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RESEARCH

Study on the Mechanical, Morphological and Wear Rate of Jute Cellulose-Reinforced Composites

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A B S T R A C T

The increasing global demand for polymer-based materials has accelerated the pursuit of sustainable and biodegradable reinforcements to enhance composite performance. In this study, cellulose was derived from jute fiber through acid hydrolysis, chlorination, alkaline extraction and bleaching. Epoxy-based composites were fabricated via the hand layup technique by incorporating varying weight fractions (5wt%, 10wt% 15wt% and 20wt%) of jute cellulose into the epoxy matrix. The mechanical performance of the fabricated composites, including tensile strength, flexural strength and hardness was evaluated in accordance with ASTM standards, along with dry sliding wear performance under abrasive conditions. Among the tested compositions, the composite containing 15wt% jute cellulose (15J) exhibited the highest mechanical performance, achieving a tensile strength of 22.30MPa, flexural strength of 65.23MPa and surface hardness of 90. Notably, it also exhibited the lowest wear rate, showing a 43.75% improvement in wear resistance compared to neat epoxy. This enhancement is attributed to improved cellulose fibril–matrix interfacial bonding and uniform dispersion. SEM analysis confirmed microstructural integrity and identified typical failure modes such as fibril pull-out and micro-voids. The results establish 15wt% jute cellulose as an effective reinforcement for developing cost-effective, biodegradable composites suited for structural and automotive applications.

1. INTRODUCTION

Natural fibres have garnered significant attention in recent years as reinforcing agents in polymer composites, primarily due to their environmental advantages, widespread availability and notable mechanical characteristics. These fibres are biodegradable, renewable and ecologically sustainable, making them ideal candidates for use in green materials and environmentally friendly structural applications [1-2]. Among their many advantages, natural fibres offer benefits such as low density, cost-effectiveness and the potential to enhance specific mechanical properties like tensile strength and stiffness when integrated into composite matrices. Despite their relatively

lower modulus of elasticity and specific strength compared to synthetic fibres, natural fibres can be employed in substantial quantities to partially replace synthetic reinforcements in composite fabrication [3]. This substitution not only reduces environmental impact but also decreases the overall production cost. Commonly used natural fibres in thermoplastic and thermoset matrix composites include hemp, flax, coir (coconut fibre), sisal and jute [3-5]. Among these, jute stands out as an economical and widely available lignocellulosic fibre. The chemical composition of jute typically includes cellulose (51–84%), hemicellulose (12–20%), lignin (5–13%), along with minor constituents such as pectin (0.2%) and wax (0.2%) [6].

Cellulose, the principal structural constituent of plant-based fibers, contributes significantly to their mechanical stability, rigidity, and stiffness [7]. Natural fibers exhibit a heterogeneous architecture composed of both crystalline and amorphous domains. The crystalline regions, defined by densely packed hydroxyl groups, are largely inert due to their limited accessibility, thus restricting their chemical reactivity. Conversely, the amorphous regions predominantly comprising hemicellulose and lignin contain loosely bound hydroxyl groups, which readily engage in interactions with polar substances, including water molecules [7-8]. This intrinsic polarity renders natural fibers inherently hydrophilic, posing a notable challenge when fabricating composites with hydrophobic polymer matrices [9]. Cellulose, as a naturally abundant and renewable biopolymer, has garnered substantial interest owing to its biodegradability, low environmental impact and cost efficiency. These attributes position it as a sustainable alternative to conventional synthetic materials, particularly in applications that prioritize ecological considerations and minimal chemical processing [7-10]. Its versatility has been demonstrated across a wide spectrum of industries such as textiles, packaging, food preservation, wastewater treatment, biomedicine, and cosmetics [7-11]. With the growing emphasis on sustainable materials, recent developments in polymer science have focused on the integration of cellulose into high-performance polymeric systems, underscoring its multi functionality and environmental compatibility [12]. Epoxy resins are widely utilized in industrial applications including adhesives, automotive components, aerospace structures, wind turbine blades and civil infrastructure, due to their superior adhesion properties and compatibility with various curing mechanisms. They also exhibit excellent thermal, mechanical, electrical and chemical performance. However, the inherent brittleness of epoxy systems resulting from their densely cross-linked molecular networks limits their crack resistance and hampers ductile behavior, often leading to subpar mechanical properties under stress [13-14]. Incorporating cellulose fibers into epoxy matrices has been shown to enhance their mechanical performance, particularly in terms of strength and stiffness [13]. The presence of higher cellulose content contributes to improved load-bearing capacity, rendering these composites suitable for automotive applications, including both exterior panels and interior components and biomedical applications [8,15]. A study reported that the incorporation of 0.75% cellulose natural fibers (CNFs) into epoxy composites yielded optimal enhancement in mechanical properties, as confirmed by scanning electron microscopy (SEM) analysis [16].

