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Microstructural Evolution and Property Enhancement of Teak (*Tectona grandis*) Wood Dust Reinforced Polymer Composites for Automotive Applications

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The increasing demand for lightweight and sustainable materials in the automotive sector has intensified research on hybrid natural-synthetic fiber composites. In this study, teak wood dust was explored as an eco-friendly particulate reinforcement for glass fiber/epoxy laminates to enhance structural performance while reducing material cost and environmental impact. The objective was to evaluate how different teak dust loadings (3, 6, and 12 wt.%) influence the mechanical, morphological, and water-resistance characteristics of the resulting hybrid composites. Composite laminates were fabricated using the hand lay-up process, where teak dust was dispersed in an epoxy matrix (10:1 resin-hardener ratio) and sandwiched between glass fabric layers. Specimens were prepared according to ASTM standards and subjected to tensile, flexural, impact, and water absorption tests. The 12 wt.% teak-reinforced composite exhibited the highest tensile strength (45.50 ± 5 MPa), flexural strength (116.24 ± 2 MPa), impact resistance (4.1 ± 1.5 J), and lowest water absorption (5.22 %), correlating strongly with improved matrix adhesion and uniform morphology. These results demonstrate that teak dust significantly enhances interfacial bonding and mechanical reliability, making the 12 % hybrid composite a promising candidate for lightweight automotive components.

Keywords: teak wood dust, hybrid composite, mechanical properties, morphological analysis, automotive applications.

1. INTRODUCTION

The increasing demand for eco-efficient, lightweight, and high-performance structural materials has intensified research into hybrid fiber-reinforced polymer composites that integrate natural fillers with synthetic reinforcements. Such systems offer reduced density, improved specific strength, lower environmental impact, and superior multifunctionality compared to monolithic composites, making them attractive for automotive, aerospace, construction, and consumer applications [1, 2]. Recent studies have shown that lignocellulosic particulates such as teak wood dust, rice husk, and tamarind seed particles can act as effective secondary reinforcements by enhancing interfacial adhesion, stress transfer, and crack-bridging mechanisms within polymer matrices [3, 4]. Additionally, the valorization of agricultural and wood-processing residues aligns with circular bioeconomy principles and promotes sustainable composite development [5]. Significant progress has been made in the incorporation of natural fillers, nano-ceramic particles, carbon-based additives, and multifunctional hybrid reinforcements to tailor the mechanical, thermal, and morphological characteristics of epoxy- and polypropylene-based composites [6, 7]. Works involving teak dust, Acacia Mangium fiber, cellulose nanoparticles, nano-Al_2O_3, eggshell nanoparticles, and carbon–glass hybrid laminates have demonstrated enhancements in tensile strength, flexural rigidity, wear resistance, and impact energy absorption due to improved fiber-matrix compatibility and microstructural refinement [8, 9]. However, despite these advancements, interlaminar shear strength (ILSS) and delamination resistance remain critical limitations in laminated composites, particularly under transverse, cyclic, or multi-axial loading. Natural particulate fillers possess intrinsic advantages such as high cellulose content, micro-scale roughness, and favorable chemical functionality, which can enhance resin anchorage and mitigate interfacial debonding [10]. Yet, the optimal incorporation level and the influence of lignocellulosic fillers on interlaminar behavior remain insufficiently resolved. A comprehensive evaluation of hybrid laminates reinforced with Tectona grandis (teak) dust, an abundant wood-processing by-product has not been systematically reported, particularly regarding its influence on ILSS, matrix cohesion, and crack-arresting mechanisms in glass fiber-epoxy composites. Although previous research has demonstrated improvements in strength and stiffness with teak-derived fillers, studies rarely address synergistic effects across tensile, flexural, impact, hardness, and interlaminar performance within a unified experimental framework [11, 12]. Natural fibre-reinforced polymer composites are increasingly being used in the automotive industry due to the need for lightweight, sustainable and high-performance materials. The use of hybrid polymer composites instead of traditional metallic parts helps to

