Flexural and Tensile Strength of Castor Oil-Based Polyurethane Composites Reinforced with Luffa Cylindrica Mats as a Sustainable Alternative to Oriented Strand Board

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Abstract - The main objective of this study was to develop and characterize a novel, eco-friendly composite material consisting of castor oil-based polyurethane (COPU) matrix reinforced with Luffa cylindrica mats hereafter referred to as luffa for potential use as structural panels and an alternative to oriented strand board (OSB). Mechanical properties were assessed through three point flexural testing, perpendicular to surface tensile testing. For benchmarking purposes, results were compared against commercial OSB panels. The luffa/COPU composites were fabricated via hand lay-up, incorporating luffa mats at 48 vol%, the maximum volume fraction permitted by the mold and available manufacturing resources. The incorporation of luffa mats significantly enhanced the mechanical performance of the COPU resin, with flexural strength and modulus of elasticity increasing by over 23 and 10 times, respectively. Other mechanical properties also more than doubled in comparison to the neat resin. Nevertheless, the notable mechanical improvements and overall performance of the composite support its viability for use in civil construction applications, particularly as a sustainable alternative to OSB.

Key Words: Luffa cylindrica, composite materials, castor oil, polyurethane, natural fiber reinforcement, oriented strand board alternative.

1. Introduction

The use of synthetic fibers has increasingly come under scrutiny due to their environmental drawbacks, particularly regarding their end-of-life disposal and the high energy demands associated with their manufacturing processes [1–3]. In response to rising global concerns about sustainability, there has been a growing trend toward replacing synthetic fibers with natural lignocellulosic fibers (NLFs), which are derived from renewable sources and exert a lower environmental impact [4–6]. NLFs offer several advantages, including relatively high specific mechanical strength and stiffness, low density, reduced cost, and favorable acoustic and thermal insulation properties [7–12]. These characteristics have supported the integration of NLF-reinforced polymer composites in a variety of industrial applications, particularly within the automotive [13,14], aerospace [15,16], civil construction [17,18] and ballistic protection sectors [19,20].

Beyond the replacement of fiber reinforcements, recent research has also explored sustainable alternatives to petroleum-derived polymer matrices. Among these, castor oil-based polyurethane (COPU) has emerged as a promising biopolymer, offering not only mechanical robustness but also being non-toxic, biodegradable, and derived from a renewable resource [21–23]. COPU has shown great potential as a matrix material in natural fiber composites [24].

A particularly interesting NLF is Luffa cylindrica, commonly referred to as luffa or sponge gourd. Distinct from many other natural fibers, luffa consists of an interwoven fibrous network that naturally forms a three-dimensional mat. This unique structure, coupled with its low density and adequate mechanical performance, has led to its investigation in diverse applications, including filtration systems, sound insulation and various civil construction uses [25]. Previous studies have reported significant improvements in mechanical properties when luffa mats are used to reinforce polymeric matrices [26].

2. Materials and Methods

2.1. Materials

Upon mixing at room temperature, the components undergo a cold-curing process, with an initial gelation time of approximately 15 minutes. The mixture reaches a non-tacky (hard to the touch) state within 60 to 90 minutes, enabling manageable handling and shaping during fabrication. This resin system was selected due to its plant-based origin, mechanical reliability, and suitability for composite manufacturing with natural reinforcements.

The OSB panels were composed of wood chips approximately 5 × 2 cm in size. The panels had a nominal thickness of 10 mm and standard commercial dimensions of 2.20 m × 1.22 m. These commercially available OSB panels were utilized as a benchmark for evaluating the mechanical and physical properties of the developed luffa/COPU composites.

2.2. Methods

2.2.1. Composite Preparation

To minimize moisture content, the fiber mats were dried at 60 °C, a temperature chosen to prevent thermal degradation. No weight variation was observed after 24 hours, indicating a stable, minimal moisture content. To enhance bonding with the resin, the hot luffa mats were immediately incorporated into the COPU matrix. Beyond improving adhesion, the drying process also contributes to biological durability by reducing the risk of fungal and bacterial growth on the fiber surface once embedded in the polymer matrix. The luffa/COPU composites were produced to resemble OSB panels, using a hand lay-up technique combined with pressure molding. Inside a metallic mold, the luffa mats were impregnated with the liquid resin mixture (in a 1:1.8 ratio of prepolymer to polyol). The mold was then closed and subjected to 10 tons of pressure at room temperature for 24 hours. Due to the low volumetric shrinkage of the COPU resin post-gelation, this extended pressurization facilitated improved fiber–resin interaction. The plates were then demolded and allowed to cure for an additional 72 hours, as recommended by the manufacturer. Control samples composed solely of neat resin were produced using the same procedure.