The tribological performance of polymer composites has been extensively studied by varying key parameters such as applied load, sliding speed and sliding distance. Neat epoxy composites exhibit the poor abrasion wear resistance and incorporating natural fibers into polymer matrices has been found to significantly enhance their resistance to abrasive wear [17]. This enhancement is primarily attributed to the reinforcing effect of the fibers, which act as a barrier against mechanical degradation during sliding, thereby minimizing material removal and improving wear longevity [18]. In particular, jute fiber-reinforced polyester composites exhibit a higher coefficient of friction with increased fiber content, while concurrently displaying lower wear rates. However, under higher loading conditions, both neat polypropylene/epoxy and its jute fiber-reinforced counterpart's exhibit increased specific wear rates [17-19]. Another study reported that the Additionally, at greater sliding speeds, the wear resistance of jute/PP composites declines due to crack development and fiber–matrix separation [20]. Previous studies have reported that cellulose-based nanostructured films, especially those combining nanofibrillated cellulose (NFC) with microcrystalline cellulose (MCC), demonstrate favorable tribological performance by offering

higher wear resistance and lower friction. Incorporating MCC into NFC films plays a significant role in tailoring their tribological response, where an increase in MCC content tends to reduce the wear rate. Owing to these characteristics, such films hold strong potential as wear-resistant surface coatings in diverse engineering applications [20–22].

Although considerable research has been conducted on cellulose-based polymer composites, limited literature is available on studies specifically involving jute cellulose extracted through conventional chemical methods such as acid hydrolysis, chlorination, alkaline treatment, and bleaching.

This study aims to develop sustainable epoxy composites reinforced with varying weight fractions of jute cellulose. The mechanical properties, including tensile strength, flexural strength and hardness, were evaluated in accordance with ASTM standards. Additionally, the dry sliding wear performance of the composites was investigated to assess their tribological behavior under abrasive conditions. Fractured surfaces were analysed using SEM to study reinforcement–matrix interaction and fracture behaviour. The research highlights the potential of jute cellulose as a green reinforcement and establishes correlations between reinforcement structure and composite performance, supporting the development of eco-friendly materials for engineering applications.

2. MATERIALS AND METHODS

2.1 Raw material

In the present research, jute fiber was sourced from Vruksha Composites, Tenali, India and utilized as the primary reinforcement in the composite fabrication. The matrix system comprised epoxy resin (LY556) and hardener (HY951), both procured from Sri Polymers Pvt. Ltd., Hyderabad, India. These materials were essential for forming a stable and durable polymer matrix. The epoxy and hardener were mixed in a standard weight ratio of 10:1, ensuring optimal curing and composite integrity. This carefully prepared mixture served as the foundation for the development of Jute-cellulose based epoxy composites in this investigation.

2.2 Synthesis of jute cellulose

Cellulose was extracted from jute fibers following a methodology adapted from Moran et al. [23]. The raw fibers were first thoroughly washed with distilled water to remove surface impurities and then cut into small segments approximately 5–10 mm in length to facilitate subsequent chemical treatment. The fibers are subjected to dewaxing process in which the fibers are boiled in toluene for 6 hours, followed by ethanol washing. The fibers are then treated with 0.1M NaOH in 50% ethanol under continuous stirring for 3 hours to make it hemicellulose and lignin free. Subsequently, the fibers are subjected to oxidative bleaching using hydrogen peroxide (H_2O_2) at concentrations of 0.1%, 1%, 2% and 3%, with continuous agitation. This mixture was further stirred for 15 hours in the presence of NaOH and sodium tetraborate decahydrate ($Na_2B_4O_7{\cdot}10H_2O$). The final purification step involved treatment with 70% nitric acid (HNO_3). The resulting cellulose was washed with ethanol and distilled water, then oven-dried at 60 °C to remove moisture. This consistent protocol was followed to obtain high-purity cellulose from jute fibers for composite fabrication.

