

# Numerical Study on Tensile and Flexural Characteristics of Sisal Fiber – Reinforced Epoxy Composites

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**Abstract.** Knee pads and other safety equipment are normally made from synthetic polymers that provide strength and durability, but they are not biodegradable, which makes them bad for the environment. To address this issue, the present work explores the use of sisal fiber, an abundant and eco-friendly reinforcement, in combination with epoxy resin for developing composite specimens. Their behavior was assessed by tensile and flexural tests, supported by finite element simulations conducted in ANSYS Workbench. Results showed that the mechanical strength and stiffness improved steadily with increasing fiber volume fraction, with the maximum tensile and flexural strengths of 170.15 MPa and 28.34 MPa, respectively, at 70% fiber loading, showing that the stiffness is improved and the stress transfer is efficient between the sisal fiber and the epoxy matrix. The estimated data were in close agreement with the experiments and the available literature, confirming the validity of the approach and presenting sisal–epoxy composites as a green option for protective gear.

## 1. Introduction

Protective equipment, such as knee pads, has a very important part to play in preventing injury for sport, industry, and the armed services. An acceptable knee pad should be durable, shock-absorbing, and easy to wear. They are traditionally made of synthetic polymers, which, being mechanically superior, are biodegradable and also produce long-term environmental problems [1-3]. With the need for more environmentally sound components, natural fibers have been progressively better-valued renewable reinforcing agents for polymer matrices. [4, 5]. Natural fibers, composed of plant, animal, and mineral origins, are a renewable and biodegradable source of fiber compared to synthetic fibers. Plant fibers like jute, hemp, flax, banana, coir, kenaf, and sisal are used primarily in composites because of their high cellulose content and good strength-to-weight ratio [6, 7]. Fibers from animals like wool and silk are valued for their resistance for deformation and insulation properties, while mineral-derived fibers like asbestos are infrequently used today due to its related health hazards. Of these forms, plant fibers display the ultimate demand in structural applications for their accessibility, mechanical

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stability, and sustainability [8].

One of the distinctive natural fibers with ultimate tensile strength, heat resistance, and economy is sisal (agave sisalana). Sisal has been used in ropes, mats, textiles, and geotextiles traditionally, however in recent times investigated as a reinforcement in polymer composites [9, 10]. Its good strength, seawater resistance, and epoxy and polyurethane matrix similarity qualify it for protection and structural commitments [11]. Sisal fiber has established as a sustainable material of extensive attention, highlighting its role in environment-friendly composites [12]. Recent studies on polypropylene reinforced composites with natural fibers like sisal, fiber and coir demonstrates that the volume fraction of the fiber critically influences the tensile behavior [13-15]. In industries, sisal is consumed in car panels, building materials, and biodegradable packaging, while by-products are used in fertilizers, animal feed, and bio-based products. This variety of applications places it as an effective, globally friendly reinforcement material [16-19].

**Table 1.** Mechanical properties of natural fibers – Comparison.

<b>Fiber</b>	<b>Tensile strength (MPa)</b>	<b>Young's modulus (GPa)</b>	<b>Fracture toughness (MPa m<sup>0.5</sup>)</b>
Sisal	400 – 700 [20]	9 – 22 [20]	5.54 [25]
Flax	300 – 1000 [21]	39 – 78 [21]	4.53 [26]
Hemp	350 – 900 [22]	9 – 70 [22]	1.68 [27]
Jute	200 – 800 [23]	10 – 30 [23]	2.95 [28]
Coir	100 – 250 [24]	4 – 6 [24]	1.41 [29]
Bamboo	140 – 800 [27]	11 – 32 [27]	5.5 [30]

Table 1 compares the mechanical properties of naturally available fibers. The fracture toughness data available in the literature are for reinforced composites. From the data in Table 1, the sisal raw fiber provides a balanced combination of strength, toughness, low moisture absorption, cost-effective and abundantly available. This study examines the sisal fiber-reinforced epoxy composite as a potential application for knee pads in knee protection.

