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Mechanical, Tribological and Morphological Characteristics of Glass and Jute Reinforced Epoxy Hybrid Composite

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Abstract: In this study, hybrid composites were created utilizing the compression moulding technique employing various weight percentages of glass and jute fibres stacked in various configurations. Glass and jute fibres underwent physical, mechanical and morphological experiments, and the impact of stacking sequencing was investigated. The best reinforcing composition for hybrid composites was decided using an order of preference method based on how closely it resembled the optimum solution model. The order of the stacking was key in determining the hybrid composites' mechanical and physical properties. The hybrid composite material with a stacking sequence of Glass-Jute-Glass, where each layer has a weight percentage of 4%. This material is noted to exhibit certain properties: The material has a tensile strength of 115.32 MPa, the hardness of the material is measured at 42 on the Vickers hardness scale (HV) and the material can absorb an impact energy of 4.50 joules per meter (J/m). The material has a void content of 0.99%. The wear of the material is measured at 65 micrometers (μm). The composite, on the other hand, displayed inferior physical and mechanical properties when glass fibres were sandwiched between the jute fibre layer; tensile strength was 71.02 MPa, hardness was 28 HV, and impact energy was 3.47 J/m. Both the glass fiber reinforced composite (GG) and the glass-glass-glass composite (GGG) have a capability to absorb less water. The impact strength of a composite with a stacking sequence of jute-jute-jute (JJJ) is equivalent to that of the glass-glass-glass (GGG) composite. This implies that the jute-based composite, despite being composed of a natural fiber (jute), can exhibit impact strength comparable to a composite made entirely of glass fibers. When comparing jute fiber composite stacking (GG to GJG), it appears that the addition of jute fibers within the glass composite (GJG) resulted in higher tensile strength compared to the pure glass composite (GG). The stacking sequence with jute (JGJ) had lesser tensile strength compared to the all-glass composite (JJ). The microstructural study of the cracked composite surface showed voids, delamination, fibre pull-out, matrix distribution, and interfacial bonding of the fibres with the matrix.

1. Introduction

Natural fiber-reinforced polymer composite research has increased recently due to increased environmental consciousness among scientists worldwide. Due to its benefits, such as being lightweight, biodegradable, and environmentally benign, natural fibre composite may take the place of synthetic fibre reinforced composite (Khalid *et al.* 2021, Sadashiva *et al.*, 2022; Tabaght *et al*, 2023).

Natural fibres' poor moisture resistance, as well as their hydration and adherence to the polymer matrix, have an impact on the structural and mechanical characteristics of composite materials. Hybrid composites that balance the advantages of both types of fibre can be made using a combination of natural and synthetic fibres to solve these issues (Sadashiva *et al.*, 2023; Akartasse *et al.*, 2022). In comparison to their respective pure composites, investigations have revealed that hybrid composites made of glass and natural fibres offer improved physical characteristics (Aslan *et al.* 2018, Giridharan *et al.*, 2019). Hybrid composites may be made at a reasonable price using natural and glass fibre reinforced composites. The researcher has shown that strengthening the epoxy matrix with ramie fibre considerably increased the resistance to wear of composites. Fibre reinforcement improved the glass fibre composite's sliding impact properties (Kumar *et al.*, 2018). The glass fibre composite's sliding wear characteristics improved with fibre reinforcement. The erosion behaviour of a glass fibre composite manufactured with granite powder was investigated, and it was discovered that adding more filler improved the composites' erosion resistance to wear. Because of their high water content, natural fibre composites may not perform as well as synthetic ones in certain situations. Fibre loading, though, can help to minimize it (Billady *et al*, 2020, Ray *et al.*, 2017). In an experimental study, it was shown that increasing the amount of jute fibre reduced the void concentration of composites made of kevlar and jute fibre. The composites' physical and mechanical characteristics were also enhanced through hybridization (Vedanarayanan et al., 2022). The ramie and glass fibre made hybrid composite that the researchers studied revealed that composites with fibres that were 45 mm in length had superior mechanical qualities than composites with fibres that were 25, 35, and 55 mm in length. The impact properties of composite materials used in products like aero planes, car bumpers, and bulletproof clothing have been greatly improved by combining Kevlar fibre with E-glass fibre (Romanzini et al, 2012, Vasudevan et al., 2020). The stacking sequence of fiber layers in composite materials can have a significant impact on their mechanical and physical properties. This is often referred to as the "laminate layup" or "fiber orientation," and it plays a crucial role in determining how the composite material responds to different types of loads and stresses. Different stacking sequences can result in variations in properties such as tensile strength, flexural strength, impact resistance, and more (Hassan et al., 2022). According to studies on the effects of layering sequence and hybridization, adding flax and kevlar fibres to the matrix of epoxy improved its mechanical characteristics (Kangokar et al., 2022). The addition of laminated flax fibre improved the fatigue strength, according to researchers who studied the hybrid flax and glass composite's fatigue behaviour. As the quantity of filler is increased, the vibratory properties of the natural fiber-reinforced composites (Rudresh et al., 2017). The arrangement and ordering of fibers within hybrid composites can indeed have a significant impact on their mechanical and physical properties, but it's not uncommon for research in this area to be limited in the literature. Composite materials research is highly specific and can vary based on factors such as the types of fibers, matrix materials, manufacturing techniques, and intended applications. Hybrid composites were developed and reinforced with epoxy polymer utilizing jute and glass fibres stacked in different configurations in order to investigate the mechanical and physical behaviour of the composite. A comprehensive study involving seven different hybrid composite variations and have used SEM (Scanning Electron Microscopy) to examine the morphological features of these materials. SEM is a powerful tool for visualizing the microstructure of materials at high magnifications, allowing to observe surface details, fiber distribution, bonding between components, and other structural characteristics. This approach can provide valuable insights into the composition and arrangement of fibers within the composites, as well as any irregularities or features that might affect their mechanical and physical properties.