2.3 Fabrication of jute cellulose composites

In this research work, the density of jute cellulose was measured using a pycnometer, yielding a value of 1.136 g/cm^3. The fabrication of composite materials was carried out using the hand lay-up method in compliance with ASTM standards. Molds were carefully prepared for evaluating tensile, flexural strengths and wear rate. Matrix phase is prepared by thoroughly mixing epoxy resin and hardener in a 10:1 weight ratio using a mechanical stirrer to ensure homogeneity. Jute cellulose was added to this mixture based on predetermined volume fractions. Care was taken during the mixing process to eliminate air entrapment, as the presence of bubbles could adversely affect the composite's mechanical performance. Once a uniform mixture was achieved, it was poured into the molds and evenly spread. The samples were left to cure at room temperature for 24 hours, after which the solidified composites were demolded with care. This process was repeated to develop various jute cellulose-based composites. The test specimens used for

mechanical testing and wear test are illustrated in Fig.1 (a) & (b) and Fig. 2, while the corresponding sample notations and composite compositions are detailed in Table 1.

Fig. 1. (a) Tensile test specimens as per ASTM D638, (b) flexural test specimens as per ASTM D790.

Fig. 2. Wear test specimen.

Table 1. Different jute cellulose compositions and sample names used in experiment.

S.No	Composition	Sample Notations
1	5wt% Jute cellulose + 95wt% Epoxy	5J
2	10wt% Jute cellulose + 90wt% Epoxy	10J
3	15wt% Jute cellulose + 85wt% Epoxy	15J
4	20wt% Jute cellulose + 80wt% Epoxy	20J

3. CHARACTERIZATION OF JUTE CELLULOSE COMPOSITES/TEST SETUP:

3.1 Mechanical characterization

Tensile strength test was conducted on cellulose composite specimens with a dog-bone shape, in accordance with ASTM D638 standards. The specimens had an overall length of 165mm, a center width of 12mm and an average thickness of 3mm, as shown in Fig.1 (a). Testing was performed using a Perceivestar Digital Universal Testing Machine (UTM) supplied by AE Engineers, India, equipped with a 3kN load cell. The crosshead speed was set to 2 mm/min and testing continued until specimen fracture. Flexural strength was evaluated using a three-point bending test, following ASTM D790 standards as shown in Fig.1 (b). These tests were conducted on the same UTM under identical speed settings. The flexural test specimens had dimensions of 125mm in length, 12.7mm in width and an average thickness of 3mm. For both tensile and flexural tests, five samples were tested for each composition of composite and average values were recorded. Furthermore, Shore 'D' hardness testing was conducted to assess the surface hardness of the composite materials, providing additional insight into their mechanical performance. The combined results provide a comprehensive understanding of the mechanical behavior of the four different cellulose composite compositions. Fig. 1 (a) &(b) illustrates the prepared specimens of tensile and flexural specimens as per ASTM standards.

3.2 Scanning electron microscopy (SEM)

The fracture surfaces of the samples were meticulously investigated utilizing a scanning electron microscope (Nova Nano SEM 450) operating at an accelerating voltage of 15 kV. SEM was employed to investigate the fractured surfaces of the tensile specimens to gain insights into the microstructural characteristics and failure mechanisms of the composite materials. The analysis focused on the surface topography and fracture patterns, providing valuable information regarding the material's behavior under stress. SEM enabled a detailed evaluation of void formation, cellulose fibrils pull-out and matrix cracking, contributing to a deeper understanding of the relationship between microstructural features and the mechanical performance of the material.