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reduce the vehicle weight, which in turn improves the fuel efficiency, greenhouse gas emission, and energy efficiency of electric vehicles. Due to their high specific strength, corrosion resistance, and ease of fabrication, glass fibre-reinforced epoxy composites are already widely used in automotive interior and semi-structural parts. The use of sustainable lignocellulosic fillers like teak wood dust (Tectona grandis) provides another chance to lower the material cost, boost environmental sustainability, and enhance selected mechanical and physical properties, while also utilizing wood-processing waste. Hence, the optimization of teak wood dust-reinforced glass fibre/epoxy hybrid composite could be used as an environment-friendly material for the door inner panel, dashboard substrate, parcel shelf, roof liner, luggage compartment panel, seat-back structure, battery enclosure cover, and interior floor panel of the automotive industry, where lightweight construction, dimensional stability, and adequate mechanical performance are required.

Furthermore, there is limited literature quantifying filler-level-dependent performance correlations, particularly at graded concentrations such as 3 %, 6 %, and 12 %, which are critical for establishing structure-property relationships and identifying optimal reinforcement thresholds. Therefore, this research aims to fill these knowledge gaps by developing and characterizing a novel glass fiber-epoxy hybrid laminate reinforced with controlled fractions of Tectona grandis dust. The study focuses on evaluating load-bearing properties, energy absorption behaviors, failure mechanisms, and ILSS following ASTM standards to elucidate the reinforcing contributions of teak particulates. This work provides new insights into the role of bio-derived fillers in advancing high-strength, low-density composite systems and establishes teak-reinforced hybrids as a promising sustainable alternative for structural and semi-structural applications.

2. MATERIALS AND METHODS

2.2. Selection of materials and their properties

The epoxy resin (bisphenol-A-based LY556) and amine hardener (HY951) were procured from a local industrial supplier and used as the polymer matrix owing to their high crosslinking efficiency, strong adhesive capability, and established compatibility with both lignocellulosic fillers and E-glass reinforcements [13]. Plain-weave E-glass fabric (0°/90°, 200 g/m²) was obtained from a certified composites textile vendor and incorporated at a constant 40 wt.% in all formulations to ensure uniform load-bearing capacity and structural rigidity comparable to conventional glass-epoxy laminates [14]. Teak (Tectona grandis) wood dust was sourced from a local sawmill, washed to remove surface contaminants, and sun-dried for 24 h, followed by oven-drying at 80 °C to minimize moisture content before mixing. The dried dust was passed through a sewing-machine mesh filter, producing a uniform particle size range of 100 μm, selected to promote homogeneous dispersion and reduce porosity during curing [15]. Teak (Tectona grandis) wood dust was used as the natural filler owing to its favorable lignocellulosic composition rich in cellulose, hemicellulose, lignin, and hydrophobic extractives. These constituents contribute to improved hardness, moderate density, fungal resistance, and potential stiffness enhancement when used in controlled proportions. The raw teak dust obtained from a local sawmill was washed thoroughly, sun-dried for 24 h, and subsequently oven-dried at 80 °C to minimize moisture-induced void formation during curing. Particle-size uniformity was ensured by sieving through a sewing-machine mesh filter, yielding a controlled size range of 150 µm, selected to promote homogeneous dispersion and reduce stress concentration sites within the matrix. Based on literature suggesting that low-to-moderate lignocellulosic filler content improves rigidity and matrix stability before agglomeration becomes detrimental, three filler loadings, 3 wt.%, 6 wt.%, and 12 wt.% teak wood dust, were adopted [16]. These three levels defined the three composite formulations investigated, enabling a systematic evaluation of filler-induced variations in mechanical behavior, interfacial bonding, and structural performance.