2. Materials and Methodology

2.1 Materials

E-glass, which stands for "electrical glass," has a grammage (gsm) of 300 and the epoxy resin LY556. The curing or hardening process is started by adding HY951 Epoxy Hardener in combination with epoxy resins. Were all supplied by UltrananoTech Pvt. Ltd. Bengaluru, India. Jute fibres were provided by Vruksha Composites in Guntur, India. The materials used in this experiment include a list of physical as well as mechanical qualities in Table 1.

2.2 Fabrication of hybrid composite

A compression-molding device called a 30 Ton Hydraulic Press was used to manufacture the composites. At a drying temperature of 80 °C, 10:1 ratios of epoxy resin and hardener were combined in a beaker without the presence of air. Jute and glass fibres were weighed and added to this combination in the amounts shown in Table 1. 4 weight percent of the matrix was put on top of the glass and woven jute fibres in the order shown in Table 1. The chemical inertness, availability, and inexpensive cost of glass fibres led to their selection. The strength of the hybrid composite was significantly increased by the addition of jute fibres to the matrix. Jute fibres were chosen because of their high mechanical and thermal resistance. Benahmed *et al.* CA-g-PCL copolymers were prepared by using di-isocyanated intermediates for more reactivity. A graftingto approach was utilized to covalently graft the cellulose acetate with PCL to different target DPs (CA-g-PCL). The characterization of ungrafted PCL and PCL-grafted cellulose acetate showed an increase in thermal stability (290 °C versus 340 °C), and the addition of cellulose acetate with different DPs of PCL did not affect the melting point of PCL (Benahmed *et al.*, 2022). In order to successfully extract the composite from the PVA Mylar sheet used in the mould (300 mm × 300 mm x 3 mm), a releasing agent was sprayed on the pane. A compression moulding device was used to compress the closed mould once it had been introduced.

Table 1. Laminate designation and stacking sequence of fibers

Sl. no	Laminates	Epoxy matrix (wt %)	Stacking sequence
1	JJJ	88	(4+4+4) wt % jute
2	JGJ	88	(4+4+4) wt % jute + glass
3	GJG	88	(4+4+4) wt % glass + jute
4	GGG	88	(4+4+4) wt % glass
5	JG	92	(4+4) wt % jute + glass
6	JJ	92	(4+4) wt % jute
7	GG	92	(4+4) wt % glass

Efforts to minimize the creation of voids during the fabrication of composites are indeed crucial to ensure optimal mechanical characteristics and material performance. Voids, which are essentially air pockets or empty spaces within the material, can have several negative effects on composite properties. The exothermic polymerization process caused a little rise in mould temperature, and this decrease in matrix system viscosity made it possible for epoxy to be impregnated into the fibres. After that, the compressive force was reduced and maintained under an identical load for an hour in order to prevent resin flash and minimize fibre disruption. In order to avoid geometrical deformation of the composite plate, the mould was chilled for 24 hours while under a compressive strain. The finished composites, which had dimensions of 300 mm x 300 mm x 3 mm, were then removed from the mould. Each composite that was manufactured had a predetermined weight of 300 g. The test samples were created in accordance with ASTM guidelines. Three comparable samples were created for testing, and the results were presented as the average reading.