3.3 Wear rate

Abrasive wear tests were performed using a pin-on-disc apparatus following ASTM G99 standards. Jute cellulose composite samples, each measuring 8 mm in diameter and 30 mm in

length as illustrated in Fig. 2, were evaluated for abrasive wear behavior using P400-grade silicon carbide abrasive paper mounted on a rotating steel disc. Each specimen was tested on a fresh track at a constant sliding distance of 33.93 m, speed of 180 rpm, duration of 3 minutes and sliding velocity of 0.188 m/s. Five specimens per composition were tested under loads of 10 N, 20 N and 30 N. The specimens were weighed before and after testing using a precision electronic balance with an accuracy of ±0.0001 g. The wear rate was computed based on mass loss (Δw, in grams), sliding distance (S_d, in cm) and the known theoretical density of each composite (ρ_c, in g/cm^3), formulation. The wear rate was calculated using the formula:

$$\text{Wear rate (W)} = \frac{\Delta w}{\rho_c \times S_d} \text{ cm}^3/\text{m} \quad (1)$$

4. RESULTS AND DISCUSSIONS

4.1 Tensile strength

The tensile behavior of the composites was evaluated to determine their load-bearing capacity. Fig. 3 presents the tensile strength of neat epoxy compared with that of jute cellulose–reinforced epoxy composites. It is evident that the incorporation of cellulose resulted in higher tensile strength values than neat epoxy for all reinforced samples. The presence of cellulose not only enhanced the strength but also improved the brittle nature of the unmodified epoxy. Neat epoxy, being inherently brittle, exhibited limited resistance under tensile loading; however, the addition of well-dispersed cellulose fibrils facilitated efficient stress transfer within the matrix, reduced brittleness, and contributed to improved toughness and overall strength. According to Fig. 3, the neat epoxy (0J) recorded a tensile strength of 16.5 MPa. As the cellulose content increased from 5J to 15J, the tensile strength showed a progressive rise, while further addition beyond this level resulted in a decline. The highest strength was obtained at 15J, where the composite reached 22.3 MPa, an improvement of about 35% compared to neat epoxy. This enhancement is mainly associated with uniform cellulose dispersion, strong matrix–cellulose fibril adhesion and effective stress transfer, which together provided better load distribution and resistance to crack growth [24–26]. Microstructural evidence (Fig. 6) also confirms enhanced cellulose fibril–matrix interlocking at this composition. Conversely, an increase in cellulose loading to 20J resulted in a decrease in tensile strength to 15.85 MPa, a value slightly below that of the neat epoxy. This reduction is primarily attributed to several factors: cellulose fibril agglomeration, inadequate wetting of the cellulose by the epoxy matrix and the formation of voids (as shown in Fig. 7). These issues collectively weakened the interfacial bonding and compromised the overall structural integrity of the composite [27,28].

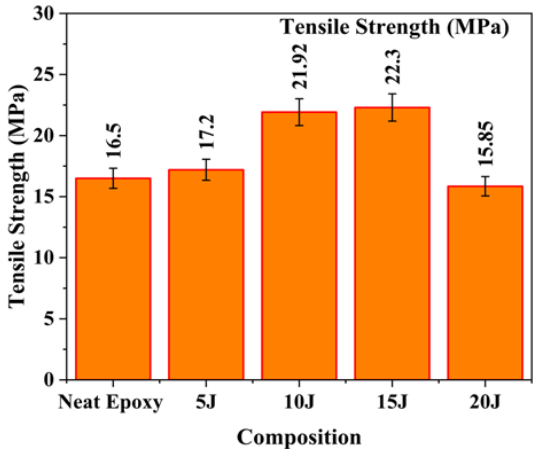

Fig. 3. Tensile strength of Jute cellulose composites.

