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ORIGINAL ARTICLE

Experimental and simulation study for mechanical properties characterisation of green natural reinforced composites

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Abstract

This study focuses on investigating the mechanical properties of a composite comprising jute fibers reinforced with a combination of cellulose and non-cellulose fillers. These fibers are infused with aloe vera gel and reinforced in an epoxy matrix. The process involves applying aloe vera gel to the jute fibers, followed by a 48-h cooling period. These treated jute fibers are then used to reinforce the epoxy matrix. Experimental tests were conducted to evaluate the tensile and flexural strengths of the composite. The epoxy matrix is reinforced with jute fiber composites that have been coated in aloe vera gel and include both cellulose- and non-cellulose-based particles. The cellulose-based fillers selected for this study are groundnut shell powder and teakwood powder, while graphene is chosen as the non-cellulose-based filler. The incorporation of graphene, teakwood powder, and crushed groundnut shell powder into the aloe vera gel-coated jute fibers improved tensile strength by 11.11%, 8.46%, and 53.43%, respectively, compared to a jute composite without particle reinforcement. Additionally, the study explores the behavior of a composite material containing two pre-existing cracks positioned differently, utilizing finite element methods. In all materials examined, transverse fractures consistently resulted in higher von Mises stresses and shear stresses compared to longitudinal cracks.

Keywords Jute fiber · Aloe vera gel · Carbon nanotubes · Graphene · Tensile strength · Flexural strength

1 Introduction

Natural composites, derived from plant-based fibers, have been effectively utilized to reinforce both thermoplastic and thermoset matrices. These composites offer several advantages, including cost-effectiveness, biodegradability, strength, lightweight properties, stiffness, and environmental friendliness. These qualities make natural composites highly desirable materials for a wide range of applications. Notably, the automotive industry is a key sector that extensively utilizes natural fiber-reinforced composites. Reducing the overall weight of vehicles by 10% through the incorporation of natural fiber-reinforced composites can result in significant gains in fuel efficiency, ranging from 6 to 8%. This, in turn, leads to a substantial reduction in CO_2 emissions. Such findings underscore the potential of natural fiber-reinforced composites in promoting more environmentally friendly

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modes of transportation and addressing sustainability concerns [1–6].

Researchers are currently exploring various techniques to enhance the mechanical characteristics, particularly the stiffness and strength, of natural composites. Some of these techniques involve blending different natural fibers, including cellulose or non-cellulose nanoparticles, and employing effective treatment methods to enhance the interaction between the fibers and the matrix. For instance, the use of sodium bicarbonate medium treatment has been found to increase the interfacial shear strength of coir natural fiber epoxy composites [7–9]. When triglycidyl isocyanurate was applied to the fiber surfaces, the composite exhibited a remarkable increase in both tensile (49.8%) and flexural (46.5%) strengths [10–13]. Research on pineapple leaf fibers has demonstrated that a hybrid fiber composition comprising 30 percent chemically modified fibers exhibits superior tensile properties [14]. Processes like alkalization and mercerization have been employed to strengthen the bonds between natural fibers and polymer matrices [15–17].

Various fiber treatment methods, including chemical bonding, mechanical interlocking, molecular interdiffusion, and electrostatic bonding, have been extensively documented [18]. In addition to these approaches, researchers have proposed the utilization of hybridization to enhance the properties of natural fiber-reinforced composites. Some authors have suggested combining synthetic and natural fibers to achieve this enhancement [19–21]. For instance, Das et al. [22] blended glass fiber with jute fiber, resulting in improved performance due to the synergistic effects of these fibers. Similarly, hemp and basalt fiber hybrid composites have shown promise for semi-structural applications due to their enhanced mechanical properties [23]. Furthermore, in automotive applications, hybrid composites made from glass fiber and sugar palm have demonstrated improved thermal characteristics. These developments in hybridization have the potential to enhance the overall performance of natural fiber-reinforced composites, with implications for a wide range of sectors and applications [24–30].

The mechanical properties of waste cotton-based composites, including their tensile, flexural, and impact strengths, have demonstrated improvement through the incorporation of cellulose and non-cellulose particle fillers. Hybridization with synthetic fibers is also crucial for enhancing the toughness of natural fibers [31]. Furthermore, the introduction of reinforcements composed of wood, apple, and coconut shell particles into the polymer matrix has led to an increase in flexural strength [32]. Jute, being one of the most widely used natural fibers, benefits from the addition of artificial silicon particles, resulting in an increased fracture damage load of jute fibers [33]. Researchers have achieved a tensile strength of 33–41 MPa by incorporating walnut particles into an epoxy matrix, suggesting this composite as a potential alternative to wood [34]. This discovery implies that the composite exhibits favorable mechanical properties, positioning it as a promising candidate for applications traditionally reliant on wood.

Incorporating both synthetic and non-synthetic fillers into the matrix has been demonstrated in several investigations of natural fiber-reinforced composites to enhance the overall performance of the composite. These fillers, when added to a composite, have been shown to significantly improve the material's mechanical properties while having only a negligible impact on the overall weight of the matrix. This indicates that fillers play a substantial role in reinforcing the composite without significantly increasing the overall weight of the matrix [35–37]. The creation of a sandwich composite using natural fibers like Aloe Vera, Kenaf, Sisal, Jute, and Flax represents a sustainable and environmentally friendly approach. Such composites can be used to predict the tensile, flexural, and impact strength [38]. Hybridizing natural fibers allows for enhancements in the physical, mechanical, and thermal properties of the composites [39]. The combination of jute fiber and aloe vera fibers has demonstrated good strength under tensile loads [37]. Additionally, numerical methods, including finite element analysis and micromechanics approaches, have been employed by various authors to characterize and analyze natural fiber-reinforced composites [40, 41]. Using finite element-based software like Ansys, the tensile and bending properties of kenaf and palm fiber-reinforced composites have been evaluated [42]. Static structural analysis has been conducted on onion/epoxy, potato/epoxy, and carrot/epoxy composites with a 10% volume fraction, and their tensile and flexural properties were assessed [43]. Finite element methods find extensive applications across diverse engineering domains, and their utilization is increasing in the current decade [44–46]. The significance of nano-fillers in enhancing mechanical properties and performance improvement is emphasized [47–57].

