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Research Article

Mechanical and Environmental Comparison of Natural Fibers and Glass Fiber in the L-RTM Method

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Abstract

The applicability of flax fiber-reinforced composites as an environmentally friendly alternative to glass fiber-reinforced plastics (GFRP), commonly used in outdoor structures such as water slides, has been investigated. While glass fiber is associated with high energy consumption and significant environmental impacts, flax fiber offers a sustainable solution due to its renewable nature, low density, and biodegradable properties. The mechanical and environmental performance of flax fiber-reinforced composites manufactured using the L-RTM (Light Resin Transfer Molding) method was evaluated, with a particular focus on sensitivity to water and moisture, and design considerations to mitigate these effects were discussed. In this method, L-RTM is employed as a vacuum-assisted, closed-mold technique particularly suited for medium-scale production of high-quality components with smooth surfaces on both sides. In this context, the essential conditions for natural fiber-reinforced composites to serve as a viable alternative to glass fiber in water slide applications have been identified.

Keywords: *Glass fiber, Flax fiber, Composite material, L-RTM, Sustainability*

1. Introduction

Today, composite materials are widely used across various industries. Among them, glass fiber-reinforced plastics (GFRP) are especially favored for large-scale outdoor structures such as water slides due to their high strength and low weight. However, the production and use of glass fiber-based composites involve significant energy consumption and contribute substantially to environmental burden. For instance, the energy required to produce glass fiber per unit weight is approximately 2 to 5 times greater than that for natural fibers, and since it is derived from crude oil, it is not carbon-neutral. In contrast, natural fibers are sourced from renewable materials and offer significant advantages such as lower density, reduced energy requirements, biodegradability, and recyclability. Unlike glass fiber dust, which can be abrasive and harmful to human health, natural fibers do not pose such risks and do not cause machine wear. These benefits have led to increasing academic and industrial interest in natural fiber-reinforced composites in recent years.

Among natural fibers, flax fiber stands out due to its high cellulose content and favorable structure, making it one of the best-performing options in terms of mechanical properties. Flax fiber-reinforced composites have demonstrated a wide range of applications, from sports equipment and marine vessels to automotive components. Particularly in outdoor sports and recreational equipment, natural reinforcements such as flax have become attractive alternatives in response to growing demand for eco-friendly products. The low density of flax fibers (~1.5 g/cm^3) enables the production of lighter composites compared to glass fibers (~2.5 g/cm^3) for the same volume. However, flax fibers have noticeably lower mechanical performance than glass fibers; when compared on an equal weight basis, glass fiber composites provide approximately four times higher strength and stiffness than flax-based ones. As a result, to achieve equivalent load-bearing capacity, flax composites require either thicker sections or more layers, partially offsetting their sustainability advantages with increased material use.

Another critical environmental consideration is the moisture sensitivity of natural fibers. Due to the hygroscopic nature of flax, water absorption within the composite can weaken the fiber-matrix interface, thereby degrading mechanical performance [1]. In outdoor applications exposed to moisture and water (e.g., water slides), flax fiber swelling due to water uptake may lead to structural deterioration over time. Thus, the use of natural fiber-reinforced composites in such environments requires careful design considerations and protective measures to ensure durability [2].

In this study, flax fiber-reinforced composites were produced using the Light Resin Transfer Molding (L-RTM) method and examined as a potential eco-friendly alternative to glass fiber-reinforced composites. Given that water slides are typically made of glass fiber polyester-based GFRP, this study comparatively evaluates the mechanical performance and environmental benefits of flax fibers in the context of such applications. The objective is to determine whether flax reinforcement can serve as a viable alternative to glass fiber in outdoor composite structures like water slides, and under what specific conditions this substitution would be feasible.

2. Materials and Methods

Two different types of reinforcement fibers were used in this study. For glass fiber reinforcement, MetycoreMax fabric produced by Metyx was selected. MetycoreMax is a glass fiber reinforcement material designed for RTM processes, consisting of a high-permeability synthetic core layer sandwiched between two chopped strand mat (CSM) outer layers. This structure enables rapid resin flow within the mold, making it suitable for the L-RTM process [3]. As the natural fiber reinforcement, a woven fabric made of 100% flax fibers was used. Flax fibers are naturally less dense and more flexible, which may lead to different resin flow and placement characteristics compared to glass fiber during the L-RTM process. In both composite types, the matrix material was a commercial isophthalic-based unsaturated polyester resin. Isophthalic polyester offers higher chemical resistance and mechanical performance than orthophthalic resins, making it more suitable for structures exposed to water and outdoor conditions. The resin was cured at room temperature using MEKP catalyst in accordance with the manufacturer’s recommendations.