High-performance safety items, i.e., knee pads, need materials that should interlink strength, toughness, and comfort. Traditional knee pads are usually made of synthetic polymers like polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate (EVA), and polyurethane (PU), offering impact resistance and shock absorption [1]. Although the materials offer durability, their non-biodegradability and petroleum-based resource dependence create long-term environmental issues. Thus, natural fiber-reinforced composites have been under research and development for sustainable composites. Natural fibers are renewable, light in weight, biodegradable, and provide competitive mechanical performance [2,3]. There has been a vast body of literature that has proven natural fibers to have immense potential for composite manufacturing. Banana, cotton, jute, PALF, and hemp fiber composites, through various studies, have shown tensile and flexural property improvement over the unreinforced polymer [2,4]. Reviews also highlight those natural fibers not only reduce the environmental impact but also decrease cost and energy demands during production [3,5]. Among them, sisal has been highlighted because of its tensile strength, thermal stability, and ready availability [6–8]. Additional studies on fiber surface treatments and orientation confirm that optimization of fiber–matrix adhesion and alignment increases strength, stiffness, and toughness in sisal–epoxy composites [6,9–11].

Even with these encouraging findings, the vast majority of the literature to date has considered general structural or automotive applications of natural fiber composites, and few, by comparison, have considered protective equipment. Fewer still have tested their impact absorption, ergonomics, or fatigue resistance, which are all material to knee pad application. Additionally, experimental data are seldom augmented by finite element modelling, which is

essential to predictive design and optimization. This gap necessitates the current work, where sisal–epoxy composite synthesis and characterization were explored to determine the extent of their application as a green substitute for synthetic polymers in safety gear.

## 2. Numerical analysis

### 2.1 Modelling and Meshing

A planar surface was generated and then assigned an appropriate thickness to match the test specimen dimensions. Figure 1a and 1b displays the tensile model with the detailed dimensions and figure 1c displays the three dimensional flexural model. The specimen is meshed using quad elements with element sizing 0.8 mm, after performing the mesh convergence study. Figure 2 displays the three dimensional model with the mesh. The material properties for sisal fiber and epoxy correspond:  $E_1 = 9.8$  GPa,  $E_2 = 3.4$  GPa, Poisson ratio for both the fiber and the matrix is 0.3 [31, 32].

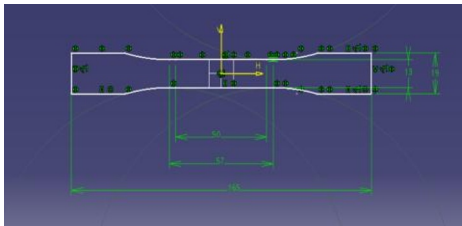


Fig 1a

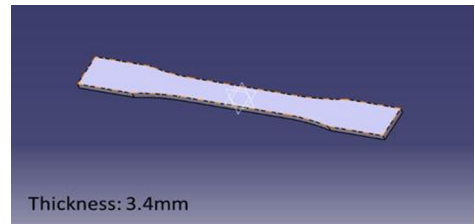


Fig 1b

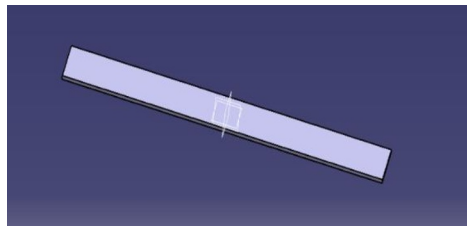
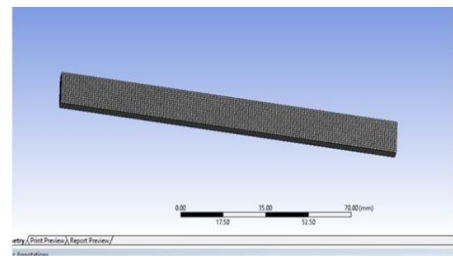
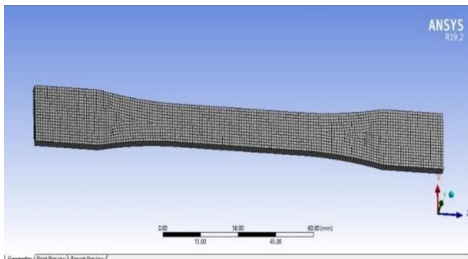