In this study, a novel approach is proposed to enhance the characteristics of natural fiber-reinforced composites while minimizing the weight percentage of epoxy material. The research focuses on creating a jute fiber composite by immersing a jute mat in aloe vera gel for 24 h, followed by a 24-h cooling period, resulting in a layer coated with both jute fiber and aloe vera gel. These layers are utilized to fabricate composite specimens, with and without fillers, in the epoxy matrix. Two types of composites are developed: jute/aloe vera/green waste powder/epoxy composites and jute/aloe vera/carbon-based powder/epoxy composites. The tensile properties of these composites are evaluated to assess their performance. Additionally, the study discusses the effects of aloe vera gel on the composite's morphological changes and the load-bearing capacity of jute fibers. This study elucidates how aloe vera gel influences the ability of jute fibers to serve as reinforcing material and how the composite's shape changes due to their combination. The material developed in this work serves as a sustainable alternative to replace existing non-biodegradable materials with biodegradable ones. This innovation has the potential to find applications in various industries, including the automotive sector, where the use of eco-friendly and biodegradable materials is increasingly sought after to reduce environmental impact and promote sustainability.

2 Material and methods

In this study, non-cellulose carbon-based nanofillers, specifically carbon graphene, are chosen as filling materials. Jute fiber is utilized in the form of a mat, while cellulose-based fillers include teakwood and groundnut shell powder. The jute mat embedded with nano carbon filler is sourced from Vruksha Composites in Tamil Nadu, India. Teakwood powder and groundnut shell powder are obtained from local markets in Vijayawada. The epoxy resin (LY556) and compatible hardener (HY951) are procured from Bindhu agencies in Vijayawada, India. These materials serve as essential components for the fabrication and characterization of the composite specimens in the research.

The samples are prepared using the hand layup process. Initially, the jute fiber mat is treated with a NaOH solution to enhance strong bonding between the components [58]. To create the composite material consisting of jute fiber enriched with aloe vera gel and various biodegradable fillers, the first step involves the preparation of aloe vera gel. Fresh and mature leaves from the aloe vera plant are carefully selected for this process. To eliminate contaminants and dust from the surface of the leaves, a thorough cleansing process is performed using distilled water. Following thorough cleaning, the aloe vera pulp is extracted from the leaves. To extract the mucilaginous pulp contained within the aloe vera leaves, the thick outer layer of the leaves is delicately removed. The clustered aloe vera component is then crushed, resulting in the formation of a gel-like solution. The extraction process utilizes a blender mixer to achieve the desired consistency. To maintain cleanliness and prevent contamination, the gel form of the aloe vera solution is carefully transferred into an antibacterial container. This solution serves as a key ingredient in the production of aloe vera jute sheets, ensuring the incorporation of the beneficial properties of aloe vera into the composite material. To achieve optimal absorption of aloe vera gel into the jute fiber, the jute mat layer is submerged in the prepared aloe vera gel and allowed to soak for three days. This soaking process ensures that the gel permeates the pores of the jute mat and saturates its surface. Following the soaking stage, the aloe vera-infused jute mat is placed in a freezer, aiding in the solidification and firming of the gel within the jute fibers. This step contributes to the overall stability and integrity of the composite material. Once the aloe vera gel has been applied to the jute mats, the mats are set aside for air-drying before proceeding with any further reinforcement or additional processing steps (as depicted in Fig. 1).

The drying process involves allowing the jute mats to naturally dry at room temperature until they reach a completely moisture-free state [59]. This period allows for the evaporation of any residual moisture, ensuring the mats are fully dried and ready for subsequent treatments or procedures. In the following step, the synthetic and cellulose-based filler particles are separately dispersed within the epoxy resin. Subsequently, ultrasonication is employed to incorporate a composite matrix comprising ultrasonicated nanofillers, ensuring compliance with the ASTM requirements, for the fabrication of the jute fiber composites. This process guarantees the uniform dispersion of fillers in the epoxy resin matrix, enhancing the overall structural integrity and performance of the composites. The size of the green waster powders is maintained at 0.3 mm in diameter [44] (Table 1).

2.1 Mechanical-thermal characterization and SEM analysis

The specimens are fabricated using fully dried layers. In this study, the weight fractions of jute fiber (30%), aloe vera gel (20%), and various fillers (such as teak wood, groundnut shell powder, green waste material, non-cellulose-based fillers, etc.) are maintained at 5% each. To assess the tensile strength, four specimens are prepared following the guidelines outlined in ASTM D638. Similarly, the flexural strength is determined according to the criteria specified in ASTM D790. Tensile strength, percentage of elongation, and tensile modulus are calculated using the Digital Universal Tensile Testing Machine (UTM). A 20 KN load cell is used for the testing. Four samples are examined for each combination of composite ingredients, and the average of those values is taken as the final finding. A three-point bending arrangement is set up for bending strength on the same UTM. The bending strength, bending modulus, and degree of deformation were noted. The thermal conductivity of the aloe vera gel-coated jute fiber reinforced with synthetic filler and green waste filler is also estimated by using the thermal conductivity of the composite material test rig. Thermal conductivity is a material property that describes the rate at which heat flows within a body for a given temperature change.

The rate of heat conducted through the specimen or sample is

$$Q = KA(T_1 - T_2)/L \quad (1)$$

where K is the thermal conductivity, A is the cross-sectional area, T_1 is the inlet temperature of the specimen and T_2 is the Outlet of the Specimen, L is the thickness of the specimen.