Luffa fiber density was determined to be 0.78 ± 0.02 g/cm³ using water pycnometry in a 50 mL flask. Because the mats contain large voids between fibers, reinforcement loading was limited to 18 layers, corresponding to approximately 50 vol% in the final composite. The main goal was to maximize luffa reinforcement content to assess the potential application of this composite as an OSB alternative. Composites were fabricated using a metallic mold with internal dimensions of 150 × 120 mm. Plate thickness was controlled (up to 12 mm) using shims, depending on the requirements of each mechanical test. Samples were then cut to the appropriate sizes defined by the respective standards.

2.2.2. Flexural Tests

Flexural strength and modulus were determined via three-point static bending tests in accordance with ASTM D790 using a universal testing machine. Nine samples of each material, sized 120 × 15 × 6 mm, were tested at a deformation rate of 2 mm/min, with a 90 mm support span. Testing was conducted until sample fracture or 100% deflection. Flexural strength and modulus were calculated using the standard equations.

2.2.3. Tensile Strength Perpendicular to Surface

To assess panel layer cohesion, tensile tests perpendicular to the surface were performed as per ASTM D1037 using 10 samples (50 × 50 × 12 mm) of the luffa/COPU composite, neat resin, and commercial OSB. Testing was conducted at 25 °C using the Instron 5520 machine, with a 2 mm/min crosshead speed. Samples were glued to metallic plates using high-performance shear-resistant adhesive. Tests were valid only if rupture occurred at the matrix/reinforcement interface. Samples with adhesive failure were retested.

3. Results and Discussion

3.1. Flexural Strength

The flexural strength (FS) and modulus of elasticity (ME) values for the three tested materials are presented in Figure 1. The luffa/COPU composite exhibited an FS of 13.3 ± 0.8 MPa and an ME of 0.19 ± 0.02 GPa. An analysis of the flexural data reveals a significant enhancement in mechanical performance due to fiber reinforcement. The neat COPU resin, as expected, demonstrated poor flexural properties. However, the incorporation of luffa mats improved the flexural strength by a factor of 23, underscoring the efficacy of luffa as a reinforcing agent.

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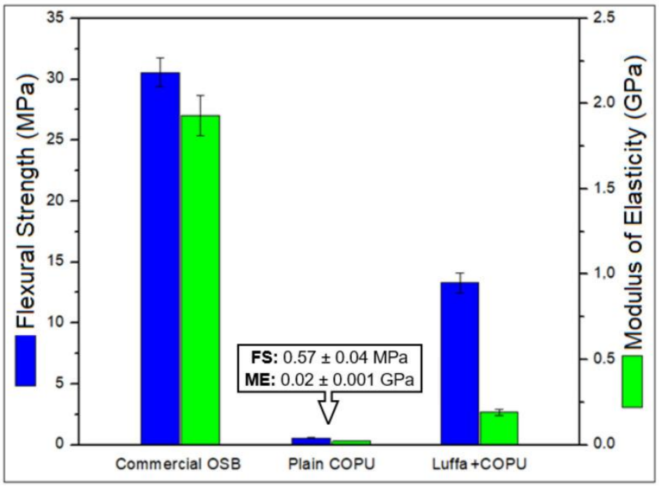

Figure 1. Flexural Strength

Despite this improvement, the luffa/COPU composite still demonstrated approximately 50% lower flexural strength than the commercial OSB reference. This outcome suggests that while the luffa/COPU system may not yet match the performance of OSB, it shows strong potential as an alternative reinforcement strategy in polymer-based composites, particularly in applications where moderate mechanical performance is acceptable or where sustainability is prioritized.

By using epoxy as a matrix, the flexural strength (FS) of luffa fiber composites can range from approximately 20 MPa to about 55 MPa depending on variables such as fiber volume, surface treatment, and processing methods. Mohanta and Acharya reported that the FS of epoxy composites could increase by nearly 60% with the incorporation of just two luffa layers, while the modulus of elasticity (ME) could improve by up to 40% compared to neat resin. Further enhancement was achieved through surface modification: in another study by the same authors, benzoyl-treated luffa fibers increased the FS of the epoxy composite by over 50 MPa—nearly 70% higher than that of composites reinforced with untreated fibers. A similar increase was observed in the ME, which improved from 2 GPa to 3.5 GPa.

These findings underscore the strong potential of luffa as a reinforcement in polymer matrix composites. Unlike synthetic woven fabrics, luffa mats consist of interlocked fibers naturally bonded at multiple points along their length, as illustrated in Figure 1. Several layers are interconnected, forming a thick, cohesive structure. To fully fracture the composite, both the resin matrix and the internal fiber mat connections must be disrupted. This structure provides a robust mechanical interlock, which is especially beneficial in composites with inherently weak fiber–matrix interfacial adhesion, such as the COPU-based system used in this work.