Fig 1c

**Fig. 1a. and 1b.** Three dimensional model of tensile specimen with detailed dimensions in mm, **1c.** flexural test specimen.



**Fig. 2.** Three-dimensional mesh of tensile specimen and flexural test specimen.

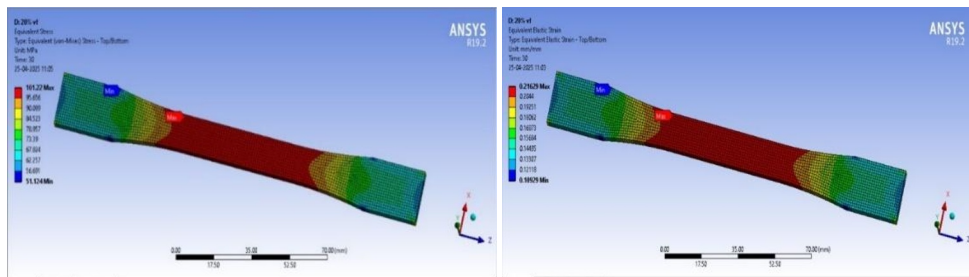
## 2.2 Boundary Condition and Loading

The mechanical performance of the Sisal Fiber Reinforced Composite (SFRC) developed for 20%, 30%, 40%, 50%, 60% and 70% fiber volume fractions were investigated computationally using ANSYS Workbench. Geometry models were developed with test sample dimensions, presuming a zero perfect element size. Mesh convergence analysis indicated that the measure has to be 0.8 mm. They calculated the effective elastic modulus and other material properties at each fiber content by the rule of mixtures and micromechanics simulation. The fibers were orientated at  $0^\circ$  to simulate unidirectional loading.

### 2.2.1 Tensile characterization

In the tensile tests, one end of the sample was fixed and the other end was pulled steadily, similar to how tensile grips operate. The simulations utilized a static structural solver with implicit time integration to accurately capture the quasi-static loading behaviour. Post-processing of the results yielded stress-strain curves, from which values for tensile strength and flexural strength were derived. The relationship between stress and increasing fiber volume fraction demonstrated close alignment with the mechanical trends observed in the computational tests, thereby confirming the accuracy and reliability of the simulation methodology.

Simulations were performed for each fiber volume fraction to determine the patterns of stress, strain, and total deformation. Furthermore, the composite material's response to tensile load was examined using force-displacement graphs and stress-strain curves.