Fig. 1 Aloe vera plant and aloe vera gel and jute fiber socked in aloe vera gel

Table 1 Composite constituent's details

S.I no	Weight fraction of jute fiber	Weight fraction of aloe vera gel	Weight fraction of filler (%)	Type of filler
1	30%	20%	5	Groundnut shell powder
			5	Teak wood powder
			5	Graphene powder

From Eq. (1), the thermal conductivity of the specimen is estimated as presented in Eq. (2).

$$K = Q \times L \div (T_1 - T_2) \times A(W/m - k) \quad (2)$$

The morphological properties of the jute fiber with aloe vera gel were examined using scanning electron microscopy (SEM). The SEM investigation was conducted using a VEGA3 Tescan SEM apparatus, operating at an accelerated voltage of 10 kV.

In this study, the primary focus was on preserving the natural jute fiber by applying aloe vera gel to it. The process involved coating the jute fiber with aloe vera gel and then using the coated jute fiber as a reinforcement medium within a particle-filled resin matrix to create the composites. To assess the adhesion between the aloe vera gel and the jute fiber, SEM images were captured and presented in the results section.

3 Results and discussion

3.1 Evaluation of mechanical characterization and thermal conductivity

The tensile strength of the composite reinforced with jute fiber coated with aloe vera gel was measured to be 42 MPa. Furthermore, the introduction of additional reinforcement in the form of synthetic and cellulose-based particles resulted in notable improvements. Precisely, the incorporation of graphene, teakwood powder, and crushed groundnut shell powder led to enhancements in tensile strength by 11.11%,

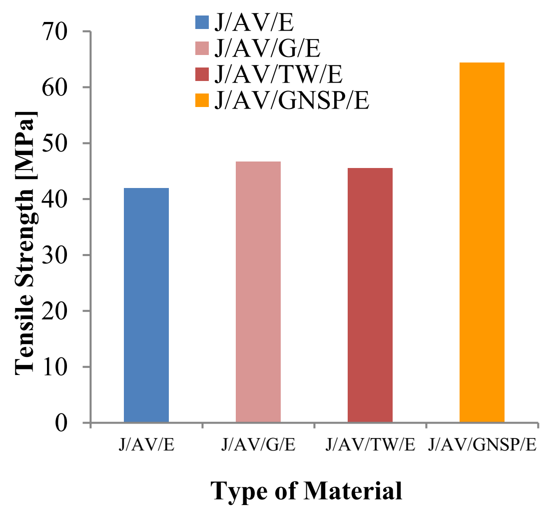


Fig. 2 Variation of tensile strength

8.46%, and 53.43%, respectively. These findings are visually represented in Fig. 2, highlighting the positive impact of the various reinforcements on the tensile properties of the composite.

The behavior of the above-mentioned composite showed different responses under tensile and flexural loading. The composite with groundnut shell powder exhibited good tensile properties, whereas graphene reinforcement demonstrated a favorable response under flexural loading. This difference in performance can be attributed to the effective bonding of the aloe vera-infused jute fiber with the respective filler material.

The incorporation of particle reinforcement has significantly enhanced the tensile modulus of the Jute/Aloe vera

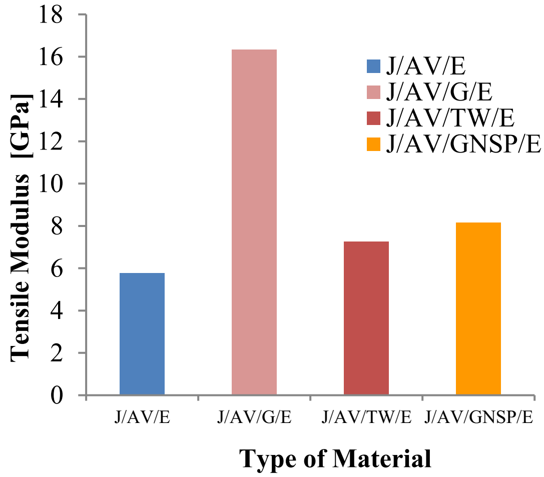


Fig. 3 Variation of tensile modulus

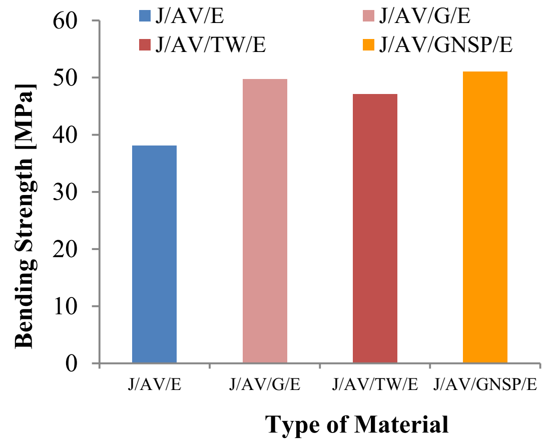


Fig. 4 Variation of bending strength

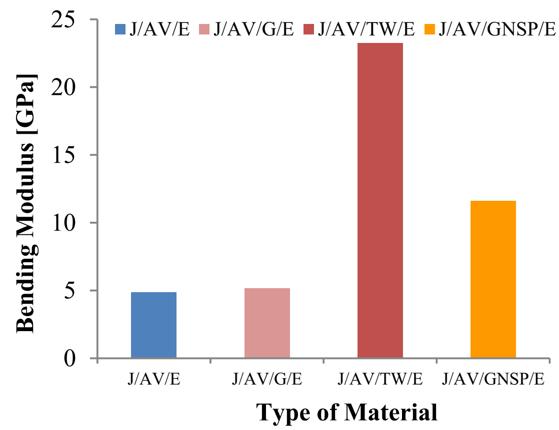


Fig. 5 Variation of bending modulus

composite. Specifically, the tensile modulus showed remarkable improvements of 182.63%, 25.61%, and 41.31% with the addition of graphene, teak wood powder, and groundnut shell powder, respectively, compared to the Jute/Aloe vera composite without particle reinforcement. These enhancements in tensile modulus highlight the beneficial effects of these reinforcements in increasing the stiffness and rigidity of the composite material.

