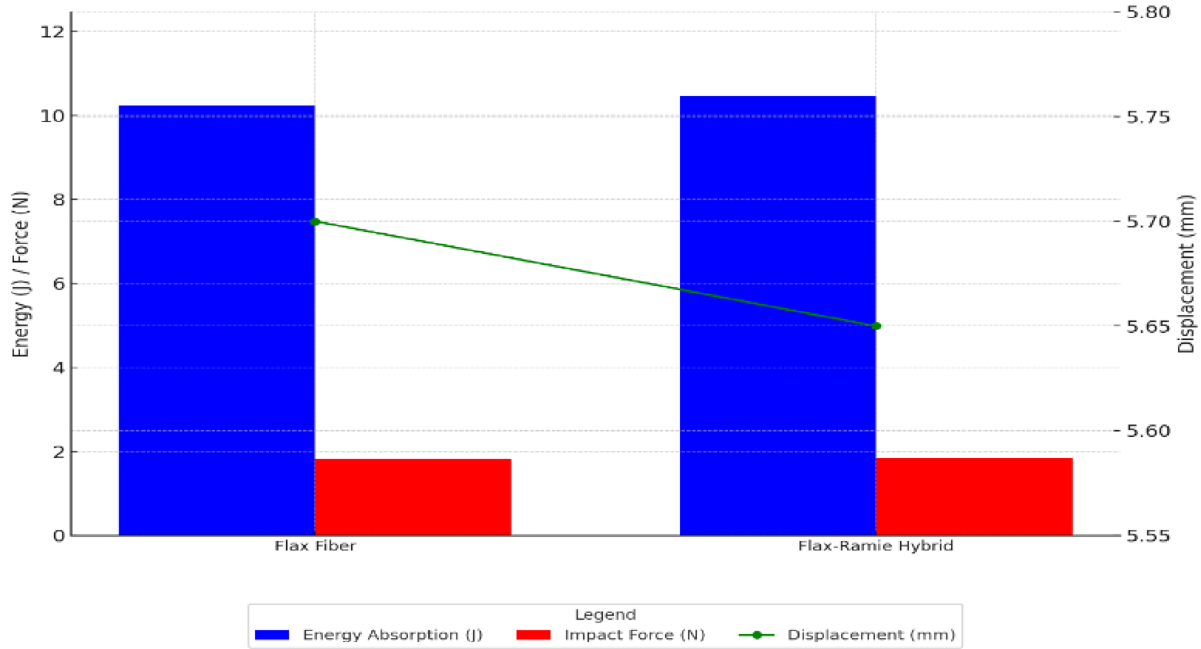

Fig 10: Energy Absorption, Impact Force, and Displacement of fiber–reinforced epoxy composite

