Finite Element Analysis of Polymeric Matrix Composites with Sisal Fiber Reinforcement

Tiago Luis Santos Silva[1*], Genilson Cunha de Oliveira Filho[1], Alexandre do Nascimento Silva[1,2]
[1]UNEB, PPGMSB; Alagoinhas, Bahia; [2]UESC, DEC, Campus Soane Nazaré de Andrade; Ilhéus, Bahia, Brazil

Recently, there has been a growing interest in investigating the mechanical properties of plant fibers, particularly in developing nations. This surge is primarily fueled by the escalating environmental concerns, which are becoming more evident and alarming. Against this backdrop, various sectors of materials engineering are actively seeking alternatives to mitigate the environmental impact across the entire lifecycle of products - from production to use and disposal. This study aims to conduct a computational analysis to examine the influence of fiber quantity on the tensile strength of composites containing sisal fibers. It compares the findings with existing experimental test results and demonstrates the outcomes using the finite element method. The research reveals that greater tensile strength in the composites is achieved with higher volumetric fractions of sisal fiber, as observed in both experimental and computational analyses. These results underscore a strong correlation between finite element analysis and experimental tests documented in the literature.
Keywords: Sisal Fibers. Composites. Finite Elements. Analysis. Polymeric Matrix.

Introduction

In mechanical engineering, the imperative to enhance materials with properties that offer alternatives for reducing environmental impact has become increasingly crucial. This necessity arises notably from the rapid escalation of environmental issues, which are growing more pronounced and alarming [1].

Brazil's industrial sector of composite materials generates approximately 13 thousand tons of waste annually. The bulk of this waste finds its way to landfills, with vehicle manufacturers and industries in the nautical sector being the primary contributors to this substantial volume of discarded materials [2].

The escalating concern over the environmental challenges posed by the poor biodegradability of synthetic fibers prompts critical inquiries into sustainability and the quest for more eco-friendly alternatives. In this context, Brazil presents a promising opportunity to explore various natural fibers with distinct mechanical, chemical, and physical properties.Renewable in nature, natural fibers like cotton, sisal, jute, hemp, or linen offer a cheaper and less environmentally impactful option. The substitution of synthetic fiber-reinforced components with those reinforced by natural fibers is strongly recommended, as it mitigates recycling issues and potential environmental impacts associated with synthetic materials [3]. These fibers also boast high electrical resistance, serving as thermal and acoustic insulators. Consequently, when incorporated into low-modulus polymer matrices, these fibers are anticipated to yield materials with superior properties suitable for diverse applications [4].

As one of the world's leading producers of sisal fiber, Brazil stands to gain economically from polymer composites reinforced with sisal fiber and their subsequent applications. Notably, these composites could serve as replacements for fiberglass, although cost-effective manufacturing techniques need to be developed [5].

Micromechanical models, mathematical tools utilized to analyze the mechanical behavior of unidirectional composites from their constituents, are prevalent. These models aim to derive composite properties based on the individual properties of their constituents and their volumetric fractions [6]. In the literature, various empirical and semi-empirical mathematical models exist for estimating the elastic properties of composite materials. Among these,

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Address for correspondence: Tiago Luis Santos Silva. BR 110, Km 03, Alagoinhas. Zip code: 48.000.000. Alagoinhas, Bahia, Brazil. E-mail: eng.tiagoluis@gmail.com.

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the Halpin-Tsai model is widely acknowledged and utilized today. Such models provide a simplified approach to predicting elastic properties, factoring in parameters like volume fraction, intrinsic properties of components, and their interactions [7]. This research aims to ascertain the influence of fiber quantity on the tensile strength of composites containing sisal fibers. This involves comparing bibliographic results from experimental tests and demonstrating the outcomes obtained through finite element analysis.

Materials and Methods

For the tensile testing modeling, the dimensions of the test specimens were determined according to the ASTM D638-14 standard (American Society for Testing and Materials), which outlines the standard test method for the tensile properties of plastics (Figure 1) [8].