Among the various particle reinforcements investigated, graphene reinforcement exhibited superior elongation properties. Consequently, the incorporation of graphene nanoparticles into the jute fiber with aloe vera gel composite contributed to enhanced tensile strength by effectively bearing the transmitted load within the matrix [60–62]. This study further emphasizes the widespread utilization of jute fiber mats as a preferred choice for fabricating composite materials reinforced with natural fibers.

The incorporation of an aloe vera gel coat in the jute fiber-reinforced composite leads to superior tensile strength compared to a composite without the gel coat. Moreover, the utilization of biodegradable waste materials such as groundnut shells and teakwood powder surpasses the performance of synthetic nano reinforcement like graphene. However, when it comes to achieving the highest tensile modulus, the use of graphene reinforcement proves beneficial. The stiffness exhibited by synthetic particle reinforcement surpasses that of cellulose-based particle reinforcement, resulting in a higher modulus for the synthetic filler (as shown in Fig. 3). This finding is significant as it highlights the potential of utilizing waste materials to reduce environmental pollution and waste accumulation.

Figure 4 illustrates the bending strength of the natural composite investigated. It is observed that the teak wood particle reinforcement exhibits higher resistance to the applied load compared to the GNSP (groundnut shell powder) and graphene reinforcements under bending loading conditions due to better bonding between the constituents. Figure 5 depicts the variation in the bending modulus of the natural composites investigated in this study. It is evident that the composites reinforced with graphene and groundnut shell powder exhibit higher bending moduli compared to other reinforcements.

The type of load acting on the material significantly influences its strength and stiffness. In this work, under longitudinal loading, the fibers are highly active, offering substantial resistance to the applied tensile load. Additionally, the fillers share the load, further enhancing the resulting strength and stiffness. In contrast, during flexural loading, where the load direction is transverse to the applied load, the material exhibits lower strength. Consequently, the contribution of fillers is not as significant compared to tensile loading.

Figure 6 presents the SEM images of the layers coated with aloe vera gel and the jute mat, respectively. This analysis

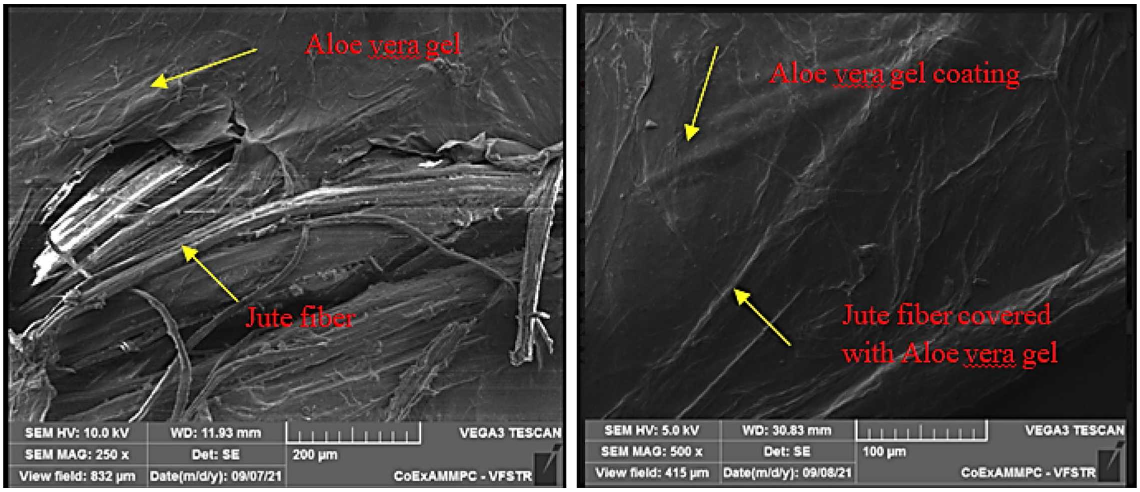


Fig. 6 SEM images of dried Jute fiber with aloe vera gel

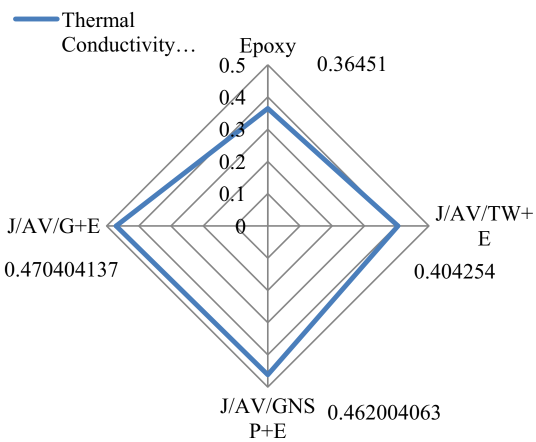


Fig. 7 Thermal conductivity of the natural composites

allows for a closer inspection of the surface features and interfacial interactions between the aloe vera gel, jute fibers, and the surrounding matrix, providing valuable insights into the composite's microstructure. These images provide a visual representation of the adhesion quality, highlighting the effectiveness of the aloe vera gel as a protective and bonding agent for the jute fiber within the composite material.

The jute fiber aloe vera gel coating and reinforcement with various synthetic and cellulose-based components improved its thermal conductivity. With the inclusion of graphene, teakwood powder, and crushed nut shell powder, the heat conductivity is increased by 29.05%, 10.90%, and 26.74% when compared to epoxy, respectively as shown in Fig. 7. The black color of graphene enables it to absorb more thermal energy during testing, contributing to its enhanced thermal conductivity.

3.2 Finite element analysis of jute fiber with AV and filler mixed composites

When characterizing the material properties, numerical studies are crucial, in addition to experimentation. This research will be employed to improve the design of structural or material properties. The objective of these numerical simulations is to accurately replicate the response of the material or structure under various loading scenarios. By analyzing factors such as stress distribution, deformation patterns, and failure mechanisms, a detailed understanding of the material's behavior can be obtained. The engineering stress–strain curve obtained from the experimental results is converted into true stress and true strain, and these data are used as material properties to perform the simulation models [5].