Manufacturing Method (L-RTM):

Composite panels were fabricated in a 50×50 cm two-part mold setup suitable for the L-RTM process. The bottom mold was made of a rigid epoxy composite, while the top mold consisted of a semi-flexible fiber-reinforced composite. Before manufacturing, a release agent and gelcoat were applied to the mold surface to ensure part release and surface quality. The reinforcement fabrics were then placed into the bottom mold: for the glass fiber composite, 4 layers of MetycoreMax (approx. 1600 g/m² total) were laid; for the flax composite, 4 layers of woven flax fabric were used to achieve equivalent volume. After closing the mold and securing it with clamps, vacuum lines were connected to the mold edges and a vacuum pressure of approximately 0.8 bar was applied. The resin was drawn into the mold through a single inlet by vacuum, spreading between the fibers. Due to the internal flow channels of MetycoreMax, the low-viscosity polyester resin rapidly impregnated the glass fiber bundles. In the flax composites, resin diffusion into the fibers was relatively slower, but homogeneous impregnation was achieved with vacuum assistance. After resin injection, the mold was kept at a constant temperature (25°C) for at least 24 hours to allow in-mold curing. The resulting composite panels were

approximately 4 mm thick, void-free, and had smooth surfaces on both sides. In the flax-reinforced samples, the fiber volume fraction was approximately 30–35%, while it reached about 40% in the glass fiber-reinforced samples. Due to the higher resin absorption and lower density of flax fibers, the same number of fabric layers resulted in thicker laminates with lower fiber volume content. Therefore, although the panel thicknesses were similar between the two composite types, the resin content was higher in the flax-reinforced composites.
Sample Preparation:

Mechanical test specimens were cut from the flat composite panels according to relevant standards. For tensile testing, rectangular specimens (width ~25 mm, gauge length 150 mm) were prepared in accordance with ISO 527-4. Aluminum tabs were bonded to the specimen ends to prevent slippage during loading. For flexural testing, bar-shaped specimens were prepared for three-point bending according to ISO 14125, with dimensions of approximately 80 mm in length and 15 mm in width; the span length was adjusted to 16 times the specimen thickness (~64 mm). For impact testing, unnotched Charpy impact specimens (80×10 mm) were prepared according to ISO 179-1. All specimens were conditioned at 23°C and 50% relative humidity for at least 40 hours prior to testing.

Mechanical Testing:

Tensile tests were conducted using a universal testing machine with a 100 kN load capacity and a crosshead speed of 2 mm/min. Five specimens were tested for each material type, and stress–strain curves were recorded. Flexural tests were carried out using a three-point bending fixture at a speed of 5 mm/min, and load–displacement behavior was monitored. For impact resistance testing, a Charpy pendulum impact tester with 15 J hammer energy was used to measure the energy absorbed upon fracture. At least five specimens from each material group were subjected to impact testing, and the average fracture energy was recorded. The test results are presented in tables and graphs, and the mechanical performances of glass fiber- and flax fiber-reinforced composites were quantitatively compared and discussed.

3. Results

The key mechanical properties of the two composite materials are summarized in Table 1. Flax fiber-reinforced composites demonstrated significantly lower strength and stiffness compared to glass fiber-reinforced composites. For instance, the tensile strength of the flax composite was approximately 40–50% lower. While the average tensile strength of the glass fiber-reinforced samples was measured around 250 MPa, the flax fiber specimens failed at approximately 150 MPa. Similarly, the tensile modulus of the glass fiber composite (~15 GPa) was about 50% higher than that of the flax fiber composite (~10 GPa). These values are consistent with literature-reported modulus ranges for polyester composites reinforced with glass and flax fibers—approximately 15 GPa for glass fiber-reinforced composites and around 10 GPa for flax fiber-reinforced counterparts. Due to the inherently lower elastic modulus and limited stress-bearing capacity of flax fibers, these composites lag behind their glass fiber equivalents in terms of maximum stress endurance.

Flexural strength results further confirmed the superior performance of glass fiber composites. Under three-point bending, glass fiber-reinforced specimens exhibited a flexural strength of approximately 220 MPa, whereas the flax fiber composites reached a maximum of around 120 MPa. Additionally, glass fiber specimens exhibited lower displacement under flexural loading (indicating stiffer behavior), while flax-reinforced samples deformed more significantly under the same loading conditions. Impact test results followed a similar trend: the unnotched impact toughness of flax composites was nearly half that of glass fiber composites. In Charpy impact testing, glass fiber composites absorbed an average of ~55 kJ/m², while flax composites absorbed ~30 kJ/m². These findings indicate that glass fiber-reinforced composites exhibit higher toughness and crack resistance under impact, whereas flax-reinforced composites show a more brittle response.