The study utilized Finite Element Analysis (FEA) conducted through Solidworks software, which has a long history of applications in structural engineering projects, including evaluating composite materials incorporating plant fibers. The dimensions of the models for both the pure resin and the composite with natural fibers align with the standard dimensions specified for testing the tensile strength of plastics. Sisal fibers (*Agave sisalana*, Agavaceae family) were the chosen natural fibers for this investigation.

The composite material matrix consisted of epoxy resin (bisphenol-epichlorohydrin), known as polyepoxide. Upon contact with a catalyzing agent, this thermosetting polymer undergoes a hardening process, transforming into a solid and rigid material. Tables 1 and 2 present the material properties utilized in the FEA computer simulation for epoxy resin and sisal fibers.

Four models were made: the first was made only of resin, and the other was made by varying the percentage of sisal fiber weight (Table 3).

Table 1. Physical properties of epoxy resin. Adapted from [9].

Physical Property	Epoxy Resin
Modulus of elasticity (kN/mm^2)	2.3
Poisson Coefficient	0.4
Density (g/cm^3)	1.1

Table 2. Physical properties of Sisal fibers (*Agave sisalana*, Agavaceae family).

Physical Property	Sisal Fiber
Density (g/cm^3)	1.20
Maximum stress(N/mm^2)	287 – 913
Elongation at break (%)	2 – 3
Moisture absorption (%)	11
Modulus of elasticity (kN/mm^2)	25
Poisson Coefficient	0.20

Adapted from Ramesh and colleagues [10].

Figure 1. Dimensions of the Type I model [8].

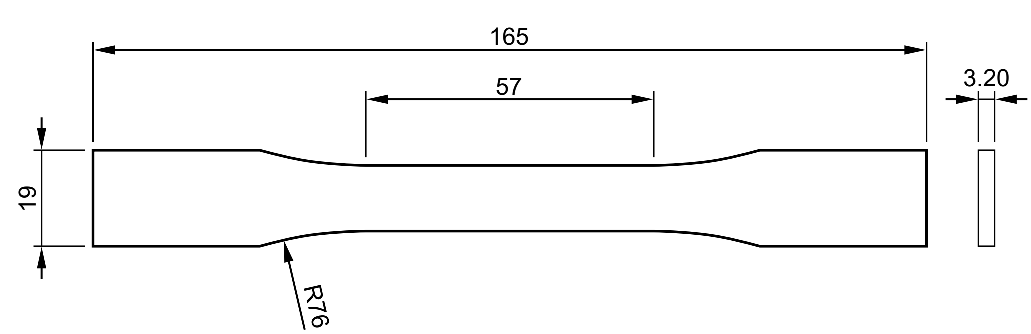


Table 3. Proof bodies used in computational analysis.

Proof Bodies	Amount of Sisal Fiber (%)
TP1	0
TP2	20
TP3	40
TP4	60

Fixed-type constraints were applied to both flat faces, mimicking the attachment of the specimen to the lower grips of the testing machine to simulate the tensile test on one of the test specimen's heads.

A load of 1900N was then applied to the area corresponding to the faces of the Test Piece (TP). Each face had an area of 475 mm² (19x25) (Figure 2).

The mesh generated for the simulation consisted of standard solid parabolic tetrahedral elements with a total of 16 Jacobian points. The element size was 1,02552 mm with a tolerance of 0.051276 mm.

The number of nodes and elements varied across the models produced (Table 4).

For the four models, the maximum Stress of von Misses, Normal Stress, Principal Stress, and Deformations were determined. Figure 3 presents the loads and restrictions applied to the models produced.

Figure 3. Distribution of loads and restrictions applied.