The same dimensions used for the experimental studies are employed to create the geometrical model. This geometrical model is then transformed into a finite element model using solid 186 elements. Figure 8 displays both the geometrical and finite element models. Each element is defined by 20 nodes, and each node has three degrees of freedom in the x, y, and z dimensions.

The jaws of the digital universal testing equipment are utilized to secure the top and bottom ends of the specimen during tensile strength testing. True stress and true strain curves obtained from experimental results are incorporated into the Ansys Workbench application as material attributes for use in simulation investigations. The analysis covers Von Mises stress, displacement, shear stress, and strain energy. The study examines epoxy composites containing jute, aloe vera, and groundnut shell powder (J/AV/G NUT/E), jute, aloe vera, and teakwood powder (J/AV/TW/E), and jute, aloe vera, and graphene (J/AV/G/E). Both with and without the presence of semi-elliptical cracks in the transverse (Crack A) and

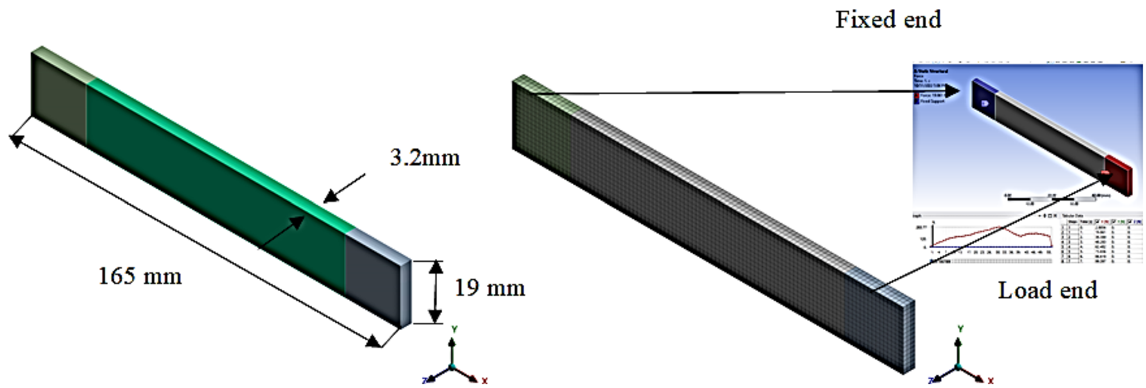
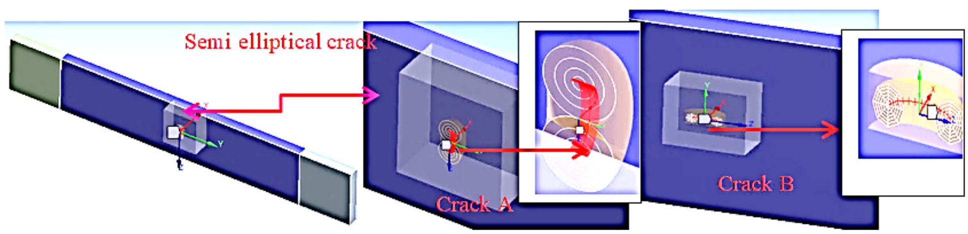


Fig. 8 Geometrical and finite element model of composite with loading and boundary conditions

Fig. 9 Crack positioned at the center of the model in transverse and longitudinal directions



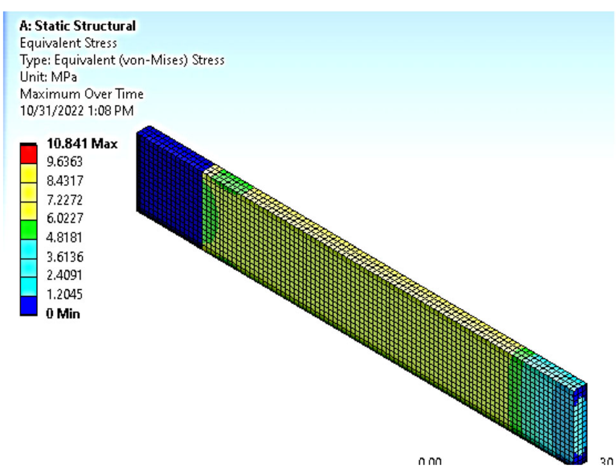


Fig. 10 FE contour of von Mises stresses without crack

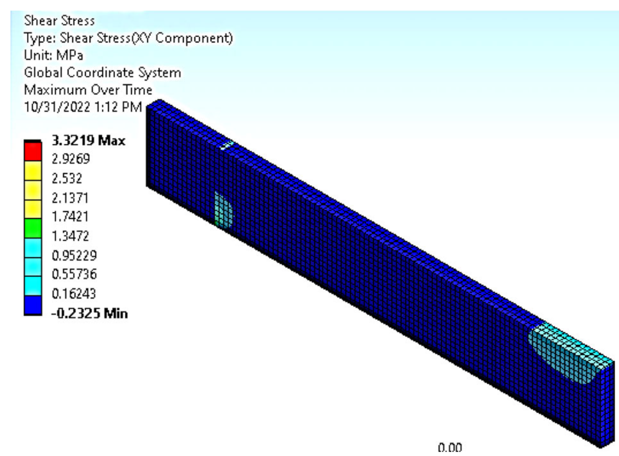


Fig. 11 FE contour of shear stress without crack

longitudinal direction (Crack B), as illustrated in Fig. 9. The finite element contours of Von Mises stresses, shear stress, strain energy release rate, and deformation are presented in Figs. 10, 11, 12 and 13.