3. Characterization

3.1 Density

Temperature The component of the density affects its physical and mechanical properties. In terms of weight fraction, the correlation was utilised to compute the theoretical density (ρth) of composites (Sadashiva et al., 2023).

$$\rho_{th} = 1/ (A_f/\rho_f) + (A_m/\rho_m) \qquad \textbf{Eqn. 1}$$

Where A_f being weight fraction of the fibre, A_m being weight fraction of the matrix, ρ_f is the fiber's density, and ρ_m is the matrix's density. The straightforward water immersion procedure of the composites was used to calculate the real density (ρexp) of the materials. The succeeding equation was used to compute the volume proportion of voids (Vv) in the composites using their ρ_{th} and ρ_{exp} densities (Sadashiva et al., 2023).

$$Vv = (\rho_{th} - \rho_{exp}) / \rho_{th} \qquad \textbf{Eqn. 2}$$

3.2 Water Absorption Test

The composite sample in the current investigation (50.8x 3 mm2) underwent a water absorption test in accordance with ASTM guidelines. Using a digital scale with a 1 mg precision, the trial weight was recorded. For 24 hours, the test specimen were submerged in water. Tissue paper was used to remove the water from the surface of the specimen after 24 hours, and the weight being recorded. This was carried out repeatedly until the test samples reached a stable state (no further water absorption by the samples). The specimens that were utilised for the water absorption test are shown in Figure 1a. The following calculation was used to determine the water content percentage (w %).

$$W = (w1-w2)/w2 *100 \qquad \textbf{Eqn. 3}$$

3.3 Wear test

The A pin disc tribometer is a testing apparatus specifically designed to simulate and measure the wear and friction properties of materials under controlled conditions. In this type of wear test, the pin is loaded against the disc, and the disc is spun while the pin remains stationary. The test specimens had dimensions of 36 mm in length, 3 mm in diameter, and a spherical tip. They were tested in accordance with ASTM G99 standard. Both the load and the rotational disc speed were maintained at 600 rpm.

3.4 Hardness test

According to ASTM guidelines, the Vickers hardness test was performed. Figure 1c's hardness samples were polished before being subjected to the test load of 5 kgf. The diamond indenter with a square base was used. A diamond indenter with a 136° apical angle was used to assess the hardness of the composite materials that were formed.

3.5 Tensile and Impact test

KIC-2-1000-C has the specific model of the UTM, These machines are capable of applying controlled forces to samples and measuring their deformation or response. ASTM D3039 is a standardized testing method developed by ASTM International, specifically for determining the tensile properties of fiber-reinforced polymer matrix composites (Jiyas *et al.,* 2024). The standard dimensions of specimens were 250 x 25 x 3 mm3. Tensile test specimens are depicted in figure 1c. Composites' impact qualities may be quantified, which benefits product liability and safety. The Charpy test was carried out for the impact test using a Charpy impact tester (NIE, Mysore) (Figure 1d). The specimen, which was 55 x 10 x 3 mm in size and with a V notch in the centre, had the impactor firmly embedded in its centre.