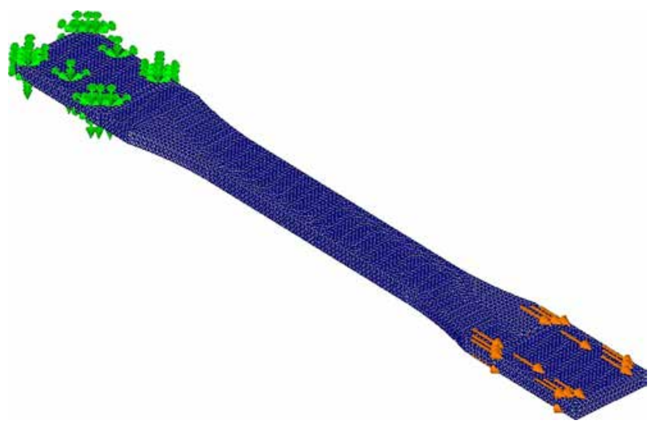


Figure 2. The area corresponding to the head face on the test specimens.

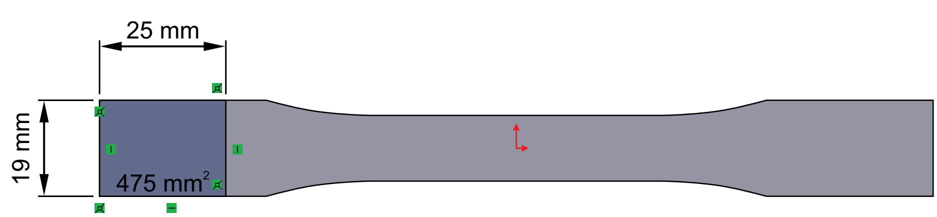


Table 4. Mesh details.

Study Name	Static Analysis
Mesh type	Solid mesh
Mesh generator	Standard Mesh
Jacobian stitches forhigh quality knitting	16 points
Element size	1,02552 mm
Tolerance	0.051276 mm
Mesh quality	High
Total nodes	88,487
Total elements	56,750
Maximum proportion	15.045
Percentage of elementswith proportion < 3	98.6
Percentage of elementswith proportion > 10	0.0793

Results

We observe the results of the longitudinal modulus of elasticity (E1) and the transverse modulus of elasticity (E2) for the Finite Element models, being composed of different volumetric fractions of fibers in the composites of epoxy matrix reinforced by sisal (Figures 4 and 5).

Figure 4. E1 by a volumetric fraction of the epoxy matrix composite reinforced by sisal.