Figure 14 illustrates the fluctuation of equivalent stress, specifically the Von Mises stress, in the jute/AV/GNSP/epoxy composite material under varying loads. The results presented in these images are derived from experimental data. It is observed that Crack-A exhibits higher stress levels compared to Crack-B and the material without any cracks. This disparity in stress levels can be attributed to the orientation and position of the cracks relative to the direction of loading. In the case of Crack-A, it is perpendicular to the loading

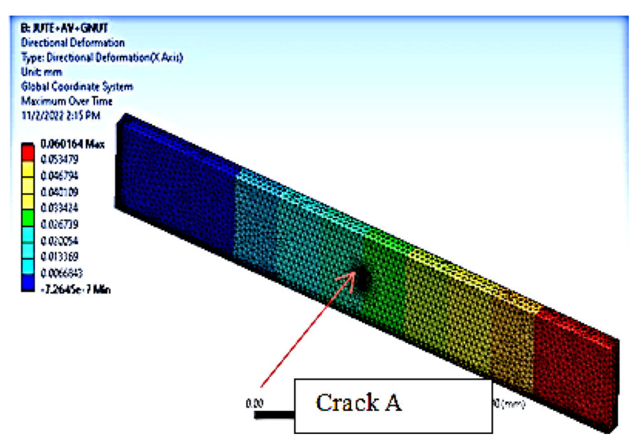


Fig. 12 FE contour of strain energy without crack

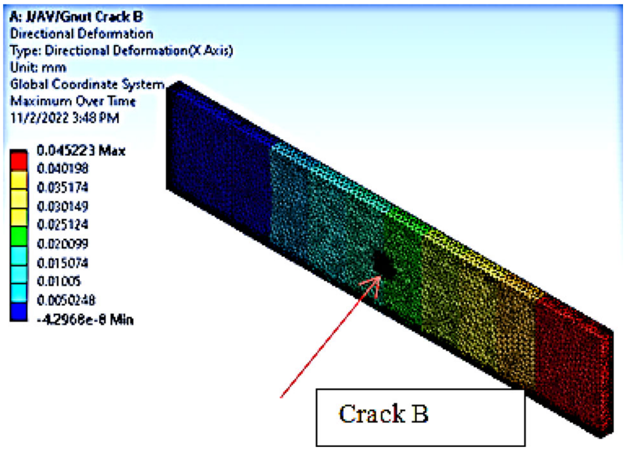


Fig. 13 FE contour of J/AV/GNSP/E deformation with crack A

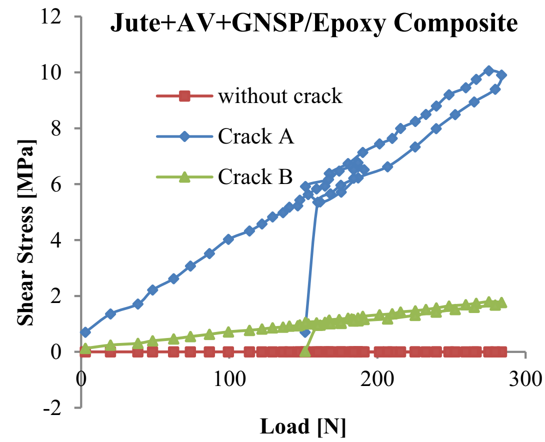


Fig. 15 Shear stress in Jute + AV + GNSP/E

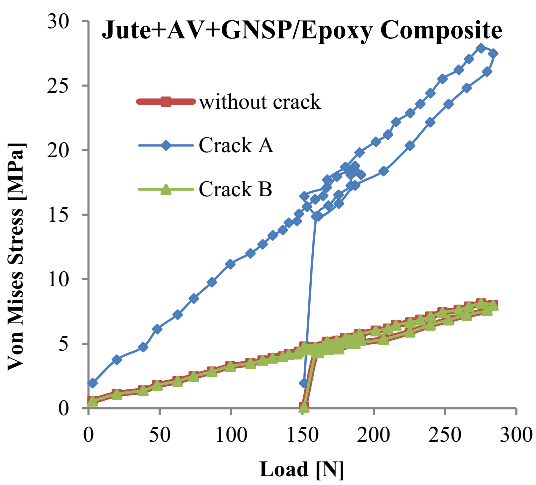


Fig. 14 Von mises stress in Jute + AV + GNSP/E

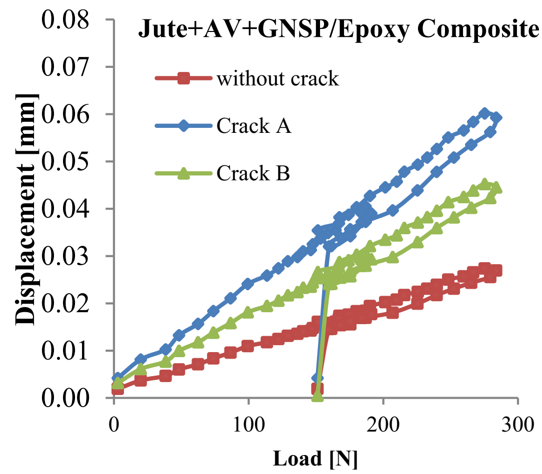


Fig. 16 Displacement in Jute + AV + GNSP/E

direction, resulting in a greater concentration of stresses at the crack tip. This leads to higher stress levels near Crack-A.

On the other hand, Crack-B and the material without any cracks experience relatively lower stress levels because they are either not aligned with the primary loading direction or do not have a crack present. Consequently, the stress distribution in these regions is more uniform and less concentrated compared to Crack-A. The material with Crack-A and Crack-B responded to von Mises stresses in the same way. The material's reaction is consistent for the considered Crack-B because the longitudinally running crack provides more barriers to crack propagation.

When cracks A and B are present, the variation in shear stresses is compared to the material without a crack. The material with Crack-A displayed greater shear stress than the material without a crack (Fig. 15). While the material with cracks exhibited increased shear stress generation with respect to load, the material without flaws exhibited almost negligible shear stresses. In the case of Crack-A, the crack is oriented in such a way that it causes an increase in shear stress in the material. This is because the orientation of the crack creates a stress concentration point that aligns with the direction of the applied shear stress, leading to an increase in stress near the crack tip. On the other hand, the material with no flaws or cracks shows almost negligible shear stresses. This is because the absence of cracks or defects in the material results in a more uniform distribution of stresses, leading to lower overall stress levels.