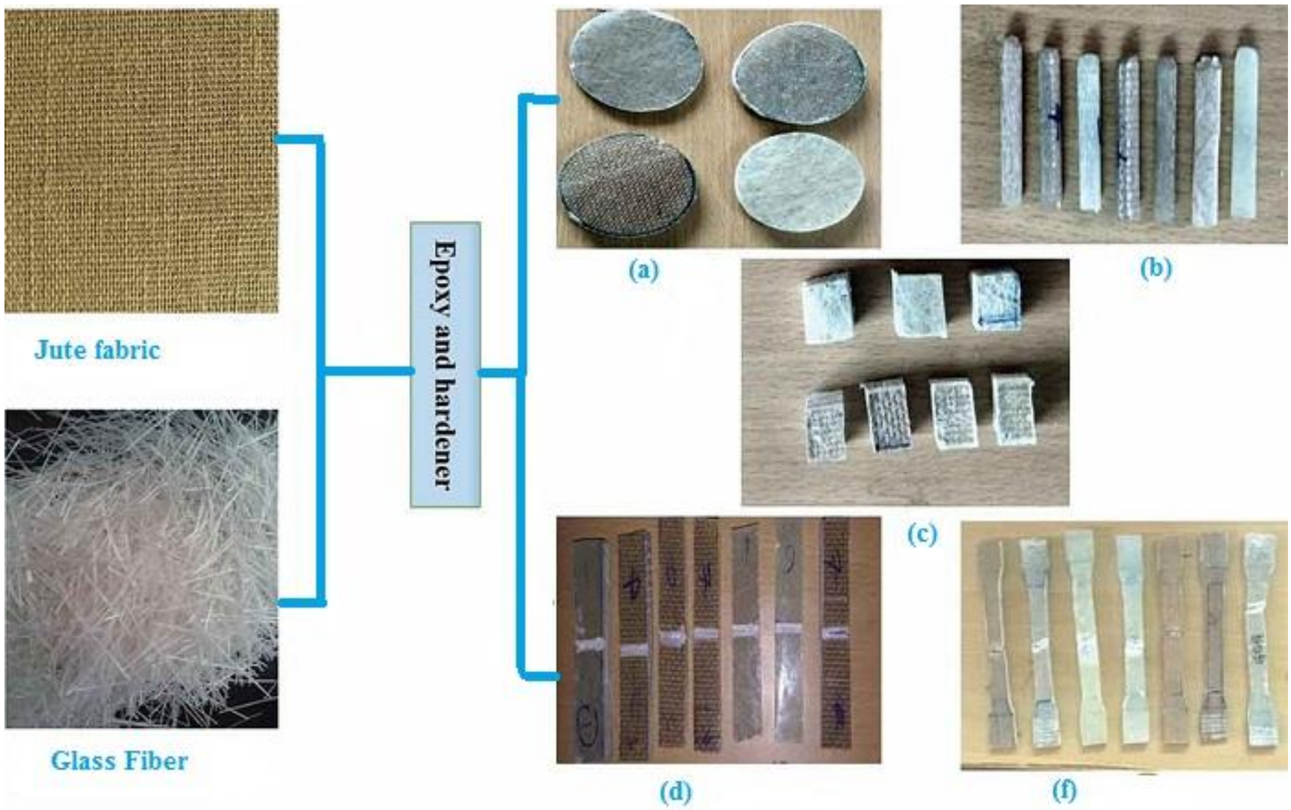

Figure 1. Flowchart illustrating the progression of this investigation, with samples for (a) water absorption, (b) pin-on-disc wear, (c) hardness, (d) impact and (e) tensile test, along with jute and glass fibre.

3.6 Microscopic Test

SEM is an advanced imaging tool used to observe the surface topography and microstructure of materials at a very high level of detail. It works by scanning a focused electron beam across the sample's surface and collecting signals generated by the interaction between the electrons and the material. The Carl Zeiss EVO 18 is a specific model of SEM manufactured by Carl Zeiss, a renowned company in the field of optical and electron microscopy. This SEM model likely offers a range of features for imaging, analysis, and characterization of materials at high resolution. Gold sputtering is a common technique used in electron microscopy, including scanning electron microscopy (SEM), to prepare samples for imaging. The cracked surfaces, the connection between the fibres and the epoxy, and the presence of voids were all assessed using the SEM images (Ali *et al.,* 2023; Girão *et al.,* 2017; Ad *et al.,* 2016).

4. Result and discussions

4.1 Physical Properties of Hybrid Composites

The theoretical density, experimental density, and voids% of the manufactured hybrid composites are shown in Table 2. Because of spaces then pores, the density values found via experiment are less dense than those obtained through theory. A number of factors, including large vacancy percentage (>5%) (Sadashiva *et al.*, 2023). The JJ composite had the lowest void percentage (0.16%), whereas the GGG composite had the highest void content (1.64%). Chop glass fibre was used to create the GGG composite. There were cavities in the GGG composite because the matrix substantial was not effectively permeate the mat made of chopped glass fibres. The warp and weft of the woven mat that made up the jute fibre layer were at a 90° angle. Due to the ease with which matrix material entered the jute fibre mat, there were less voids. The void content increased as fibre stacking of glass or jute fibre improved. Similar patterns have already been identified in research.