4.2 Flexural strength

The ability of a composite material to withstand bending stresses was evaluated using a flexural test. The obtained results are illustrated in Fig. 4, which shows the variation of flexural strength for jute cellulose–reinforced epoxy composites in comparison with neat epoxy. It was observed that the incorporation of jute cellulose markedly enhanced the flexural performance of the composites. This improvement can be linked to several important factors. The presence of cellulose increased the wettability of the reinforcement within the epoxy resin, leading to stronger interfacial adhesion. In addition, the uniform distribution of cellulose particles within the matrix and the effective penetration of resin into the fibrous structure minimized weak zones, thereby enhancing stress transfer efficiency. As a result, the composites displayed superior resistance to bending loads compared to the unreinforced epoxy [28]. Fig. 4 shows that the neat epoxy (0J) displayed a flexural strength

of 41 MPa. With the incorporation of jute cellulose, the flexural strength progressively increased and reached its peak value of 65.23 MPa at the 15J composition, representing an improvement of about 34% compared to the neat epoxy. This enhancement can be attributed to effective stress transfer from the epoxy matrix to the cellulose particles, uniform load distribution, and strong interfacial adhesion between the filler and the resin [24,29]. However, when the filler loading was further increased to 20J, the epoxy matrix became insufficient to bond all cellulose surfaces, reducing stress transfer efficiency. Additionally, the cellulose fibrils tended to cluster together, creating agglomerated regions that acted as crack initiation sites under flexural stress. As a result, the flexural strength decreased to 38.43 MPa, which is slightly lower than that of the neat epoxy. This decline is primarily associated with poor particle dispersion, increased porosity, reduced wettability and weaker interfacial bonding, all of which hinder uniform stress transfer [24–30].

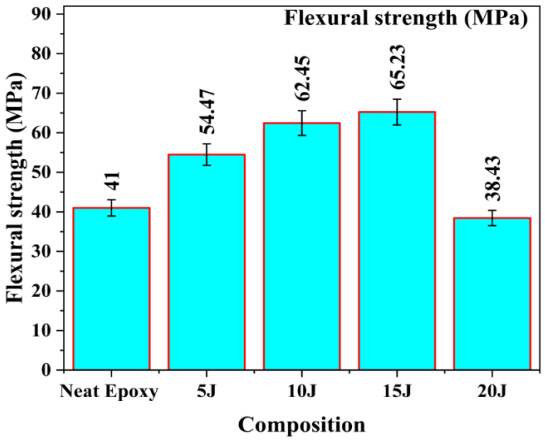

Fig. 4. Flexural strength of Jute cellulose composites.

4.3 Hardness

The hardness behavior of jute cellulose–reinforced epoxy composites was evaluated using a Shore 'D' hardness tester, and the results are shown in Fig. 5. The neat epoxy recorded a baseline hardness value of 80. With the incorporation of jute cellulose, the hardness progressively increased up to the 15J composition, where the maximum value of 90 was achieved. This improvement can be attributed to the uniform dispersion of cellulose fibrils in the epoxy matrix, which enhances resistance to localized surface deformation and allows effective stress transfer under indentation loading [31-33]. However, when the cellulose loading was further increased to 20J, the hardness dropped to 78, falling slightly below that of neat epoxy. The decline in performance at higher cellulose loading can be attributed to inadequate dispersion of the fibrils, which promotes agglomeration and void formation and consequently weakens the cellulose–matrix interfacial bonding. Additionally, the presence of an insufficient matrix phase and the increased brittleness resulting from high cellulose concentrations further diminish the ability of the composite to withstand indentation effectively [34-35].

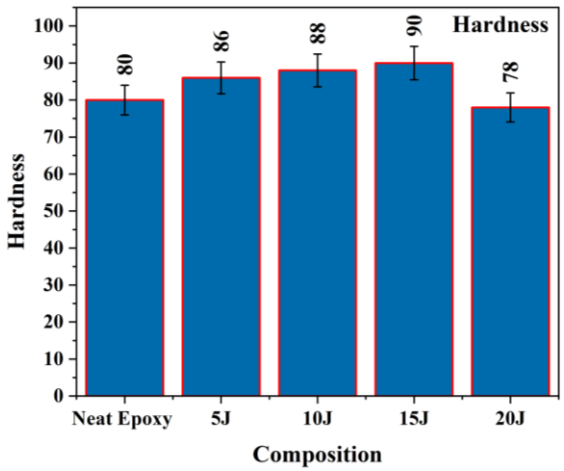

Fig. 5. Hardness of Jute cellulose composites.