Figure 16 shows the displacement variation produced in the composite material (J/AV/GNSP/E) both with and without cracks. The presence of a fracture weakens the material, reducing its resistance to the applied stress. As a result, the material deforms more when there is a crack, especially one that runs in a transverse direction. When there is no crack in the composite material, the displacement variation is relatively uniform across the material, with no localized regions of high deformation. However, when a crack is present in the material, the displacement variation is concentrated near

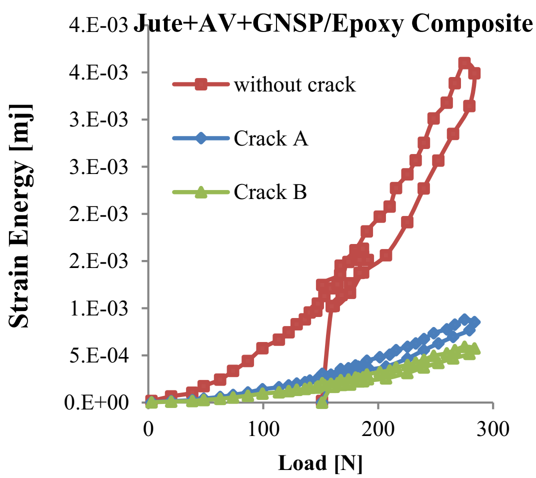


Fig. 17 Strain energy in Jute + AV + GNSP/E

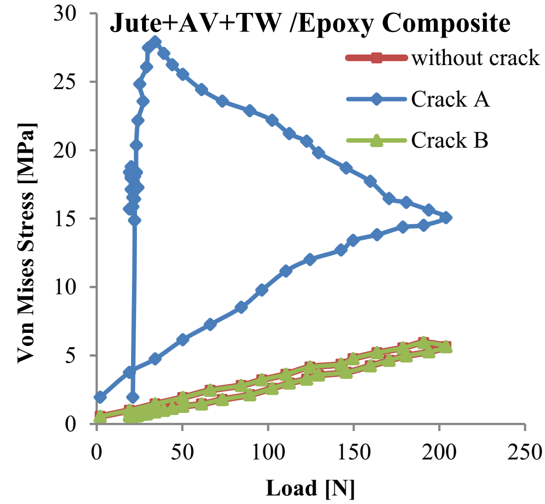


Fig. 18 Von mises stress in Jute + AV + TW/E

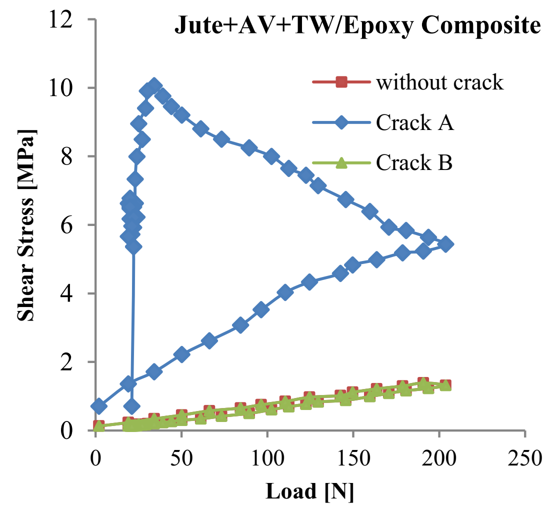


Fig. 19 Shear stress in Jute + AV + TW/E

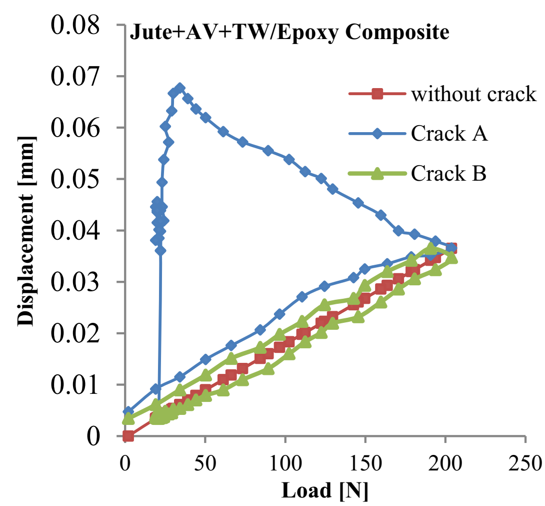


Fig. 20 Displacement in Jute + AV + TW/E

the crack tip. This is because the presence of a crack creates a stress concentration point, which causes a localized increase in stress and deformation near the crack tip. When a transverse crack is present in the composite material, the displacement variation is more significant because the crack causes a loss of stiffness in the material in the direction perpendicular to the crack. This loss of stiffness results in increased deformation in the transverse direction, which can cause the crack to propagate further and lead to failure of the material.

Figure 17 illustrates the strain energy produced in the composite material under consideration with and without a crack under an applied load. The amount of strain energy that can be stored in a material without a crack is quite high; however, the same strain energy diminishes when a crack is present. The energy stored in the material must be used to provide resistance to the applied load, which causes the strain energy to decrease. This is because a crack or a defect in the material creates a stress concentration point, which causes a localized increase in stress. As the applied load is increased, the stress at the crack tip reaches a critical value, known as the fracture toughness of the material. At this point, the crack will propagate, and the stored strain energy will be released as fracture energy. The reduction in strain energy storage in a material with a crack is because the presence of the crack creates a weak point in the material, which reduces its overall strength and stiffness.

The von Mises stresses shear stresses, deformations, and strain energy stored in the material are shown for both J/AV/TW/E and J/AV/G/E in Figs. 18, 19, 20, 21, 22, 23, 24 and 25. These materials exhibit similar responses to various stress types, with the only variation being in the magnitude of these responses. These discrepancies in the outcomes are attributed to differences in the mechanical properties of the materials.