Table 2. Density test of various laminates

Laminate	Theoretical density (g/cc)	Experimental density (g/cc)	Void content (%)
JJJ	1.283	1.276	0.54
JGJ	1.299	1.285	1.08
GJG	1.314	1.301	0.99
GGG	1.331	1.310	1.60
JG	1.287	1.282	0.39
JJ	1.272	1.270	0.16
GG	1.303	1.296	0.56

Jute composites JJ weight percentages of 8 and 12 were lower than GG and GGG in glass fibre composites. This is caused by the limited packing ability of the glass fibre and the compatibilization of jute fibre with epoxy polymer matrix. As glass fibre concentration in hybrid composites increased, the water absorption in the composites reduced as a result of glass fiber's hydrophobic character. The JJJ composite showed the highest level of water absorption, whereas the GG sample showed the lowest level. Jute is a natural fibre that absorbs moisture more effectively than synthetic fibres. Comparing the JJ and JJJ composites, the former has an inferior water absorption rate due to its lower jute fibre content. This is due to the high polar hydroxyl band present in jute fibre, which causes a high moisture absorption level. Figure 2 depicts how composite materials absorb water. After 72 hours of immersion, a steady state was reached for all of the composite samples. Similar patterns for composites reinforced with natural fibres have been documented by other studies. The steady states were reached much earlier (approximately 24 h) for glass fibre reinforced composites (GG and GGG).

4.2 Mechanical Priorities of hybrid composites

The fibre loading, stacking, and reinforcement have an impact on the composite's hardness. At different locations on both sides, the composites' hardness has been assessed, furthermore the data for average hardness are provided. Figure 3 depicts the composites that were created's behaviour with regard to hardness. It was found that the GGG composite had the greatest hardness, followed by the GJG and GG composites. This resulted from the increased weight percentage of glass fibre that has more durability than a polymer matrix. By substituting 4 weight percent of glass fibre for 4 weight percent jute fibre, the composite JG hardness increased by 23.92%. Jute fibre and glass fibre sides of the composite JG had average hardness of 23 ± 0.7 and 41 ± 0.5 HV, respectively. When glass fibre was utilised in lieu of jute fibre (JJ), the hardness improved by 39.30% (GG). This was caused by the glass fibres' greater toughness as compared to jute fibres. When the fibre loading weight percentage (JJ and JJJ, 8 to 12 wt %) increased, the composite's hardness increased. Furthermore, the hardness improved as the weight percentage of glass fibre (GG and GGG) increased from 8 to 12 wt%. The data above suggest that the hardness increased along with the fibre content. Due to the hardness of glass fibre, the addition of fibres increased hardness in comparison to the addition of jute fibres. Other research have noted similar tendencies (Rudresh et al., 2017).

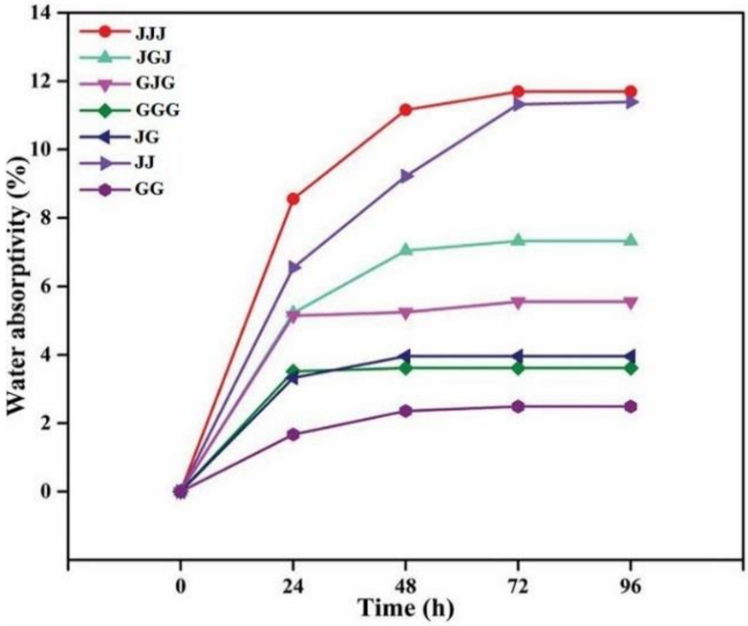

Figure 2. The composite samples' water absorption characteristics.