4.4 SEM analysis

The analysis of the fractured surfaces of tensile-tested composite materials was conducted using a scanning electron microscope (SEM). The fracture surface of the 15J cellulose composite under tensile loading is presented in Fig.6. The microstructural examination shows no major surface flaws such as interfacial gaps, voids, or severe fiber clustering, which confirms a reasonably effective adhesion between the cellulose reinforcement and the epoxy phase [24,27,33]. The incorporation of 15J appears to promote efficient stress transfer from the matrix to the cellulose fibrils, thereby contributing to the enhancement of tensile strength at this composition. The fractured surfaces of the 15J composites (Fig. 6) revealed distinct wave- or river-like features, characteristic of brittle failure. These river patterns, together with the rough fracture morphology, imply that the composites fractured in a brittle mode while offering considerable resistance under tensile loading. [35].

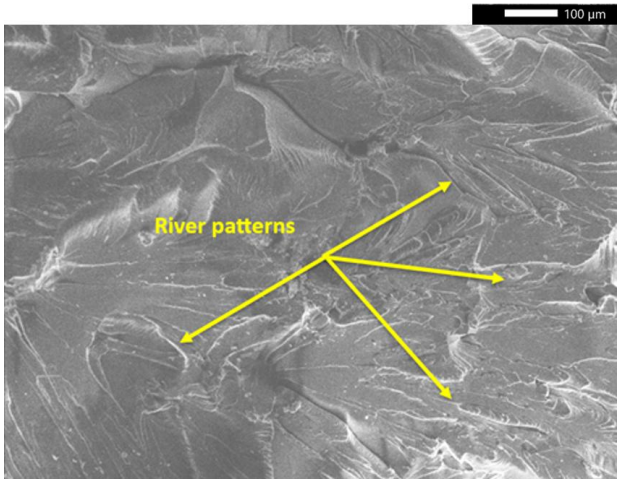

Fig. 6. Morphology of 15J cellulose composites fracture under tensile load.

Fig. 7, it illustrates the morphology of the fractured surface of a tensile specimen with a 20J composite. Here, it's evident that lumps of cellulose microfibers are distributed randomly within the epoxy resin. It also highlights the presence of numerous void formations and clumps of clusters cellulose fibrils. The increased number of voids in these composite materials, coupled with the higher concentration of cellulose, leads to the stress concentration further results initiation of cracks and pre-rupture under loading conditions [24,26,36]. As a result, the reduced tensile and flexural strength observed in the 20J cellulose composites can be attributed to void formation and poor interfacial bonding. In comparison to the 15J composites, cellulose fibrils pullout and a greater number of voids formation are relatively more pronounced.

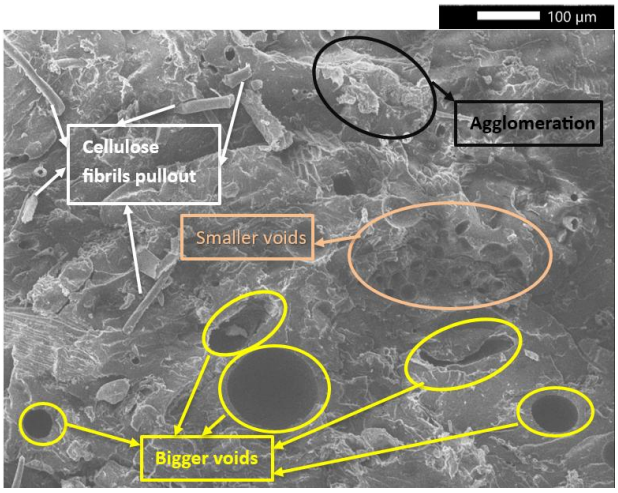

Fig. 7. Morphology of 20J cellulose composites fracture under tensile load.

The incorporation of 20J jute cellulose fibrils into the epoxy matrix results in poor interfacial bonding due to insufficient epoxy matrix, leading to a relatively rougher surface and non-uniform dis-agglomeration (as shown in Fig. 7), in contrast to the tensile fracture surface of the 15J composites (Fig. 6).

4.5 Wear rate

Fig. 8 illustrates the effect of applied load on the wear rate of jute cellulose–reinforced epoxy composites in comparison with neat epoxy. As expected, neat epoxy, being a brittle thermoset polymer, exhibited the highest wear rate under all loading conditions due to brittle fracture and its limited ability to resist abrasive sliding and thermal softening [37].