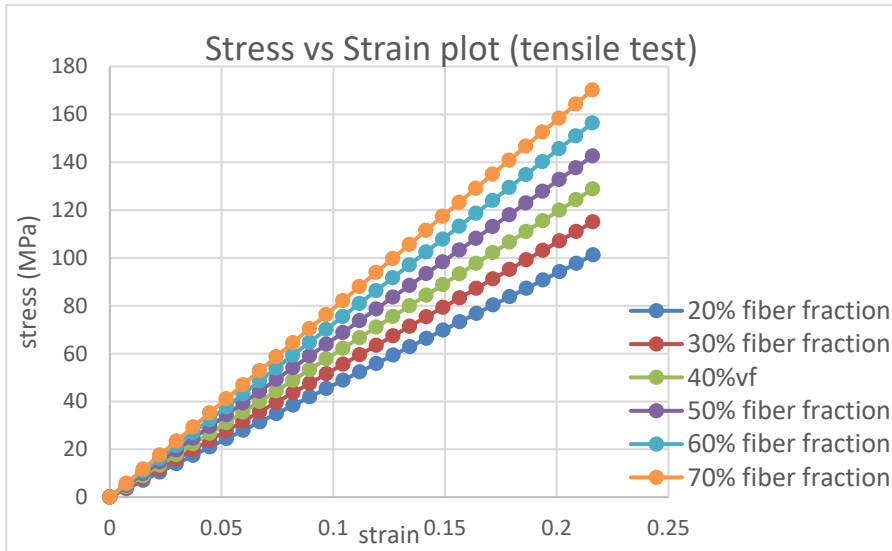


**Fig. 3.** Von-Mises Stress and equivalent strain profiles for tensile test at 20% volume fraction.

**Table 2.** Results from the tensile test.

S.No.	Volume Fraction ( $V_f$ ) (%)	Max Von-Mises stress (MPa)
1	20	101.22
2	30	115.02
3	40	128.81
4	50	142.59
5	60	156.37
6	70	170.15

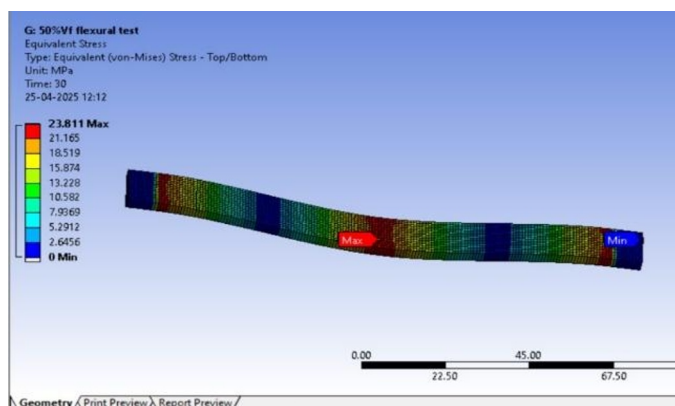
The maximum stress and strain profiles obtained from the numerical study are presented in figure 3, which shows that the maximum stresses and strains are present in the gauge length of the specimen. The tensile test data reveal the evolution of the maximum tensile stress with increasing volume fraction of the reinforcement. As shown in Table 2 and figure 4, the tensile stress increases significantly with the increase in the volume fraction of the reinforcement material.



**Fig. 4.** Stress Vs Strain plot – Tensile test.

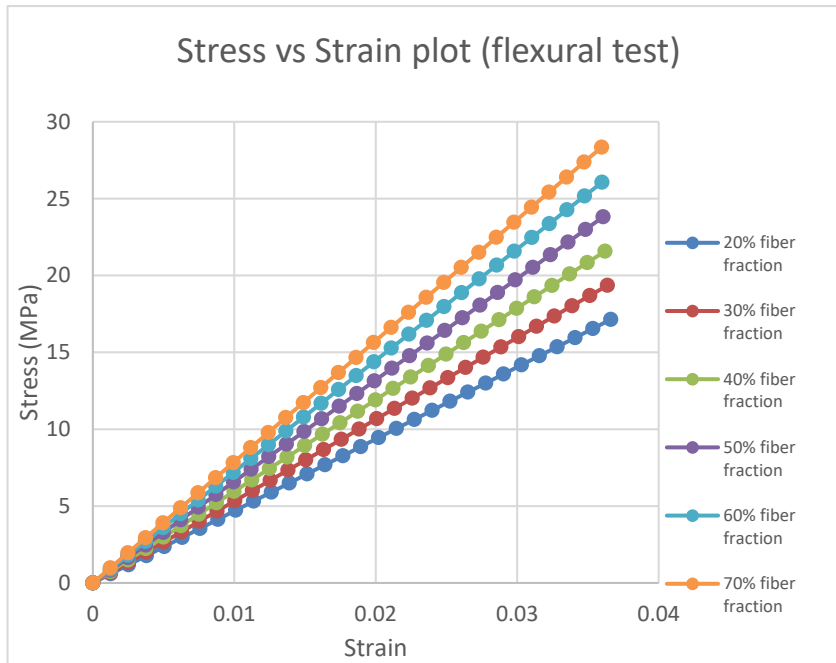
From the data, it can be observed that the tensile strength increases almost linearly as the volume fraction increases. This behaviour suggests that a higher volume fraction of the reinforcement contributes to improved load-bearing capacity of the composite under tensile forces. The trend also indicates that the reinforcement material is effectively enhancing the tensile strength of the composite as the volume fraction increases, with a noticeable rate of increase between 50% and 70% volume fraction.