Natural lignocellulosic fiber (NLF)-reinforced composites are generally known to suffer from weak interfacial bonding due to the hydrophobic nature of the polymer matrix and the hydrophilic nature of the fibers. This issue has been reported for luffa/polyurethane systems, where the fiber–matrix interface and the effect of surface treatment on mechanical behavior were both documented.

In terms of potential applications, the flexural properties of the luffa/COPU composite suggest that it could be used as oriented strand board (OSB) for non-structural interior panels. According to the Brazilian standard NBR 14810, this composite meets the flexural property requirements (FS ≥ 13 MPa and ME ≥ 0.19 GPa) for internal, dry-use panels of 6–10 mm thickness. Likewise, the EN 300 standard specifies minimum FS and ME values of 11 MPa and 0.14 GPa, respectively, for Type 3 OSB panels (10 mm), which the composite also fulfills. Furthermore, per the ANSI A208.1 standard, the composite qualifies as a commercial-use MS category panel, which requires minimum FS and ME values of 12.5 MPa and 0.19 GPa, respectively.

3.2. Perpendicular to Surface Tensile Strength

The results of the perpendicular-to-surface tensile strength tests for each material are presented in Figure 2. It is evident from the data that the commercial OSB exhibited superior tensile strength compared to the luffa/COPU composite. This performance difference may be attributed to the characteristics of the adhesive used in the fabrication of the OSB, which likely provides better interfacial bonding than the COPU matrix employed in the composite studied in this work.

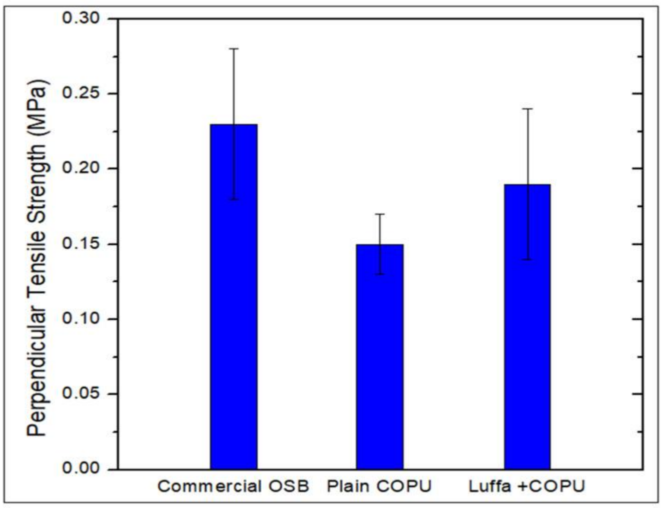

Figure 2. Perpendicular Tensile Strength

As shown in Figure 2, there was no statistically significant difference between the flexural performance of the novel luffa/COPU composite and that of the commercial OSB, despite a clear difference between the plain COPU resin and the commercial OSB. This was confirmed by an analysis of variance (ANOVA), which yielded a p-value greater than the significance threshold of 0.05 for the comparison between the composite and the OSB. These findings demonstrate that the incorporation of luffa mats significantly enhanced the mechanical performance of the plain resin. However, neither the luffa-reinforced COPU composite nor the commercial OSB met the minimum flexural strength and modulus of elasticity criteria established by any of the three referenced standards. The mechanical behavior observed in both the luffa/COPU composite and the plain resin is likely influenced by the inherently weak interfacial bonding between the hydrophobic polymer matrix and the hydrophilic luffa fibers. Nonetheless, the improved performance of the composite relative to the neat resin is attributed to the unique structure of the luffa mat. The interconnected fiber network within the luffa acts as a mechanical anchor for the matrix. This structural interlinking likely contributes to the superior mechanical response observed in the composite.

4. Conclusion

The amount of luffa mat reinforcement possible to be incorporated into castor oil polyurethane (COPU) matrix composite, according to the manufacturing method adopted, was a mass fraction of 39.2%, corresponding to 48 vol% of fiber. It should be highlighted that there was a general increase in the mechanical behavior of the luffa mat-reinforced COPU matrix regardless of the weak interface between the two. Comparatively, the mechanical properties of the investigated composite were superior to those of both the COPU matrix and a commercial oriented strand board (OSB), except for flexural strength; however, it was still superior to what is required by the OSB standards. Furthermore, considering the other properties, especially the impact resistance, it is possible to assert that luffa mat acts as reinforcement for the COPU matrix.

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