2.2. Fabrication method

The hybrid composite laminates were fabricated using a conventional hand lay-up process followed by compression under uniform load at ambient conditions. Before fabrication, the teak wood dust was oven-dried at 80 °C for 24 h and stored in airtight containers to ensure low moisture content and prevent premature resin incompatibility. A stainless-steel mold was cleaned, polished, and coated with a thin silicone-based release agent to facilitate smooth demolding. The epoxy matrix was prepared by mixing LY556 resin with HY951 hardener in a 10:1 stoichiometric ratio as recommended by the supplier. The teak dust, corresponding to 3 %, 6 %, and 12 wt.% loadings, was gradually incorporated into the resin-hardener blend and gently stirred to achieve uniform dispersion while minimizing air entrapment and preventing particle agglomeration. A thin resin film was initially applied to the mold surface, followed by placement of the bottom E-glass woven fabric and rolling to ensure complete fiber wet-out.

The teak dust-modified epoxy mixture was then uniformly spread over the impregnated fiber layer, after which the top E-glass fabric sheet was positioned to form a glass/wood-epoxy/glass hybrid laminate configuration. The assembled laminate was then compressed under a uniform static load to enhance consolidation, promote resin flow, and minimize void content. Curing was carried out at ambient temperature for 24 – 48 h, followed by an optional post-curing cycle at 60 – 80 °C to improve the cross-linking density and enhance mechanical stability. Upon curing, the laminates were demolded, trimmed, and machined into test specimens according to relevant ASTM standards for mechanical and physical property evaluation. For each composite formulation, five specimens were prepared for each test, and the final results were reported as the mean of five measurements to ensure statistical reliability and minimize experimental variability.

3. EXPERIMENTAL TESTING

The mechanical and physical performance of the three hybrid epoxy-glass-teak wood dust laminates (3, 6 and 12 wt.%) was evaluated through a comprehensive set of standardized tests following established ASTM guidelines to ensure inter-study reproducibility and methodological rigor [17]. All laminates were cut using a diamond-edge cutter to prevent thermal or mechanical edge damage, and for each formulation five replicate specimens were prepared to obtain statistically reliable mean values [18]. Tensile behaviour was assessed using an Instron 3369 universal testing machine (50 kN) in accordance with ASTM D3039, employing 250 × 25 mm specimens fitted with bonded end tabs to ensure uniform load transfer [19]. Flexural performance was measured via three-point bending following ASTM D790 using 125 × 13 mm samples with a 16:1 span-to-depth ratio, providing flexural strength and modulus from load–deflection curves [20]. Impact resistance was quantified using a Tinius Olsen IT504 pendulum impact tester following ASTM D256 with 65 × 13 mm unnotched specimens, enabling the evaluation of crack initiation resistance and energy absorption capability in hybrid laminates [21]. Interlaminar shear strength (ILSS), critical for assessing matrix-fiber-filler integrity was determined using ASTM D2344 short-beam testing on 20 × 6 mm specimens on the Instron machine at 1 mm/min, reflecting the laminate's resistance to delamination and the effectiveness of teak dust dispersion in the matrix [22]. Water absorption behaviour was evaluated using ASTM D570, where oven-dried specimens (76 × 25 mm) were immersed in distilled water and periodically weighed to estimate diffusion-controlled mass gain, a key indicator of hydrophilic filler-matrix interaction [23]. Composite density and void content were determined using ASTM D792 with a digital densitometer based on buoyancy principles, enabling comparison between experimental and theoretical densities computed through rule-of-mixtures [24]. Together, these protocols form a robust multimodal characterization framework commonly adopted in hybrid composite research [25, 26], allowing for a systematic comparison of mechanical efficiency, structural integrity, and durability across varying teak dust loadings. For each composition, five specimens were tested under identical conditions. The reported values represent the arithmetic mean ± standard deviation (SD).