### 2.2.2 Flexural behavior



**Fig. 5.** Von-Mises stress profile for flexural test at 50% fiber volume fraction.

The numerical flexural test was performed utilizing a three-point bending configuration, wherein the specimen was supported at both extremities and subjected to a central downward force, in alignment with the CAD model designed to comply with the ASTM standard.



**Fig. 6.** Stress Vs Strain plot – Flexural test.

**Table 3.** Results from the flexural test.

S.NO.	Volume Fraction ( $V_f$ ) (%)	Max Von-Mises stress (MPa)
1	20	17.135
2	30	19.355
3	40	21.578
4	50	23.811
5	60	26.063
6	70	28.344

The equivalent stress profile for 50% volume fraction subjected to the bending test is shown in figure 5. The flexural test data provides insights into the bending stress of the composite material. As shown in Table 3 and figure 6, the flexural strength also shows a positive correlation with the volume fraction of the reinforcement.

A gradual increase in the flexural strength is noticed with the increase in volume fraction of fibre. The composite material's resistance to bending or flexural deformation progresses with the addition of further reinforcement. The data disclose that the flexural strength improves gradually, with the most significant growth occurring between 50% and 70% volume fraction. The relation between volume fraction and flexural strength shows that

higher reinforcement levels contribute considerably to the bending rigidity of the composite.

### **2.2.3 Comparison of tensile and flexural test results**

In general, the strength observed from both the tensile and flexural tests, increase with the volume fraction of the reinforcement. Yet, it is essential to note that the tensile strength displays a much higher rate of increase in comparison with the flexural strength. For example, at 70% volume fraction of fibre, the tensile strength reaches 170.15 MPa, whereas the flexural strength only reaches 28.344 MPa. This difference could be attributed to the different varieties of stress and failure mechanisms involved in tensile and flexural loading conditions.

Though both properties increase with the volume fraction of the fibre, the tensile test data proposes that the material turn into considerably stronger in tension with higher reinforcement, while the flexural strength, though improving, does not show the similar scale of increase.

## **3. Conclusion**

This study examined the mechanical properties of sisal fiber-reinforced epoxy composites using a numerical simulation. The primary aim was to evaluate their suitability for its usage in protective equipment, particularly knee pads.

- The output from the numerical study obtained from ANSYS Workbench for both tensile and flexural loading conditions are closely comparable with the available literature, thus validating the modelling methodology and endorsing the mechanical integrity of the material.
- The data obtained from the study displays that at a fiber volume proportion of 70%, the composite had a ultimate tensile strength of 170.15 MPa and a flexural strength of 28.344 MPa.
- These results established that the sisal-epoxy composites' potential for low- to medium-load applications, predominantly when looking for ecologically approachable replacements to synthetic materials.

However, the composite was not used to make a finished product, such as knee pad, this study efficiently begins a performance baseline and inspires the sustained expansion of natural fiber composites for practice in protective gear and other technical applications.

## **4. Future Scope**

In addition to tensile and flexural testing, the subsequent work will need to include impact strength, drop testing, and durability to long-term environmental conditions. The works can be done extended by fabricating samples of all volume fractions and perform tensile tests and bending test.

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