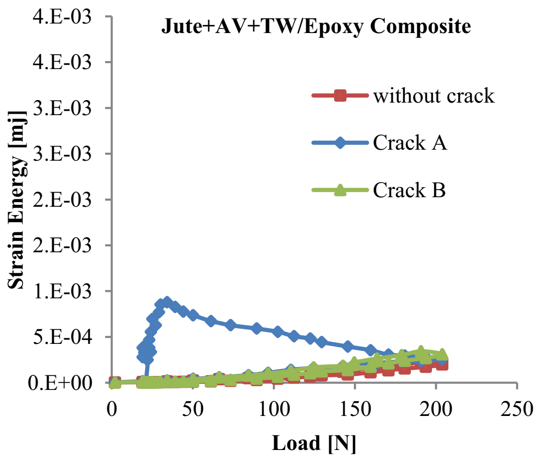


Fig. 21 Strain energy in Jute + AV + TW/E

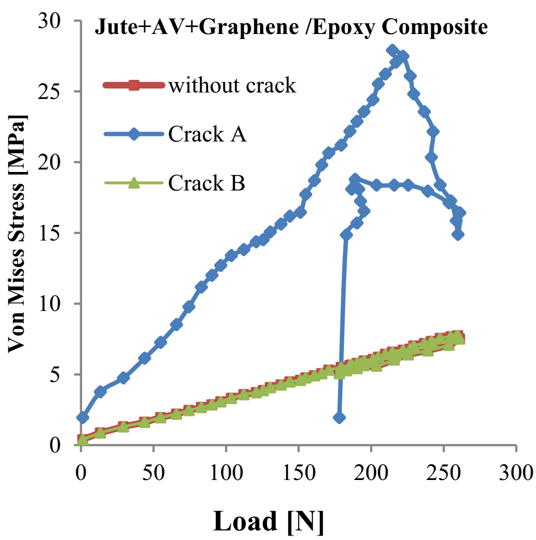


Fig. 22 Von mises stress in Jute + AV + Graphene/E

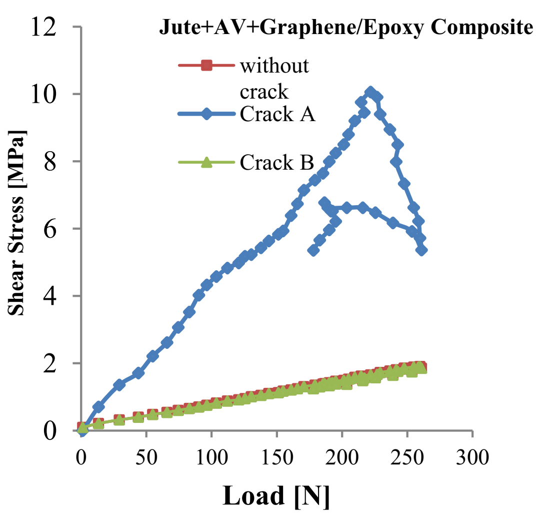


Fig. 23 Shear stress in Jute + AV + Graphene/E

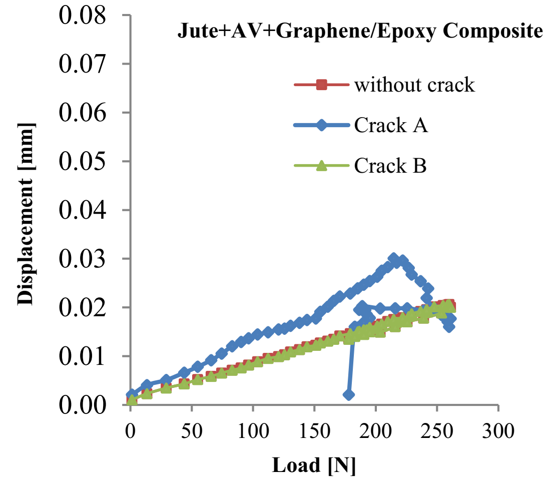


Fig. 24 Displacement in Jute + AV + Graphene/E

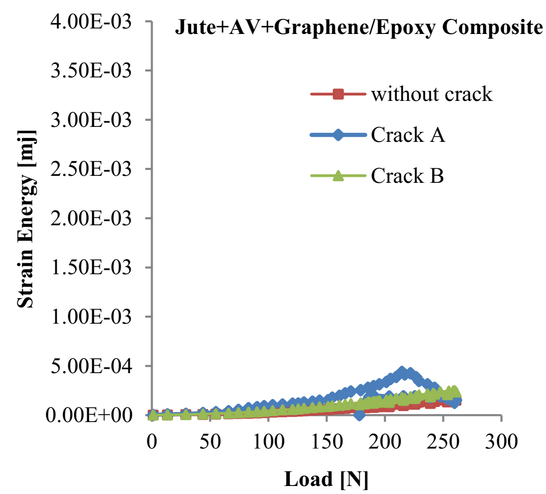


Fig. 25 Strain energy in Jute + AV + Graphene/E

4 Conclusions

The major reinforcement phase is jute fiber with an aloe vera gel coat, and synthetic and green waste nanoparticles are also employed to estimate the tensile, bending, and thermal conductivity of the resulting novel composites. The tensile, bending, and thermal conductivity of jute fibers were increased by applying aloe vera gel to them.

- Among the composites with the same percentage of aloe vera-coated fiber (20%), the highest tensile strength is achieved when reinforced with groundnut shell powder, while the highest tensile modulus is observed with graphene reinforcement.
- In contrast to tensile properties, the addition of fillers has a lesser impact on bending strength and bending modulus.

The greatest improvement in bending strength and modulus is attained with teak wood powder.
- The thermal conductivity of the jute coated with aloe vera gel-coated composite shows significant enhancement with the addition of graphene.
- Numerical results indicate that equivalent stresses and shear stresses are higher for transverse cracks than longitudinal cracks in the composite material.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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