4. RESULTS AND DISCUSSION

4.1. Tensile strength

The tensile strength of the fabricated hybrid composites was greatly affected by the teak wood dust content as depicted in Fig. 1. The composite with 3 wt.% teak wood dust had a tensile strength of 32.80 ± 2.45 MPa and the composite with 6 wt.% teak wood dust had a slight decrease to 36.87 ± 2.38 MPa. The composite with 12 wt.%, on the other hand, had the highest tensile strength of 45.50 ± 2.72 MPa, which is about 41.7 % and 55.6 % higher than the 3 wt.% and 6 wt.% composites, respectively. Based on the results, it can be concluded that the hybrid laminate with 12 wt.% teak wood dust is the most effective reinforcement to enhance the tensile load-bearing capacity of the hybrid laminate. The enhanced tensile performance is believed to be due to the effective contribution of teak wood dust to resist the axial loading. The stiffening effect of the rigid, lignocellulosic particles and the uniform distribution of tensile stresses throughout the laminate were observed. At the same time, the woven E-glass fabric was the major load-bearing reinforcement and the teak particles prevented local deformation of the matrix, which delayed the initiation of cracks and enhanced the ultimate tensile strength.

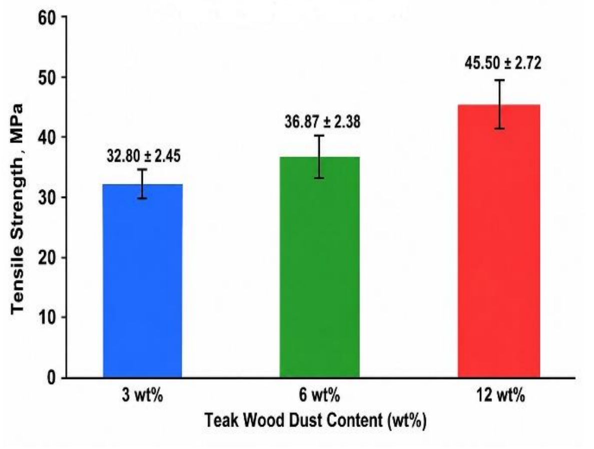


Fig. 1. Tensile strength of Teak (*Tectona grandis*) wood dust-reinforced hybrid composites

4.2. Flexural strength

The flexural strength of the fabricated hybrid composites was found to vary with the teak wood dust content, as shown in Fig. 2. The flexural strength of the composite with 3 wt.% teak wood dust was 85.40 ± 1 MPa, while the composite with 6 wt.% teak wood dust was 95.20 ± 4 MPa. The composite reinforced with 12 wt.% teak wood dust, however, had the highest flexural strength of 116.24 ± 2 MPa, which is about 22.4 % and 32.2 % higher than the 3 wt.% and 6 wt% composites, respectively. The results showed that the 12 wt % formulation had the highest resistance to bending deformation of the composites studied. Flexural loading causes the upper surface of the laminate to be under compression and the lower surface under tension, so the integrity of the fiber–matrix interface and the rigidity of the composite core are critical to resisting crack initiation.