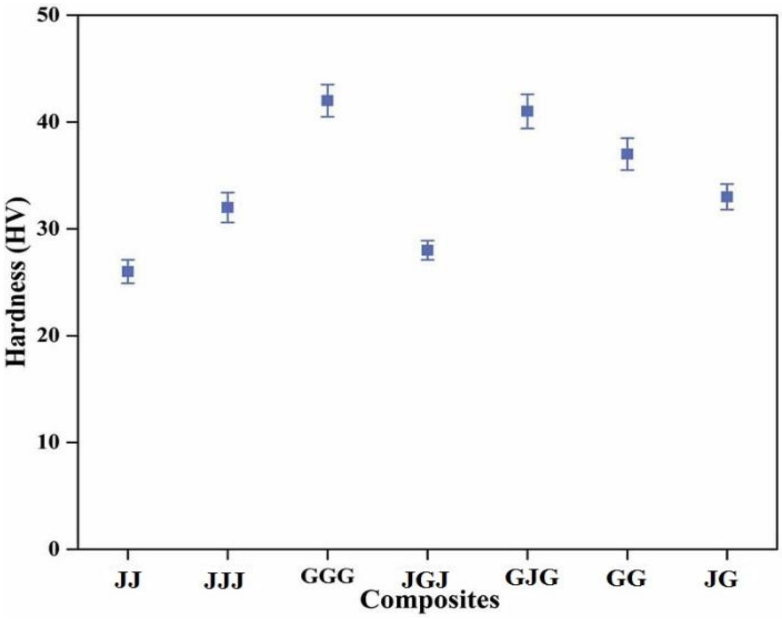

Figure 3. Hardness values of the various laminates

The tensile behaviour of the manufactured composites are depicted in Figure 4. The tensile strength of the composites increased along with the glass fibre content. However, produced composite samples developed cavities due to an excessive amount of glass fibre content. As a result, the GGG had somewhat lower tensile strength than GJG with a 12 weight percent fibre loading. The results of this study revealed that composites using solely glass fibre as a reinforcement had higher tensile strength than composites with only jute fibre. This was attributable to the glass fibres' superior tensile qualities (Giridharan *et al.,* 2019). Tensile strength improved with larger weight percentage of fibre content. Because there are more fibres available to withstand the same amount of distortion, this is explained. Based on these findings, it might be stated that the hybridised had greater tensile strength than either natural fibre or synthetic fibre did on their own. In comparison to prior experiments, the composites that were created demonstrated greater tensile strength. The highest tensile strength for GJG composite was 115.32 MPa while for JJJ it was 68.30 MPa. It was determined that glass fibre hybridization increased tensile strength more than jute fibre hybridization. The composites without hybridization also shown excellent tensile behaviour in comparison to previous literature (Giridharan et al., 2019). Impact strength is a measure of a material's toughness or capacity to withstand high-speed forces. The impact behaviour of the manufactured composites is shown in Figure 5. Regardless of the fibre types (glass and jute fibres), the composites' impact strength increased as their fibre content increased. Because more fibres are resistant to high-speed loading, maximum impact energy for the GGG composites was 4.63 J/m, while minimum impact energy for the composite was 2.83 J/m. The glass fibre composites, as in the cases of GGG and JJJ and JJ and GG, demonstrated greater impact strength when comparing materials with the same weight percentage of glass and jute fibre.