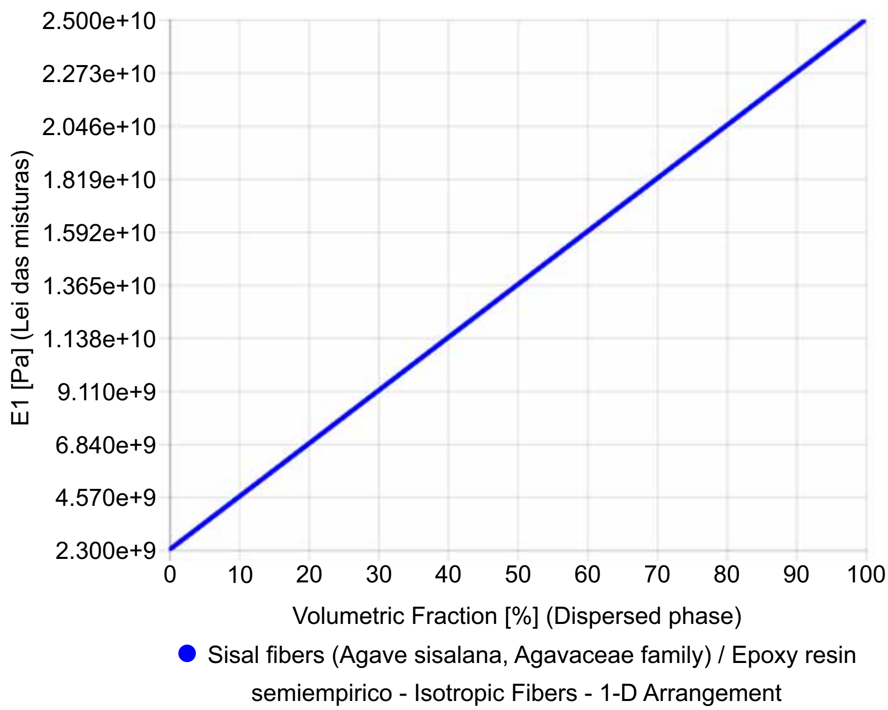


Figure 5. E2 by a volumetric fraction of the epoxy matrix composite reinforced by sisal.

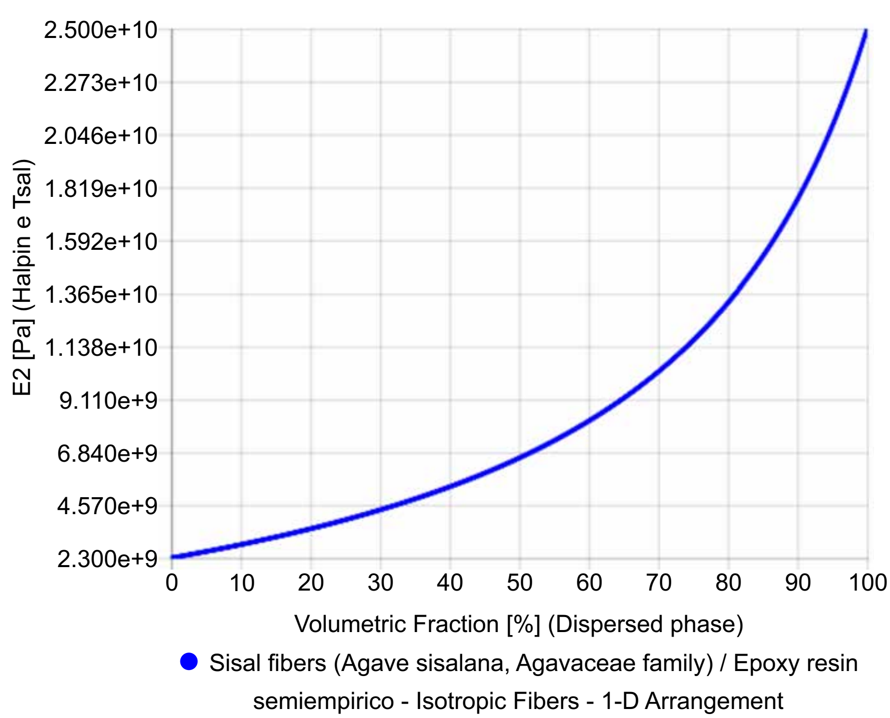


Table 3 illustrates the utilization of fiber percentages in the test specimens, while Table 5 presents the results obtained from all the models analyzed using the finite element method. Notably, tensions and displacements exhibit a decrease with the increase in the number of fibers. This implies that the composite material can withstand greater forces, consequently breaking at higher stresses, aligning with the findings of Snitsky [11].

Furthermore, upon examining the stresses in the resin, it becomes evident that the augmentation of fibers in the composite leads to a reduction in resin stresses. This phenomenon enables the resin to endure more significant loads and fail at higher stresses. These outcomes bear a resemblance to those observed in the experimental section.

Table 6 presents the results from the tensile tests, showcasing that the augmentation of fiber content in the composites escalates the tensile effort.This increase in tensile strength is particularly notable in composites reinforced with sisal fibers.

Conclusion

Based on the results of this work, increasing the amount of sisal fibers in epoxy resin matrix composites increased the composite's tensile strength.

This increase in resistance was more noticeable when more significant volumetric fractions were used (Figures 6 and 7).