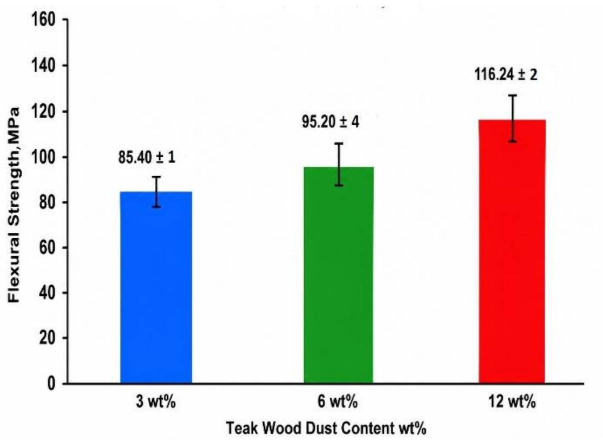


Fig. 2. Flexural strength of hybrid composite

The flexural strength of the 12 wt.% composite is higher than that of the other composites, indicating that the teak wood dust has improved the stiffness of the epoxy matrix, which allowed for more uniform stress distribution between the matrix and the woven E-glass reinforcement. The stiff lignocellulosic particles limited the local matrix deformation and enhanced resistance to crack initiation and propagation in bending. This behaviour is confirmed by the SEM observations fractured surface exhibited a relatively uniform distribution of teak wood dust within the epoxy matrix, together with good resin impregnation around the glass fibres. The fibres were well bonded to the matrix and only minimal debonding at the interface and fibre pull-out were seen, suggesting good load transfer during flexural loading. Additionally, the well-dispersed teak particles helped to deflect cracks and extend the fracture path, thereby delaying catastrophic failure and enhancing the energy needed to propagate the crack.

4.3. Impact strength

The impact strength of the hybrid glass fiber/epoxy composites increased progressively with increasing teak wood dust content, as illustrated in Fig. 3. The composite reinforced with 3 wt.% teak wood dust exhibited an impact strength of 2.30 ± 1.2 J, while the 6 wt.% formulation showed a moderate increase to 3.20 ± 1.0 J. The highest impact resistance was obtained for the 12 wt.% composite, which recorded 4.1 ± 1.5 J, corresponding to improvements of approximately 32.3 % and 13.9 % compared with the 3 wt.% and 6 wt.% composites, respectively. These results indicate that increasing the teak wood dust content enhanced the ability of the hybrid laminate to absorb impact energy before fracture. Unlike tensile and flexural loading, impact loading involves rapid crack initiation and propagation under dynamic conditions. The improved impact resistance observed for the 12 wt.% composite suggests that the dispersed teak wood dust particles effectively interrupted crack propagation by promoting multiple energy-dissipation mechanisms during fracture.

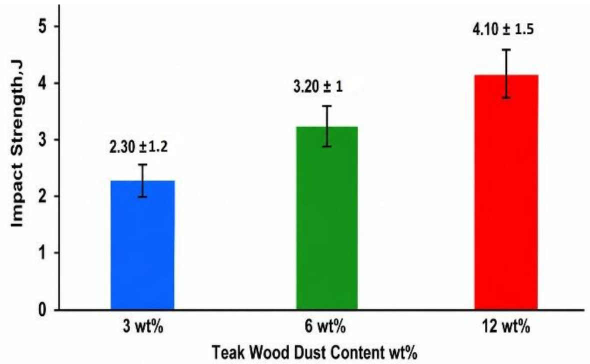


Fig. 3. Impact strength of Teak (*Tectona grandis*) wood dust-reinforced hybrid composites

The rigid lignocellulosic particles acted as crack deflection sites, forcing advancing cracks to change direction and increasing the fracture path. Simultaneously, the woven E-glass reinforcement contributed to fibre bridging, thereby delaying complete crack propagation and increasing the energy required for catastrophic failure. The fracture morphology observed and confirms these mechanisms. SEM examination revealed good integration of teak particles within the epoxy matrix and strong matrix encapsulation around the glass fibres. The fractured surface exhibited evidence of crack branching, localized matrix deformation, and limited fibre pull-out, indicating that fracture occurred through progressive energy absorption rather than rapid brittle failure. Furthermore, the relatively uniform particle distribution reduced localized stress concentration, allowing the impact load to be distributed more effectively throughout the laminate.

4.4. Interlaminar shear strength (ILSS)

The interlaminar shear strength (ILSS) of the hybrid glass fibre-epoxy composites was greatly affected by the teak wood dust content, as shown in Fig. 4. The composite with 3 wt.% teak wood dust had an ILSS of 21.02 ± 2 N/mm² while the composite with 6 wt.% teak wood dust had an ILSS of 15.29 ± 2 N/mm². The highest value of ILSS was obtained for the 12 wt.% composite with a value of 25.00 ± 3 N/mm², which is about 19.0 % and 63.5 % higher than the 3 wt.% and 6 wt.% composites, respectively.