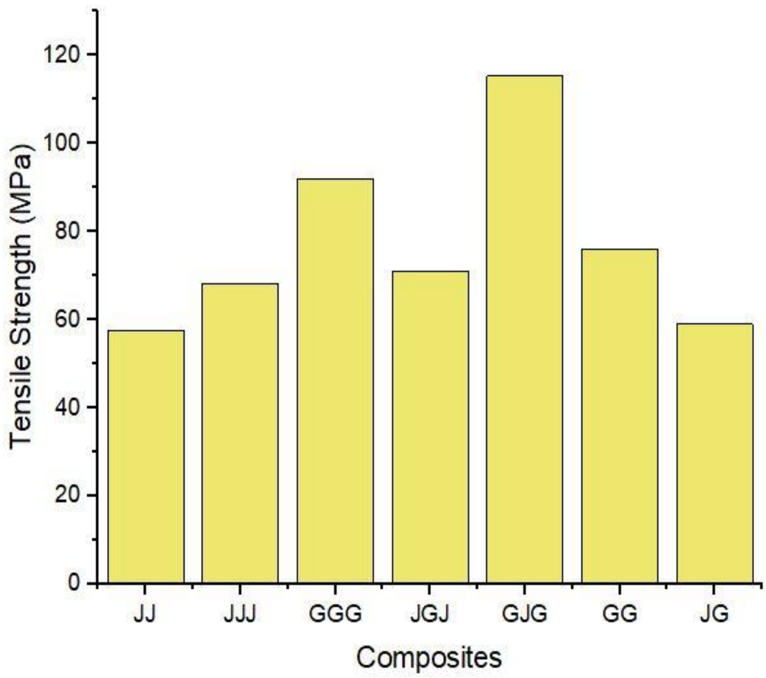

Figure 4. Tensile strength of various laminates

This results from glass fibres' superior bonding qualities compared to jute fibres. This led to the glass fibre composites producing improved energy dissipation. The superior impact behaviour of the GJG composite over the JGJ composite may be attributed to the same factor. According to the data discussed above, the composite's ability to withstand impact loading grew as the fibre content did. Glass fibre reinforced composites performed better than jute fibre reinforced composites when it came to impact resistance.

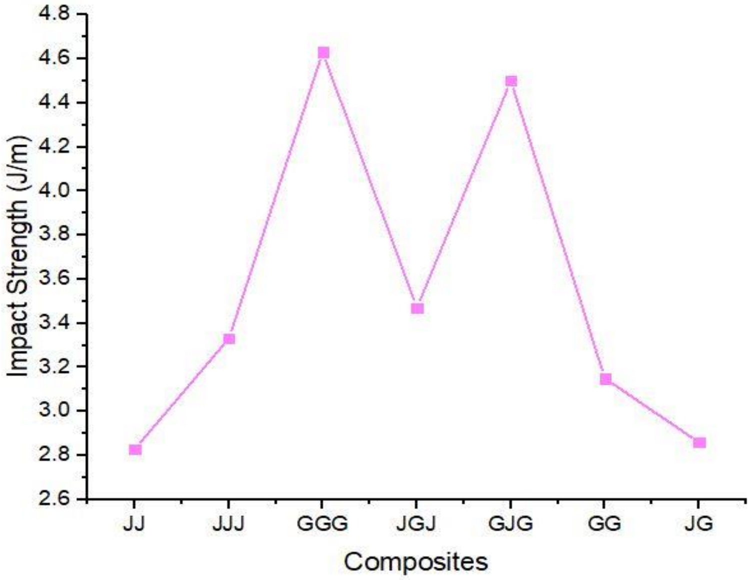

Figure 5. Impact strength of various laminates

4.3 Tribological test

Figure 6 demonstrates the difference in wear between jute and glass fibre reinforcement and the highest wear occurring with the former. In Table 2, it was detailed how much weight each composite lost throughout the wear tests. During the test, the composite's epoxy and fibres deteriorated, and identical wear on each of the two sides of the composite was noted.

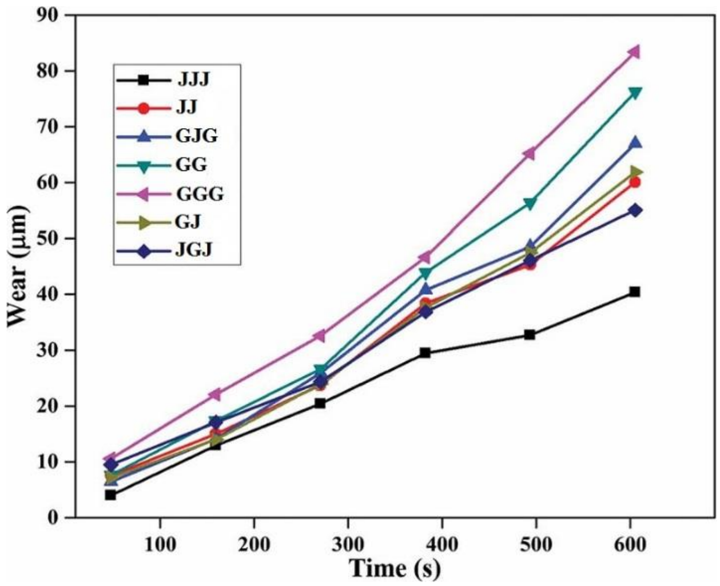

Figure 6. Wear priorities of various laminates

GGG had the most wear (83 µm), followed by GG (75 µm) and GJG (64 µm). These voids in the GGG composites are responsible for this. Based on these results, it can be inferred that hybrid jute and glass fibre reinforced composites, such as the JGJ (56 µm) composite, which demonstrated decreased wear, may be used to circumvent the constraint of glass fiber's poor abrasion resistance. JJJ, however, had the lowest wear measured (35 µm), despite having a lower hardness.