Table 1: Comparison of the Mechanical Properties of Glass Fiber and Flax Fiber-Reinforced Composites (Average Values)

Property	Glass Fiber-Reinforced Polyester	Flax Fiber-Reinforced Polyester
Fiber Volume Fraction (%)	40	30
Tensile Strength (MPa)	250	150
Tensile Modulus of Elasticity (GPa)	15	10
Tensile Strain at Break (%)	2	1,5
Flexural Strength (MPa)	220	120
Flexural Modulus (GPa)	13	8
Impact Strength (kJ/m²)	55	30

Figure 1 illustrates the differences in stiffness and strength between the two composite materials.

The glass fiber-reinforced composite specimens, due to their higher elastic modulus, sustained greater stress under the same strain and fractured at approximately 2% elongation. In contrast, the flax fiber-reinforced composites exhibited a lower-slope stress–strain curve, fracturing at around 1.5% strain. The linear curves observed in Figure 1 indicate that both composites behaved elastically up to the point of failure, with no plastic deformation occurring. The relatively low strain at failure in the flax composite is attributed to the brittle nature of flax fibers and the weaker fiber–matrix interface compared to glass fibers. The glass fiber composite specimens, on the other hand, failed at higher stress levels, confirming their superior tensile performance.

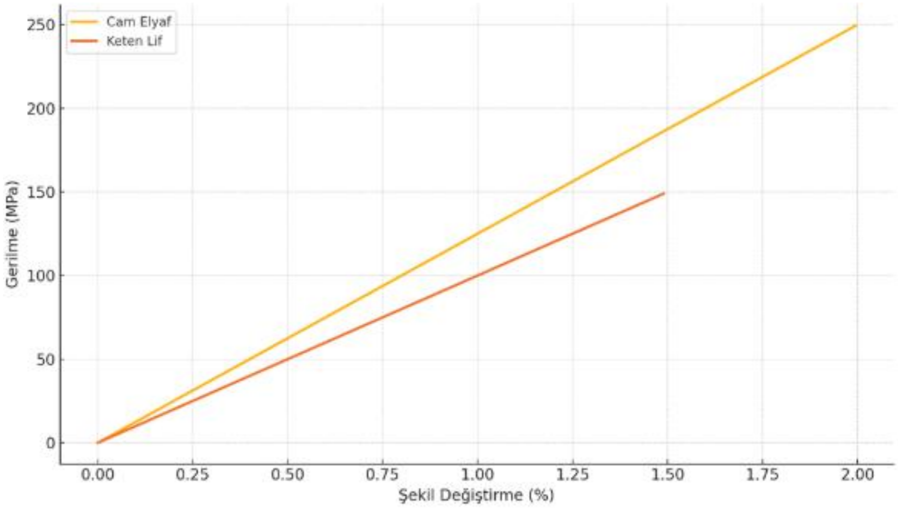

Figure 1: Stress–Strain Curve

Due to its higher flexural stiffness, the glass fiber-reinforced composite was able to carry a greater load than the flax fiber composite at the same displacement. As shown in Figure 2, the load–displacement curve of the glass fiber composite has a steeper slope and reaches its fracture load (~900 N) at around 8 mm displacement. In contrast, the flax fiber-reinforced composite exhibits a gentler slope and fractures at approximately 450 N at around 9 mm displacement. This result indicates that, at equal thickness, the flax composite can withstand only about half the flexural load of the glass fiber composite. During flexural testing, the glass fiber specimens failed abruptly and in a brittle manner, while the flax fiber specimens exhibited partial fiber pull-outs and interlayer delaminations. This behavior is likely due to weaker bonding between the flax fibers and the resin matrix compared to the stronger adhesion found in glass fiber composites. Poor fiber–matrix adhesion can result in a portion of the fracture energy being dissipated through fiber pull-out mechanisms. As a result, the glass fiber-reinforced composites demonstrated superior flexural performance by withstanding higher loads and undergoing less deformation.