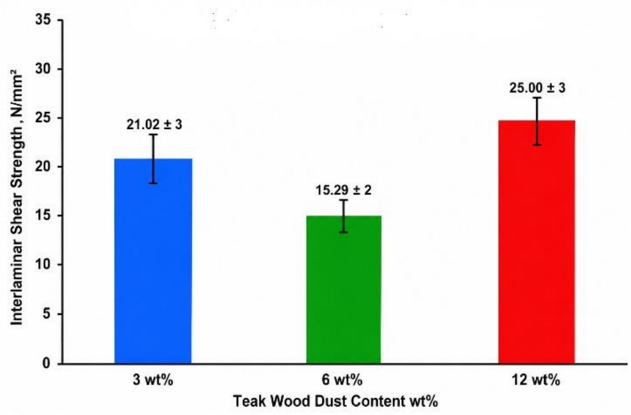


Fig. 4. Interlaminar shear strength of hybrid composites

The results show that the 12 wt.% teak wood dust reinforcement gave the best resistance to interlaminar shear failure of the laminates studied. The ability of adjacent laminate layers to withstand separation under through-thickness loading is the factor that controls interlaminar shear strength. The enhanced ILSS of the 12 wt.% composite suggests that the teak wood dust was an effective reinforcement of the interlayer region containing epoxy, which enhanced resistance to propagation of interfacial cracks and delamination. The dispersed lignocellulosic particles increased the rigidity of the matrix layer between the woven glass fabrics, which allowed for more uniform distribution of shear stresses throughout the laminate thickness and delayed the onset of interlaminar failure during short-beam loading. The fractured surface showed good resin continuity around the teak particles and satisfactory impregnation of the woven glass fibres, leaving only limited microvoids, and a compact laminate structure. The matrix continuity was good, which helped to slow down the propagation of cracks along the fibre–matrix interface, and the presence of the teak particles embedded in the matrix provided resistance to delamination by increasing the fracture path during shear loading. In addition, the low fibre pull-out and cohesive matrix fracture suggest that failure was mostly within the matrix, further supporting the enhanced structural integrity of the hybrid laminate. The improvement in interlaminar properties of laminated composites with 12 wt.% teak wood dust is especially useful for automotive structural and semi-structural parts which are subjected to complex bending, vibration and impact loads during service. The developed hybrid composite is a promising sustainable material for next-generation automotive applications, as it improves resistance to delamination, which increases the reliability of the structure and extends the service life of lightweight components like door inner panels, roof liners, parcel shelves, seat-back structures, luggage compartment panels, battery enclosure covers, interior floor panels, and underbody protective panels.

4.5. Water absorption

The water absorption behaviour of the fabricated hybrid composites after 35 days of immersion is shown in Fig. 5. The moisture uptake was found to decrease with the increase of teak wood dust content. The composite with 3 wt.% teak wood dust had the highest water absorption of 9.00 %, followed by the composite with 6 wt.% teak wood dust (6.00 %), and the lowest water absorption was recorded for the composite with 12 wt.% teak wood dust (5.22 %). Absorption curves for all compositions exhibited a steep rise in the first 7 – 14 days, then a gradual rise until equilibrium was reached at around 28 – 35 days. This behaviour is typical of moisture transport in polymer composites, where the first phase is controlled by capillary diffusion in accessible pores until saturation is reached. The lower moisture uptake of the 12 wt.% composite suggests that the composite structure was more compact and prevented the water from penetrating the composite.