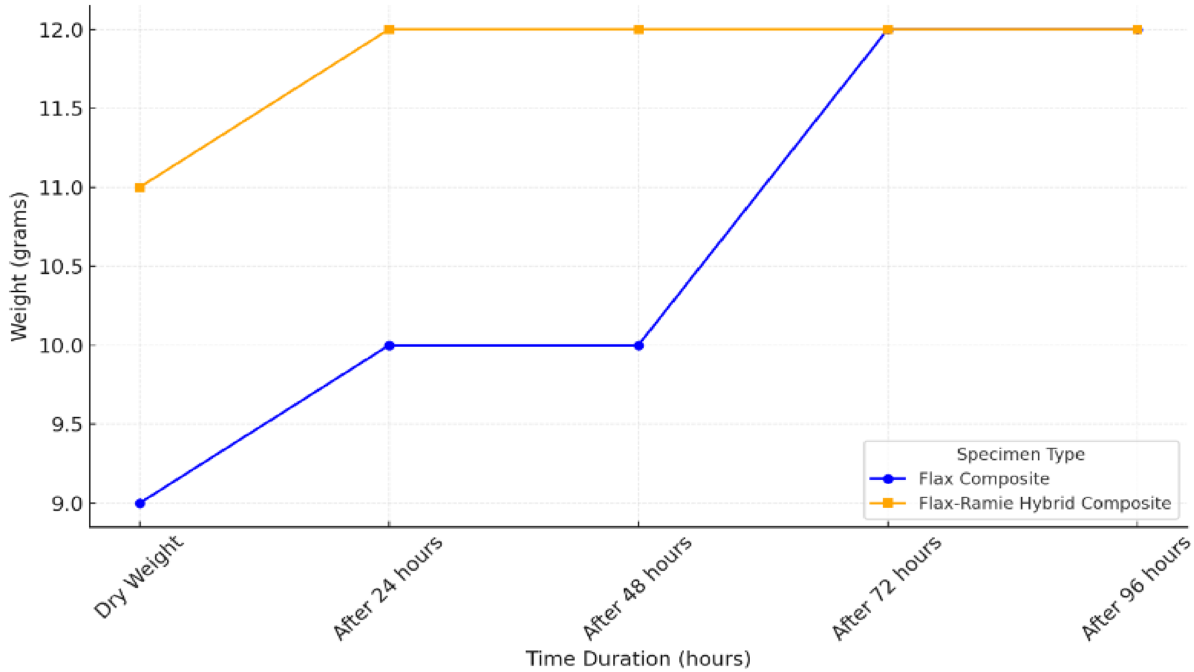

Fig 11: Water absorption test results of fiber–reinforced epoxy composite

However, flax also contains a greater amount of lignin (2-3.8%) than ramie (0.6-0.7%), which would typically suggest a reduction in water uptake. Despite this, the pure flax composite exhibits a higher density (1.36 g/cm^3) than the flax-ramie hybrid composite (1.17 g/cm^3), indicating less porosity. These observations align with prior research on the relationship between fiber density, porosity, and water absorption (8,6).

Generally, higher density correlates with lower water absorption; however, the hybrid composite may absorb more moisture due to the combined hydrophilic effects of cellulose and hemicellulose from both fibers. The graph, as shown in Fig. 11, illustrates the moisture content for the two specimens—Flax Composite and Flax-Ramie Hybrid Composite—over time. Initially, both composites show an increase in weight after 24 hours, with further increments observed in the Flax Composite at 72 hours. This trend indicates higher moisture absorption in the Flax Composite, which reached 33.3% at both 72 and 96 hours. In contrast, the Flax-Ramie Hybrid Composite maintained a stable moisture content of 11.1% throughout the testing period, suggesting lower porosity and water absorption. These observations underscore the importance of understanding the interplay between fiber composition and moisture behavior, which can influence the suitability of these materials for applications where moisture resistance is crucial (10,15).

When used in phenol-formaldehyde-based hybrid composites, the flax-ramie hybrid demonstrates superior performance compared to pure ramie or flax composites (19). The hybrid composite's balanced combination of flax and ramie fibers offers an optimal blend of mechanical strength, reduced porosity, and enhanced moisture resistance. Flax provides higher tensile strength and lignin content for durability, while ramie contributes exceptional tenacity and hydrophobicity, which mitigate excessive water absorption. This synergy results in a hybrid material with improved dimensional stability and lower susceptibility to moisture-induced degradation. Thus, the hybrid composite is a more robust and versatile solution for demanding applications requiring both mechanical integrity and moisture resistance (11,16).

4. Conclusions

Flax composite and flax-ramie hybrid composites were successfully developed using the hand-layup technique. Comparative analysis revealed that the flax-ramie hybrid composite outperformed the flax composite in terms of vibration control, impact resistance, and moisture absorption, demonstrating superior structural integrity, stability, and dynamic performance for applications subjected to varying environmental and mechanical conditions. The hybrid composite's reduced moisture absorption and better vibration damping make it particularly suitable for applications where durability and reliability are critical. These results highlight the potential of hybrid composites as a more reliable material for advanced engineering and impact-prone applications. Further research could explore optimizing fiber orientation, investigating fatigue behavior under dynamic loads, and expanding the hybridization of natural fibers to enhance composite performance further.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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