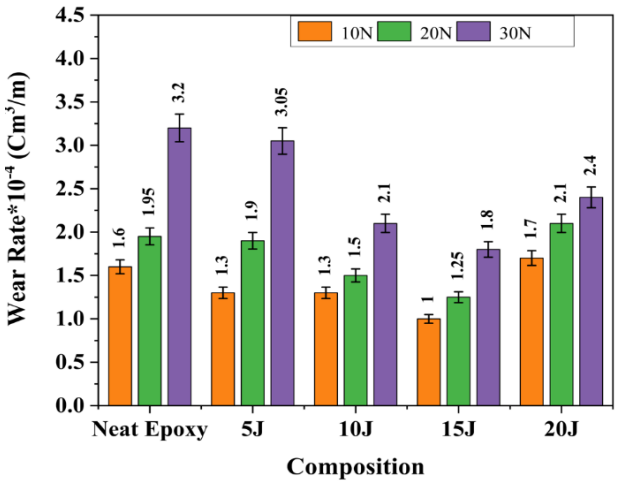

Fig. 8. Wear rate of neat epoxy and jute cellulose-reinforced epoxy composites

The incorporation of jute cellulose significantly improved wear resistance, with the degree of enhancement strongly dependent on filler loading. At lower to moderate cellulose contents (5J and 10J), the composites showed a noticeable reduction in wear rate compared to neat epoxy, demonstrating that the addition of fibrils enhances surface hardness and restricts plastic deformation through better stress transfer [17, 37–38]. The 15J composite exhibited the most pronounced improvement, with wear resistance increasing by nearly 35–40% across the tested loads. This superior performance is attributed to optimum filler dispersion, strong interfacial adhesion, and uniform stress distribution, which collectively restrict crack propagation and reduce material removal [37]. Furthermore, this observation is consistent with the higher hardness recorded for this composition (Fig. 5).

However, further increasing the filler content to 20J led to a deterioration in wear resistance. The excessive cellulose loading caused particle agglomeration, void formation, and weak matrix–filler adhesion, creating localized stress concentration zones. These weak regions acted as crack initiation sites during sliding, which accelerated wear through ploughing and debris formation [37–39]. Overall, the results clearly indicate that moderate cellulose reinforcement is beneficial, with 15J providing the optimum balance of interfacial bonding, hardness, and wear resistance. This composition not only demonstrated the lowest wear rates but also showed improvements in mechanical properties such as tensile and flexural strength, confirming its potential for enhanced tribological applications [37–38].

5. CONCLUSION

In this experimental study, a series of jute cellulose-reinforced epoxy composites were fabricated with varying cellulose weight fractions to investigate their mechanical and microstructural behavior. The influence of jute cellulose loading on tensile strength, flexural strength, hardness and wear resistance was systematically evaluated. The major findings from the present research are as follows:

- The 15wt% jute cellulose reinforced composite exhibited the best mechanical properties, with a tensile strength of 22.3 MPa, flexural strength of 65.23 MPa, and hardness of 90. This enhancement is attributed to strong cellulose–matrix bonding, uniform dispersion, and efficient stress transfer.
- Increasing the cellulose content to 20wt% significantly reduced performance. Tensile strength dropped to 15.85 MPa, flexural strength to 38.43 MPa, and hardness to 78—lower than neat epoxy—due to agglomeration, voids, and poor wetting of cellulose fibrils.
- Fractography revealed poor interfacial adhesion, voids, fibril pull-out, and delamination in the 20wt% composite, causing premature failure.
- The 15wt% composite also showed the lowest wear rate, with a 43.75% improvement over neat epoxy, owing to better hardness and fiber–matrix bonding. In contrast, the 20wt% sample had the highest wear due to weak adhesion.
- Thus, 15wt% jute cellulose is identified as the optimal loading for enhanced mechanical and wear performance.
- Its biodegradability, improved durability, and mechanical performance make it suitable for automotive components such as dashboards, door trims, and interior panels—providing a sustainable alternative to synthetic composites.

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