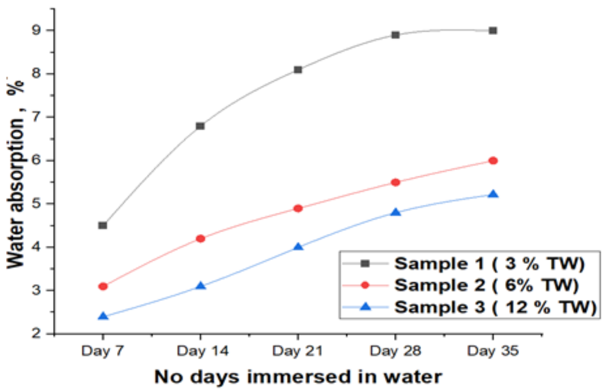
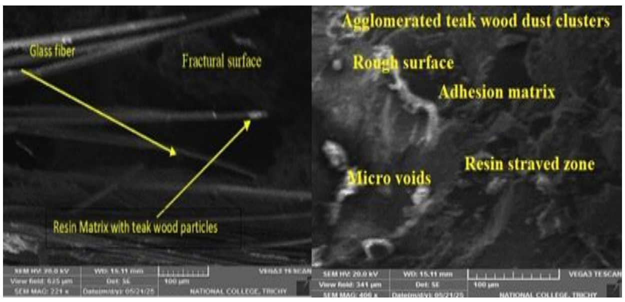


Fig. 5. Water absorption characteristics of teak wood dust composites

The higher teak wood dust content resulted in better packing of teak wood in the epoxy matrix, which led to the reduction of interconnected microvoids and the limitation of the continuous diffusion pathway. Furthermore, the natural extractives, waxes and lignin in Tectona grandis have relatively hydrophobic properties, which reduce the attraction of the reinforcement to water molecules. Thus, the hybrid composite showed good moisture resistance despite the moisture-absorbing properties of the lignocellulosic filler. The enhanced moisture resistance exhibited by the 12 wt.% hybrid composite is beneficial for applications where moisture or fluctuating environmental conditions are present. Reduced water absorption leads to improved dimensional stability, mechanical property retention over extended service life and durability. The developed hybrid composite is suitable for use in lightweight parts of the interior of the car, such as door trim panels, roof liners, dashboard substrates, luggage compartment panels, seat-back structures, and interior flooring, where moisture resistance and long-term structural reliability are critical

4.6. Microstructural analysis

The microstructural observations shown in Fig. 6 further support the tensile behaviour (Fig. 1). The SEM examination of the fractured composite showed intimate contact between the epoxy matrix, teak wood dust particles and glass fibres over most of the fracture surface, which means that the bonding between the epoxy and the wood dust and glass fibres is satisfactory. The rough surface morphology of the teak particles allowed mechanical interlocking with the surrounding epoxy and the embedded particles acted as obstacles to crack propagation, which increased the fracture path and delayed catastrophic failure. Some clusters of particles and small areas of resin deficiency were found, but they did not have a significant influence on the fracture process and the overall reinforcing effect was still better for the 12 wt.% composite. In addition, the fractured surface of the specimens showed limited fibre pull-out and matrix cracking, indicating that the failure of the hybrid laminate was after the effective stress transfer between the fibre and matrix, which further confirmed that the structural integrity of the hybrid laminate was improved. The results suggest that optimizing biofiller content is crucial for achieving improved load-bearing capacity, and the 12 wt.% formulation demonstrates promising potential for applications requiring enhanced tensile performance, particularly in semi-structural and lightweight engineering components.



a b

Fig. 6. Morphological characteristics of 12 % Teak wood dust hybrid composite

The scanning electron microscopy (SEM) analysis of the fracture surface of the 12 wt.% teak wood dust reinforced hybrid composite (Fig. 6 a and b) is in accordance with the superior mechanical performance observed during tensile, flexural, impact, and interlaminar shear testing. The fractured surface shows relatively uniform distribution of teak wood dust particles in the epoxy matrix and good impregnation of the E-glass fabric, which confirms the good consolidation of the composite during the hand lay-up process. No significant particle segregation or large resin-rich areas were found, indicating that the processing parameters used were adequate for good dispersion of the filler in the laminate. Fig. 6 a shows that the teak wood dust particles are well embedded in the cured epoxy matrix and there are only small gaps between the particles and the surrounding resin. The surface morphology of the lignocellulosic teak particles is irregular which enhances the mechanical interlocking with the epoxy matrix and better stress transfer during external loading. The fractured surface also shows that there was no significant debonding of particles, but rather matrix deformation around the particles, suggesting that the applied tensile load was well transferred through the filler–matrix interface before fracture. This microstructural feature is consistent with the highest tensile strength that was achieved for the 12 wt.% composite.