The longitudinal modulus of elasticity (E1) and the transverse modulus of elasticity (E2) yielded a Pearson correlation coefficient of 0.984461315 compared to the experimental results cited in the literature. This indicates a robust correlation between the variables, with results exceeding 0.90. The computational simulation results align closely with the experimental findings referenced in the bibliography. Hence, it can be confidently asserted that the Finite Element Method is a reliable tool for analyzing composite materials containing plant fibers.

Table 5. Numerical results of each proof body.

Model	Stress max.by von Mises (MPa)	Stressmainmax. (MPa)	Deformation (.10−3)
TP1	108.6	108.6	50.38
TP2	163.6	139.4	8.199
TP3	152.8	131.1	5.190
TP4	147.6	125.2	3.884

Table 6. Results of experimental tests.

Model	Stress Effort (MPa)	Modulus of Elasticity E1 (GPa)
TP1	44.6	2.3
TP2	118.8±8.69	6.2±0.55
TP3	211.4±11.30	11.2±0.48
TP4	251.8±18.98	13.8±0.96

Adapted from Snitsky [11].

Figure 6. Effect of the amount of sisal fibers in the composite in epoxy resin matrix.

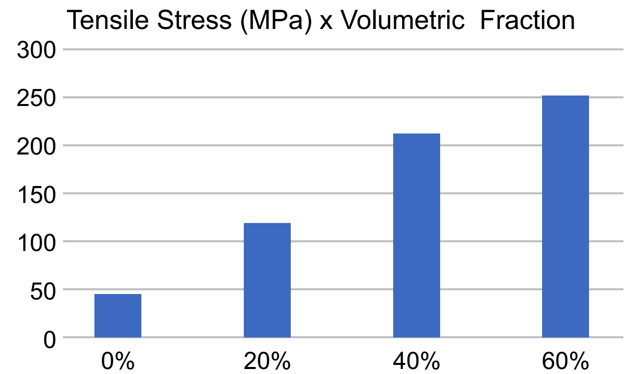
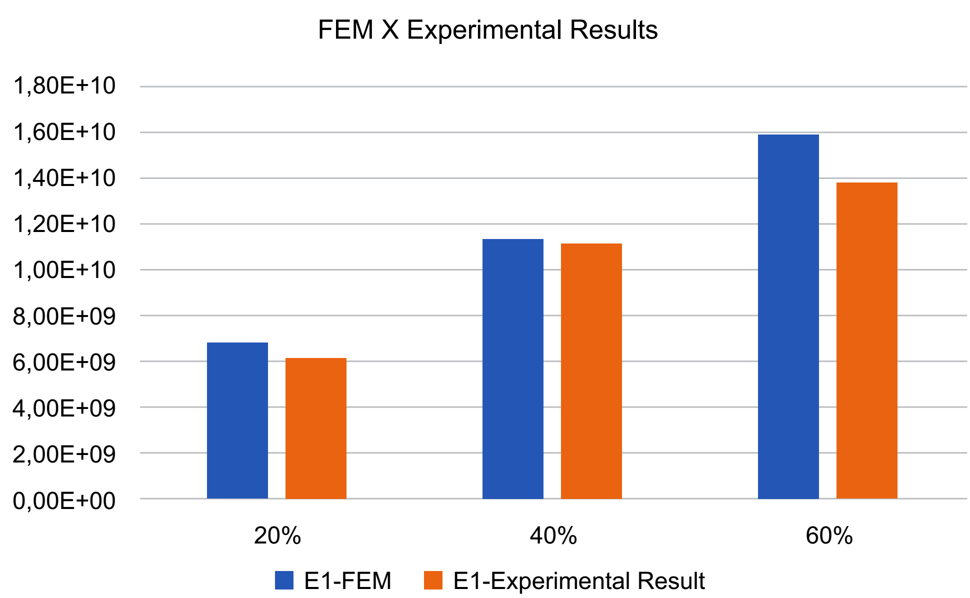


Figure 7. Effect of the amount of sisal fibers in the composite in epoxy resin matrix.



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