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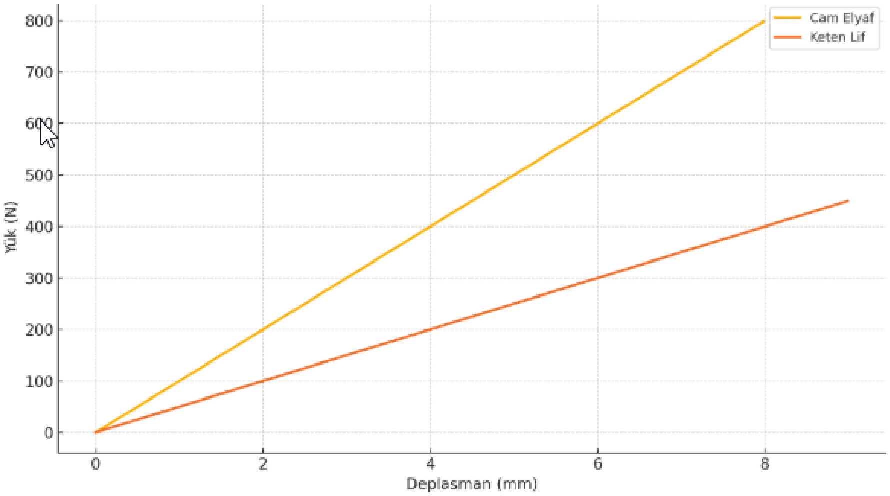

Figure 2: Three-Point Bending Test Load–Displacement Curve

As shown in Figure 3, the impact resistance of flax fiber-reinforced composites is significantly lower than that of glass fiber-reinforced composites. Glass fiber composites are capable of absorbing a higher amount of energy upon impact, indicating a tougher structural behavior. In contrast, flax fiber composites tend to fracture more easily under impact and absorb less energy before failure. This disparity can be attributed to the higher tensile strength of glass fibers and their stronger interfacial bonding within the matrix, which slows down crack propagation during impact. Flax fibers, on the other hand, are unable to effectively dissipate impact energy due to relatively weak fiber–matrix interfaces, leading to easier fiber pull-out and premature failure.

Moreover, although glass fibers are brittle in nature, their dense and rigid structure can partially hinder crack propagation during impact loading. In the case of flax fibers, despite their inherent capacity to absorb moisture and deform elastically, their lower adhesion strength with the matrix means that much of the impact energy leads to crack formation rather than dissipation. Consequently, in applications such as water slides—where impact loads may occur—glass fiber-reinforced composites offer a higher safety margin, while the lower impact resistance of flax fiber composites should be carefully considered in the design process.

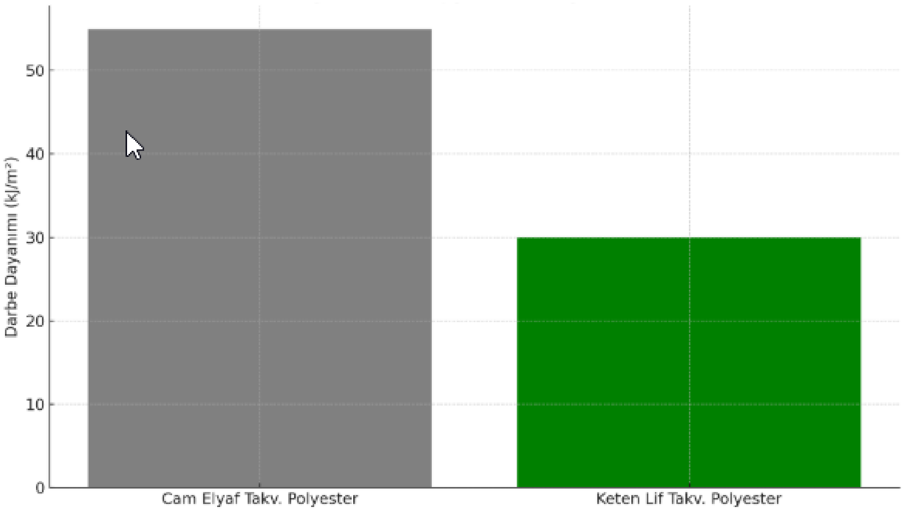

Figure 3: Charpy Impact Strength

Although the mechanical test results clearly demonstrated that flax fiber-reinforced composites are mechanically inferior to their glass fiber-reinforced counterparts, certain advantages were observed in terms of processability and environmental impact. The processability of flax fibers during the L-RTM process exhibited some distinctions. The flexible and “springy” nature of woven flax fabric tended to create gaps (bridging) at mold corners during layup. However, with proper vacuum application, close contact between the fibers and the mold surface was achieved, largely mitigating this issue.