The area with high fiber content (Fig. 7 b) indicates good wetting of the woven e-glass fibers by the epoxy matrix, and good adhesion between the reinforcement and surrounding polymer. After fracture, most of the fibers are still embedded in the matrix and only a small amount of fiber pull-out is seen. This means that the propagation of cracks involved not only debonding of the fibers from the matrix but also cracking of the matrix, which means that more energy was needed for failure. The continuous resin layer around the glass fibers further indicates that the impregnation is good and this is responsible for the highest ILSS value obtained for this composition. At higher magnifications, several crack arresting mechanisms are also seen, which helped to achieve the better mechanical response. Microcracks were locally deflected around the teak particles, and crack branching and particle bridging increased the fracture path length before complete failure. These mechanisms decrease the stress concentration and slow down the propagation of cracks under tensile, flexural and impact loading. In addition, the rigid teak particles and woven glass fibers gave a synergistic reinforcing effect, which enabled the applied load to be distributed more evenly throughout the laminate and thereby prevented localized failure. A few isolated microvoids were seen, but the number of these microvoids was very small and did not significantly affect the overall fracture behaviour. The low void content and uniform distribution of teak particles is responsible for the lower water absorption obtained for the 12 wt.% composite, which reduces the diffusion path of water in the matrix.

5. CONCLUSIONS

The hand lay-up technique was used to successfully produce hybrid glass fibre/epoxy composites with Tectona grandis (teak wood dust) as reinforcement material and the mechanical, physical and microstructural properties were systematically investigated. Based on the experimental results, the following conclusions can be drawn:

1. The performance of the hybrid composites was greatly affected by the addition of teak wood dust. The overall performance of the investigated formulations was compared, and the composite with 12 wt.% teak wood dust showed the best overall performance, which is the optimum reinforcement efficiency and laminate integrity.
2. The highest composite tensile strength was 45.50 ± 5 MPa, flexural strength was 116.24 ± 2 MPa, impact strength was 4.10 ± 1.5 J and interlaminar shear strength was 25.00 ± 3 N/mm², which showed significant improvement in load-bearing capacity, bending resistance, impact energy absorption and interlaminar bonding compared to the lower filler loadings.
3. The water absorption of the composites reduced gradually with the increase of teak wood dust content, and the composite with 12 wt.% teak wood dust showed the lowest water absorption of 5.22 % after 35 days of immersion, which indicated that the composite had better dimensional stability and higher resistance to moisture diffusion when it was exposed to the environment for a long time.
4. The SEM analysis showed that the teak wood dust was relatively evenly distributed in the epoxy matrix and that the woven E-glass fibres were well impregnated. The small size of the microstructure, the low amount of microvoids, the good matrix continuity and the good fibre encapsulation led to better crack resistance, delayed delamination and better mechanical performance.
5. The experimental and microstructural results show that teak wood dust is a good and eco-friendly bio-reinforcement for glass fibre-epoxy hybrid composites. The developed material provides a good balance of mechanical strength, moisture resistance and lightweight properties, which are suitable for use in automotive interior and semi-structural parts such as door inner panels, roof liners, parcel shelves, seat-back structures, luggage compartment panels, dashboard substrates and battery enclosure covers, where reduced weight and improved durability are desired.
6. Surface modification of teak wood dust to further improve fibre–matrix compatibility, optimization of filler particle size and loading, study of fatigue, creep, thermal stability, wear behaviour and fire resistance, and long-term environmental durability under hygrothermal and UV aging conditions are suggested for future research. Further, the potential of advanced manufacturing processes like vacuum-assisted resin infusion or compression moulding should be investigated to reduce void content and to scale up the use of these sustainable hybrid composites for industrial automotive and lightweight engineering applications.

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