4.4 Microscopic study

Figure 7 depicts the SEM micrographs of the cracked hybrid composites reveal the harm that the fracture did to the fibres. The jute fibre sustained significant damage (fibre pull out and fibre breaking). The SEM scans showed that the damages caused fibre breakage. Debonding between the matrix and fibre was also evident. The fiber/matrix adhesion determines the fracture propagation process and, in turn, the mechanical strength of the composite (Djafar et al., 2020). The matrix included the fibres. However, the composite developed several spaces.

A B

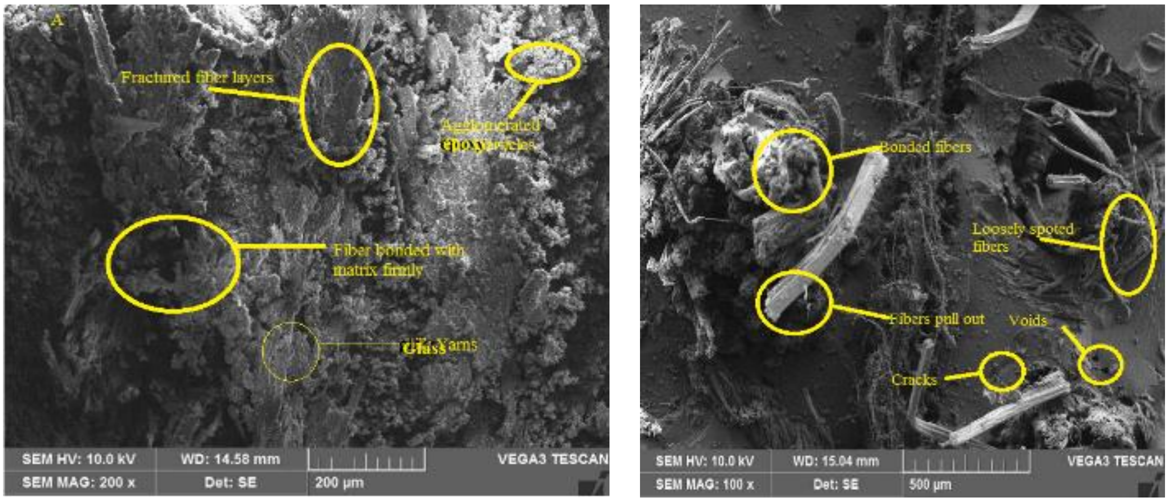

Figure 7. Hybrid composites with fractures as seen in SEM micrographs

Conclusion

Epoxy resin and hardener were used with different ratios to enhance the interlaminar bonding of glass and jute hybrid composites. Compared to composites reinforced with jute fibre, glass fibre reinforced materials demonstrated a lower water absorption percentage. In comparison to the GGG composite, the JJJ composites demonstrated a higher water absorption rate of 1.15 %.Composites' tensile strength became as glass fibre content and fibre loading increased. The GGG composite, which is made entirely of glass fibre, had a 33.42% higher tensile strength than the JJJ composite, which is made entirely of rubber fibre. This resulted from the glass fiber's higher strength compared to jute fibres. Although jute is a natural fibre, composites made of it have an impact strength that is on equal with composites made of glass fibre. The sample composed of perfect jute JJJ had an impact strength of 3.33 J/m compared to 4.63 J/m for the specimen made of pure glass GGG. The performance of composites made with a single type of fibre was inferior to that of hybrid composites. Composites bonded with glass fibres demonstrated remarkable mechanical qualities. Glass fibre has a lesser abrasion resistance, nevertheless. While the other attributes of glass fibre composites suffered less loss, the wear resistance of the composites increased with the addition of natural fibre. As a result of JJJ composite's better wear resistance than GGG composite, bearing components were made out of such composites. Jute fibre composites revealed higher moisture content than glass fibre composites, which absorbed very little moisture. The hybrid composites also displayed enhanced moisture properties. In order to reduce the amount of glass fibres in composite materials, a blend of natural and glass fibre can be employed. In SEM investigation of glass and jute samples, the strong bonding of jute and glass fibres was seen. The study's findings support the hypothesis that jute-reinforced epoxy composites could replace epoxy polymers for increased mechanical and environmental performance. The results further demonstrate that natural fibre hybridization and altering the fibre staking sequence have a substantial impact on the physical and mechanical properties of natural fibre composites. The manufactured composites can be used in a variety of medium structural applications.

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