During resin infusion, the flax fibers rapidly absorbed resin and swelled, drawing a relatively higher resin volume into the laminate. Consequently, flax composites typically exhibit higher resin content. In fact, for vacuum-infused woven flax composites, the fiber/resin weight ratio is often around 33%/67%. Similarly, in this study, the flax composite panels were found to contain more resin than their glass fiber counterparts. Although the higher resin content slightly increased the overall material density, the low intrinsic density of flax fibers still resulted in a lower composite weight [4]. The density of flax fiber-reinforced panels was around 1.5 g/cm^3, whereas glass fiber panels exhibited approximately 1.8 g/cm^3. This ~17% weight reduction may provide a significant advantage in transportation or mobile system applications.

From a cost perspective, flax fiber—being an agricultural product—can be more economical than glass fiber if cultivated under favorable regional conditions. While glass fiber production requires energy-intensive furnace processes, flax fibers are obtained through farming and relatively simple industrial operations. Nevertheless, achieving equivalent mechanical performance with flax composites may require additional layers or greater thickness, which could offset the material cost advantage. For example, designing a structure with equal load-bearing capacity using flax composites might necessitate increased resin use and labor, diminishing the cost benefit.

Furthermore, at the end of their service life, glass fiber composites pose challenges in disposal (e.g., grinding or landfilling), which can be costly and environmentally burdensome. In contrast, flax fiber composites may theoretically be incinerated with reduced ash generation or composted under controlled conditions. From this perspective, while large-scale glass fiber structures such as decommissioned water slides present significant waste management issues, natural fiber alternatives offer the potential for environmentally benign end-of-life disposal [5].

4. Discussion and Conclusion

In this study, glass fiber- and flax fiber-reinforced polyester composites produced via the L-RTM method were comparatively evaluated. From a mechanical perspective, the results clearly demonstrate that flax fiber-reinforced composites are significantly weaker than their glass fiber counterparts. The tensile and flexural strengths of flax composites were found to be approximately half those of glass fiber composites, and their impact toughness was also notably lower. Due to the low intrinsic strength of flax fibers and weak fiber–matrix interfacial bonding, structures made from flax composites exhibit reduced structural load capacity compared to glass fiber-based equivalents. This restricts their direct substitution in large-scale, dynamically loaded structures such as water slides.

However, from an environmental and economic standpoint, flax fiber offers notable advantages. As a renewable and carbon-neutral resource, flax requires significantly less energy and emits fewer greenhouse gases during production compared to glass fiber. The CO_2 absorbed by the plant during growth reduces the material's overall environmental footprint. Furthermore, being biodegradable, flax fibers do not generate hazardous waste at the end of their service life, thereby contributing to a more sustainable material lifecycle[6,7].

For use in water slide applications, several conditions must be met to ensure the feasibility of flax reinforcement.

First, design safety factors should be increased, and the flax-reinforced composite elements should be dimensioned with greater thickness or multiple layers compared to standard glass fiber designs. This would allow the structure to achieve the required load-bearing capacity despite the lower strength of the natural fibers.

Second, due to the moisture sensitivity of flax, water impermeability must be ensured in constantly wet environments such as water slides. To address this, it is recommended to apply a high-quality gelcoat on the composite surface and ensure full resin saturation during manufacturing. Additionally, pre-treatment of flax fibers—such as silane coating or alkaline treatment—can enhance fiber–matrix adhesion and reduce water absorption. Third, considerations related to UV resistance and biological degradation should not be overlooked. As flax fibers can degrade under UV exposure over time, the composite structure should be protected using UV-blocking additives or coatings. In outdoor environments, protection against microbial or fungal attacks may also be necessary through the use of suitable coatings or resin additives.

In conclusion, flax fiber-reinforced composites present significant environmental benefits over conventional glass fiber-reinforced composites, aligning with global sustainability goals. However, based on the findings of this study, flax composites alone do not provide sufficient mechanical performance for high-strength, long-term outdoor applications such as structural water slide components. The data suggests that while flax composites are not suitable for primary load-bearing elements, they may be effectively used in non-structural applications such as decorative theming panels or other components subject to lower mechanical stress.

As an intermediate solution, a hybrid reinforcement strategy is proposed. Hybrid composite systems combining flax and glass fibers can reduce environmental impact by increasing natural fiber content, while still benefiting from the superior mechanical performance of glass fibers.

For future studies, research is recommended on resin system modifications, fiber surface treatments, and advanced composite design strategies to improve both water resistance and mechanical performance of natural fiber composites [6]. These efforts may enable the development of durable, eco-friendly composite materials suitable for demanding outdoor conditions.

5. Acknowledge

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